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September 21-23
2020
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Depositional settings of Cretaceous rocks in Central Indus Basin of Pakistan; a review

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Key Words: Central Indus Basin, Cretaceous rocks, Sedimentation, Paleogeography, Depositional setting, Indian Plate,

Abstract

There is a growing need for improved understanding of tectonic and sedimentary processes that occurred in the geological past, and apply this knowledge for better constraining the paleogeography, basin configuration and depositional settings.

The Cretaceous was one of the most important and longest periods in the geological history. Break-up of Gondwana supercontinent and northward drifting of Indian plate, made the latter a separate and isolated island where initiation and development of new sedimentary basins took place. Sediments deposited during Cretaceous times are of major interest. Almost the complete stratigraphic sequence ranging from Late Tithonian through Neocomian to Maastrichtian is well developed and known as hydrocarbon bearing succession in Indus Basin of Pakistan.

The study area is located in the central part of Pakistan which is known as Central Indus Basin, encompassing of Sulaiman fold-and-thrust belt, Sulaiman foredeep and Punjab Platform. An attempt has been made here to constrain depositional settings by critical review of published literature on Cretaceous paleogeography of the Indian Plate and detailed investigation of sedimentary rock sequences, comprising about one-third of the territory.

Litho-facies maps of Sembar and Goru Formations, Parh Limestone, MughalKot and Fort Munro Formations and Pab Sandstone were prepared by incorporating available surface and subsurface geological information. The results indicate the existence of a broad shelf (Peri-cratonic basin), that was highly influenced by transgression and regression caused by sea level changes. No volcanic and orogenic activity has been identified in the study area during Cretaceous times. The stratigraphic succession comprises alluvial to deep marine sedimentary rocks. However, towards the east all sedimentary Cretaceous rocks are thinning out or are truncated.

Introduction

The study area is located in the northwestern most part of Indian plate. Geographically it is situated in Pakistan which is bordered by Afghanistan in west, Iran in southwest, India in east and China in north. The Arabian Sea marks the southern boundary.

The Indus Basin is one of the largest sedimentary basins in geological times. The Greater Indus Basin is subdivided into three parts i.e.; Upper, Central and Southern Indus Basin. Upper Indus Basin is also known as the Kohat-Potwar Plateau which comprises of east-west trending fold-and thrust belts. The Central and Southern Indus Basins are characterized by relatively flat flood plains to the east and rugged terrains of Sulaiman and Kirthar fold-and-thrust belts in the west as shown in Figure 1.

The studied Central Indus Basin extends up to Sargodha High and Jacobabad High in north and south respectively, the Axial Belt (Katawaz-Pishin Basin) in the west and Punjab Platform in the east. It covers an area of about 210,000 Square kilometers.

Structurally, the Central Indus Basin is divided into a fold-belt and fore-land regime. The fold-belt part includes the tightly folded Sulaiman Range along the western boundary of the Indian continent. The latter gradually loses it amplitude eastward and merges with the foredeep zone known as Sulaiman Depression. Gently westward dipping sediments extends up to the Indian boarder (Bikaner-Nagaur Basin) which is known as Punjab Platform area (see Figure 2).

Cretaceous Period

The Cretaceous period is the longest period of the Phanerozoic Eon, and started about 145.0 million years ago and ended 66 million years ago, spanning about 79 million years.

The Cretaceous period is divided into two major subdivisions, Lower/Early and Upper/Late, which correspond to units of time known as the Early and the Late Cretaceous Epochs. Both the Lower and the Upper Cretaceous epochs are further subdivided into six stages. For Lower Cretaceous, the stages are the Berriasian, Valanginian, Hauterivian, Barremian, Aptian and Albian. For Upper Cretaceous, the stages are Cenomanian, Turonian, Coniacian, Campanian and Maastrichtian. In these stages, the longest one corresponds to Aptian, about 12 million years while the Santonian is the shortest, with about 3 million years (see Figure 3).

Paleogeography of Indian Plate (Cretaceous times)

The tectonic history of the Indian plate began with rifting of the Gondwana supercontinent during late-Early Jurassic (Scotese,1991, 1997; Jokat et al., 2003). The latter supercontinent comprised of South America, Africa, Madagascar, India, Antarctica, Australia and few micro-continents, such as Seychelles (Dietz and Holden, 1970). During the Middle Jurassic, initial rifting between East and West Gondwana, and the configuration of the Indian plate changed dramatically when it broke sequentially apart from Gondwana, East Gondwana, Madagascar, and finally from the Seychelles in the Cretaceous (Acharyya et. al., 1991; Chatterjee and Scotese, 1999), as shown in Figure 4. Once separated from Australia and Antarctica, India began its journey northward, which culminated in the later collision with Eurasia during the Cenozoic Era.

Paleogeographic reconstruction suggests that during its northward journey the Indian plate was an isolated island and for long Cretaceous time-lapse, it remained as a peninsular continent (see Figure 5). Sea level was higher during most of the Cretaceous times (Scotese 1988), which was a major factor allowing marine waters to inundate the Indian Plate.

It is interesting to note that the study area was located at the NNW of the Indian plate during Cretaceous period as shown in Figure 6. The paleogeographic study and reconstruction of tectonic plates by different authors (Scotese, 1988, 1991& 1999; Ali, 2005 & 2008; Chatterjee, 2010 & 2013; Gibbons, 2013) validate this point. The position of the Indian plate changed gradually during the northward drifting.

Cretaceous strata

During the Cretaceous the north margin of Indian plate was considered as a stable part (no volcanic or orogenic activity reported). The sedimentary rocks of Cretaceous age show considerable variation in their lithological characteristics and thickness. Relative sea level, local tectonic, sediments source and climate conditions are chiefly responsible for the recorded lithostratigraphic variations.

The sedimentary rocks of the Cretaceous period are widely exposed in some parts of the Sulaiman fold-and-thrust belt. Except for few local disconformities, a complete sedimentary sequence of the Cretaceous period ranging from Berriasian to Late Maastrichtian is present (Kadri, 1995; Kazmi and Jan, 1997; Shah, 1997; Shamim et al., 1999; Kazmi and Abbasi, 2008). The succession is about 2.5 km thick, and consist of a sequence of fossiliferous siliciclastic and carbonate sediments, starting from Sembar Formation of Neocomian age, Goru Formation of Aptian to Coniacian age, Parh Limestone of Santonian to Early Campanian age, Mughal Kot and Fort Munro Formations of Late Campanian to Early Maastrichtian age and Pab Sandstone of Late Maastrichtian to Early Danian age as shown in Figure 1.

In northern part of study area (Kohat-Potwar region), the Early Cretaceous consists of marine sandstone and shale (Chichali Formation and Lumshiwal Formation) and Limestone (Kawagarh Formation) in the Late Cretaceous. Sediments of Cenomanian, Turonian and Maastrichtian stages are missing here and are marked by disconformities. Farther northward of the study area, the Kohistan-Ladakh magmatic arc contains a thick sequence of volcanic and meta-sediments (Kazmi and Abbasi, 2008). Possible lateral extension of Cretaceous sediments towards the Central Indus Basin is marked on the basis of available surface and subsurface data (Wandrey and Shah, 2004) as shown in Figure 7.

Methodology and Approach

Detailed review of published literature and lithofacies encountered in various drilled wells are incorporated in this study to develop a model for the understanding of lateral extension of Cretaceous rocks and facies variations in part of the Central Indus Basin.

Based on available published subsurface well data; an attempt is made to highlight the possible extent of each formation by a red dotted line in figures 8-13. The latter however do not necessarily define the basin or depositional limits; as a number of major tectonic events occurred after Cretaceous sedimentation which affected the strata so that present-day wells data do not necessarily transect Cretaceous strata in the subsurface.

A brief description of Lower to Upper Cretaceous sedimentary sequences is given below and lithofacies maps are prepared to document the maximum extent of formations and facies variations in the study area to identify possible depositional settings.

Sembar Formation:

Age: Lower Cretaceous (Neocomian)
Thickness: Thickness varies within the Sulaiman lobe from 1 km to few hundred meters.
Lithology: Sembar Formation is mainly composed of black shale interbedded with siltstone and intercalation of sandstone (in some areas)
Environment: Deep Marine to Continental slope

The shales of Sembar Formation are quite uniform and widely present in the Central Indus Basin (Fatmi, 1977; Ahmed et. al., 2013). It has been encountered in several wells. However, in the eastern part of the study area it thins out and is truncated in the Punjab Platform area (Figure 8).

During Early Cretaceous, the rifting from Antarctica caused the up-lifting of the southern portion of Indian Plate which provided a gently northward sloping continental shelf that makes up the foreland and extends from the northern margin (present day; western margin of Sulaiman fold-belt) and up to India-Pakistan geographic boundary (present day; eastern margin of Punjab Platform) in the Central Indus Basin.

Lithofacies of the study area support the subsidence, and rise of sea level as well as low sediment supply during Neocomian age. However, some wells of central and eastern part of Sulaiman fold-and-thrust belt encountered sandstone beds in the lower part of Sembar Formation which suggest regression or sea level fall during Berriasian or Valanginian times.

Goru Formation:

Goru Formation of Aptian to Coniacian age is widely distributed in the Indus Basin. At its type-locality in the Sulaiman fold-and-thrust belt area, a relatively thick sequence of interbedded limestone, shale and siltstone overlies the Sembar Formation whereas in eastward subsurface well data the lower part comprises sandstone interbedded with shale and siltstone (Williams, 1959; Fatmi, 1977). Based on sedimentary facies record the Goru Formation is divided into two parts i.e., Lower Goru and Upper Goru Formations.

Lower Goru Formation:

Age: Lower Cretaceous (Aptian - Albian)
Thickness: 250 - 100 meter
Lithology: Lower Goru Formation is mainly composed of sandstone interbedded with shale and siltstone (eastern part of Sulaiman Range)
Environment: Barrier bar to lower shore facies to deltaic

The lateral extension of the lithostratigraphic section reflects the continuous subsidence of Indian Plate accompanying with frequent transgressions and regressions or sea level rise and fall. In the western part of the study area the Lower Goru sedimentary facies consists of argillaceous limestone and in its eastern part it consists of sandstone which alternate with shale beds. In Southern Indus Basin these siliciclastic sediments are well developed (Ahmad et al., 1996; Ahmed et al., 2004 & 2012). However, in the eastern part of the study area its thickness decreases and it has been truncated in the Punjab Platform (Figure 9).

Upper Goru Formation:

Age: Upper Cretaceous (Cenomanian – Coniacian) The age is designated by Williams (1959), based of fossil record.
Thickness: 500-400 meter
Lithology: Upper Goru consists of shale and argillaceous limestone
Environment: Deep - shallow marine

The upper part of Goru Formation consists of interbedded argillaceous limestone and shale in the west, while eastward, it consists of shales interbedded with siltstones and claystone in the Central and southern Indus Basin. However, in the eastern part of the study area it thins out and is truncated in the Punjab Platform area. This lithostratigraphic variation reflects the eastward rise of sea level during Cenomanian to Coniacian age (see Figure 10).

Parh Formation:

Age: Upper Cretaceous (Santonian – Early Campanian)
Thickness: 250 - 50 meter
Lithology: Parh Formation mainly consists of Limestone
Environment: Shallow marine

Largely thin bedded mostly uniform hard limestone. This distinct and persistent rock formation is extensively exposed in the Sulaiman Range. It has been encountered in several wells in the Central Indus Basin. Its thickness decreases in the eastern part of the study area (Figure 11).

Mughal Kot and Fort Munro Formation:

Age: Upper Cretaceous (Early Campanian – Early Maastrichtian)
Thickness: 1600 - 500 meter
Lithology: Mughal Kot Formation consists of shale with intercalation of quartzose sandstone and argillaceous limestone. Fort Munro Formation is consisting of hard limestone.
Environment: Shallow marine

In Sulaiman fold-and-thrust belt sandstone of Mughual Kot Formation is well developed. However, the thickness decreases eastward. The Mughal Kot Formation was mainly deposited in shallow water (Shahid et al., 2016).

In Sulaiman fold belt, Fort Munro Formation comprises of thick bedded limestone, which conformably overlies the Mughal Kot Formation (Williams, 1959; Fatmi, 1977). Its thickness ranges from 50 – 250 meter in the Central Indus Basin. In the eastern part of the study area it thins out.

Pab Sandstone:

Age: Upper Cretaceous
(Early Maastrichtian – Late Danian)
Thickness: 300 - 500 meter (truncated eastward in Punjab Platform area)
Lithology: Mainly consisting of sandstone
Environment: alluvial plain to deltaic.

Quartzose sandstone of Maastrichtian age is well exposed in the eastern part of Sulaiman Range. Pab Formation is dominated by sandstone, with minor shale and mudstone components (Shahid et al., 2016; Khan, 1999; Kadri, 1995). It conformably overlies on Fort Munro Formation. However, in some places, it overlies the Mughal Kot Formation unconformably (Shahid et. al., 2016). The abrupt contact between Pab Sandstone and Limestone of Fort Munro Formation indicates the rapid change in sea level. It may be due to Deccan volcanic activity in the western portion of the Indian Plate.

Conclusion

During the entire Cretaceous period, the Indian plate remained a peninsular which is reflected by the development of a broad shelf sedimentary basin of Peri-cratonic nature.

In Cretaceous times the Indus Basin was located on the northern margin of Indian plate (Figure 6) and it was shifted in northwest direction during its long travel towards the north in Paleogene time (Figure 1).

Sedimentary facies in the central part of the Indus basin indicate the subsidence of the basin which was highly influenced by transgression and regression reflecting sea level changes.

No volcanic and orogenic activity has been identified in the study area during Cretaceous times.

The entire stratigraphic succession comprises of alluvial to deep marine sedimentary rocks. However, towards east all sedimentary rocks of Cretaceous age are thinning out or are truncated.

Recommendations for future work

It is strongly recommended to integrate all surface sections and acquired well data to obtain good control on deposited sediments, facies variation and their distribution to develop comprehensive three-dimensional depositional models during the Cretaceous of the Greater Indus Basin.

Acknowledgements

I thank Prof. Dr. Rudy Swennen to provide me the opportunity as PhD candidate to work on Cretaceous sediments of Central Indus Basin and KU Leuven to give the access of worldwide published literature. I also thank to Mr. M. Athar (Consultant Geologist in Dewan Petroleum Private Limited-Pakistan), Nusrat k. Siddique (author of Petroleum Geology, Basin Architecture and Stratigraphy of Pakistan, 2016) and M. Amjad (Exploration Geologist in Oil and Gas Company Limited-Pakistan) for their valuable contribution in writing and modification.

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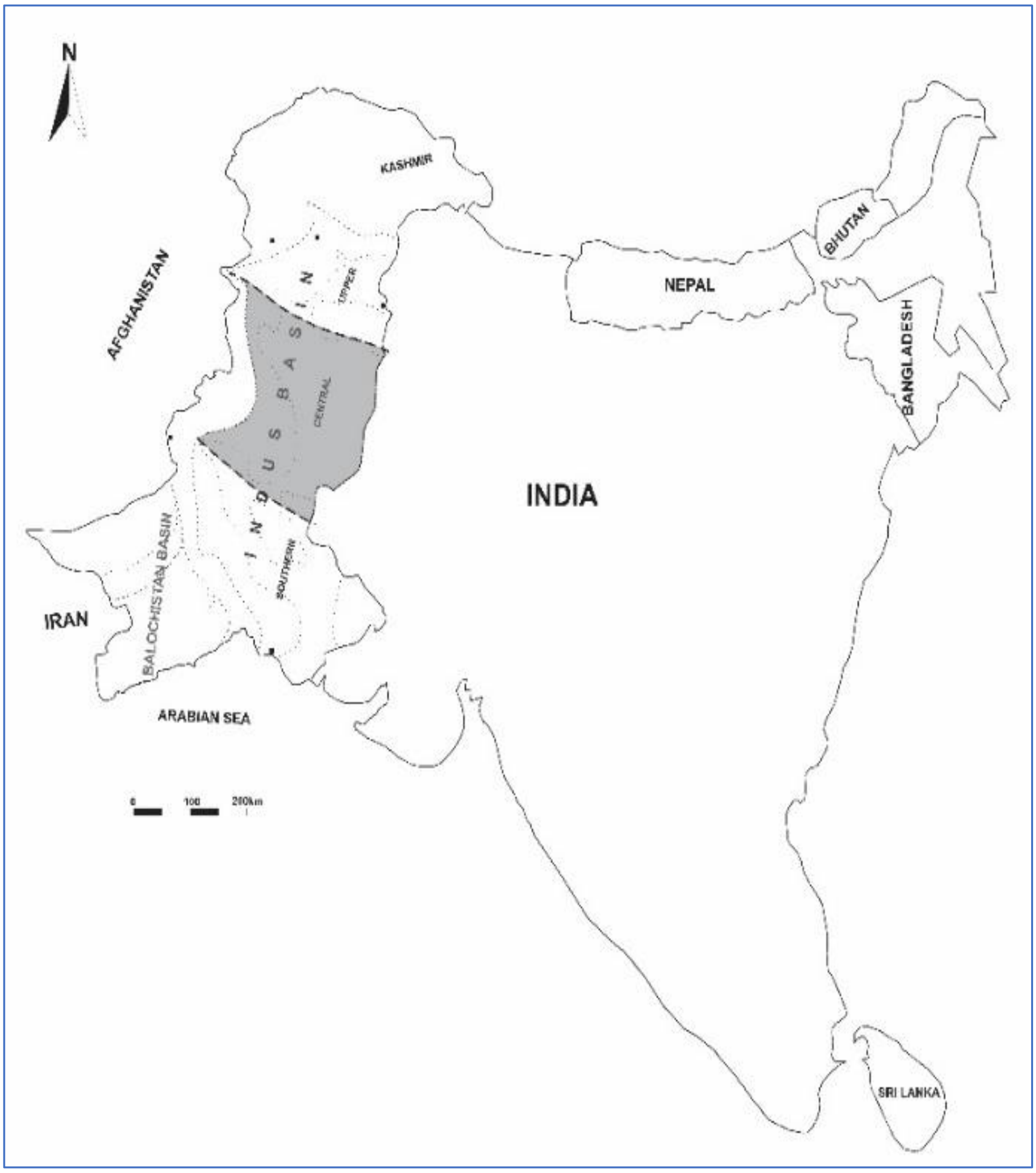

Figure 1: Great Indus Basin on the western margin of Indian Plate. Highlighted area showing the Central Indus Basin (study area).

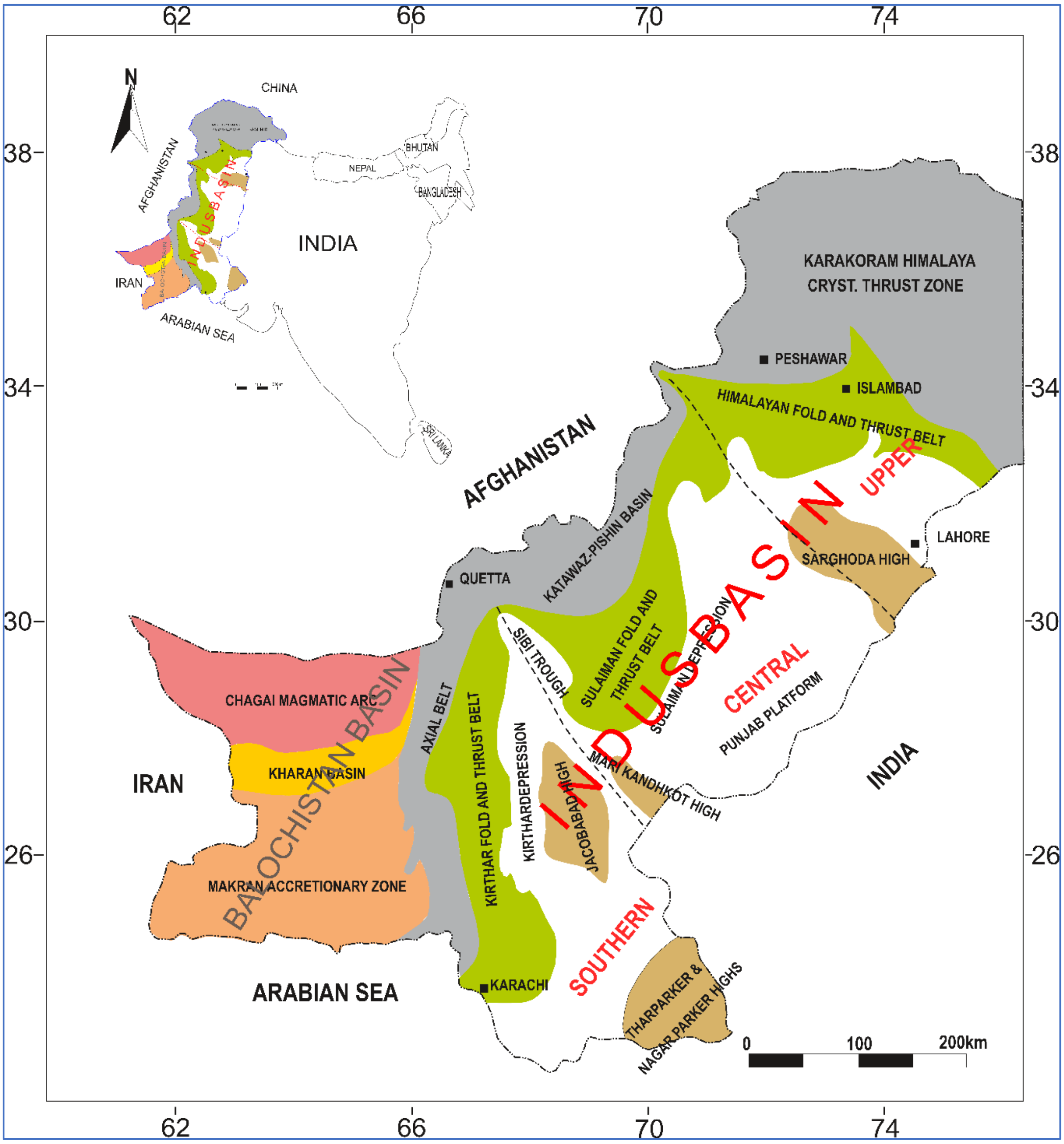

Figure 2: Tectonic map of Pakistan. The Central Indus Basin is indicated by dotted lines, with Sargodha High in the north and Mari-Kandhkot and Jacobabad Highs in the south.

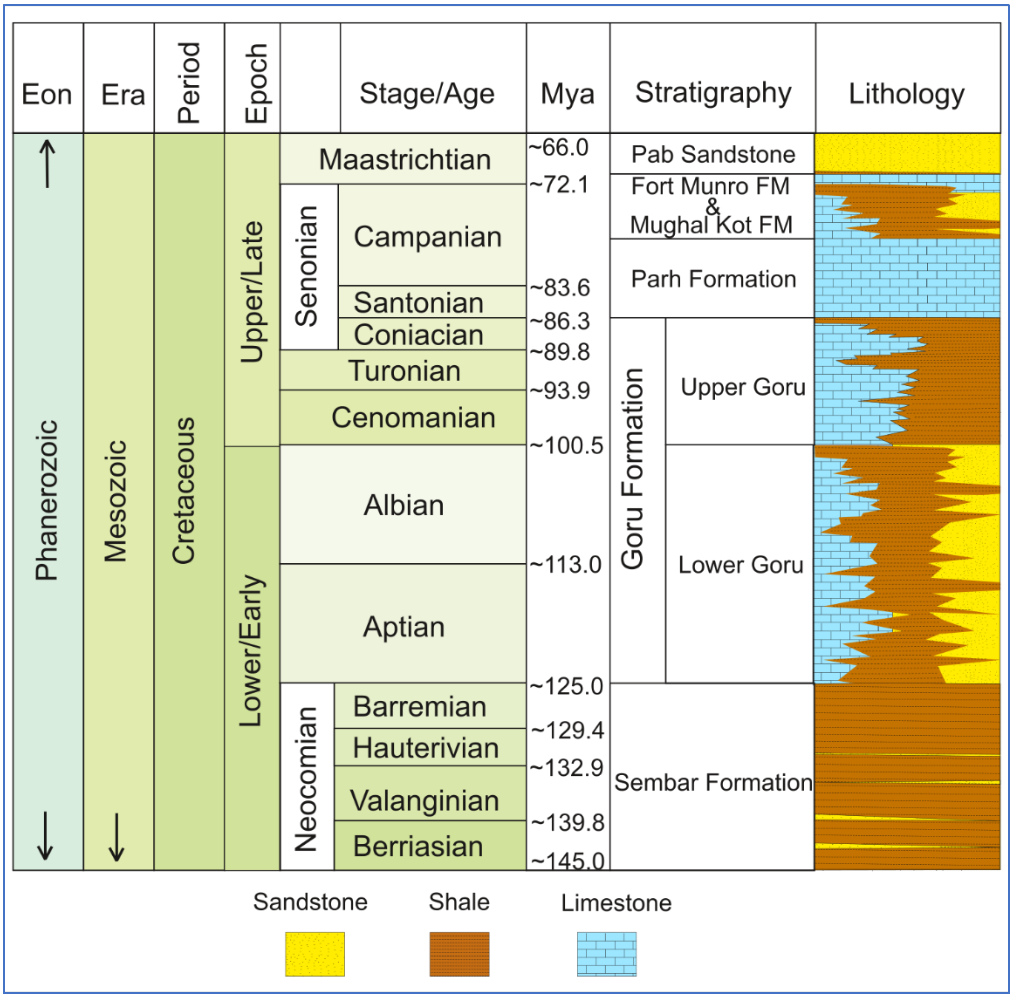

Figure 3: Geological time scale of the Cretaceous, showing sub-divisions and ages, and generalized stratigraphy of Central Indus Basin- Pakistan.

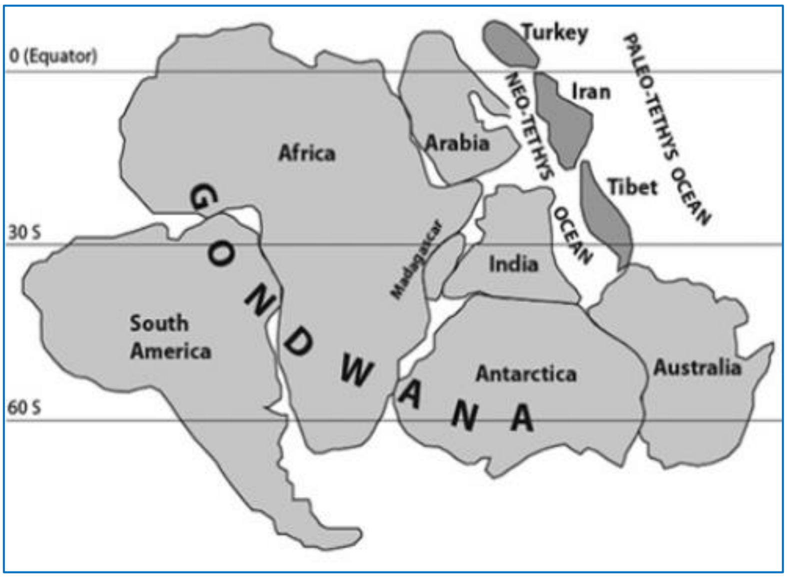

Figure 4: Paleo-geography of Gondwana Supercontinent approximately 220 million years ago (modified from Chatterjee, 1999)

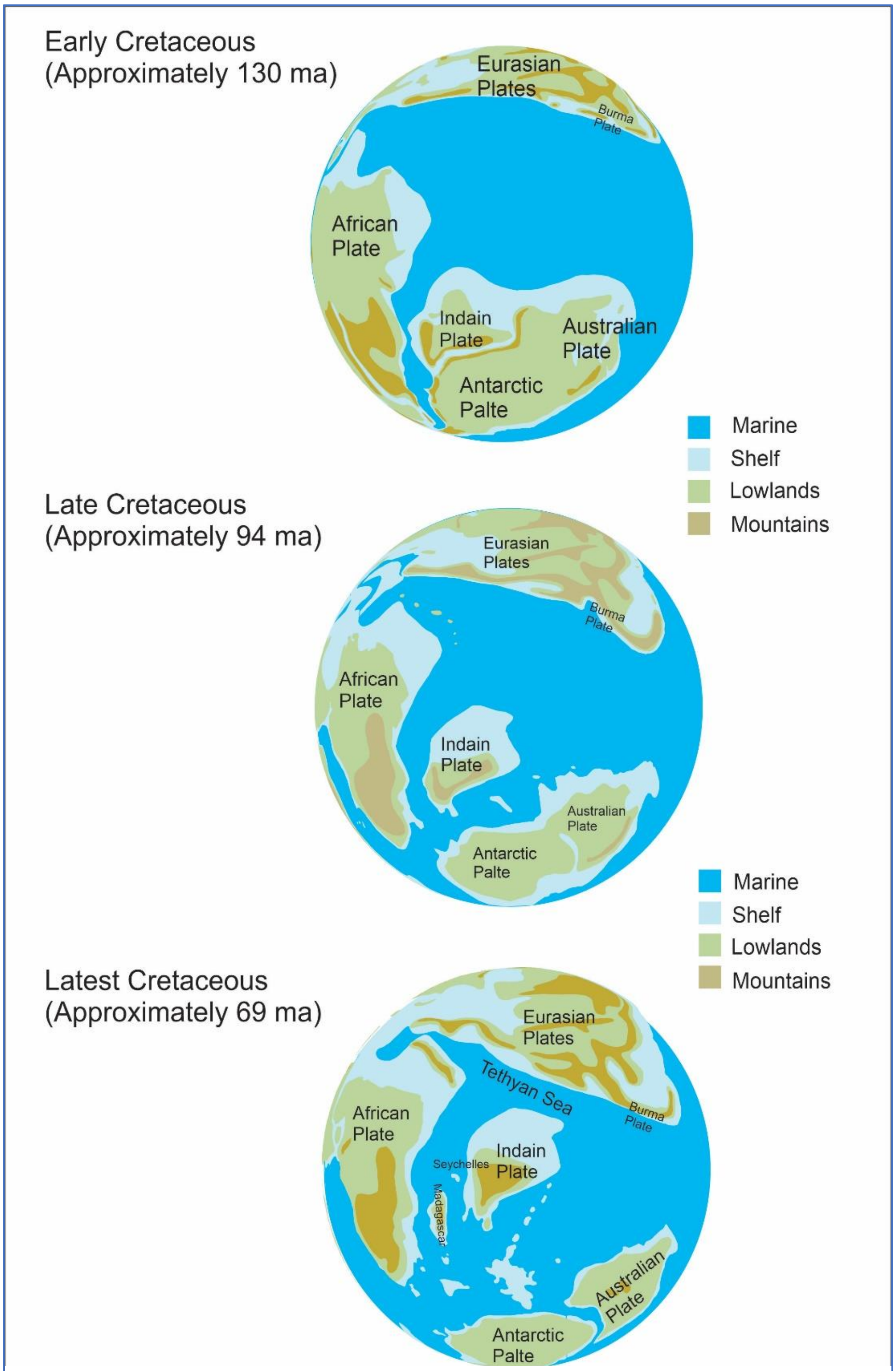

Figure 5: Map showing the Indian Plate location during Cretaceous time (Early – 130ma, Late – 94ma, and Latest- 69ma). Modified from Scotese et. al., 1988.

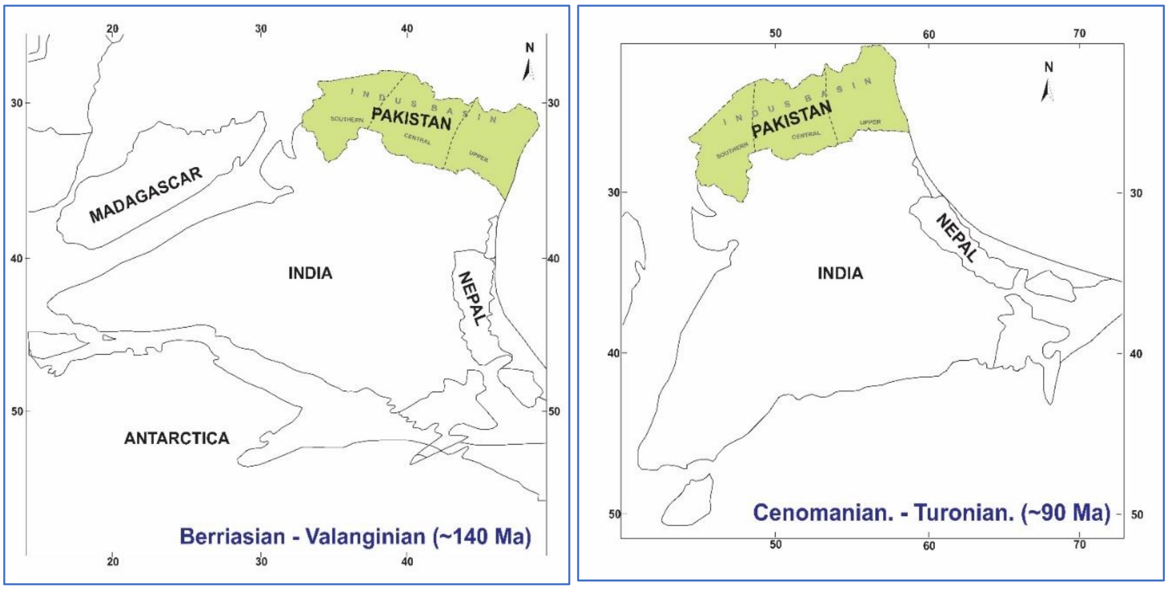

Figure 6: Indian Plate showing the location of Pakistan (Indus Basin) in the north during Lower Cretaceous (140 Ma) and north - northwest in Upper Cretaceous (90 Ma). Modified from Chatterjee and Scotese, 2010.

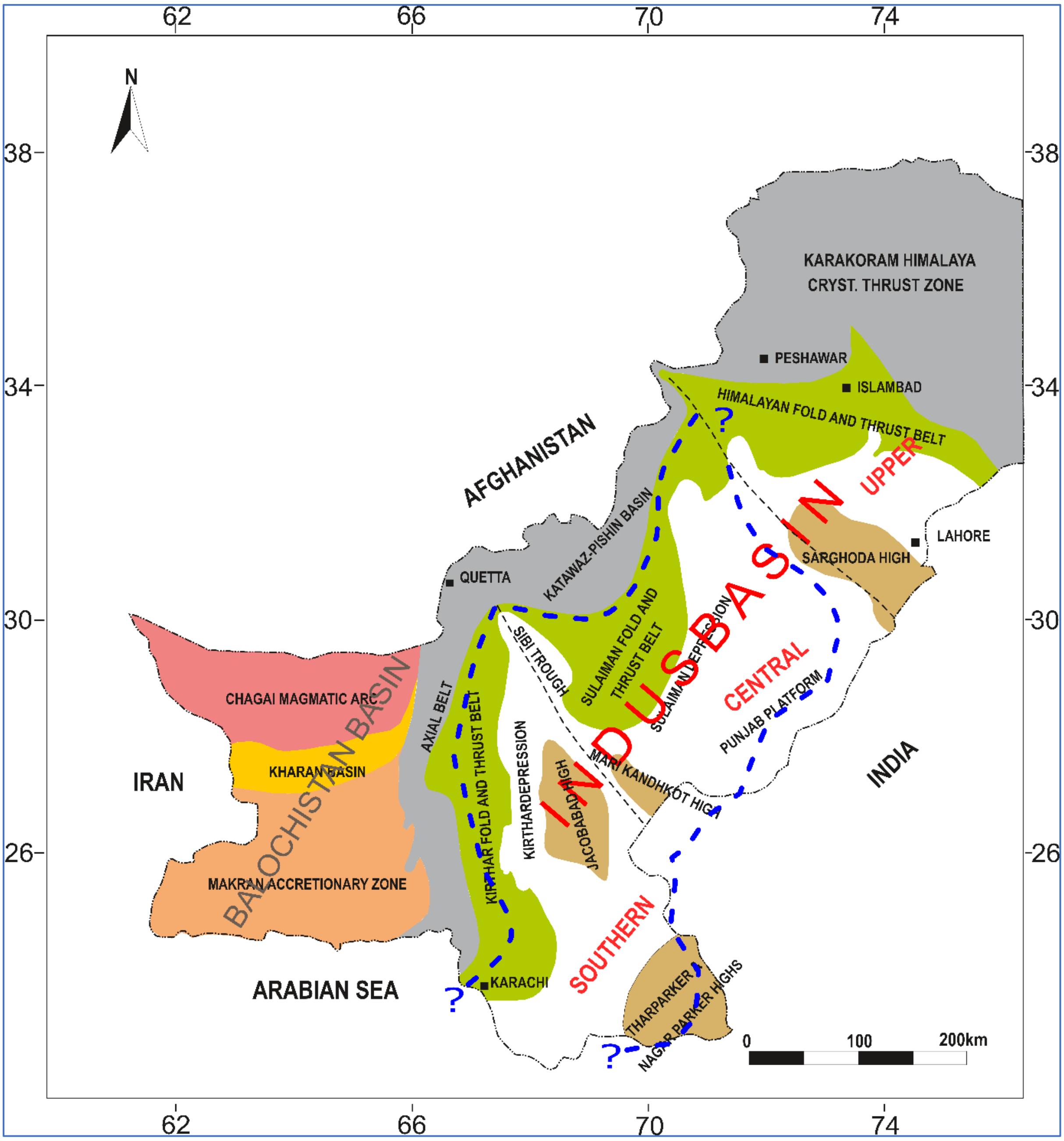

Figure 7: Tectonic map of Pakistan showing the maximum extent of Cretaceous sediments in the Central Indus Basin (modified from Wandrey and others, 2004).

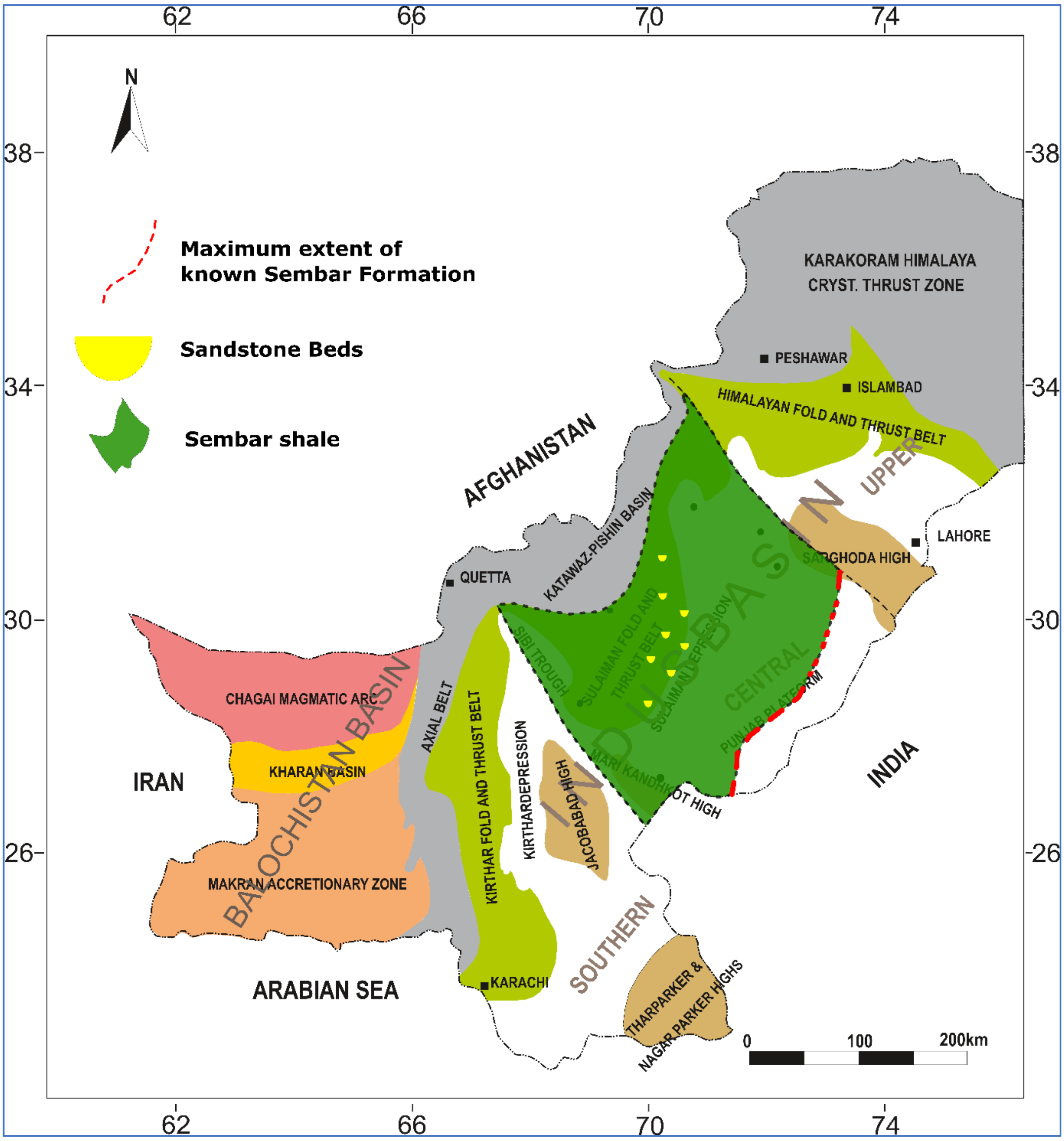

Figure 8: Map showing the lateral extension of Sembar Formation (Neocomian) in green. Reported sandstone beds in yellow and red dotted line in the east marking the maximum extent of Known Sembar Shale.

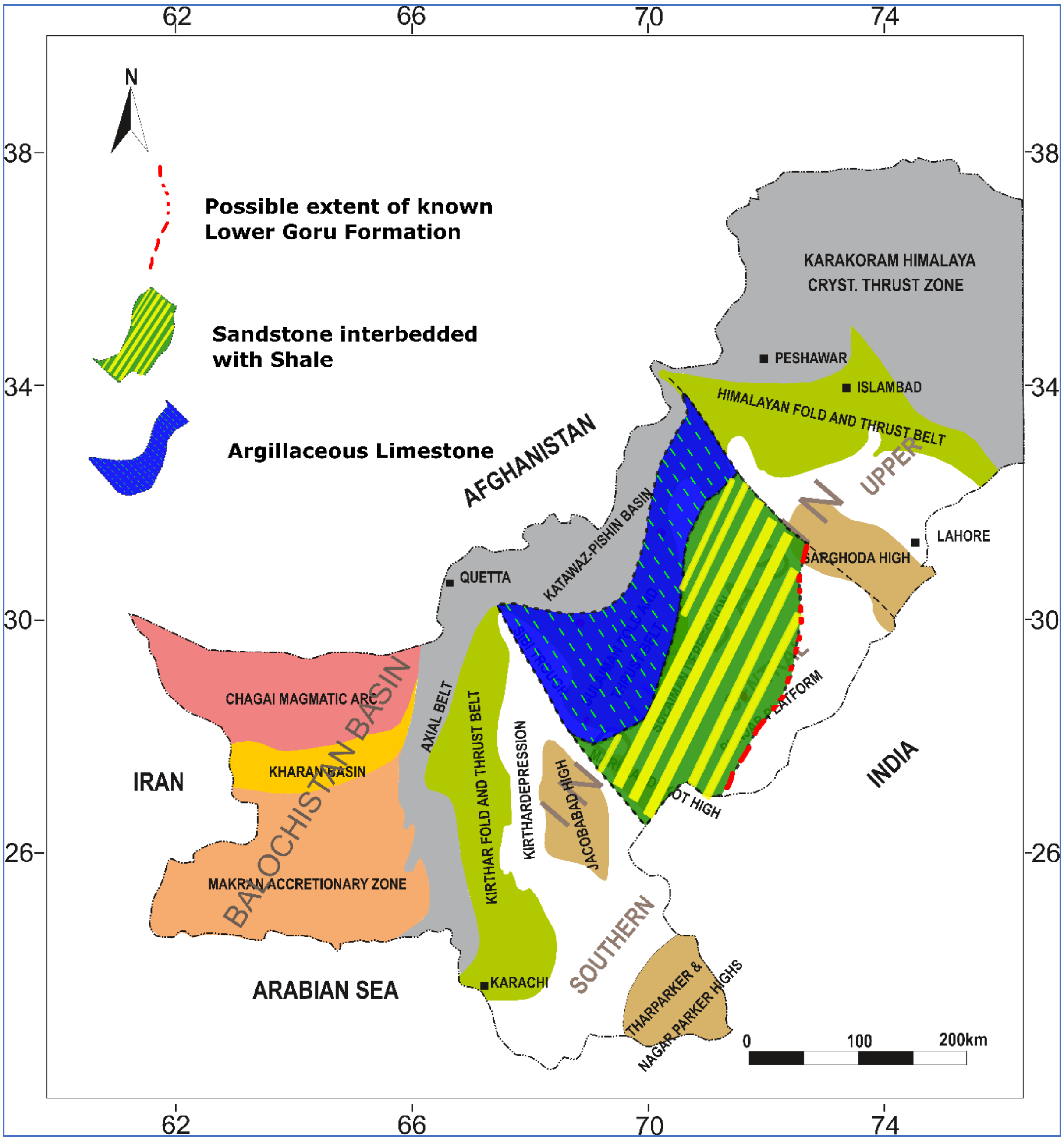

Figure 9: Map showing the lithofacies variation in the Central Indus Basin during Lower Goru Formation (Aptian – Albian). Western part consists of shale and argillaceous limestone whereas the eastern part comprises of sandstone with interbedded shale. A possible boundary accentuating some lateral variation is deduced on the basis of subsurface drilling data. Lower Goru Formation possible extent in eastward direction is marked by a red dotted line.

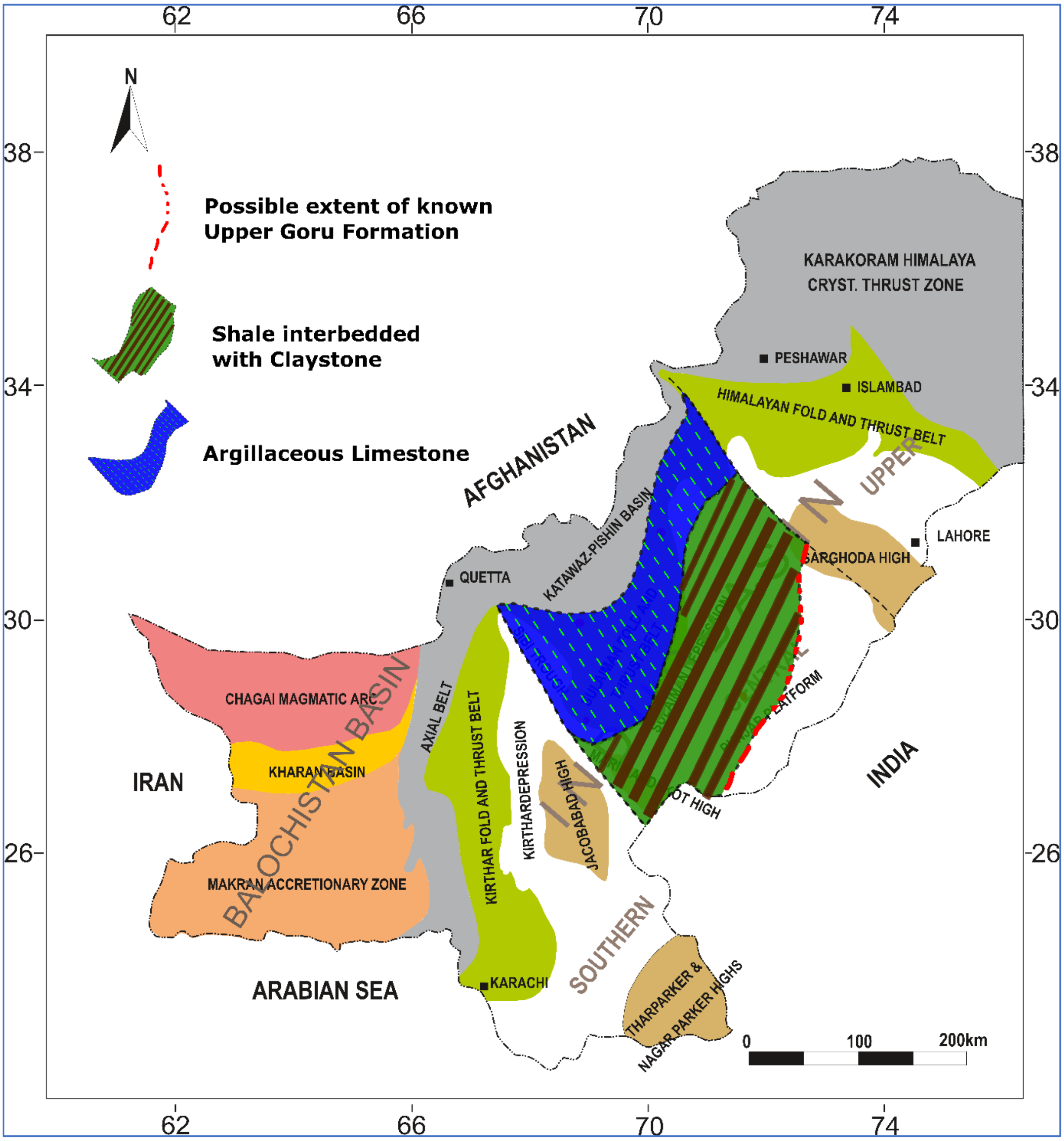

Figure 10: Map showing the lithofacies variation in the Central Indus Basin for the Upper Goru Formation (Cenomanian – Coniacian). The western part consists of shale and argillaceous limestone whereas the eastern part comprises of shale and claystone. A possible boundary for lateral variation is deduced on the basis of subsurface well data. As of Lower Goru Formation, the Upper Goru possible truncation is marked with a red dotted line.

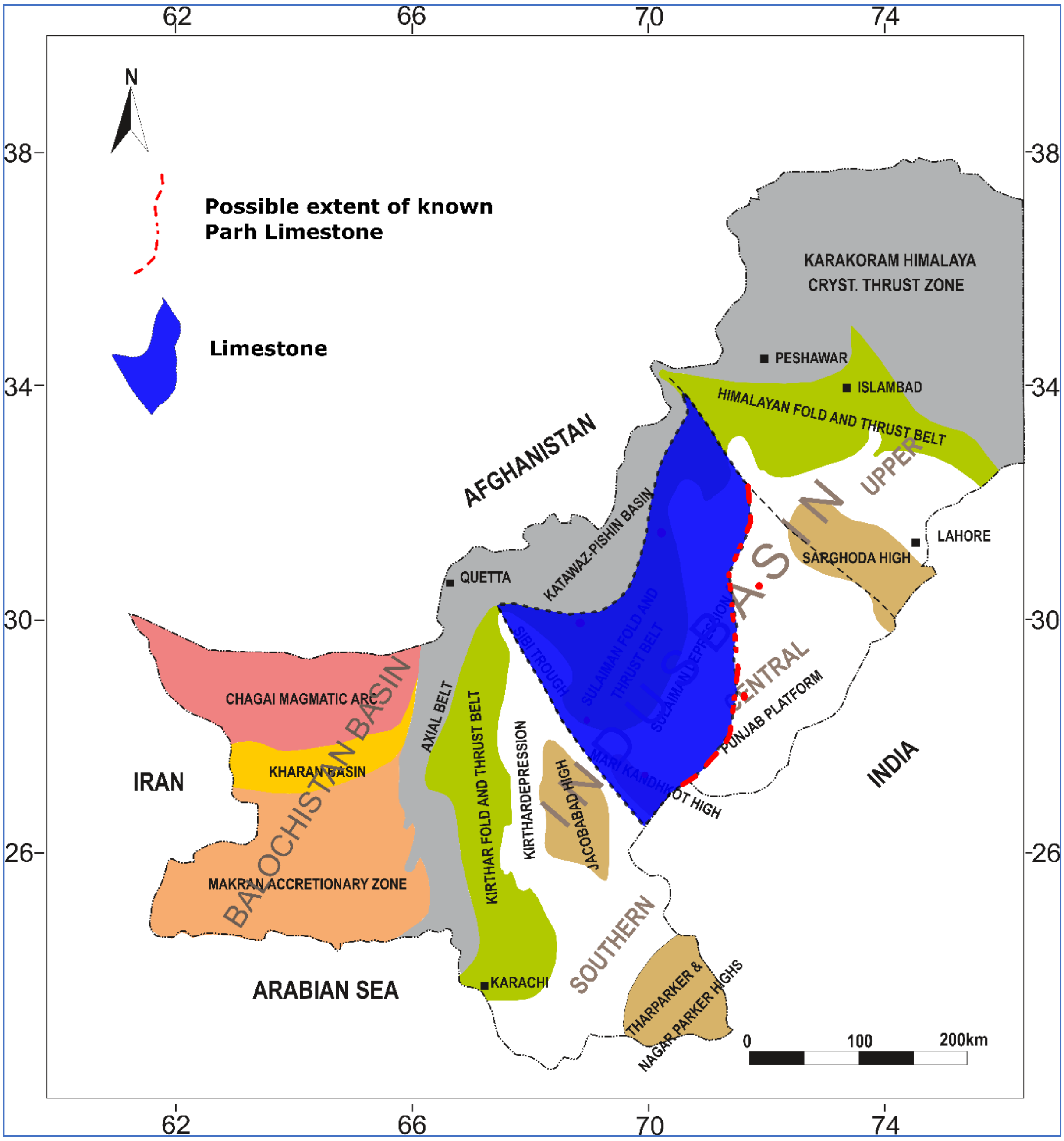

Figure 11: Parh limestone (Santonian – Early Campanian) indicates a sea level rise. Based on subsurface drilled information the possible lateral extent toward east is marked in red dotted line.

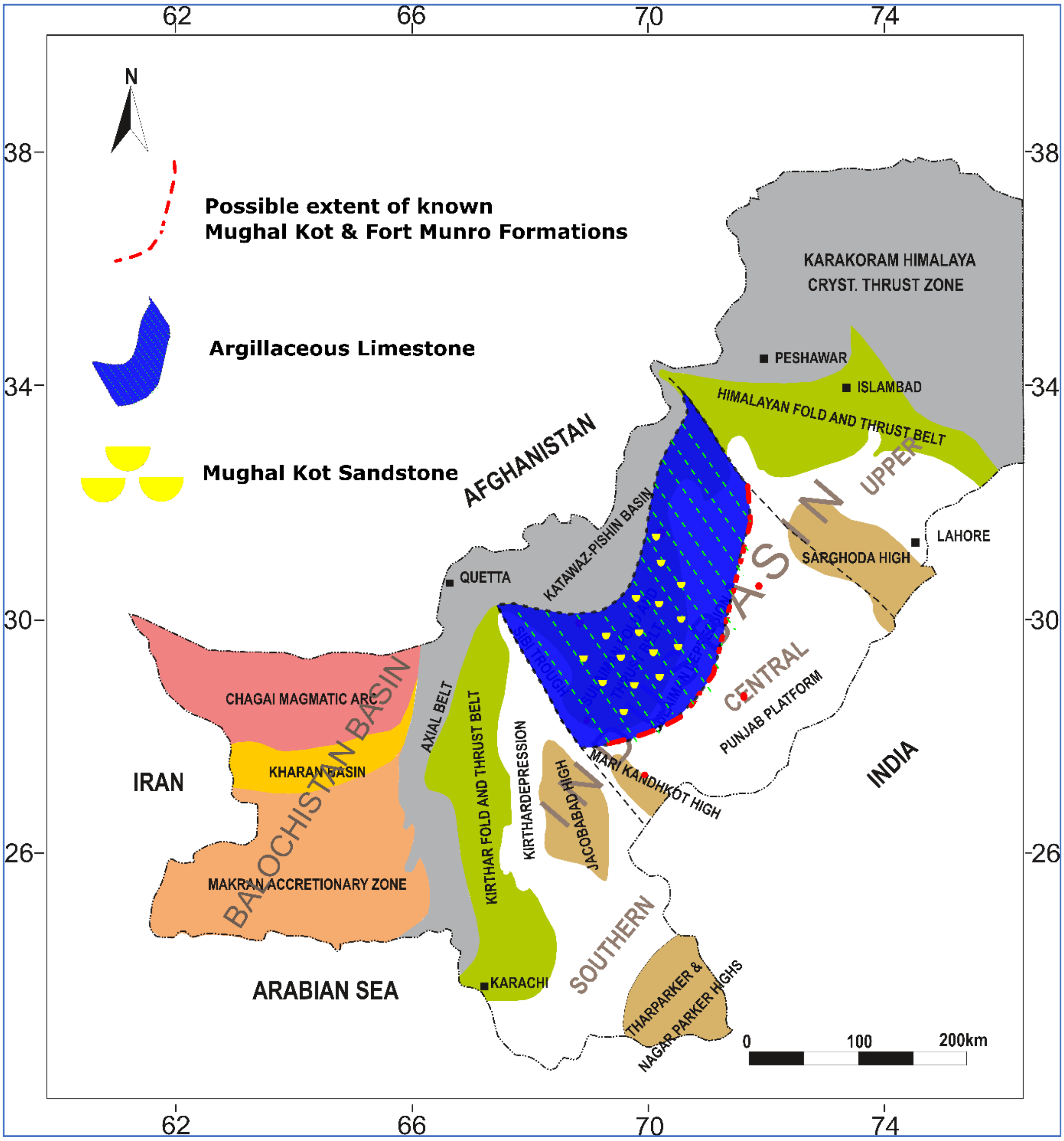

Figure 12: Mughal Kot and Fort Munro Formations (Early Campanian – Early Maastrichtian) maximum known extension is marked with dotted red line in the eastern side. Sandstone of Mughal Kot Formation (in yellow) present in central part of Sulaiman fold-belt (based on subsurface well data). Limestone of Fort Munro Formation overlies the Mughal Kot Formation mark the local disconformities in the area and not encountered in eastern part of fold and thrust belt.

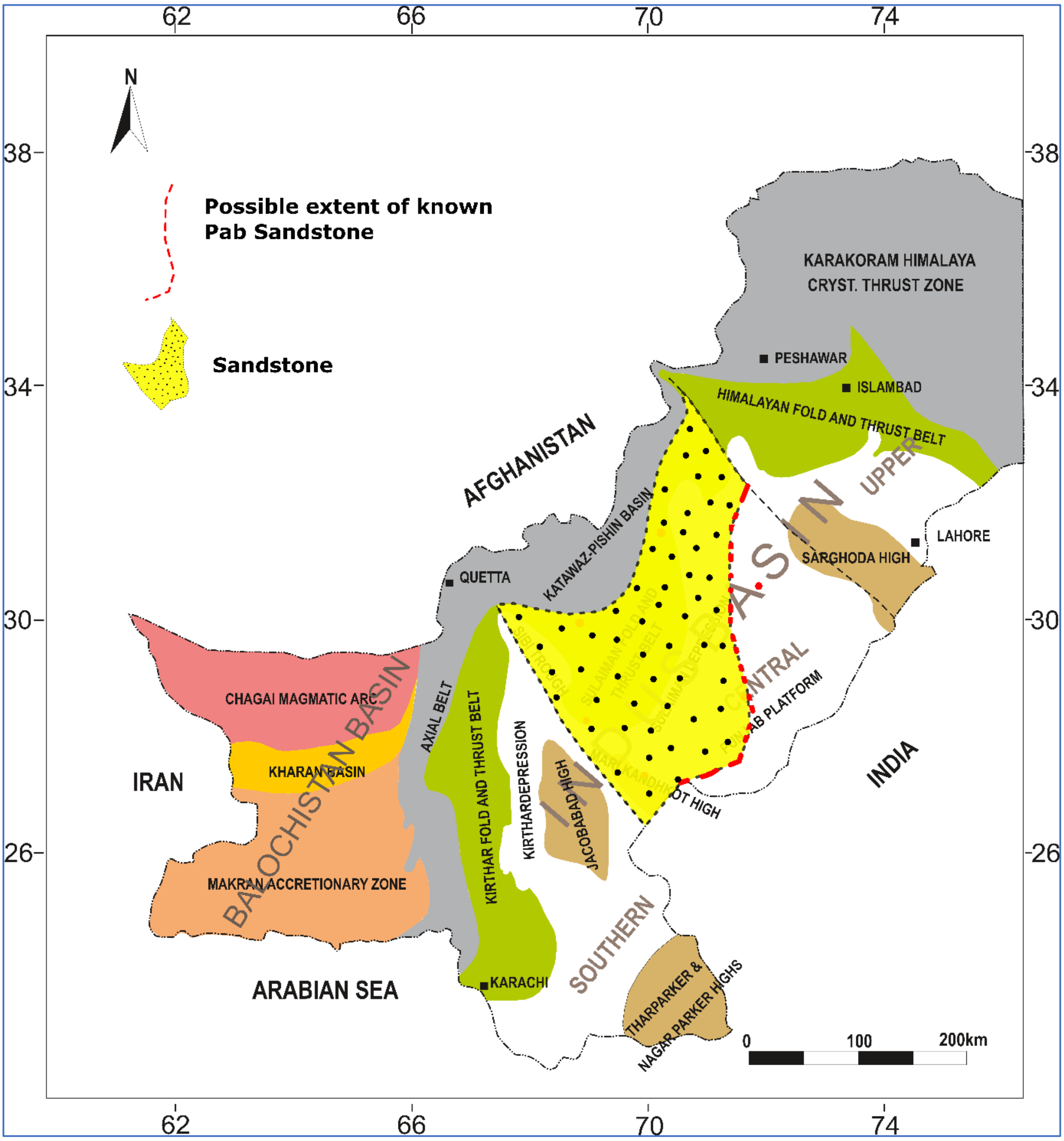

Figure 13: Map showing the maximum lateral extension of known Pab Sandstone (Early Maastrichtian – Late Danian). Lithofacies indicates the sea level fall and increase of sediment supply, and shifting the delta plain towards the west.