



# Eocene carbonate microfacies distribution of the Chorgali Formation, Gali Jagir, Khair-e-Murat Range, Potwar Plateau, Pakistan: approach of reservoir potential using outcrop analogue

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## Abstract

A detailed study on the microfacies and depositional setting in the context of reservoir assessment of the Eocene Chorgali Formation exposed in the Khair-e-Murat Range, Pakistan, has been conducted. The investigation is based on carbonate rock samples collected from two stratigraphic sections. Five microfacies are identified including (1) non-laminated mudstone, (2) algal laminated mudstone, (3) dolomitized mudstone, (4) wackestone, and (5) siliciclastic mudstone. The Chorgali Formation was deposited in a predominantly tidal environment. The vertical distribution of the facies shows cyclicity that affects reservoir characteristics. All three genetic porosity types (i.e., depositional, diagenetic, and fracture porosity) are observed. The primary porosity types include fenestral and intracrystalline/intraparticle porosity (modified and enhanced by diagenesis, i.e., dissolution), while the secondary pore types identified are intercrystalline, moldic, vuggy, and fracture porosity. The vuggy and fracture porosities are the dominant secondary porosities disclosing that diagenesis and fracturing played a vital role in the development of porosity of the Chorgali Formation.

**Keywords** Microfacies · Reservoir · Chorgali Formation · Khair-e-Murat Range · Pakistan

## Introduction

The present study area (part of Khair-e-Murat Range) belongs to the Northern Potwar Deformed Zone (NPDZ), Potwar Plateau, Pakistan. It belongs to toposheet no. 43-C/11 of Survey of Pakistan. The Potwar Plateau is the former oil-producing province of Pakistan where the introductory profitable discovery was made at Khaur in 1914 (Kadri 1995). The major source of hydrocarbon in the Potwar Plateau is the Paleocene-Eocene carbonate rocks. In the Salt Range and Potwar Plateau, the Eocene stratigraphic sequence is deposit-

ed by the prevailing open marine platform conditions including the Nammal Formation, Sakesar Limestone, Chorgali Formation, and Margalla Hill Limestone respectively (Gee 1989; Shah 2009). The Eocene Chorgali Formation is a distinctive stratigraphic unit identifiable over a wide area of the Upper Indus Basin, Pakistan. It is the most pronounced lithologic unit of Eocene carbonates in the Cenozoic strata of the Khair-e-Murat Range (KMR), Potwar Plateau, Kala-Chitta Range (KCR), Salt Range, and Hazara area (Kazmi and Rana 1982; Khan et al. 1986; Jurgan and Abbas 1991; Fig. 1a). The Chorgali Formation is named after its type locality at the Chorgali Pass Section, KMR, Punjab, Pakistan. At the type locality, the formation is divided into two units. The lower unit is composed of dolomite with interbedded shale while the upper unit consists of limestone and interbedded shale (Kazmi and Abbasi 2008). According to Wells (1984), there are five main facies within the Chorgali Formation of KMR, i.e., marl, miliolid-ostracodal micrites, shale, unfossiliferous marly to dolomitic siltstones with possible algal beds, and nummulitic limestone. The facies depicts a single regression late in the Early Eocene that left the land dry during the Middle Eocene (Wells 1984). In the Salt Range, the formation consists of two units. The lower part is composed of shale and

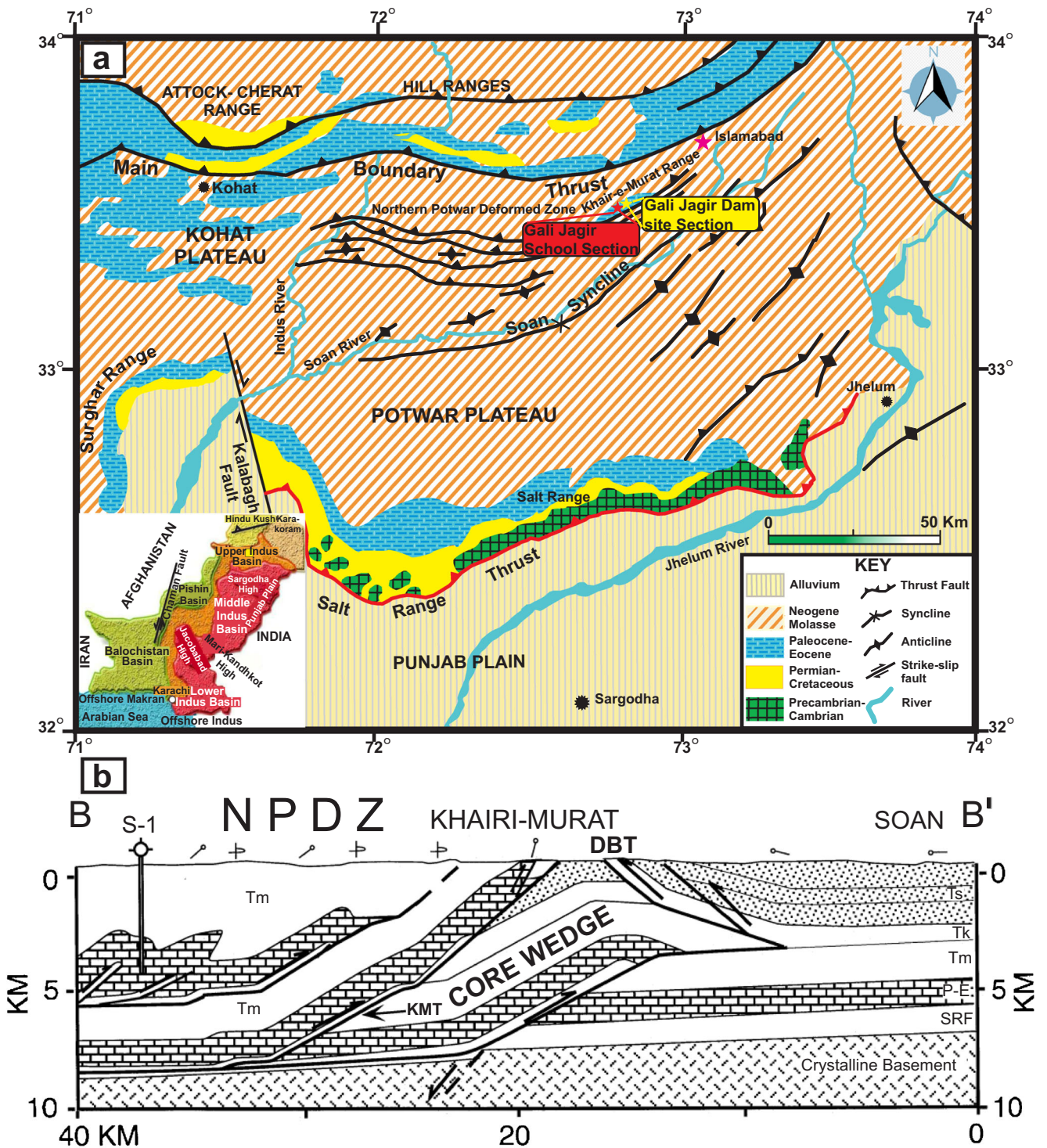
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**Fig. 1** Geological map of Upper Indus Basin and cross-section of North Potwar Plateau. a Tectonic division of Kohat-Potwar plateaus (from Kazmi and Rana 1982; Khan et al. 1986). The studied outcrop sections are marked by red (Gali Jagir School Section) and yellow (Gali Jagir Dam site Section) stars. In the lower left corner, Pakistan map with yellow box showing the study area. b Cross-section along traverse line BB' (Fig. 2 of

Jadoon et al. 1999). KMT, Khair-e-Murat Thrust; NPZ, Northern Potwar Deformed Zone; DBT, Dhumal Back Thrust; S-1, Saddal-1 well; SRF, Salt Range Formation; P-E, Permian to Eocene; Tm, Tertiary Murree Formation; Tk, Tertiary Kamlial Formation; Ts, Tertiary Siwalik Group and Potwar Silt (Jadoon et al. 1999)

limestone. The upper portion is dominated by limestone (Kazmi and Abbasi 2008; Shah 2009). In the KCR, the

formation is composed of limestone with subordinate marl (Kazmi and Abbasi 2008).

The present research involves the investigation of the Chorgali Formation exposed in the KMR, NPDZ, Pakistan (Fig. 1). Different researches have been conducted based on biostratigraphy, sedimentology, microfacies analysis, diagenesis, petrophysical and fracture analysis and petroleum system potential of the Chorgali Formation (Benchilla et al. 2002; Jadoon et al. 2007; Ghazi et al. 2010; Rafiq 2013; Sameeni et al. 2013; Ghazi et al. 2014; Awais 2015; Awais et al. 2015; Jamal et al. 2015; Mehmood et al. 2015; Awais et al. 2016a, b; Shah and Abdullah 2016; Khan et al. 2017; Mehmood et al. 2018; Awais et al. 2019, 2020). Benchilla et al. (2002) did research work on sedimentology and diagenesis of the Chorgali Formation in the Potwar Plateau and Salt Range. Ghazi et al. (2010) interpreted that the Chorgali Formation has been deposited in inner shelf depositional settings based on shallow water Larger Benthic Foraminifera (*Alveolina* sp., *Assilina* sp., *Lockhartia* sp., and *Nummulites* sp.). On the basis of modern shallow benthic biozones (SBZ-9), Upper Ilerdian (i.e., Early Eocene) age has been assigned to the Chorgali Formation (Sameeni et al. 2013). The Chorgali Formation has been studied in the context of microfacies and depositional setting in the Central Salt Range at Khajula, Tatal, Badshah-Pur, and Karuli sections (Ghazi et al. 2014). The interpreted microfacies include bioclastic mudstone, bioclastic wackestone, bioclastic packstone, and bioclastic grainstone (Ghazi et al. 2014). Jamal et al. (2015) and Khan et al. (2017) interpreted different microfacies within the Chorgali Formation such as bioclastic wacke-packstone, larger foraminiferal wacke-packstone, mixed bioclastic wacke-packstone, and mud-wackestone. Jamal et al. (2015) interpreted the depositional environment to be a low-energy carbonate shelf; however, Khan et al. (2017) interpreted the depositional settings to be a low-energy, distally steepened ramp.

The Eocene Chorgali Formation is one of the most important Eocene rocks with hydrocarbon potential in the Potwar Plateau (Kadri 1995). It is a producing reservoir rock in different hydrocarbon fields of Potwar Plateau such as Balkassar, Chak Naurang, Dakhni, Dhulian, Dhurnal, Fimkassar, Joya Mair, Meyal, and Turkwal (Kadri 1995; Khan and Hasany 1998; Jadoon et al. 2003; Hasany and Saleem 2012). The hydrocarbon saturation values in the Chorgali Formation penetrated in Fimkassar-01 and 02 (Fimkassar Oil Field) and Turkwal deep-01 (Turkwal Oil Field) wells are 66%, 71%, and 0% (Rafiq 2013). In the Meyal Oil Field, the Chorgali Formation has 16.51% average porosity, 85.94 mD permeability, 58.73% hydrocarbon saturation, and 41.27% water saturation (Mehmood et al. 2015). According to Shah and Abdullah (2016), the Chorgali Formation of the Balkassar Oil Field (Balkassar well 7) contains average to good reservoir capability having 21.1% average porosity, 66.5% hydrocarbons saturation,

and 33.5% water saturation. In Minwal X-01 well (Joya Mair Oil Field), the Chorgali Formation has fair to good hydrocarbon saturation (Mehmood et al. 2018).

In the Potwar Plateau, the carbonate reservoirs are recorded to have almost 3.5% secondary porosity in Eocene Chorgali/Sakesar limestone (Jadoon et al. 2002; Shami and Baig 2002). The petrographic studies of the Chorgali Formation of Potwar Plateau show the presence of secondary moldic, intercrystalline, and fracture porosity. Similarly, the greater porosity values in the Chorgali Formation (i.e., 28%) may largely show secondary diagenetic and fracture porosity in the Potwar Plateau (Jurgan et al. 1988). According to Jadoon et al. (2006), the Chorgali Formation has 1–3.5% (low/non-matrix) porosity and can be considered as Nelson (1981) type 1 reservoirs, in which fractures lead to essential porosity and permeability. In the Fimkassar Oil Field, the Chorgali Formation is a tight reservoir with 0–0.3 mD matrix permeability on the basis of core analysis and 3500–4200 mD fracture permeability calculated by well test analysis (Jadoon et al. 2006). In the core samples of the Fimkassar Oil Field, the Chorgali Formation contains 6.5% porosity and 5 mD average permeability (Jadoon et al. 2002; Shami and Baig 2002).

The Chorgali Formation is underlain by potential and proven hydrocarbon source rocks, i.e., Nammal shales and Patala shales in the Potwar Plateau and Salt Range (Kadri 1995). Likewise, it is overlain by potential and proven seal rocks, i.e., clays of Kuldana and Murree formations (Akhter et al. 2010). Therefore, the present study has taken into consideration the distribution of carbonate microfacies and related reservoir characteristics on the basis of field and petrographic studies of the Eocene Chorgali Formation. This study is aimed to evaluate reservoir characteristics in relation to carbonate microfacies. This work can be useful in the development of the Chorgali Formation as a hydrocarbon reservoir in the future.

## General geology

The Potwar Plateau is a part of the north-west Himalayan fold and thrust belt, Pakistan. The northern and southern boundaries of the Potwar Plateau are marked by the Main Boundary Thrust (MBT) and Salt Range Thrust (SRT), while the eastern and western boundaries are marked by left lateral Jhelum and right lateral Kalabagh faults respectively (Kazmi and Jan 1997; Fig. 1a). NPDZ consists of east-west striking geological structures (Kazmi and Jan 1997). The NPDZ is extremely folded and faulted having Miocene and older rocks. In the Potwar Plateau, the main hydrocarbon-producing fields are situated in the eastern and northern portions. This exemplifies the presence of structural traps developed by tectonic stresses (Kazmi and Jan 1997). The main structural features in the area are MBT, Khair-e-Murat Thrust (KMT), Dhurnal Back Thrust



(DBT), Triangle Zone, Khair-e-Murat Anticline, and Soan Syncline (Jaswal 1999; Fig. 1). The KMR is a part of southern NPDZ and demonstrates thin-skinned deformation (Jaswal et al. 1997; Fig. 1). The KMR is positioned in the north-eastern portion of the Potwar Plateau (Kamran and Siddiqi 2011; Fig. 1). KMR came into existence by tectonic uplifting along south-verging KMT (Jaswal et al. 1997). KMT connects the Eocene succession of KMR to the Siwaliks in the south. In the KMR footwall further to the South, Siwaliks are thrust over by a north-facing Dhurnal Fault. A triangle zone has been formed between KMT and Dhurnal Fault (Jaswal et al. 1997; Jaswal 1999; Jadoon et al. 2008; Fig. 1b). According to Kamran and Siddiqi (2011), the main folds of KMR are striking in the northeast to southwest direction. An anticline called Khair-e-Murat Anticline is the main fold in the area. Margalla Hill Limestone occupies the core of anticline; Chorgali, Kuldana, and Murree formations rest in the northern limb of anticline, while the southern limb is faulted by KMT (Jadoon et al. 1997).

The Potwar Plateau is composed of platform rocks of Cambrian to Eocene age underlain by Precambrian evaporites and overlain by Miocene-Pliocene molasses (Moghal et al. 2007). The surface outcrop stratigraphy of KMR is composed of Eocene Margalla Hill Limestone, Chorgali Formation, Kuldana Formation, and Miocene Rawalpindi Group and Siwaliks (Kazmi and Abbasi 2008; Awais et al. 2020). However, in the subsurface (borehole data of Dhurnal Oil Field and Khudadad-01 well), KMR is composed of Eocambrian to Pleistocene succession (Jaswal et al. 1997). These rocks have been folded and faulted due to Tertiary Indian and Eurasian plates collision (Kazmi and Jan 1997; Kamran and Siddiqi 2011).

The Eocene period marks the deposition of sedimentation in response to the transgression of the sea throughout the Indus Basin (Shah 2009). During Early Eocene, open marine platform conditions prevailed and deposited thick carbonate successions exposed today in the Salt Range, Trans-Indus ranges, Potwar Plateau, KCR, and Hazara area (Kazmi and Abbasi 2008). The Chorgali Formation is a part of the Chharat Group which is widely distributed in Kohat-Potwar plateaus and Hazara area. Eocene (Early to Middle) age has been assigned to the Chharat Group based on foraminifera and molluscs. The Chharat Group consists of Bahadur Khel Salt, Chorgali Formation, Gurguri Sandstone, Jatta Gypsum, Kohat Formation, Kuldana Formation, Margalla Hill Limestone, Nammal Formation, Panoba Shale, Sakesar Limestone, and Shekhan Formation (Shah 2009). In the Kohat Plateau, the group consists of Bahadur Khel Salt, Jatta Gypsum, Kohat Formation, Kuldana Formation, Panoba Shale, and Shekhan Formation. In northern Potwar Plateau (eastern part of Kohat Plateau), Hazara area, and KCR, the group contains the Chorgali Formation, Kohat Formation, and Margalla Hill Limestone. In the southern Potwar Plateau, Salt Range, and

Trans-Indus ranges, the group is composed of the Chorgali Formation, Kuldana Formation, Nammal Formation, and Sakesar Limestone. The Chharat Group has lower conformable and upper unconformable contacts with Patala Formation and Rawalpindi Group respectively (Shah 2009). In the Salt Range and southern Potwar Plateau, the Chorgali Formation has lower conformable contact with Sakesar Limestone, while in northern Potwar Plateau, Hazara area, and KCR, it has conformable lower contact with the Margalla Hill Limestone. Likewise, in the Salt Range and southern Potwar Plateau, it has unconformable upper contact with the Murree Formation, while in northern Potwar Plateau and KCR, it has conformable upper contact with the Kuldana Formation (Shah 2009; Sameeni et al. 2013)

## Materials and methods

The study area consists of two stratigraphic sections including Gali Jagir School Section (latitude-longitude, 33° 25' 55" N - 72° 38' 07" E) and Gali Jagir Dam site Section (latitude-longitude, 33° 25' 55.5" N - 72° 41' 01.5" E) (Fig. 1a). The stratigraphic logs of the Chorgali Formation for two sections were constructed (Figs. 2 and 3). Only representative fourteen (14) carbonate intervals were sampled, and blue-dyed thin sections were prepared. The thin sections were treated with alizarin red solution, prepared by following the methods of Evamy (1963) and Dickson (1965), i.e., a beaker containing 100 ml distilled water is modified by adding 1.5 ml concentrated HCL. 0.1 gram alizarin red powder is put into the beaker and is allowed to be dissolved, and then the alizarin red solution is ready. This study employed a couple of approaches such as microscopic porosity using a polarizing microscope and scanning electron microscopy (SEM) to study the reservoir aspect of the Chorgali Formation. The microfacies were identified based on the classification proposed by Dunham (1962), Folk (1959), and Wilson (1975).

## Results and discussion

During the geological field for this research work, the five main facies earlier noted by Wells (1984) at the KMR are identified and confirmed but there is a contrast between the thicknesses of the units given by Wells (1984) and observed in this study. The thicknesses of lower nummulitic limestone, dolomite, and shale are 10.7 meter (m), 29.5 m, and 4.2 m respectively. It is then overlain by 1m micrite and 17.1m marl, but the marl unit also contains shale. The whole sequence is

**Fig. 2** Lithological log and vertical distribution of microfacies of the Chorgali Formation in the Gali Jagir School Section, KMR

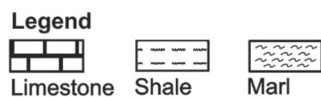
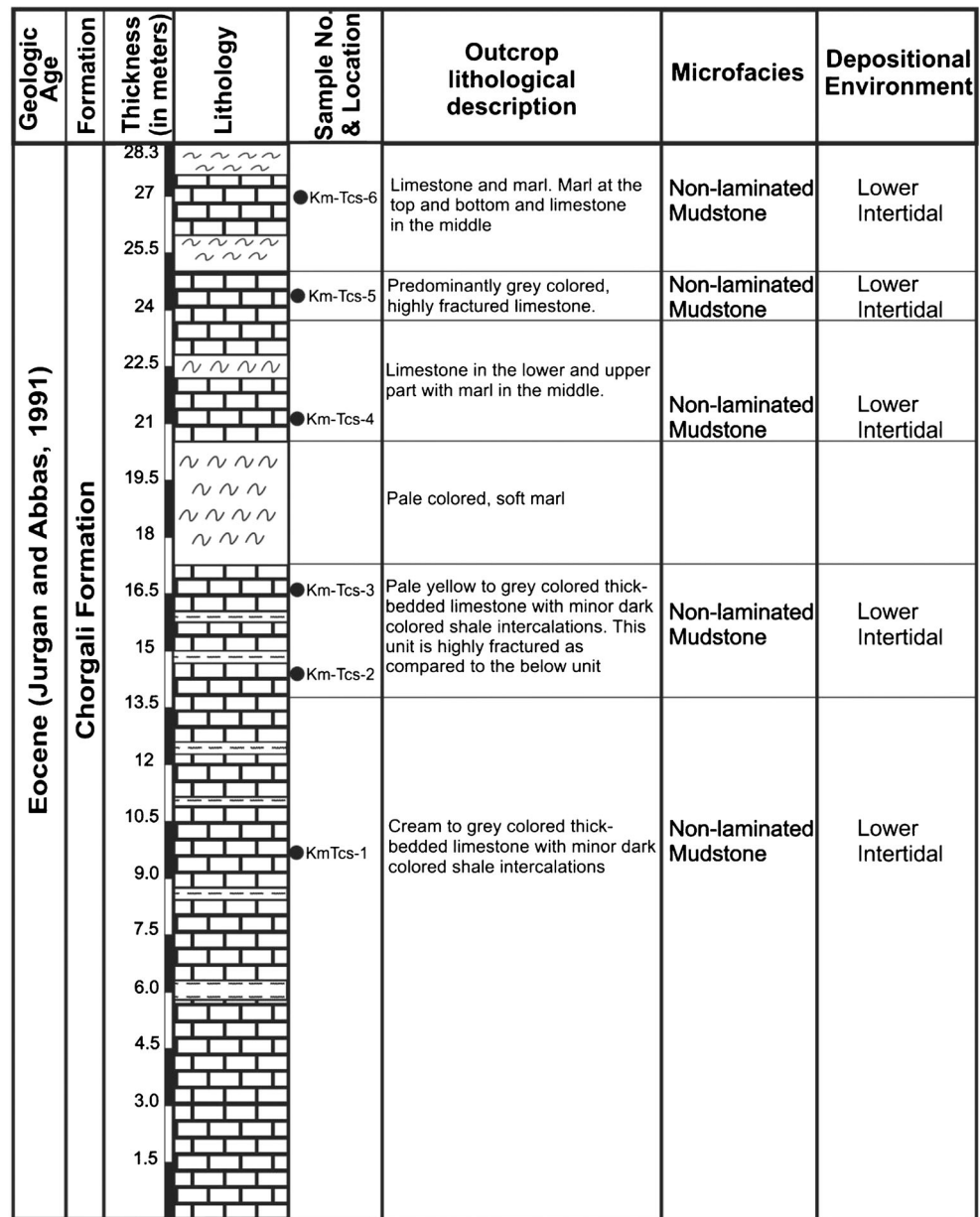
Geological Age	Formation	Thickness (in meters)	Lithology	Sample No. & Location	Outcrop lithological description	Microfacies	Depositional Environments	
Eocene (Jurgan and Abbas, 1991)	Chorgali Formation	62.5	~ ~ ~ ~	● Km-Tc-8	Pale yellow to yellowish brown colored marl	Siliciclastic Mudstone	Upper Supratidal	
		61.6						
		58.8						
		56						
		53.2	~ ~ ~ ~		Marl			
		50.4	-----		Shale			
		47.6	~ ~ ~ ~		Marl			
		44.8	▣ ▣ ▣ ▣	● Km-Tc-7	Red brown colored limestone	Wackestone	Subtidal	
		42	-----		Dominantly greenish-yellowish green shale			
		39.2	▧ ▧ ▧ ▧		Shale and dolomite interbeds. Shale at lower part and dolomite in the upper part			
		36.4	▧ ▧ ▧ ▧					
		33.6	▧ ▧ ▧ ▧					
		30.8	~ ~ ~ ~	● Km-Tc-6	Dominantly greenish-grey marl unit but dolomite is present in the lower and upper parts	Siliciclastic Mudstone	Upper Supratidal	
28	~ ~ ~ ~							
25.2	▧ ▧ ▧ ▧							
22.4	▧ ▧ ▧ ▧	● Km-Tc-5	Cream colored thin to thick bedded dolomite with minor shale intercalations	Dolomitized Mudstone	Supratidal			
19.6	▧ ▧ ▧ ▧							
16.8	▧ ▧ ▧ ▧	● Km-Tc-4	Cream colored dolomite with dark colored shale intercalations	Non-laminated Mudstone	Lower Intertidal			
14	▧ ▧ ▧ ▧	● Km-Tc-3						
11.2	▧ ▧ ▧ ▧	● Km-Tc-2	Algal mats and gypsum are present in dolomitic unit	Algal laminated Mudstone	Upper Intertidal-Lower Supratidal			
8.4	▧ ▧ ▧ ▧							
5.6	▧ ▧ ▧ ▧	● Km-Tc-1	Cream to greyish white limestone with intercalations of dark colored shale. The limestone is highly fractured	Non-laminated Mudstone	Lower Intertidal			
2.8	▧ ▧ ▧ ▧							

**Legend**

- ▣ ▣ ▣ ▣  
Limestone
- ▧ ▧ ▧ ▧  
Dolomite
- Shale
- ~ ~ ~ ~  
Marl
- ▧ ▧ ▧ ▧  
Algal mats
- ▧ ▧ ▧ ▧  
Gypsum
- ▧ ▧ ▧ ▧  
Interval not sampled

Km-Tc short for "Khair-e-Murat/Tertiary Chorgali Formation".

**Fig. 3** Lithological log and vertical distribution of microfacies of the Chorgali Formation in the Gali Jagir Dam site Section, KMR



Km-Tcs short for "Khair-e-Murat/Tertiary Chorgali Formation second section".

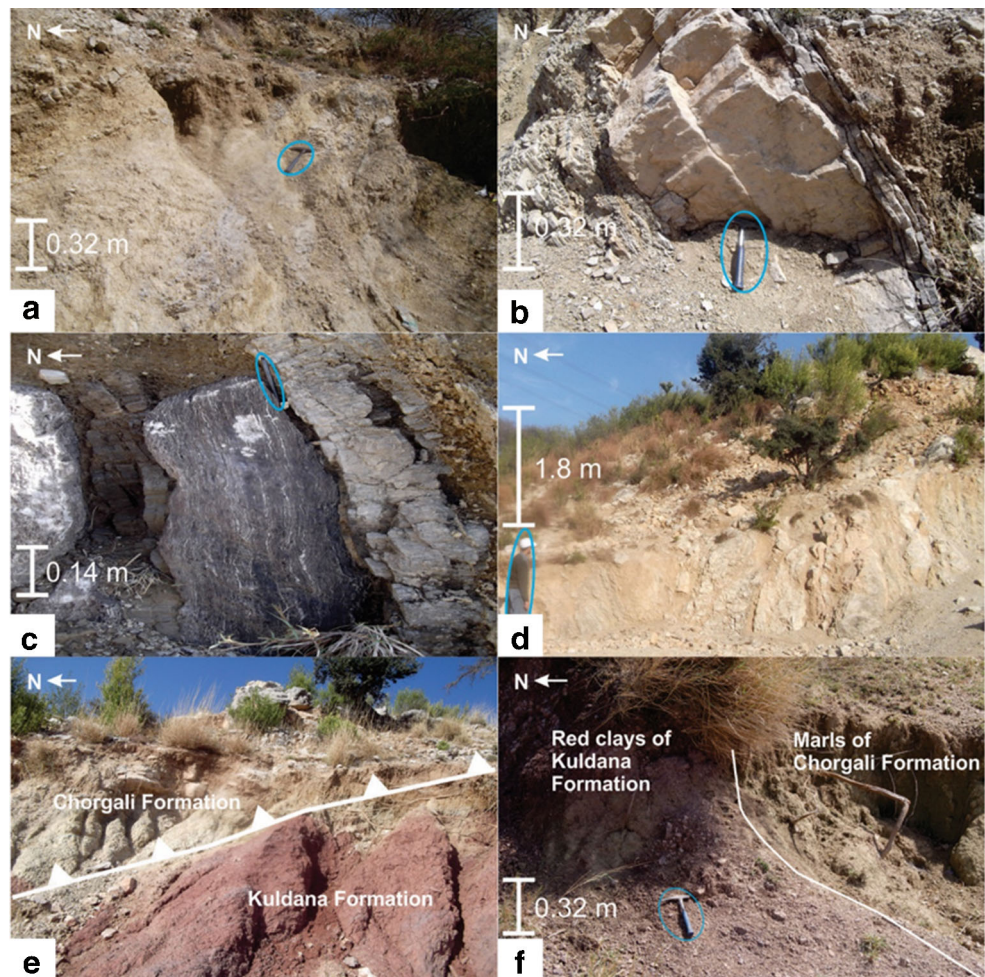
not that clean as mentioned by Wells (1984) because there are regular shale intercalations throughout the formation (Fig. 2).

In the Gali Jagir School Section, the Chorgali Formation consists of limestone, dolomite, shale, and marl units from bottom to top (Fig. 2). There are regular shale intercalations in the limestone unit. The limestone is highly deformed (Fig. 4a). This limestone is overlain by dolomite which consists of regular grey to greenish shale intercalations (Fig. 4b). The dark-colored algal mats and white gypsum are present within this unit (Fig. 4c). The dolomitic unit is thin- to thick-bedded

and yellowish to whitish grey in color and is devoid of fossils. Similarly, the Chorgali Formation consists of thick-bedded limestone, marl, and shale intercalations in the Gali Jagir Dam site Section (Figs. 3 and 4d). The lower contact is faulted with the Kuldana Formation in both the Gali Jagir School Section and Gali Jagir Dam site Section (Fig. 4e). At the Gali Jagir School Section, the upper contact is conformable with the Kuldana Formation, while at Gali Jagir Dam site Section, this contact is either not exposed or covered (Fig. 4f). The measured estimated thicknesses of the Chorgali



**Fig. 4** Field photographs of the Chorgali Formation. a The lower limestone unit of the Gali Jagir School Section, camera facing east-north-east. b Dolomitic unit of the Chorgali Formation at Gali Jagir School Section, camera facing east-north-east. c Algal mats and gypsum in dolomitic unit of the Chorgali Formation, Gali Jagir School Section, camera facing east-north-east. d Chorgali Formation at Gali Jagir Dam site Section, camera facing due east. e Faulted contact of Chorgali and Kuldana formations, Gali Jagir Dam site Section (camera facing northeast, not to scale). f Conformable contact of Chorgali and Kuldana formations in Gali Jagir School Section, camera facing due east



Formation at the Gali Jagir School Section and Gali Jagir Dam site Section are  $\sim 62.5$  m and  $\sim 28.3$  m respectively (Figs. 2 and 3).

### Microfacies of the Chorgali Formation

The following five microfacies have been recognized in the Chorgali Formation:

#### Non-laminated mudstone

This microfacies is characterized by mudstone depositional texture. It is represented by samples Km-Tc-(1, 3, and 4) in the Gali Jagir School Section and samples Km-Tcs-(1, 2, 3, 4, 5, and 6) in the Gali Jagir Dam site Section (Figs. 2 and 3). The micrite is ranging from 30 to 95% with an average of 81.6%, the allochems are ranging from 2 to 28% with an average of 2.4%, and the spar varies from 0 to 21% with an average of 13.5%. Under the polarizing microscope, the visual porosity is ranging from 0 to 8% with an average of 2.5%. The microfacies is named as non-laminated mudstone because it is predominantly composed of micrite having no laminations

and the allochems are less than 10% (Fig. 5a). The allochems include forams (miliolid, uniserial, biserial), algae, and bioclastic debris. Primary sedimentary fabrics such as burrows are also observed (Fig. 5b; Table 1). This microfacies is named mudstone and micrite following the classifications of Dunham (1962) and Folk (1959) respectively.

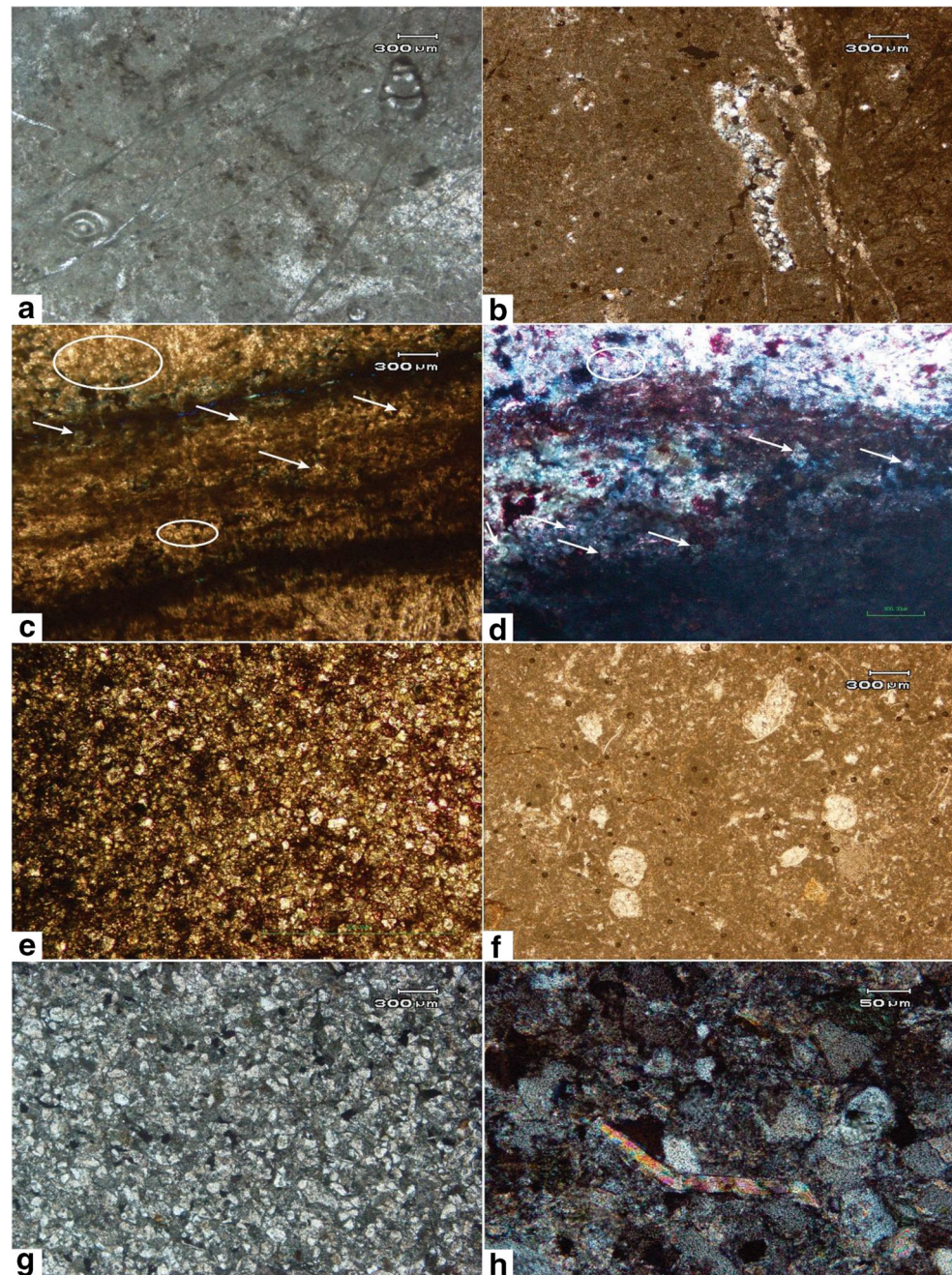
The microfacies represent deposition in the lower intertidal zone. The laminations usually do not survive in the lower intertidal zone (Flügel 2010). On the basis of the absence of diagnostic marine fossils (few allochems present seem to be transported), laminations, and presence of burrow(s), the microfacies is interpreted to be deposited in lower intertidal settings (Flügel 2010; Fig. 6). This microfacies is equivalent to standard microfacies (SMF) 23 of Wilson (1975), i.e., non-laminated homogeneous micrite without fossils.

#### Algal laminated mudstone

This microfacies is also characterized by mudstone depositional texture. It is represented by sample Km-Tc-2 in the Gali Jagir School Section (Fig. 2). The micrite varies from 32 to 70% with an average of 59.5%, and this microfacies



**Fig. 5** Photomicrographs of microfacies of the Chorgali Formation. **a** Non-laminated mudstone, plane polarized light (PPL), sample no. Km-Tc-1. **b** Burrow in non-laminated mudstone-(PPL), sample no. Km-Tc-1. **c** Algal laminated mudstone-(PPL), sample no. Km-Tc-2. **d** Algal laminated mudstone-(PPL and alizarin red stained), sample no. Km-Tc-2. **e** Dolomitized mudstone-(PPL), sample no. Km-Tc-5. **f** Wackestone-(PPL), sample no. Km-Tc-7. **g** Siliciclastic mudstone-(PPL), sample no. Km-Tc-8. **h** Siliciclastic mudstone having (a) muscovite and (b) glauconite, cross polarized light (CPL), sample no. Km-Tc-8. All the thin sections were impregnated with blue-dye-stained resin



lacks allochems. The dolomite ranges from 20 to 60% with an average of 37%. It is present as scattered rhombic crystals. The thin sections were treated with alizarin red staining, and the unstained crystals are identified to be dolomite (Fig. 5c, d). There is also gypsum which is quite prominent on the outcrop scale (Figs. 4c and 5c, d). The visually estimated porosity is ranging from 1 to 7% with an average of 3.5% (Table 1). This microfacies is called as algal laminated mudstone due to the presence and abundance of micrite and algal laminations. It is named algal boundstone and biolithite following the classifications of Dunham (1962) and Folk (1959) respectively.

The algal laminated mudstone is interpreted to form in the upper intertidal and reached up to the overlying lower supratidal zone (Flügel 2010; Fig. 6). This interpretation is based on the absence of marine diagnostic fauna, occurrence of algal mats/laminations, and presence of dolomite and fenestrae. This microfacies is equivalent to SMF 21 fenestral bindstones of Wilson (1975).

#### Dolomitized mudstone

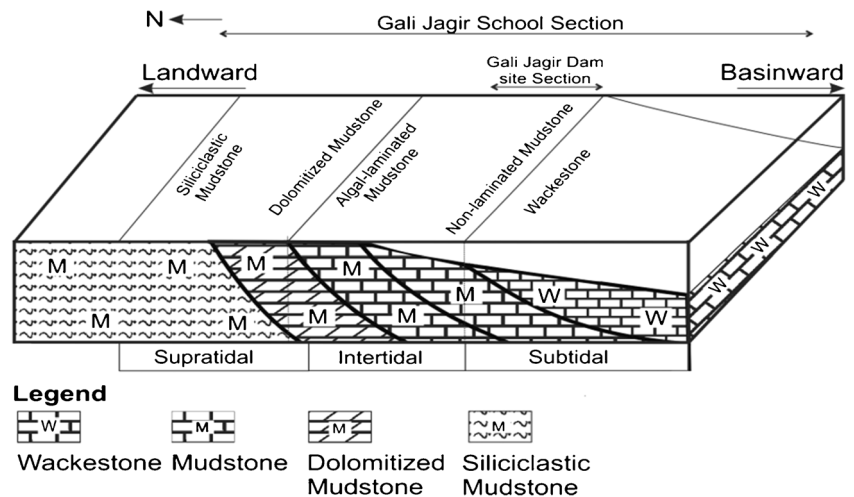
The dolomitized mudstone microfacies is represented by sample Km-Tc-5 in the Gali Jagir School Section (Fig. 2). The



**Table 1** Allochemical-orthochemical, clastic constituents, and porosity types within the Chorgali Formation

Microfacies	Sample code	Allochemical, orthochemical, and clastic constituents	Depositional texture	Sedimentary structures	Facies belt	Porosity types
Siliciclastic mudstone	Km-Tc-8	Algae, micrite, clastics, opaque minerals	Mudstone	-	Upper supratidal	Fracture
	Km-Tc-6	Unidentified allochems, micrite, spar, clastics				Intercrystalline, vuggy
Wackestone	Km-Tc-7	Ostracods, bioclastic debris, micrite, spar	Wackestone	-	Subtidal	Intracrystalline, intercrystalline
Dolomitized mudstone	Km-Tc-5	Micrite, dolomite	Mudstone	-	Supratidal	Fracture, intercrystalline, vuggy
Algal laminated mudstone	Km-Tc-2	Micrite, dolomite, gypsum	Mudstone	Algal laminations and fenestrae	Upper intertidal–lower supratidal	Fenestral, fracture, intercrystalline
Non-laminated mudstone	Km-Tc-4	Forams (miliolids, uniserial, biserial), algae and bioclastic debris, micrite, spar, dolomite (in Km-Tc-1, -3, -4)	Mudstone	Burrows (in Km-Tc-1)	Lower intertidal	Fracture, intercrystalline, moldic, vuggy
	Km-Tc-3					Fracture, intercrystalline, vuggy
	Km-Tc-1					Vuggy
	Km-Tcs-6					Fracture, vuggy
	Km-Tcs-5					Fracture, vuggy
	Km-Tcs-4					Fracture, vuggy
	Km-Tcs-3					Fracture, vuggy
	Km-Tcs-2					Fracture, moldic, vuggy
	Km-Tcs-1					Vuggy

**Fig. 6** A depositional model evincing the interpreted environments of deposition of the Chorgali Formation. The symbols used are copied from Shell Standard Legend (Witt 1995). N for north arrow



main components of the microfacies are micrite and dolomite, and it is also devoid of allochems. The micrite varies from 70 to 85% with an average of 78.5%, and dolomite is ranging from 15 to 30% with an average of 20%. The visual porosity ranges from 0 to 5% with an average of 1.5%. It is named as dolomitized mudstone due to the abundance of micrite and dolomite. Under high resolution, there are well-developed rhombs of dolomite. In addition, the dolomite presence is confirmed by using alizarin red staining (Fig. 5e). The rock is classified as mudstone by Dunham (1962) and as micrite by Folk (1959) (Table 1). Due to the presence of unfossiliferous micrite and dolomite, the dolomitized mudstone is interpreted to be deposited in lower supratidal conditions (Shinn 1983; Fig. 6). This microfacies corresponds to SMF 23 non-laminated unfossiliferous fine-grained dolomicrite of Wilson (1975).

### Wackestone

The wackestone microfacies is represented by sample Km-Tc-7 in the Gali Jagir School Section (Fig. 2). The dominant constituents in this microfacies are allochems and micrite. The allochems are ranging from 12 to 26% with an average of 19.34%, while the micrite is ranging from 70 to 84% with an average of 78.0%. The spar ranges from 2 to 4% with an average of 2.0%. The visual porosity varies from 0 to 4% with an average of 0.66%. It is named as wackestone because it is mud-supported rock and contains > 10% allochems (Table 1). The dominant allochems are ostracods and bioclastic debris (Fig. 5f). This microfacies is named as wackestone and biomicrite following the classifications of Dunham (1962) and Folk (1959) respectively.

On the basis of the presence of micrite, ostracods, and bioclastic debris, the microfacies has been assigned subtidal environment of deposition (Flügel 2010). This is considered to be shallow subtidal because there is no such diversity of fauna, i.e., only ostracods and bioclastic debris are present

(Flügel 2010; Fig. 6). This microfacies is equivalent to SMF 8 whole fossil wackestone of Wilson (1975).

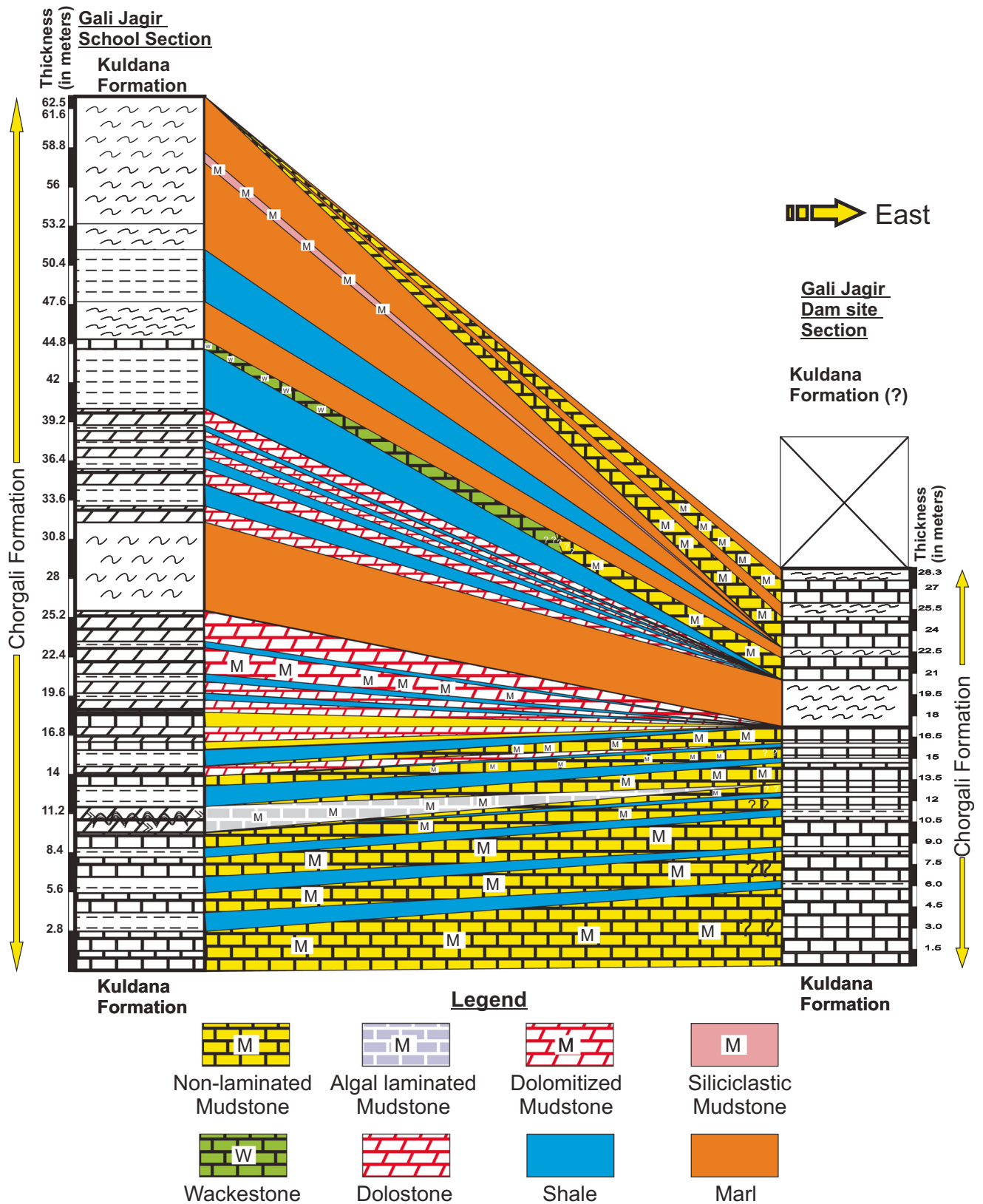
### Siliciclastic mudstone

The siliciclastic mudstone microfacies is represented by samples Km-Tc-6 and Km-Tc-8 in the Gali Jagir School Section (Fig. 3). This microfacies is dominantly composed of clastic silt-sized sediments and micrite. The clastic sediments include quartz, feldspar (very less), and mica group minerals. The quartz is ranging from 29 to 43% with an average of 36.87%, and mica is ranging from 1 to 4% with an average of 1.5%. The allochems are very less and constitute about 4% of the microfacies. The micrite is in the range of 50 to 58% with an average of 52.5%. The visually estimated porosity varies from 0 to 4% with an average of 3.13%. There are also opaque minerals ranging from 3 to 6% with an average of 2% (Fig. 5g, h; Table 1).

The siliciclastic mudstone is predominantly composed of quartz and micrite. The quartz is fine grained and sub-rounded to angular and represents deposition by the wind along the coastal area in the tidal environment(s). This microfacies is a mix of clastic and carbonate sediments, while the clastic sediments dominate (Fig. 5g, h). This microfacies may act as evidence of the regression of the Eocene sea. On the basis of the presence of unfossiliferous micrite and clastic sediments, the siliciclastic mudstone has been assigned upper supratidal environment (Flügel 2010; Fig. 6). This microfacies is not corresponding to any of the SMF type.

It can be concluded that the Chorgali Formation evinces carbonate deposition in shallow marine, reasonably arid climate, and low-energy carbonate platform type of tidal depositional settings (Fig. 6). The Chorgali Formation shows shallowing upward cycles, from intertidal mudstone to supratidal siliciclastic mudstone. This shallowing upward cycle is similar to the modern Persian Gulf sabkha cycle. According to De Matos (1989), the Abu Dhabi coastal area

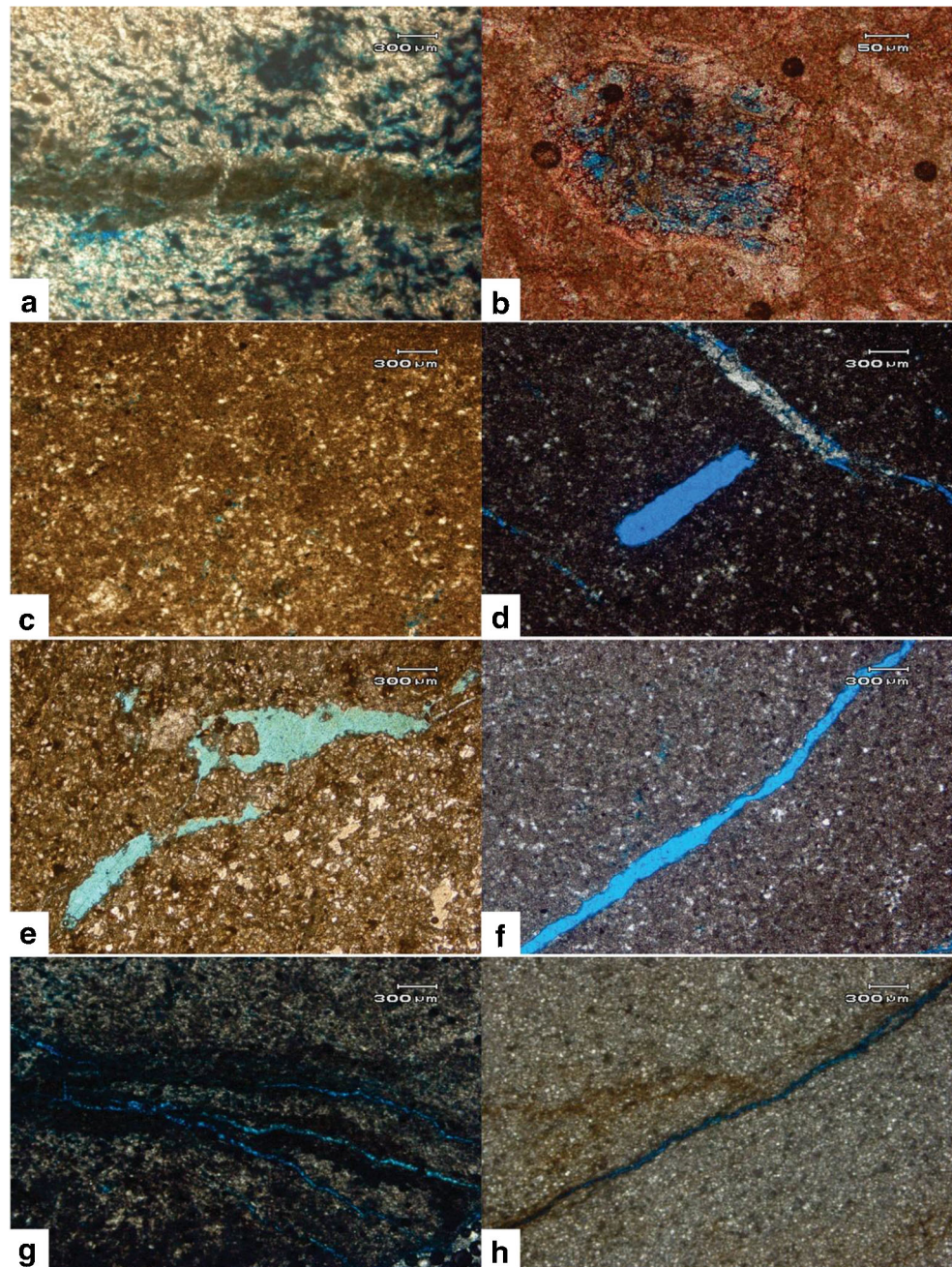




**Fig. 7** Stratigraphic correlation chart of the Chorgali Formation of Gali Jagir School (left) and Gali Jagir Dam site (right) sections, KMR. Cross at the top of Gali Jagir Dam site Section shows covered area. Symbols missing in the figure can be found in Figs. 2 and 3



**Fig. 8** Photomicrographs of different microscopic porosity types of the Chorgali Formation. a Fenestral porosity in algal laminated mudstone, sample no. Km-Tc-2. b Intracrystalline/intraparticle porosity in wackestone, sample no. Km-Tc-7. Alizarin red stained, high magnification  $\times 20$ . c Intercrystalline porosity in dolomitic part of the non-laminated mudstone, sample no. Km-Tc-3. d Moldic porosity in non-laminated mudstone, sample no. Km-Tc-3. e Vuggy porosity in siliciclastic mudstone, sample no. Km-Tc-6. f Fracture porosity in non-laminated mudstone, sample no. Km-Tc-3. g Fracture porosity in algal laminated mudstone, sample no. Km-Tc-2. h Fracture porosity in dolomitized mudstone, sample no. Km-Tc-5. All thin sections are impregnated with blue-dye-stained resin, and all photomicrographs are taken in plane polarized light (PPL)



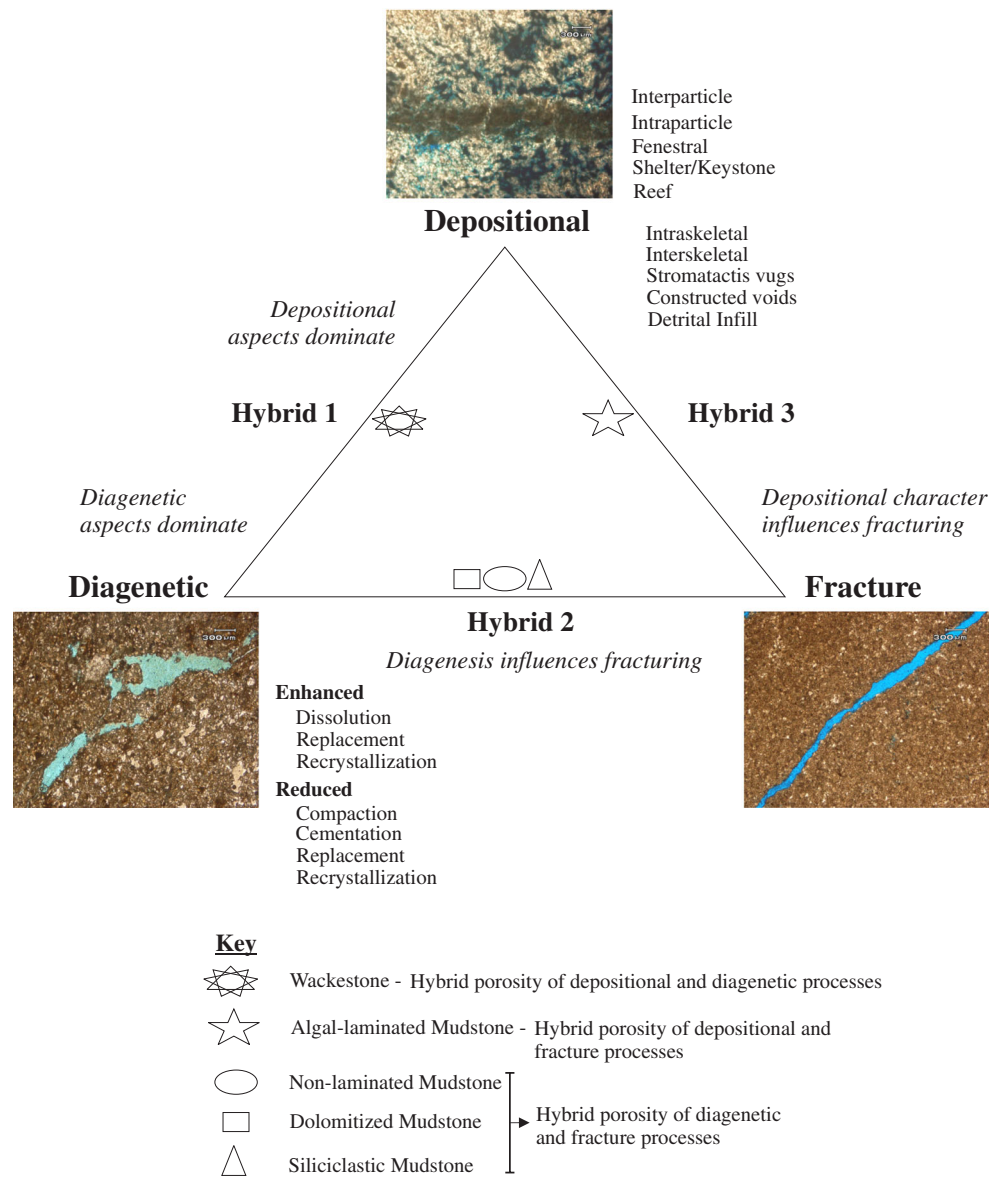
consists of several small shoals, islands, protected lagoons, channels and deltas, an intertidal zone (algal mats are well developed), broad supratidal salt flat zone, and typical sabkha evaporites (gypsum, anhydrite, and dolomite). Such features are very much corresponding in facies to that of the Chorgali Formation.

A stratigraphic correlation chart of both sections of the Chorgali Formation has been constructed to showcase lateral and vertical lithofacies and microfacies variations (Fig. 7). The Chorgali Formation of Gali Jagir School

Section lithofacies are multiple, i.e., limestone, dolostone, shale, marl, algal laminations, and gypsum, while that of Gali Jagir Dam site Section are relatively simple containing limestone, shale, and marls (Figs. 2, 3, and 7). Similarly, Gali Jagir School Section is composed of majority of microfacies of the Chorgali Formation (non-laminated mudstone, algal laminated mudstone, dolomitized mudstone, siliciclastic mudstone, and wackestone) reflecting variations in depositional settings during deposition of the Chorgali Formation in this part of the basin (Figs. 2, 3, and 7). However, Gali



**Fig. 9** A genetic classification for porosity in carbonate rocks (modified after Ahr et al. 2005)



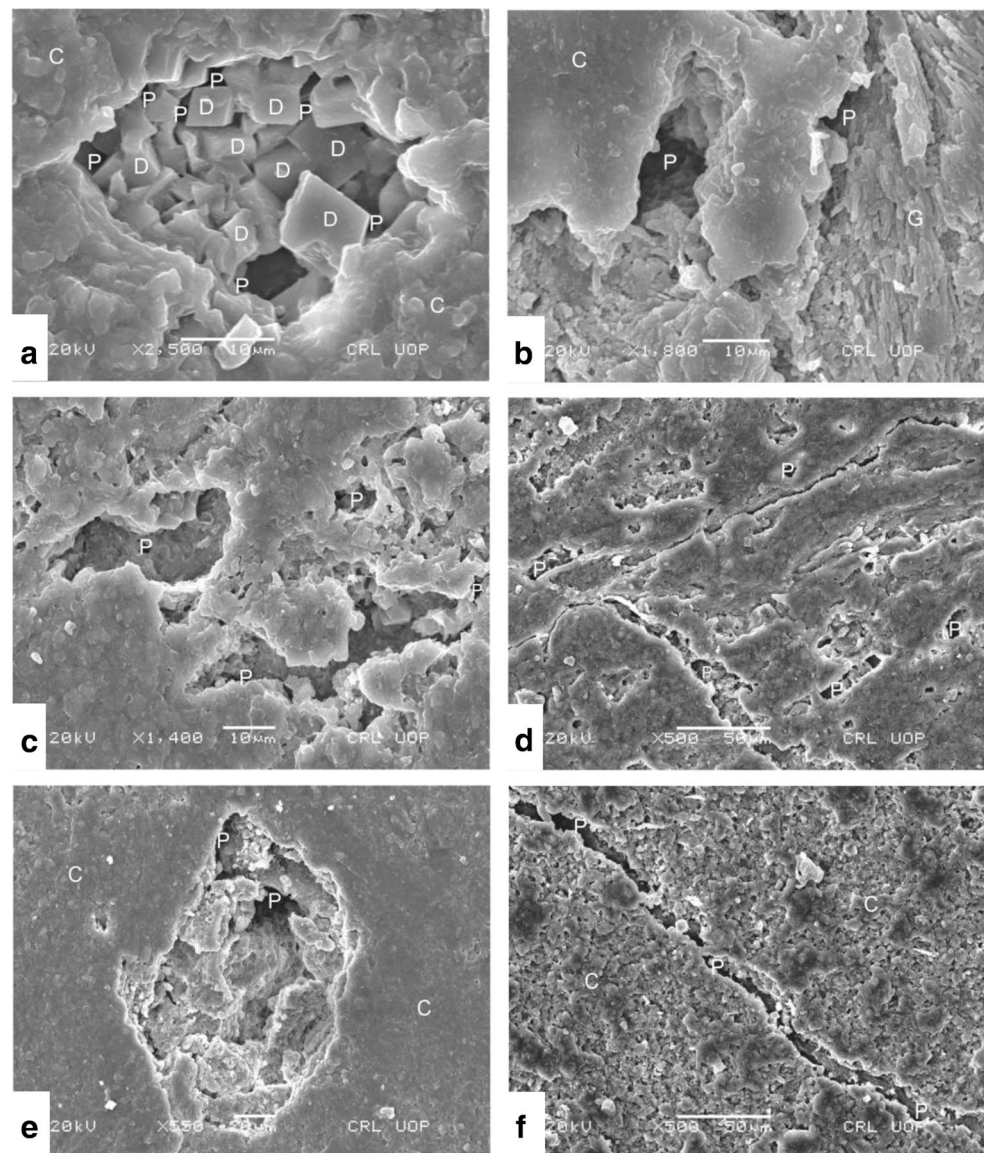
Jagir Dam site Section is comparatively homogenous in the context of microfacies and containing non-laminated mudstone only (Figs. 2, 3, and 7).

**Reservoir characterization**

The reservoir characterization of the Chorgali Formation is conducted in the context of porosity/permeability analysis. The different porosity types are named using Choquette and Pray (1970) Classification. The microscopic porosity is grouped according to microfacies. The fenestral porosity is possessed by the algal laminated mudstone (Fig. 8a). The intracrystalline/intraparticle porosity is present in the wackestone microfacies (Fig. 8b). The intercrystalline

porosity is identified in dolomitized mudstone and non-laminated mudstone (Fig. 8c). The moldic porosity is preserved in the non-laminated mudstone. The moldic porosity is recognized as biomoldic porosity (Fig. 8d). The vuggy porosity is owned by the non-laminated and siliciclastic mudstone respectively. The vugs are usually identified to be separated vugs (Fig. 8e). The fracture porosity is discerned in almost all of the microfacies (Fig. 8f-h). In addition, the classification of carbonate pores by Ahr et al. (2005) is utilized. The non-laminated mudstone, dolomitized mudstone, and siliciclastic mudstone consist of composite pore types of diagenetic and fracture processes, i.e., hybrid 2 pore system. The algal laminated mudstone is composed of porosity developed by depositional and fracture processes, i.e., hybrid 3 pore

**Fig. 10** SEM images of selected samples of the Chorgali Formation. a SEM image of non-laminated mudstone showing dolomite rhombs (D) in a cavity, intercrystalline porosity (P), and calcite (C), sample no. Km-Tc-1. b SEM image of algal laminated mudstone showing porosity (P), calcite (C), and gypsum (G), sample no. Km-Tc-2. c SEM image showing vuggy porosity (P) in siliciclastic mudstone, sample no. Km-Tc-6. d SEM image showing vuggy and fracture porosity (P) in siliciclastic mudstone, sample no. Km-Tc-6. e SEM image showing secondary intracrystalline/intraparticle porosity (P) in wackestone, sample no. Km-Tc-7. f SEM image showing fracture porosity (P) in non-laminated mudstone, sample no. Km-Tcs-6



system. The pore types are a mix of depositional and diagenetic processes in the wackestone, i.e., hybrid 1 pore system (Fig. 9). All the observed porosity types are secondary in origin except fenestral and intracrystalline/intraparticle porosity being primary depositional porosity; however, the intracrystalline/intraparticle porosity seems to be a combo of primary and secondary dissolution porosity (Figs. 8b and 9). It was initially primary; i.e., in Fig. 8b, some vacant chambers can be envisaged but later on, it has been modified and enhanced by diagenesis, i.e., dissolution.

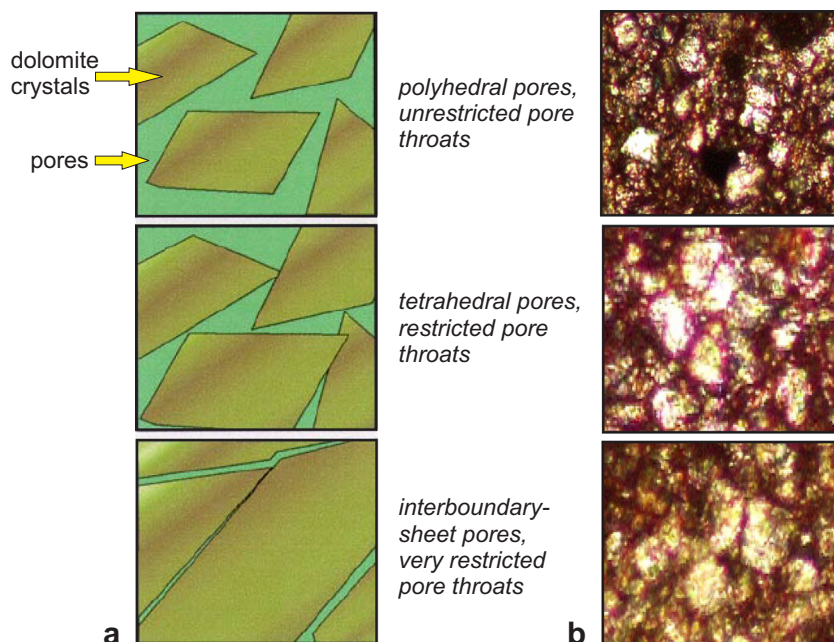
Under SEM, the fracture porosity is dominant in microfacies of the selected samples while the other porosity types include intercrystalline in non-laminated mudstone, secondary (dissolution) intracrystalline/intraparticle in wackestone, and vuggy in siliciclastic mudstone (Fig. 10).

Hence, the Chorgali Formation contains multiple-porosity systems.

As different types of porosities are noted in different microfacies, however, the potential of permeability depends on the interconnectivity of these pores. The presence of fractures and their interconnectivity is a good evidence to support permeability (Figs. 7h and 8f). There is a very less quantity of cement to prevent the hydrocarbon flow. The matrix porosity is less; however, dissolution, dolomitization (very little contributor in this case), and fracturing enhanced the reservoir quality. If there is interconnectivity of fenestral, intercrystalline, intraparticle, moldic, vuggy, and fracture porosity, then the hydrocarbons can very easily move along this path. On the contrary, the separate pore types having no



**Fig. 11** Types of pore throats in dolomites. (a) Intercrystalline pores and pore throats in dolomites (Mazzullo 2004). (b) Intercrystalline pores and pore throats in dolomites of the Chorgali Formation



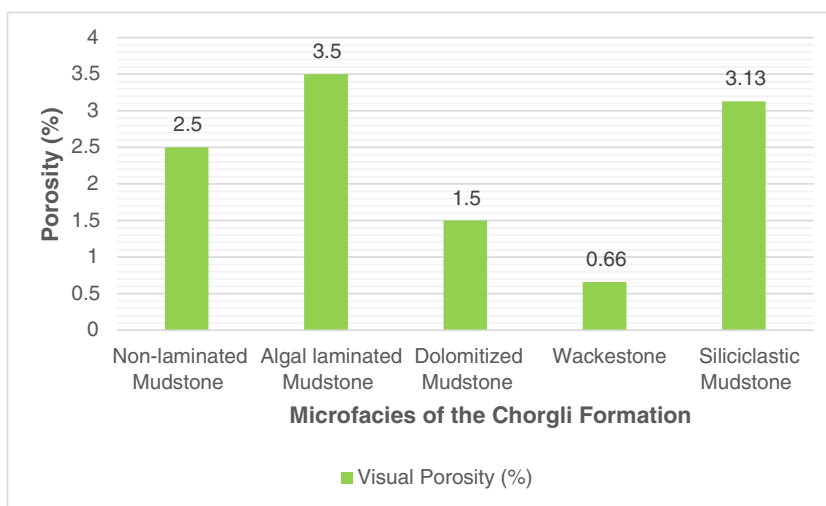
interconnectivity can hold hydrocarbons but it will be of no economic value due to lack of permeability and for a reservoir presence of both porosity and permeability are of utmost importance.

Similar to limestone, the nature of pore throats in dolostone controls permeability and, as a general rule, intercrystalline pore throat sizes reduce with reducing crystal size and degree of dolomitization. According to Mazzullo (2004), there are three types of pore throats in dolomite, i.e., unrestricted pore throats, restricted pore throats, and very restricted pore throats (Fig. 11a). Within the dolomites of the Chorgali Formation, there is dominance of unrestricted pore throats and very limited restricted and very restricted pore throats. However, all of the pore throats are occupied by micrite (Fig. 11b). If the studied sections have been exposed to the subaerial

conditions, then there are chances of dissolution of calcite (micrite) and hence there will be a generation of intercrystalline porosity between the dolomite crystals.

According to the visual estimated microscopic porosity, algal laminated mudstone has the highest porosity and then in descending order followed by siliciclastic mudstone, non-laminated mudstone, dolomitized mudstone, and wackestone (Fig. 12). The algal laminated and siliciclastic mudstone can be reservoir microfacies. In the studied sections, evaporites (gypsum) are present in algal laminated mudstone and can act as a seal, while for siliciclastic mudstone, shales of the Chorgali Formation and clays of overlying Kuldana Formation can act as seal. The non-laminated mudstone can also be good reservoir microfacies if the filled fractures are

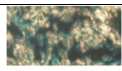

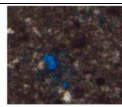
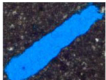
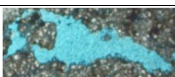
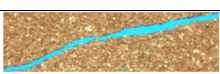
**Fig. 12** Visual estimated microscopic porosity (%) of different microfacies of the Chorgali Formation



reactivated and come in interconnectivity with open fractures and thereby enhancing permeability. The dolomitized mudstone could be a good reservoir if the intercrystalline and fracture porosity are interconnected. Similarly, in dolomitized mudstone, the pore throats are not open but micrite is much in abundance and hence reducing the porosity/permeability. The wackestone microfacies, with the least porosity, is a poor reservoir microfacies and can act as carbonate seal. Hence, such microfacies can help in the development of reservoir compartmentalization within the Chorgali Formation. The Chorgali carbonate units are relatively thick and can be favorable horizons for hydrocarbons. Apart from the carbonate microfacies, there are also regular shale (non-reservoir) intervals which are also a good sign because for a reservoir; seal rock is also a necessity.

### Inferred paragenetic sequence of porosity types

Within the Chorgali carbonates, the different porosity types are developed with the passage of time and diagenesis. The fenestral and intracrystalline/intraparticle porosity are developed earlier in the depositional stage followed by the formation of intercrystalline porosity in hypersaline settings caused by dolomitization. The moldic and vuggy porosity are caused by dissolution as the carbonates are exposed due to regression and or tectonic uplift. At last, fracture porosity is formed (Fig. 13).

Porosity type	Early	Late
Fenestral		
Intracrystalline/intraparticle		
Intercrystalline		
Moldic		
Vuggy		
Fracture		

**Fig. 13** Inferred paragenetic sequence of porosity types (shown in blue color) within the Chorgali carbonates (not to scale)

## Conclusions

The study of the Chorgali Formation from two outcrop sections using outcrop samples treated with different tests resulted in several points which might improve our understanding and assessment of the reservoir characteristics of the Eocene Chorgali Formation. These points are:

- Five microfacies are identified within the Chorgali Formation, i.e., non-laminated mudstone, algal laminated mudstone, dolomitized mudstone, siliciclastic mudstone, and wackestone.
- The Chorgali Formation depositional environment is interpreted to be subtidal to supratidal.
- All three genetic porosity types depositional (fenestral, intracrystalline/intraparticle), diagenetic (intercrystalline, moldic, vug), and fracture are noted.
- The secondary porosity is very important in carbonates of the Chorgali Formation.
- The algal laminated and siliciclastic mudstones can be good reservoir microfacies followed by non-laminated and dolomitized mudstones while the wackestone is a poor reservoir microfacies.
- The identification of various microfacies with different porosity types and amounts provides information about the variations in the reservoir potential and quality of the Chorgali Formation in the studied area.

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