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Carbonate deposition during the terminal closing stage of the eastern Neo-Tethys Ocean: The Chorgali Formation of the Potwar and Hazara Sub-basins, Northern Pakistan

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Summary

The Chorgali Formation is late early Eocene carbonate strata that occur in the Potwar and Hazara basins of the Upper Indus Basin. The formation was deposited at a time when the Indus basin was closing as the Indian Plate collided with the Eurasian Plate. The Paleocene-early Eocene epochs defined extensive carbonate deposition on the marine foreland basin between the two plates. However, as India moved northward, the basin was getting narrower until its total closure in late Eocene time. Deposition of the Chorgali Formation occupies at this crucial stage of basin closure. Although recognized lithofacies units of the formation are dominated by mudstone to packstone rock types that are interpreted as subtidal accumulations, there are several features that indicate shallowing nature of the depositional environment, possibly followed by exposure of the carbonate platform. These features include 1) localized sandy facies at the top of the formation, 2) localized dolomitic mudstone at the top of the formation with Oxygen and Carbone isotopic signatures that suggest mixed marine-meteoric origin, 3) localized pedogenic features and 4) mixed marine clastic-carbonate to purely continental siliciclastic deposits of middle to late Eocene Kuldana Formation that overlie the Chorgali Formation. Post-Eocene rocks of the study area contain continental deposits of the Himalayan molasse accumulations.

Introduction

The Chorgali Formation is a hydrocarbon-producing unit that occurs in the upper Indus Basin of northern Pakistan. The Indus Basin was part of an expansive Neo-Tethys Ocean which separated the terrane of the Gondowanaland from those of Laurasia (Eurasian-North America). The post-Jurassic northward migration of the Indian Plate resulted in gradual restriction of the

Indus Basin (i.e., eastern Neo-Tethys Ocean). As a result of the convergent tectonics and Indian-Eurasia collision, the Indus Basin became divided into sub-basins, such as Kala Chitta, Hazara, Kohat and Potwar (Fig. 1) (Afzal et al. 2009; Umar et al., 2015). The Chorgali Formation is well preserved in the Potwar and Hazara sub-basins. It occupies the upper part of a very thick carbonate succession deposited in the Upper Indus Basin of the Neo-Tethys Sea. It conformably overlies the early Eocene Sakesar Formation of the Potwar Sub-basin and Margala Hills Limestone of the Hazara Sub-basin. The Chorgali Formation is either covered by the Miocene continental deposits of the Muree Formation (Himalayan molasse deposits) or middle Eocene mixed clastic-carbonate succession of marine to continental beds of the Kuldana Formation (Fig. 2) (Shah, 1977; Benchilla et al., 2002; Bilal and Khan, 2017). The formation represents deposition during the latest stage of the closure of the eastern Neo-Tethys Ocean and, consequently, the demise of the carbonate platform. This study addresses the sedimentologic properties of this formation and implications to the closing nature of the Upper Indus Basin.

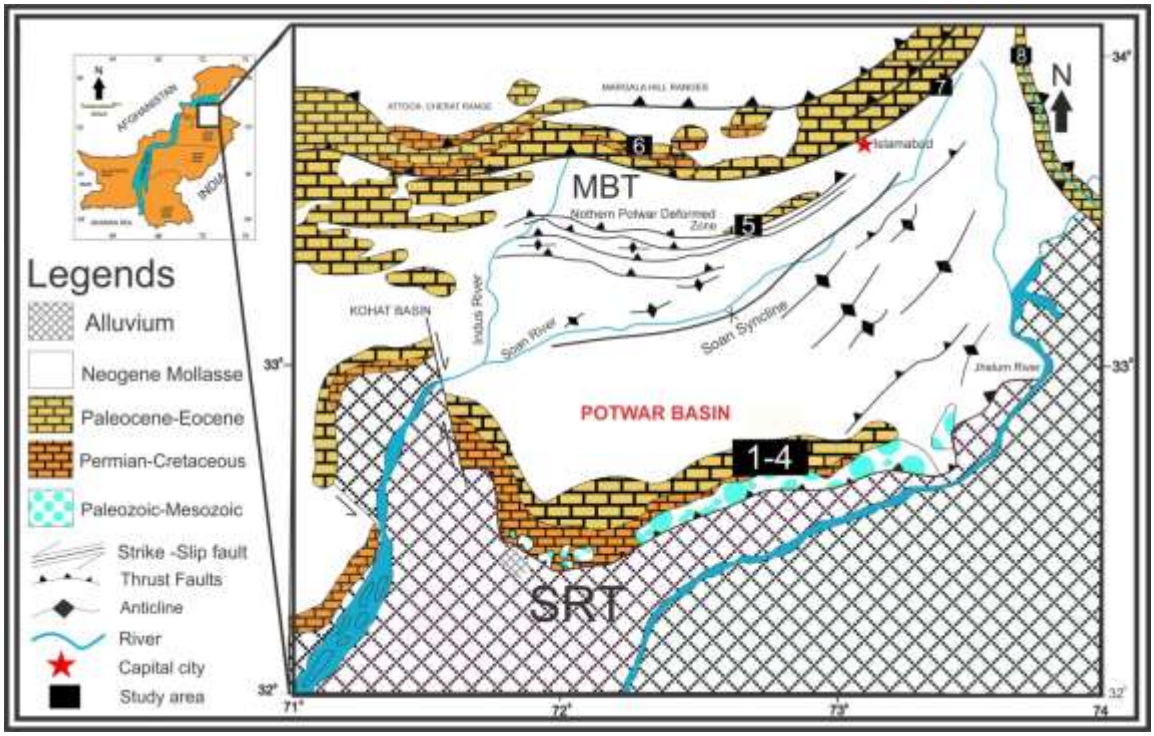

Fig. 1: Map of the study area with the locations of the studied sections (1-8). Map is modified from Kazmi and Rana (1982); and *Jamal et al., (2015).*

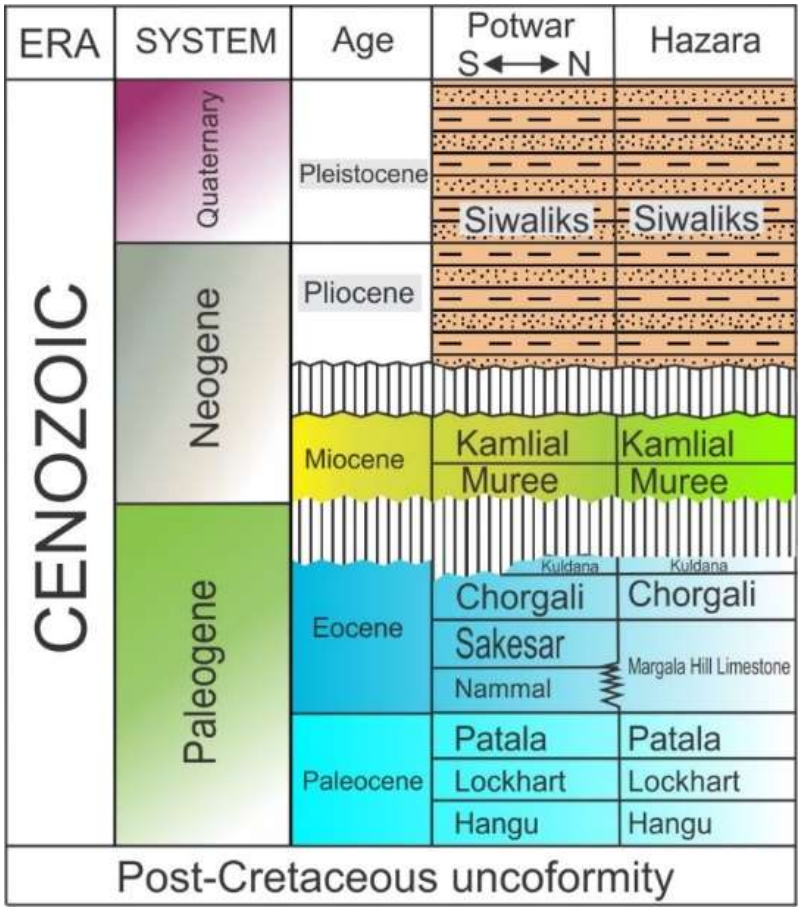

Fig. 2: The stratigraphic chart. The chat shows the Cenozoic stratigraphy of the Potwar and Hazara Basin in northern Pakistan (Modified from Ghazi et al., 2015; Shah 1977a).

Lithologic properties of the Chorgali Formation

The Chorgali Formation is well exposed in the study areas of Potwar and Hazara sub-basins. Eight sections were studied, and they offer an average thickness of 30 m for the formation. The field observation and petrographic analysis of the studied sections recognize nine lithofacies units (LF1-LF9) for the Chorgali Formation. These lithofacies include Sandy Mudstone (LF1), Dolomitic Mudstone (LF2), Algal-miliolid Mudstone (LF3), Coralline algae Mudstone (LF4), *Assilina-Nummulites* Wacke-Packstone (LF5), Mixed benthic-planktonic foraminifera wackestone (LF6), benthic foraminifera rudstone (LF7), shale lithofacies ((LF8), and Planktonic Mudstone (LF9). (Figure 3A-3F) shows field photos and petrographic photomicrographs from the different lithofacies types. Moreover, field and petrographic properties along with prominent fossil content and hydrodynamic conditions of the various lithofacies units are summarized in Table 1.

Table 1: Lithofacies types recognized from the Chorgali Formation of the study area. The field and petrographic properties and hydrodynamic conditions at the deposition site are shown.

Lithofacies type	Field properties	Petrographic properties	Prominent fossil content	Hydrodynamic properties
Sandy Mudstone (LF1)	Grey color, medium to thick-bedded, siliciclastic limestone	Quartz grains in calcareous mud matrix	fossil fragment	low to medium energy
Dolomitic Mudstone (LF2)	Grey color, thin to thickly bedded, calcite vein	Grains are dolomitized Calcite veins	No fossil were seen	Quiet / low energy
Algal-miliolid Mudstone (LF3)	Grey color, lack of fossils, thin to thickly bedded	Matrix-supported. Foraminifera, Algae, Bivalve, Calcite veins *Lockhartia*	*Nummulites, Assilina, Alveolina*	Low energy
Coralline Algae Mudstone (LF4)	Off white color, medium to thickly bedded	Matrix-supported. Skeletal fragments, Algae, *Nummulites*	Coralline algae *Lockhartia, Nummulites*	Low energy
Assilina-Nummulites Wacke-Packstone (LF5)	Off white color, medium to thickly bedded. Larger benthic-foraminifera.	Grains-supported. Bivalve, Gastropods *Nummulites,* algae, *Lockhartia*	*Assilina, Nummulites,* Algae	Moderate depositional energy
Benthic foraminifera Rudstone (LF6)	0ff white color, medium to thinly bedded,	Grains-supported, *Assilina, Nummulites, Lockhartia*	*Assilina, Nummulites, Lockhartia*	Moderate to high energy, subtidal
Mixed-benthic planktonic foraminifera Wackestone (LF7)	Off white color, weathers to grey, medium to thickly bedded	Grains-supported Algae and Planktons	*Assilina, Nummulites*	Moderate to high energy, subtidal
Shale (LF8)	Dark brown, thin to thickly bedded.	Fissile layers	No fossils were seen.	Low energy
Planktonic Mudstone (LF9)	Off white, weathers to grey, medium to thickly bedded mudstone.	Planktonic organisms With some benthic forams	Planktons *Lockhartia*	Low energy

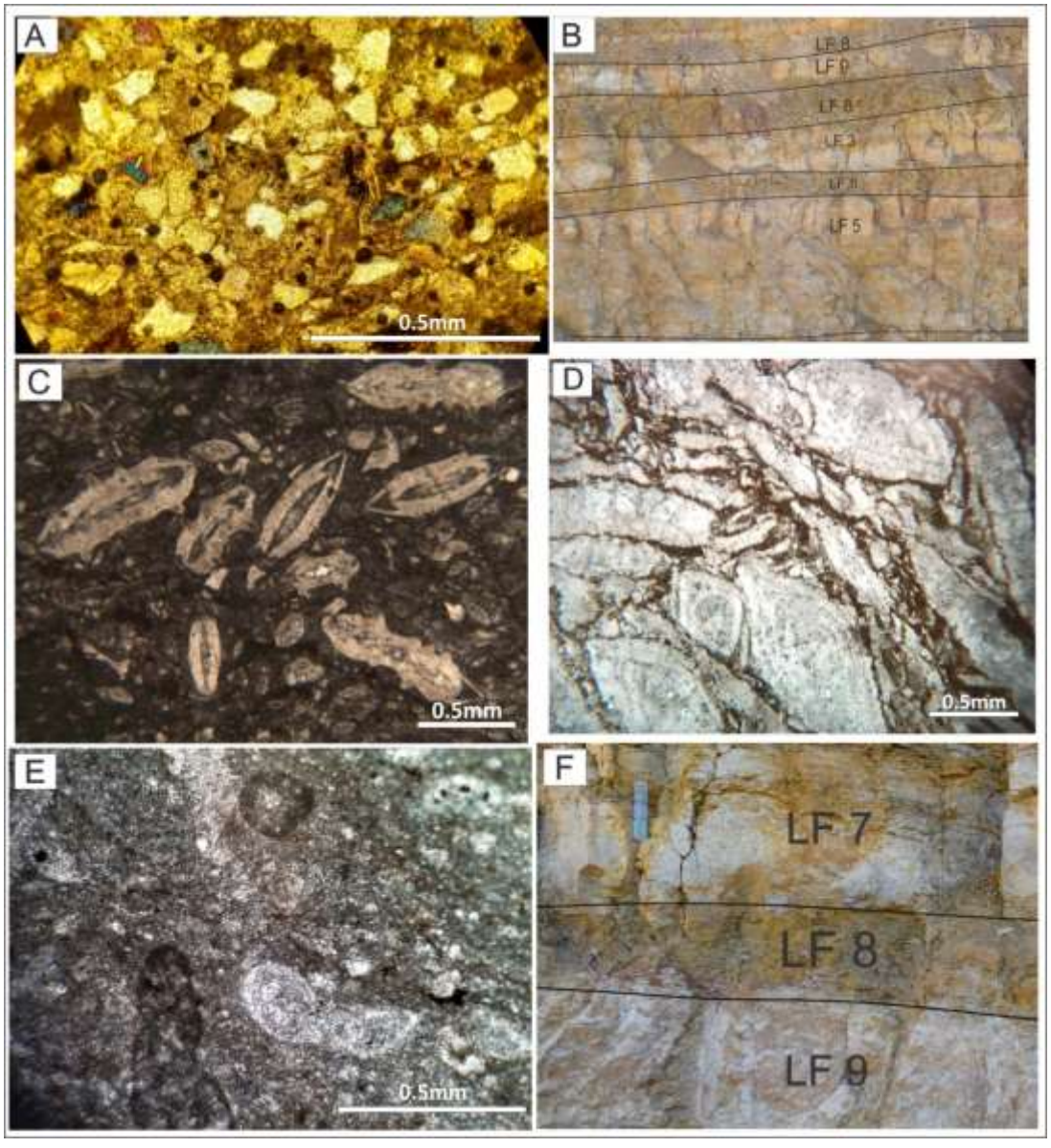

Fig. 3A-3F: Figure (A) represents Sandy mudstone (LF1), (B) showing various field lithofacies, (C) represents *Assilina-Nummulites* Wacke-Packstone (LF5) and (D),(E),(F) represent benthic foraminifera rudstone (LF7), Planktonic Mudstone (LF9), and Shale lithofacies (LF9) respectively.

Depositional Setting

The sedimentary features, fossils associations and hydrodynamic conditions of the various lithologic units of the formation suggest that deposition took place in a homoclinal carbonate ramp characterized by low to moderate energy levels. The various facies can be grouped into two lithofacies associations. The LF1 to LF5 association represents the inner ramp, whereas LF6 to LF9 association represents mid ramp accumulations (Fig. 4). The presence of the mud-dominated lithofacies and planktonic fossils, along with the absence of intertidal and supratidal signatures, further suggests that deposition has taken place in an entirely subtidal environment.

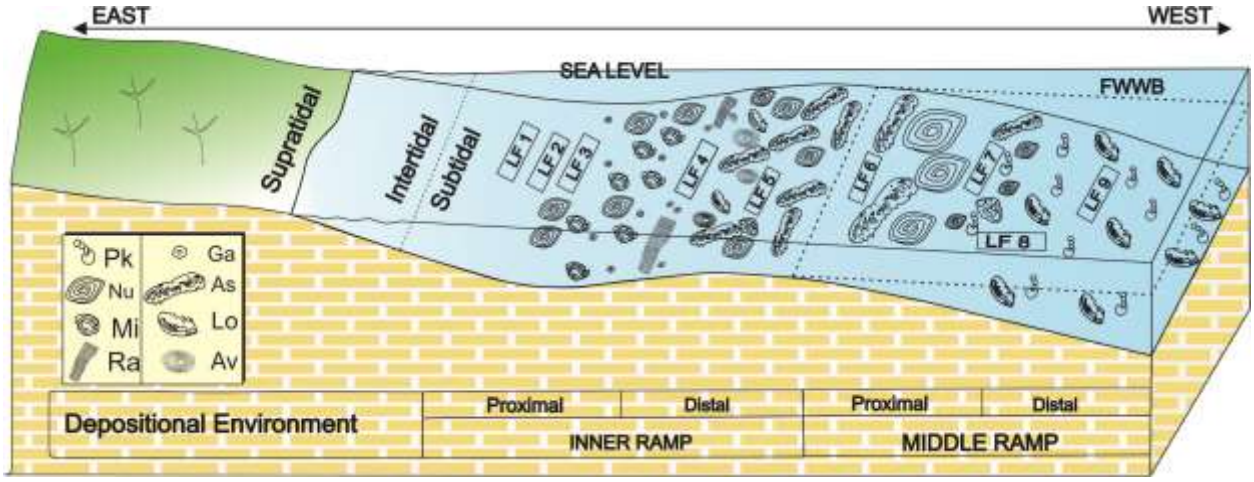

Fig. 4: Depositional setting envisaged for the Chorgali Formation of the study area. All recognized facies occur within the subtidal environment where LF1 to LF4 accumulated in an open lagoon, lithofacies 5 represents moderately agitated distal inner ramp above the fair weather wave base and LF6 to LF9 are interpreted as transitional deposits from proximal to distal middle ramp setting. Pk = planktonic foraminifera, Mi = miliolids, Ra = red algae, Ga = green algae, *As = Assilina, Nu = Nummulites, Lo = Lockhartia and Al = Alveolina.*

Biostratigraphy of the Chorgali Formation

The Chorgali Formation contains a number of larger benthic foraminifera that are deemed to be useful for age determination. Such index fossils include *Nummulites globulus, N. atacicus, N. Mammillatus, Assilina granulosa, A. laminose, A. spinose, and Lockartia conditi* (Fig. 5A-5F). They indicate an age range of late Paleocene to middle Eocene. By considering the age ranges of these index fossils and the formation's stratigraphic position (i.e., between early Ypresian Sakesar/Margala Hills formations and Lutetian Kuldana Formation), the Chorgali Formation can

be regarded as early Eocene (late Ypresian, ~ 49 Ma) to possibly the lowest part of the middle Eocene (early Lutetian, ~ 46 Ma) in age.

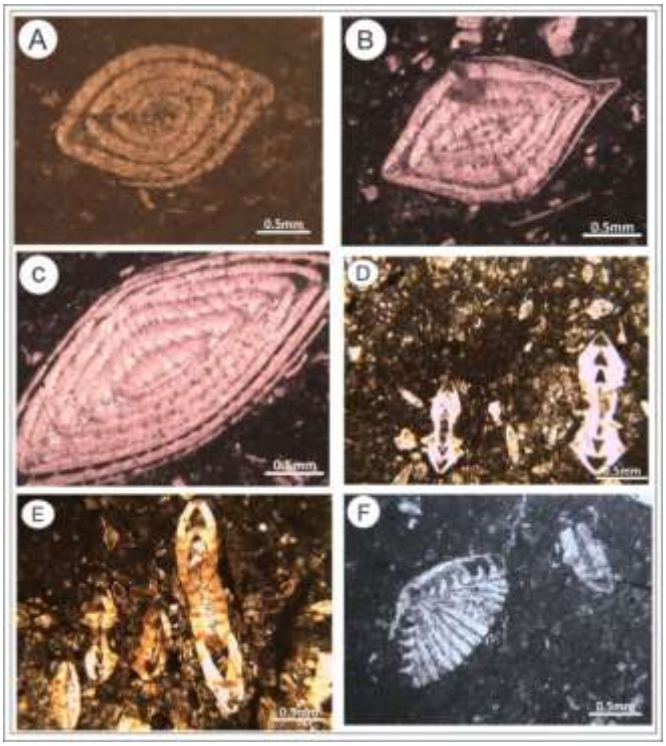

Fig. 5A: Figures (A), (B), and (C) represent Nummulites family such as *Nummulites Mammillatus, N. globulus, and N. atacicus, respectively, while figure D, E represent Assilina sub species such as Assilina Spinosa, A granulosa, and F represents Lockhatia conditi.*

Implications for the closure of the Upper Indus Basin

The stratigraphic position and age of the Chorgali Formation indicate that it evolved in a time in which the Neo-Tethys Sea was getting more restricted as the Indo-Pakistan plate moved farther north and got closer to collide with the Eurasian Plate. The collision event was diachronous (~ 52 Ma to 41 Ma, from east to west). Thus, deposition of the Chorgali Formation took place at the stage of the initial collision, basin closure and withdrawal of the marine conditions. Sedimentologic properties that indicate signatures of basin closure are present in the upper part of the formation. These include 1-Sandy mudstone facies at the uppermost part of the formation; 2- Localized dolomitization in the uppermost part of the formation. Oxygen and carbon isotope data from these dolomites suggested a mixed marine-meteoric water origin for the dolomite, 3-Localized pedogenic sediments and karstification features at the top of the Chorgali Formation (Benchilla et al., 2002). 4) The clastic-dominated, shallow marine to continental deposits of the Kuldana Formation (Cooper et al., 2009)that succeed the shallow marine carbonates of the Chorgali Formation. No marine carbonates occur above the Kuldana

Formation (including the Kohat Formation) in the study area, and the post-Eocene strata of the region are represented by the continental deposits of the Himalayan molasse (i.e., Rawalpindi and Siwaliks groups).

Conclusions

Total eight sections of the Chorgali Formation in Potwar and Hazara Basins studied in detail.

The field observation and petrographic analysis recognized nine lithofacies units (LF1-LF9) of the Chorgali Formation. These lithofacies include: The LF1 to LF5 represent inner ramp whereas LF6 to LF9 represent mid ramp accumulations. The sedimentary features and fossils associations of the formation suggest that deposition of the formation took place in a homoclinal carbonate ramp characterized by low to moderate energy hydrodynamic conditions. The Chorgali Formation contains a number of larger benthic foraminifera that are deemed to be useful for age determination. Such index fossils include *Nummulites globulus, N. atacicus, N. Mammillatus, Assilina granulosa, A. placentula, A. laminose, A. spinose, and Lockartia conditi.* They indicate an age range of late Paleocene to middle Eocene. By considering the age ranges of these index fossils and the formation's stratigraphic position (i.e., between early Ypresian Sakasar/Margala Hills formations and Lutetian Kuldana Formation), the Chorgali Formation can be regarded as early Eocene (late Ypresian, ~ 49 Ma) to possibly the lowest part of the middle Eocene (early Lutetian, ~ 46 Ma) in age. The Larger benthic foraminifera abundant in the southern parts of the Potwar basin suggests that the depositional environment is shallower relative to the Hazara basin and northern part of the Potwar basin.

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