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Key Points:
- The late Eocene-early Miocene unconformity of the NW Indian plate intraplate basins is unrelated to Himalayan-induced compression or flexure
- The unconformities of the NW Indian plate intraplate basins and the Himalayan peripheral foreland basin are approximately coeval
- A common mechanism is proposed for the foreland and intraplate basin unconformities related to mantle circulation

Supporting Information:
- Supporting Information S1

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The Late Eocene-Early Miocene Unconformities of the NW Indian Intraplate Basins and Himalayan Foreland: A Record of Tectonics or Mantle Dynamics?

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Abstract A well-developed late Eocene to Miocene unconformity, termed the base Miocene unconformity (BMU), is found throughout the intraplate basins of northwestern India and has previously been ascribed to Himalayan tectonics. This hypothesis is investigated by first describing the nature and age of the BMU in the northwest (NW) Indian intraplate basins and then reconstructing the location of the BMU relative to the Himalayan deformation front at the time it formed. We suggest that formation of the BMU in western India cannot be related to Himalayan tectonic processes associated with plate loading and flexure unless the Indian plate had an elastic thickness of $>$125 km, which is highly unlikely. Furthermore, the resumption of deposition post unconformity rules out inversion due to compression associated with India-Asia convergence as a cause, as these compressive forces are still present. We note the coeval nature of the unconformity in the NW Indian plate intraplate basins and the Himalayan peripheral foreland basin. If the unconformities of the Himalayan peripheral foreland basin and the NW Indian intraplate basins were formed by a common process, uplift due to circulation in the mantle is the only possible regional-scale mechanism. Such circulation could be the result of the intrinsically time-dependent high-Rayleigh number convection in the mantle, which has resulted in well-documented unconformities elsewhere, or be the result of subducting slab break-off beneath the Himalaya.

1. Introduction

The far-field effects of continental collisions extend beyond the immediate realm of the orogen they create (Cunningham, 2005; Otto, 1997; Replumaz & Tapponnier, 2003). At least two processes may cause regional stress changes associated with such collisions, which are expressed as folds, faulting, and regional unconformities. First, compressional stresses are laterally propagated for long distances into the foreland, for example, as is documented in the western interior of the U.S. and the Alpine orogen (e.g., Dezes et al., 2004; Dickinson & Snyder, 1978). Second, flexure of the previously subducting plate occurs in the foreland due to loading by the mountain range and the underthrusting slab (e.g., DeCelles et al., 1998; Lyon-Caen & Molnar, 1985). To interpret the forces driving the creation of geological structures in the foreland of mountain ranges therefore requires distinguishing between flexural and far-field compressive effects, as well as separating these from deformation relating to subplate processes such as mantle convection and slab break-off.

In the case of the India-Asia collision, the Indian plate is under ~north-south compressive stress due to the forces arising from the central Indian Ocean mid-ocean ridge and the Tibetan Plateau (Coblentz et al., 1995; Copley et al., 2010). The resulting deformation has been documented in a number of places and takes the form of kilometer-scale reactivations of preexisting faults (e.g., Copley et al., 2014; Müller et al., 2015), thrust-faulting earthquakes (e.g., Craig et al., 2011), and folding and reverse faulting in the central Indian Ocean (e.g., Krishna et al., 2009). Flexure of the Indian plate has resulted in the development of the Himalayan foreland basin ahead of the southward migrating Himalayan thrust front, with a peripheral forebulge probably present to the south of this (Bilham et al., 2003). Migration of the forebulge either away from or toward the mountain range due to redistribution of the load and the motion of the Indian plate (relative to the Himalayan range front) through this region are commonly proposed as the cause of the widespread late Eocene to early Miocene unconformity recorded throughout the peripheral foreland basin rocks now incorporated into the sub-Himalayan thrust belt (Bera et al., 2010; DeCelles et al., 1998, 2004; Irfan et al., 2005;

Najman et al., 2005; Najman & Garzanti, 2000). By contrast, Clift and VanLaningham (2010) suggest that redistribution of the load due to climatically induced increased erosion of the orogen resulted in flexural unloading, unflexing of the Indian plate and consequential basin uplift, and formation of the late Eocene to early Miocene foreland basin unconformity. Mantle dynamics, including the break-off of subducting slabs and the presence of hot thermal anomalies due to mantle upwelling, are additional suggested causes (e.g., Husson et al., 2014; Maheo et al., 2002).

The Barmer Basin is an inverted failed rift basin of Paleogene age (Naidu et al., 2017), with its northern end situated ~800 km south of the Himalayan front and 400 km east of the Kirthar Mountains of central Pakistan (see Figures 1 and 2). Compton (2009), Dolson et al. (2015), and Bladon, Clarke, and Burley (2015) suggested that India-Asia collisional tectonics resulted in postrift compressional features in the basin, including uplift of cross-rift basement ridges, inversion of the northern part of the basin (which has removed >1 km of sediment), and the major late Eocene to lower Miocene unconformity, termed the base Miocene unconformity (BMU). Compton (2009) correlated the BMU into the Jaisalmer/Middle Indus Basin, considered to be a retreating foreland basin by DeCelles (2012). The BMU is also traceable through a number of other basins distal to the Himalaya, including the Cambay, Kutch, Bombay, and Indus Basins, up to 1,400 km south of the Himalayan front, with decreasing intensity southward (Figures 1 and 2). We term these basins the northwest (NW) Indian intraplate basins. The purpose of this paper is to describe the nature and extent of the BMU in the NW Indian intraplate basins distal to the Himalaya and to consider mechanisms for its formation in view of the previously proposed Himalayan influence. The description focuses on that part of the unconformity preserved in the Barmer Basin, Rajasthan, as a type example of the unconformity in the NW Indian intraplate basins, from where we interpret a wealth of subsurface data made available by Cairn India.

2. Geological Background: The NW Indian Intraplate Basins

The BMU is documented and regionally mapped in the Barmer, Cambay, Kutch (Chowdhary, 1975; Chowdhary & Singh, 1978; Kundal et al., 2005), and Bombay (Mumbai) Basins (Basu et al., 1982; Mehrotra et al., 2010; Mohan, 1995; Wandrey, 2004) as an erosional event of generally decreasing erosional depth southward (Figure 1, panels 5–7). In subsurface data sets, it is recognized as a regional seismically correlatable reflection event (Figure 3). An equivalent unconformity is recognized in the onshore Jaisalmer Basin (Figure 1, panel 4; Quadri & Shuaib, 1986; Wandrey et al., 2004). The offshore Indus Basin (Figure 2) also records early Miocene erosional events (Carmichael et al., 2009; Clift et al., 2001; Quadri & Shuaib, 1986).

There are other less pronounced unconformities throughout the Paleogene and Miocene successions in the NW Indian intraplate basins (e.g., Chowdhary, 2004; Mehrotra et al., 2010). To the north, many of these are progressively eroded out by the BMU and merge onto the BMU surface, the erosional depth of which increases northward. In the Sanchor and Cambay Basins, the BMU erodes out progressively less of the Eocene and Oligocene successions until in depocenters of the southern Cambay Basin and the Bombay Offshore Basin almost complete Oligocene and Eocene successions are present (see Figure 1).

Local tectonics give rise to considerable variation in the architecture of the unconformities. For example, in the Cambay Basin the extent and intensity of these unconformities vary across rotated fault blocks in the basement. These are long-lived fault-bounded basement highs that in some cases include tilted Mesozoic sedimentary rocks (Chowdhary & Singh, 1978; Mathuria et al., 2011; Mohan et al., 2008; Sahoo & Choudhuri, 2011) onto which the oldest Miocene sediments on-lap (Dolson et al., 2015; Kaila et al., 1990; Mathuria et al., 2011; Valdiya, 1976). Similarly, in the Bombay Offshore Basin, the depth of erosion is greatest across the larger fault blocks, such as the Bombay High (Bhandari & Jain, 1984; Wandrey, 2004). Some structures in which the BMU is pronounced are associated with recent block uplift and inversion (Huggett et al., 2015; Pangtey, 1996; Sanyal et al., 2012) complicating the interpretation of erosional history. However, in general (Figure 1), the Jagadia Formation is regionally present across >600 km as the basal (oldest) continental Miocene sequence above the BMU in the Cambay and Barmer Basins (Dolson et al., 2015; Kundal et al., 2005; Naidu et al., 2017).

3. The Barmer Basin, Rajasthan: the BMU in a NW Indian Intraplate Basin

In order to document the BMU in detail, in a region distal to the Himalayan front, the Barmer Basin has been studied because of its excellent seismic and exploration well coverage available from Cairn India. Seismic

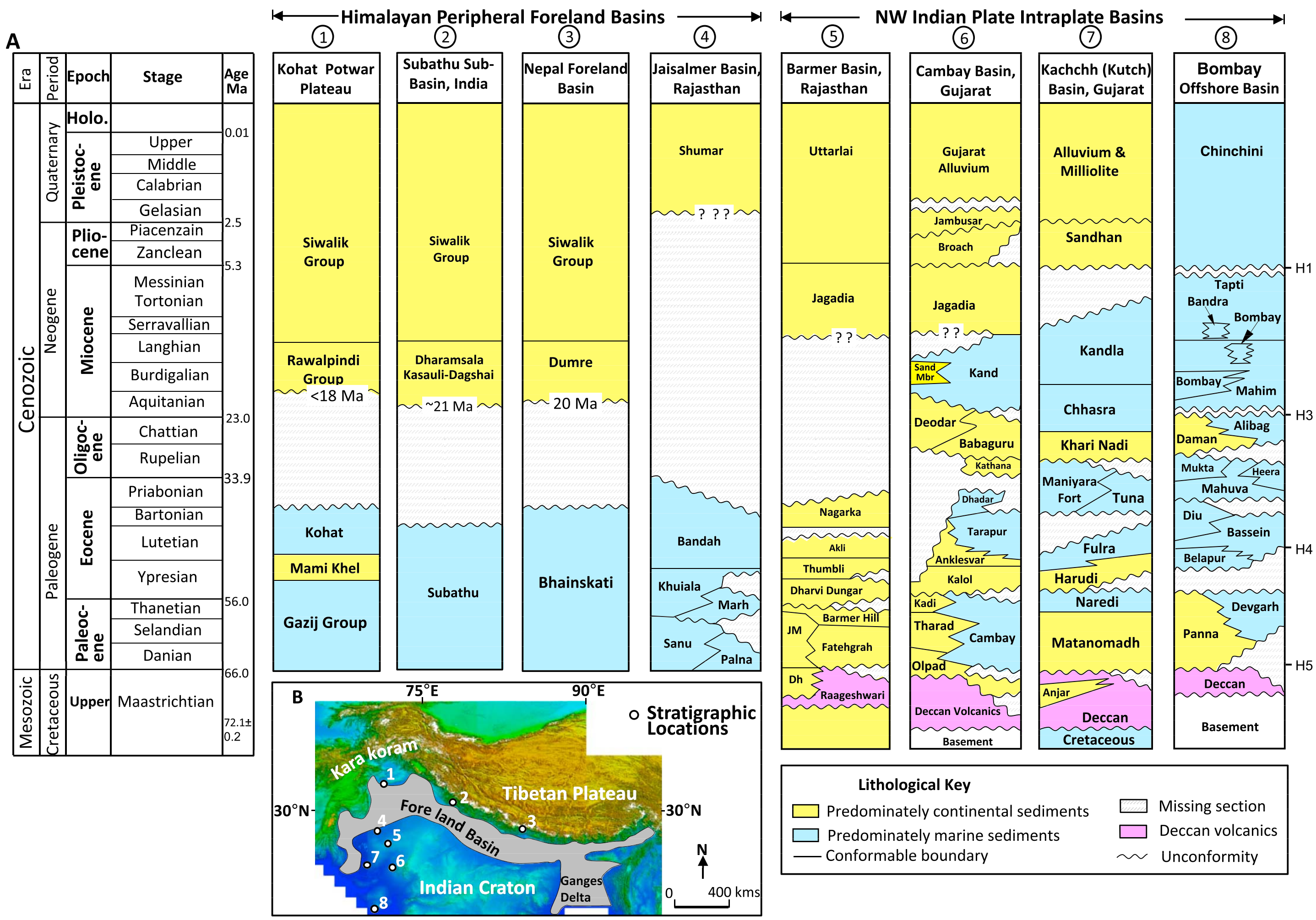

Figure 1. Stratigraphic summary columns of key reference sections of the Himalayan peripheral foreland basin (panels 1–4) and NW Indian plate intraplate basins (panels 5–8) highlighting the presence of the ~late Oligocene to early Miocene (BMU) unconformity. Inset map shows the location of the stratigraphic panels. JM = Jogdia Mandir Formation, Dh = Dhandlawas Formation. H numbers refer to the regionally mapped erosional events in the Bombay Basin (Chowdhary, 1975; Chowdhary & Singh, 1978; Kundal et al., 2005). The NW Indian plate intraplate basins (panels 5–8) are described and referenced extensively in the text. Considering the peripheral Himalayan foreland basin, furthest west, in the Kohat and Potwar Plateaus of Pakistan (panel 1), Miocene continental facies of the Rawalpindi Group (Murree and overlying Kamlial Formations) unconformably overlie Eocene marine facies of various formation names. In the Kohat Plateau, the youngest marine facies are the Kohat Formation of middle Eocene age (Pivnik & Wells, 1996) and rocks of similar age are recorded to the east in the Potwar Plateau (Shah, 2009). The Murree Formation of the uppermost Rawalpindi Group is considered to be of early Miocene age, based on mammal fossil evidence (Shah, 2009). In the Potwar Plateau, the base of the Rawalpindi Group overlying the Eocene rocks is magnetostratigraphically dated at 18 Ma (Johnson et al., 1985). In northern India (panel 2), the top of the marine Subathu Formation is dated biostratigraphically as Lutetian (Batra, 1989; Mathur, 1978). The overlying continental red beds are called the Dagshai or Dharamsala Formation, depending on location. Best dated is the Dharamsala Formation, which magnetostratigraphic analysis constrains to date from 20 Ma, with the lowest 250 m being undatable by magnetostratigraphy due to lack of continuity of the section (White et al., 2002). Maximum depositional ages provided by Ar-Ar dates of detrital white mica support the magnetostratigraphic dating, with modal mica ages at the base of the measured section of 22–24 Ma. Micas dated in samples from the thin unit below the magnetostratigraphic section yield similar Ar-Ar ages. The age of the Dagshai Formation has only been constrained using detrital minerals to provide a maximum depositional age, with an age of <31 Ma suggested for the base of the section by zircon fission track analysis (Najman et al., 2004) and < 25 and < 22 Ma from detrital mica Ar-Ar ages from samples within the unit (Najman et al., 1997). In Nepal (panel 3), the upper part of the marine Bhainskati Formation underlying the unconformity is considered to be of middle to late Eocene age in Central Nepal (Sakai, 1989), while late Paleocene to early Eocene fossils are reported in West Nepal (Fuchs & Frank, 1970). Above the unconformity, the base of the red beds of the Dumre Formation are dated at 20 Ma by magnetostratigraphy (Ojha et al., 2008), consistent with the maximum age of the formation dated at <19 Ma from detrital Ar-Ar dating of white micas (DeCelles et al., 2001). BMU = base Miocene unconformity.

data cover almost 85% of the Barmer Basin, and more than 300 exploration wells have been drilled in the basin. Approximately 3,000 line-km of vibroseis two-dimensional seismic were acquired by Cairn India between 1995 and 2000, while several generations of three-dimensional seismic data were joined into a mega-merged volume in 2013 and together cover ~6,200 km^2 of the basin, providing excellent seismic coverage for regional mapping.

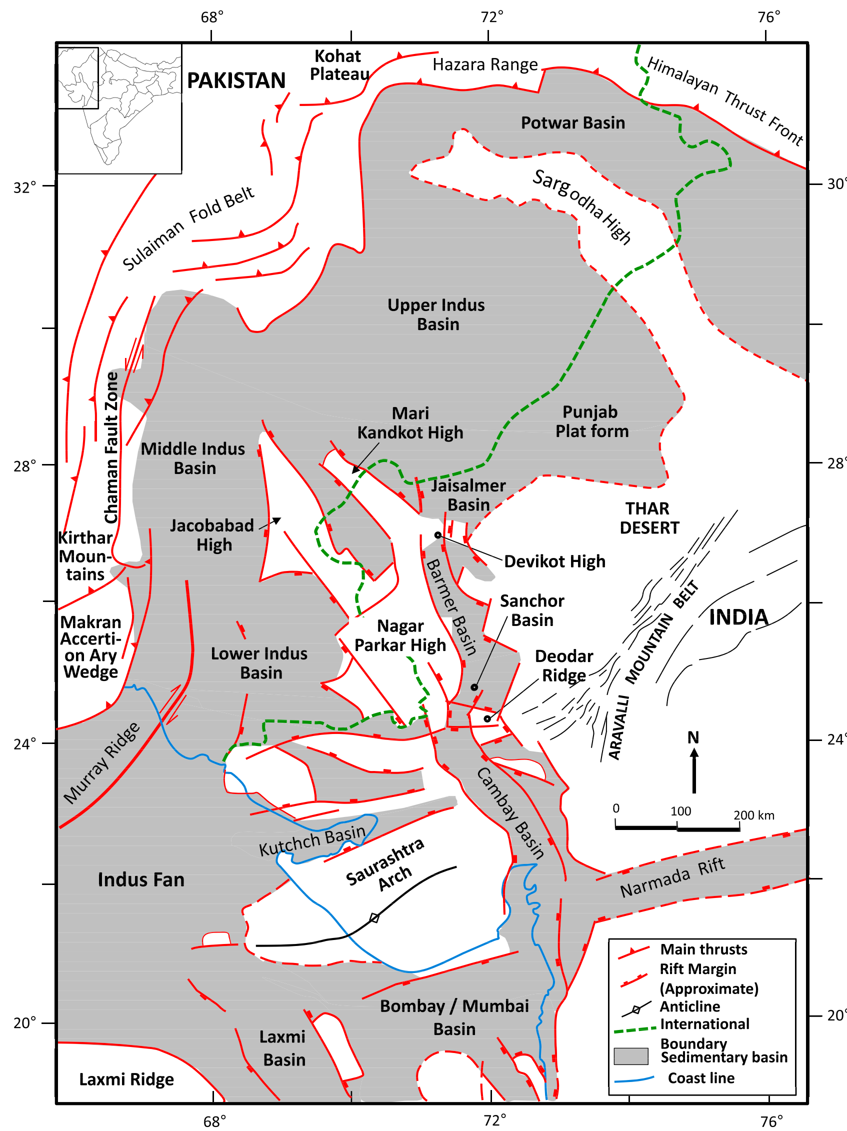

Figure 2. Outline sketch map of the main sedimentary basins of northwest India and southern central Pakistan. White areas denote where basement is either at or very close to surface. Thrust lines in the Sulaiman and Kirthar fold belts are indicative.

The BMU and its enclosing stratigraphy are not cored anywhere in the Barmer Basin. However, in the >300 wells drilled in the basin cuttings, samples were taken every 2 m and their lithology described, while a comprehensive suite of wireline logs was run in each well that included gamma ray (GR), neutron density, resistivity, and sonic logs. These data in 38 key reference wells, along with biostratigraphic, apatite fission track, and vitrinite reflectance (VR) data, form the basis of the descriptions provided below.

3.1. Basin Setting

The Barmer Basin, and its extension as the Sanchor sub-basin to the south (Figures 2 and 3), is a Cenozoic failed continental rift. The basin is the linear northward extension of the Cambay Basin within the West Indian Rift System, which extends for another 800 km southward into the Mumbai/Bombay Offshore Basin (Biswas, 1987; Calvès et al., 2011; Wandrey et al., 2004). The Barmer Basin is separated from the Cambay Basin to the south by the southwest-northeast aligned Deodar Ridge/Mehsana High, which are fault-bounded basement horsts of the Proterozoic Delhi Fold Belt (Bhandari & Chowdhary, 1975; Kaila et al., 1990). The Barmer Basin is separated from the Jaisalmer Basin to the north by the Devikot High (Siddiquie, 1963), a long-lived basement structure with a thin Mesozoic sequence preserved across the top of the high.

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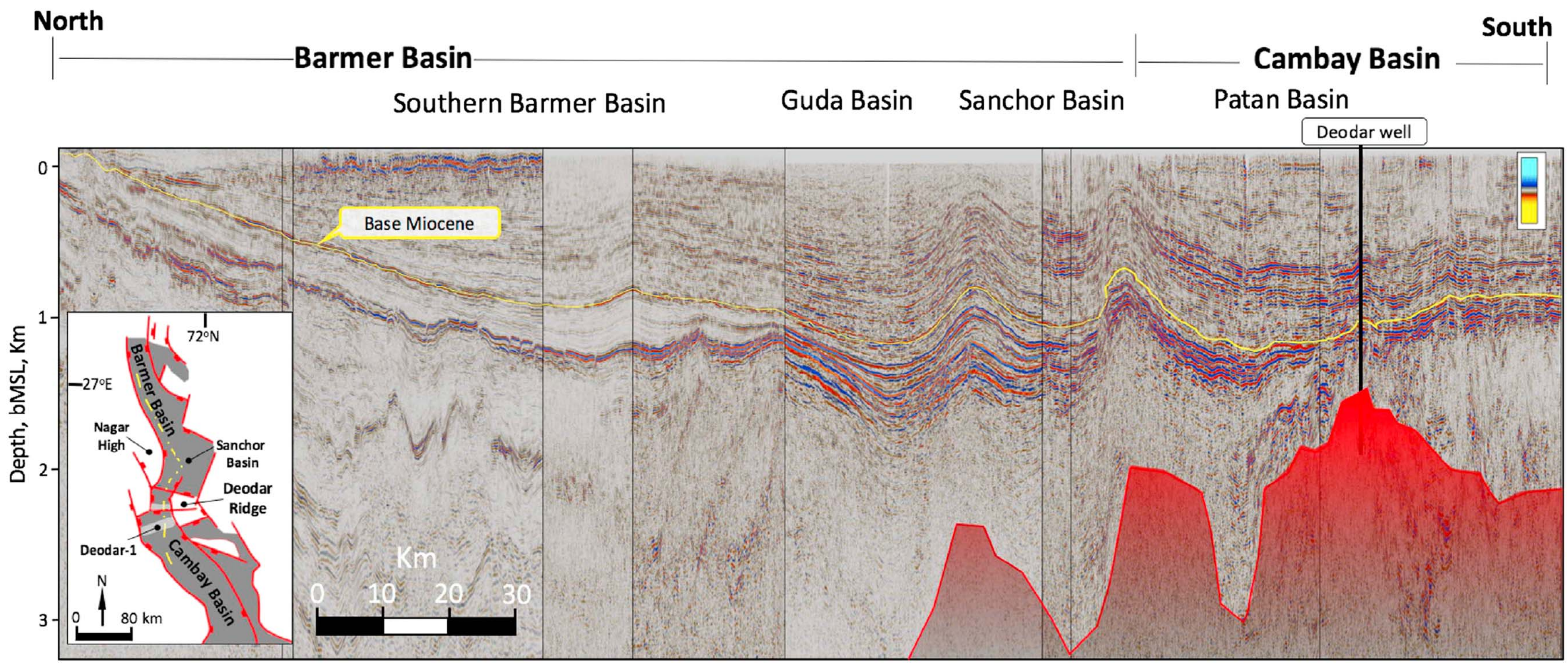

Figure 3. North-south oriented seismic section showing correlation of the base Miocene unconformity (BMU) through the Barmer, Sanchor, and Cambay Basins. Color bar on top right indicates seismic amplitudes from low (blue) to high (yellow). The BMU reflector is highlighted in yellow. Inset shows location of seismic line in the Barmer Basin, which can be located in Figure 2. Red overlay indicates the interpreted presence of basement as penetrated in the Deodar-1 well in the Patan Basin in the northern part of the Cambay Basin.

Gravity modeling indicates a depth to the Moho of 25–40 km across the Barmer Basin, consistent with regional studies of the crustal thickness of the Indian plate (Kaila et al., 1990; Singh et al., 2015).

3.2. Cenozoic Basin Stratigraphy

The Barmer Basin preserves a thick Neoproterozoic to Miocene stratigraphy overlain by Quaternary deposits (Dhir & Singhvi, 2012). The full stratigraphy of the basin is detailed in Compton (2009), Bladon, Burley, et al. (2015), and Dolson et al. (2015) and summarized below to provide context for the Cenozoic sediments and their relationships to the BMU.

At least 6 km of Jurassic to recent deposits overly the Neoproterozoic basement (Sharma, 2007). Mesozoic successions within the basin that precede the Cenozoic rifting comprise fluvial Lower Jurassic Lathi Formation and fluviolacustrine Lower Cretaceous Ghaggar-Hakra Formations. Paleocene-early Eocene syn-rift deposits within the Barmer Basin are dominated by fluvial, alluvial fan, lacustrine, and lake-delta facies of the Jogmaya Mandir, Fatehgarh, Barmer Hill, Dharvi Dungar, and Thumbli Formations. These rocks are overlain by the middle to late Eocene postrift continental facies of the Akli and Nagarka Formations, the latter recording the infilling of the rift basin topography.

Oligocene strata are absent in the Barmer Basin, and the BMU erodes into the underlying Eocene rocks across much of the basin, although the intensity of erosion decreases southward. Above the BMU, Miocene to recent deposits of the Jagardia and Uttarlai Formations comprise continental alluvial deposits. Recent alluvium and stabilized eolian dunes complete the basin fill.

3.3. The BMU in the Barmer Basin

3.3.1. Recognition and Mapping of the BMU in the Subsurface

In the seismic reflection data, the BMU within the Barmer Basin is imaged as a regional ~middle Eocene to early Miocene erosion surface. Due to erosion following regional southward tilting across a major structural hinge line that is one of the prominent Aravalli-trending basement ridges, the BMU is only preserved south of the Kaameshwari and Saraswati Fields (Figure 4); the BMU deepens southward, from only 600–700 m beneath the subsurface in the Raageshwari Field to 1,200 m subsurface in the Guda area. The unconformity surface has been folded and cut by later fault reactivations around the basin (Figure 5). Within the central and southern regions of the Barmer Basin and southward into the adjoining Sanchor sub-basin, the BMU is identified using two- and three-dimensional seismic data sets supplemented by wireline well logs, cuttings, and log correlations (Figure 6). Vertical seismic resolution is ~20 m within the Eocene-Miocene sequences.

In the northern part of the Barmer Basin, the younger regional uplift has resulted in erosion of progressively older stratigraphic units including the BMU (Figure 4). Consequently, the pre-erosion extent of the BMU across the northern part of the Barmer Basin remains speculative. However, projection of the uniform dip of the unconformity surface (~2°) northward indicates a missing section of ≈1 km above the northern outcrops. This is consistent with apatite fission track data that indicate that ~1 km of uplift and erosion have taken place in the northern part of the basin (Dolson et al., 2015). In comparison, the southern Barmer Basin underwent much less post-Oligocene erosion (typically $<$200 m) and preserves up to 250 m of Nagarka Formation sediments, although individual fold structures (such as in the Guda Field area) indicate as much as ~300 m of inversion where the Nagarka Formation has been completely removed.

The BMU is represented in the seismic reflection data by a clear, bright, regionally correlatable reflector, and evidence of scouring and channeling into the underlying sediments is seen on seismic sections (Figure 5). The lacustrine facies that make up the Eocene sequence below the BMU are recognized from the regionally extensive lignitic, sand-poor intervals separated by thick lacustrine shales (Dolson et al., 2015).

Above the BMU, the continental facies of the Jagadia Formation is typically ~250 m in thickness (Dolson et al., 2015). The base of the Jagardia Formation is marked by a sudden influx of predominantly fine-grained, carbonaceous sandstones, and the formation is characterized by an upward increase in shale as depicted in the GR logs (Figure 6).

Wireline logs in representative wells (Figure 6) reveal the lithological contrast at the BMU. In the sonic log in particular, a distinct change to higher acoustic velocities is observed beneath the unconformity, since these sediments are typically more compacted and/or cemented compared to those above.

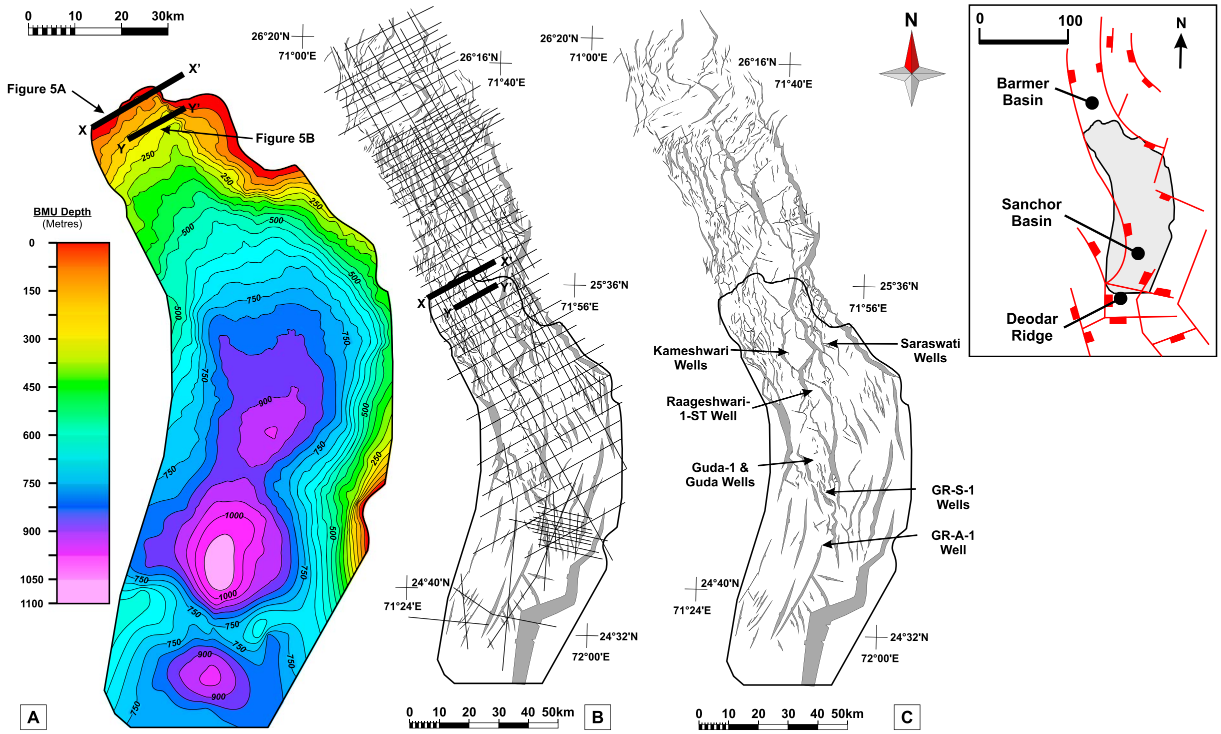

Figure 4. (a) Map of the base Miocene unconformity (BMU) surface, colored for true vertical depth in meters as determined from seismic and well data sets. (b) Map of the extensional fault network in the Barmer Basin displayed on the prerift (base Cretaceous) unconformity horizon. The gray shaded areas represent the hade of the faults, showing the horizontal displacement between footwall and hanging wall. The location and extent of the BMU surface is shown by the bold solid line, which is equivalent to the region shown in Figure 4a. Straight black lines show the extent of the merged three-dimensional seismic grid and selected regional two-dimensional lines. (c) Locations of wells referred to in the text displayed on the same fault map as in Figure 4b.

3.3.2. Dating the BMU

While the majority of the Nagarka Formation, beneath the BMU, comprises lacustrine sediments, a brief but distinct shallow marine incursion deposited thin calcareous shales that provide good biostratigraphic control. Bower et al. (2004; supporting information) document the occurrence of *D. Barbadiensis* and *Cribrocentrum reticulatum,* indicating that the Nagarka Formation is aged between the base of calcareous nannofossil zone NP17 and top NP19/20 (Agnini et al., 2014; Wade et al., 2011). The presence of *Helicosphaera lophota*, less commonly used as a range fossil, would restrict the upper age limit to NP18. Thus, the Nagarka Formation ranges between ~40 and 35 Ma in age, that is, middle to late Eocene. This is consistent with published work depicting a Bartonian-Priabonian (Naidu et al., 2017) or Priabonian (Compton, 2009; Dolson et al., 2015) age for this formation.

Above the unconformity in the Barmer Basin, the biofacies of the Jagardia Formation comprise an impoverished assemblage consisting of non-age diagnostic, long-ranging pollen species (supporting information; Bower et al., 2004). However, in the Cambay Basin, where the Jagadia Formation is defined, the age of the Jagadia Formation is constrained by its locally conformable lower contact with the well-dated marine part of the Kand Formation, established to be of lower-middle Miocene (Burdigalian) age (Chowdhary, 2004). The Jagadia Formation is thus considered to range from middle to upper Miocene in the Cambay Basin, and the base of this formation is seismically correlated from the Cambay Basin through to the Barmer Basin (Figure 3).

Dolson et al. (2015) used VR and apatite fission track analysis (AFTA) data to constrain the timing of erosion in the basin, which led to the formation of the BMU. Naidu et al. (2017) used the VR data of Dolson et al. (2015) to model exhumation as occurring from late Oligocene to Pliocene with the most pronounced exhumation occurring between 26 and 11 Ma while noting that precise dating was difficult to define.

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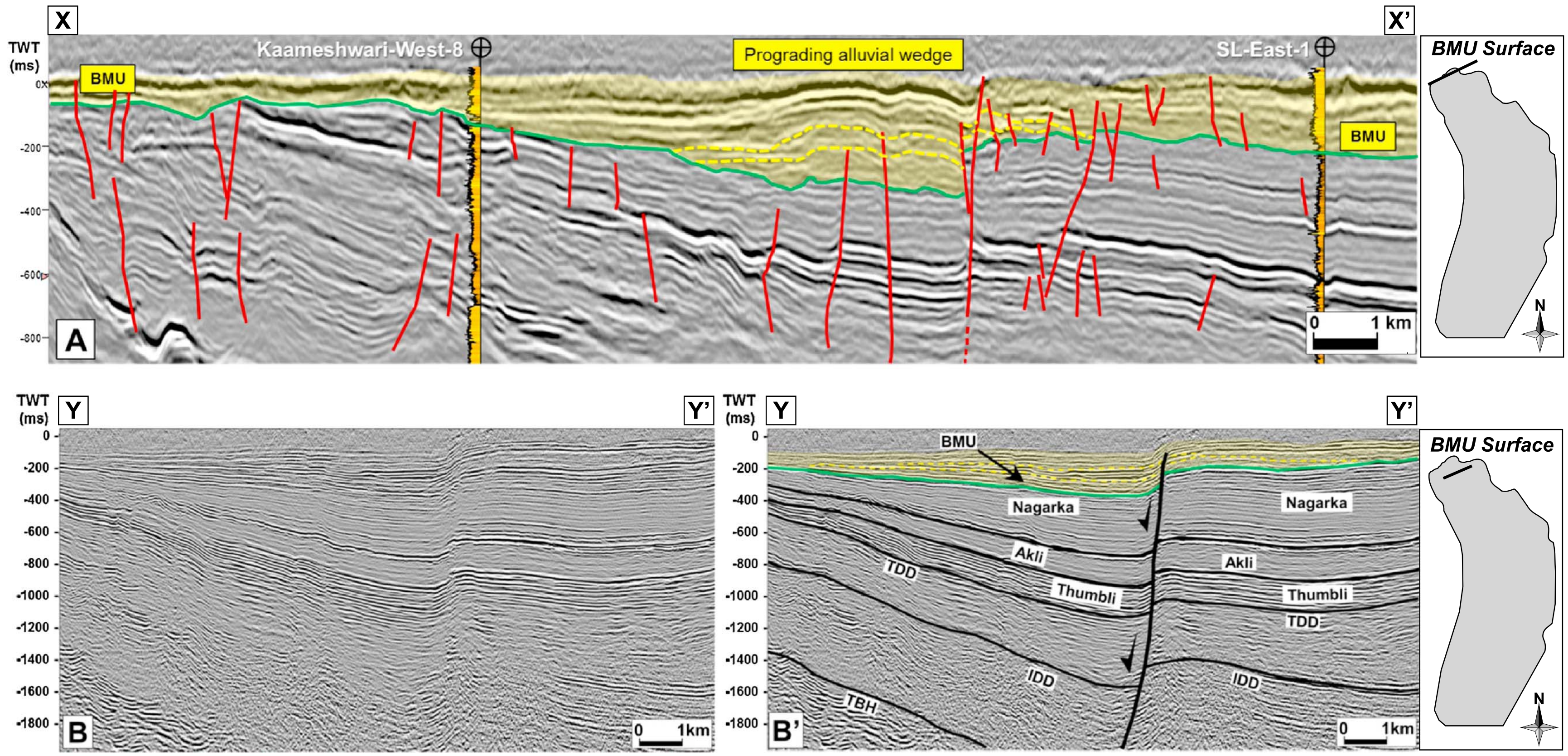

Figure 5. High-resolution grayscale dip seismic lines through representative west-east cross-sections of the base Miocene unconformity (BMU) showing surface features. Location of the seismic lines are shown in right hand insets and in Figure 4. Abbreviated horizons TDD = Top Dharvi Dungar; IDD = Intra-Dharvi Dungar; TBH = Top Barmer Hill. (a) The BMU is present as a bright, gently undulose reflector across the Barmer Basin, highlighted in green, locally cut by reactivated faults that extend from deeper in the section. The base of the BMU is clearly erosional and an alluvial wedge progrades across the normal fault in the center of the section. Truncation of older sediments under the BMU is clearly visible. Wells with gamma ray profile shown tied to the BMU surface.
(b) Example of the BMU surface cut by post-BMU fault activity within the central Barmer Basin. Note the strong truncation surfaces beneath the BMU. (left) Without interpretation, and (right) with picked horizons.

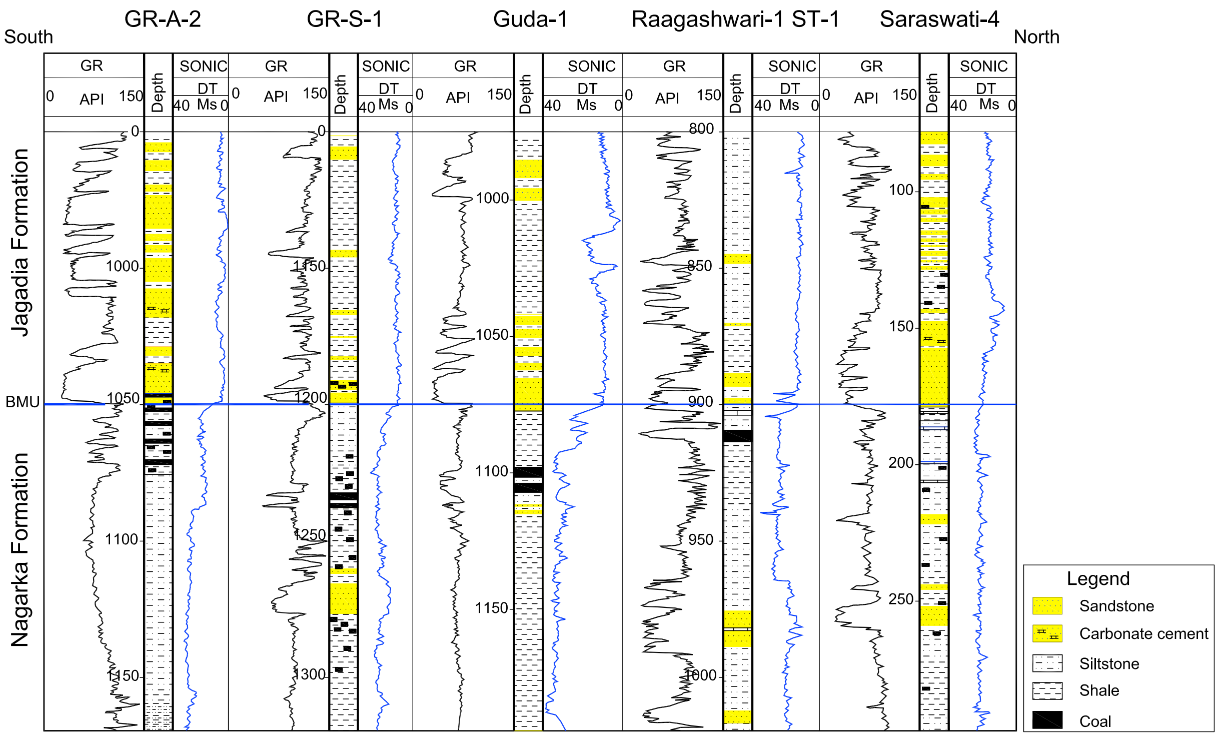

Figure 6. Summary wireline and lithogical logs of the Nagarka and Jagadia Formations, allowing identification of the base Miocene unconformity (BMU) in representative wells along a north-south transect across the southern Barmer Basin. Note the presence of ~10-m-thick, stacked, sharp-based sandstones in the Jagadia Formation and an overall sonic "slowness" of this formation. By contrast, the Nagarka Formation is dominated by coals and coaly shales with only thin sandstones and siltstones being developed. GR is the gamma ray log measured in API units from 0 clean sandstone to 150 units radioactive shale. Sonic log shows the interval transit time (Δt) of the rocks, the inverse of velocity, measured in microseconds per foot. The higher sonic velocities reflect greater burial and compaction of the sediments beneath the BMU. Wells located in Figure 4. Numbers give depth in meters.

4. Causal Mechanism for the Base Miocene NW Indian Plate Intraplate Basin Unconformities

4.1. BMU Development in the NW Indian Intraplate Basins Associated With Himalayan Tectonics?

Some previous research considered the formation of the BMU as related to Himalayan tectonics. Compton (2009) noted the similarity in age of the BMU in the Barmer Basin with an equivalent unconformity in the Jaisalmer Basin and related it to tectonics associated with the India-Asia collision (Figure 3 in Compton, 2009). Dolson et al. (2015) also considered the Barmer Basin BMU to be the result of inversion related to the India-Asia collision. We consider this potential relationship further below.

Rift basin inversion is common in orogenic forelands due to the compressive stress field (e.g., Hansen & Nielsen, 2003). In general, basin inversion begins when the neighboring orogenic zone has reached a sufficient elevation to impose significant forces on the foreland and lasts until the end of mountain building. However, the return to deposition above the BMU in the NW Indian intraplate basins (Figure 1), in rocks that continue to be affected by the stress field relating to the India-Asia collision, strongly suggests that this inversion is not responsible for the creation of the BMU in the NW Indian intraplate basins.

Regarding the possibility of formation of the BMU related to plate loading and flexure associated with the Himalayan orogeny, uplift in a flexural forebulge is also a frequently proposed mechanism to explain the occurrence of the Oligocene unconformity in the Himalayan peripheral foreland basin (e.g., Bera et al., 2010; DeCelles et al., 1998, 2004; Irfan et al., 2005; Najman et al., 2005; Najman & Garzanti, 2000). In the Himalayan peripheral foreland basin, a late Eocene to early Miocene unconformity has been consistently recorded along strike length of the basin, from Pakistan, through India, to Nepal (Figure 1, panels 1–3). If passage through a flexural forebulge were the cause of all the unconformities in the northern Indian basins, the age of these unconformities would be expected to decrease away from the mountain range,

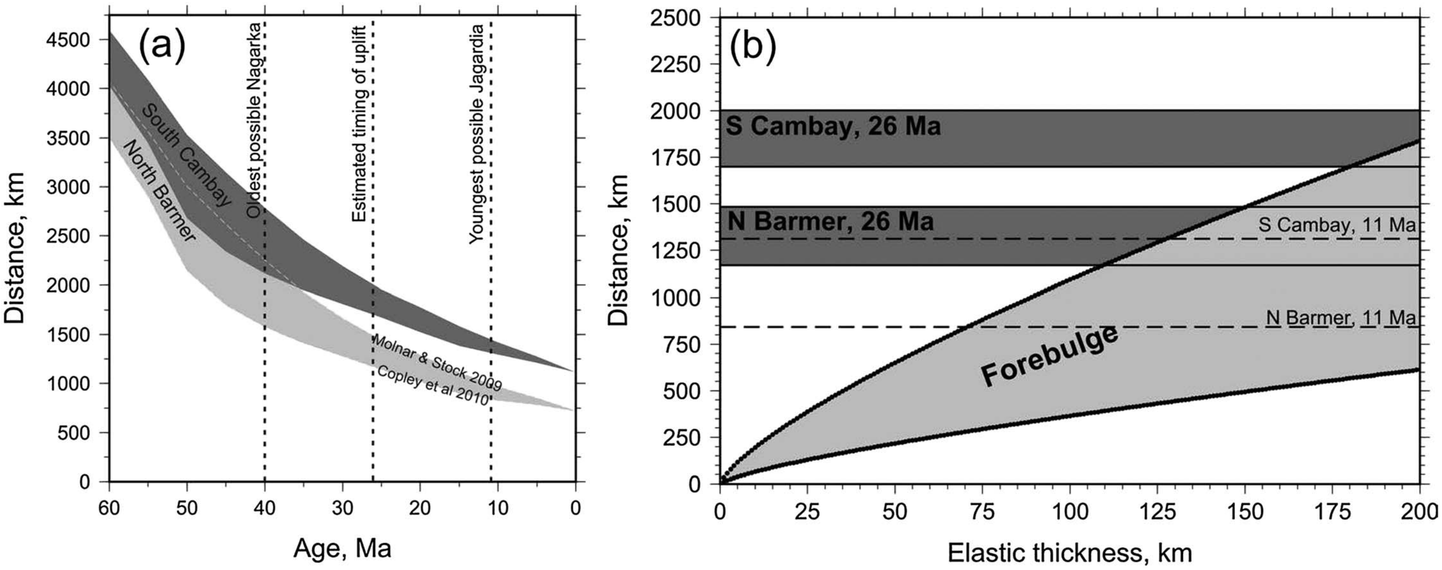

Figure 7. (a) The distance between the north Barmer (pale gray) and south Cambay (dark gray) basins and the migrating Himalayan deformation front. Shaded polygons define the range of possible distances, calculated by varying the age of collision, the amount of postcollision shortening within Asia, and the rotation poles used. (b) The pale gray polygon shows the distance between a load and the near and far margins of the associated flexural forebulge, as a function of the elastic thickness of the flexing plate. Horizontal shaded regions show the possible distances between the Himalayan front and the north Barmer and south Cambay Basins at 26 Ma (when the base Miocene unconformity is likely to have formed), taken from the calculations shown in Figure 7a. The horizontal dashed lines show the smallest possible distances, at the youngest possible age of the unconformity (11 Ma).

as the more distal basins would have entered the forebulge region at a later time. The broadly synchronous age of the unconformities in the NW Indian intraplate basins, and those exposed in the uplifted peripheral foreland basin in the Himalaya, therefore implies that the basins do not share a common flexural origin. However, if the elastic thickness is large enough, flexural forebulges can be hundreds of kilometers wide (e.g., ~600 km for an elastic thickness of 75 km; see calculations below). It would therefore be possible to create a synchronous unconformity over a large area as a result of, for example, base-level fall superimposed on a wide flexural forebulge. Therefore, in order to test whether flexure could have played a role in the formation of the BMU in the NW Indian plate intraplate basins, including the Barmer Basin, we have undertaken plate reconstructions, flexural modeling, and a comparison with estimates of the elastic thickness in the region.

All flexural effects relating to mass changes in the proto-Himalaya (such as due to thickening or erosion) have a horizontal length scale of effect that depends upon the elastic thickness of the Indian lithosphere. This length scale arises because the elastic thickness of the lithosphere determines the distance between the orogenic load and the forebulge that flanks the foreland basin. Any cause of the unconformity related to flexural loading or unloading in the Himalaya and Tibetan Plateau therefore only operates over this length-scale. Here we test whether proposed causes of the unconformity relating to Himalayan tectonics, as outlined in the Introduction, are compatible with the location of the BMU in the NW Indian intraplate basins.

4.1.1. Plate Reconstructions

We have used plate reconstructions to determine the distance between the NW Indian intraplate basins and the migrating Himalayan-Tibet deformation front during the Cenozoic. This is achieved by using the India-Somalia-NW Africa-North America-Eurasia plate circuit to calculate the distance between the Barmer Basin and stable Eurasia (based upon oceanic magnetic anomalies) and geological estimates of shortening in the India-Asia collision zone to infer the distance between stable Eurasia and the proto-Himalayan deformation front. We have calculated the maximum (i.e., southern Cambay Basin) and minimum (i.e., northern Barmer Basin) distances between the migrating deformation front and the BMU in the NW Indian intraplate basins. To calculate the location of the basins relative to stable Eurasia, we use the GPlates software package (http://www.gplates.org; Boyden et al., 2011). The reconstructions presented here use the India-Asia rotation poles of Molnar and Stock (2009) and Copley et al. (2010). We infer the location of the proto-Himalayan deformation front relative to stable Eurasia using the estimate of 900 km of shortening within Asia since the India-Asia collision from Van Hinsbergen et al. (2011) and Huang et al. (2015). As this value is difficult to determine, error bars of ±50% are used on this estimate. We assume that this shortening occurred at a steady rate since the collision, which we have taken to occur at the maximum and minimum generally accepted collision date values of ~60 Ma to by 50 Ma (DeCelles et al., 2014; Hu et al., 2015; Najman et al., 2010; Wang et al., 2011; Wu et al., 2014). By assuming that the shortening rate in Asia has been constant through time, we are likely to underestimate the distance between the deformation front and the BMU in the NW Indian intraplate basins, if the shortening rate actually decreased through time in tandem with the overall convergence rate (e.g., Molnar & Stock, 2009). By using a range of rotation poles, collision ages, and amounts of postcollision shortening within Asia, our models encompass a range of possible sizes of "greater India." Our estimated variation through time of the distance between the BMU in the NW Indian intraplate basins and the deformation front is shown in Figure 7a. The calculated polygons include the range of distances produced by varying the parameters described above.

4.1.2. Flexural Models

The late Oligocene, ~26 Ma, is the time suggested by AFTA and VR data for the formation of the BMU in the Barmer Basin (see section 3.3.2). At this time, the northern Barmer and southern Cambay Basins were located between ~1,200 and ~2,000 km from the paleodeformation front (Figure 7a). The range in this estimate represents the most extreme values calculated by varying the point of interest (i.e., northern Barmer or southern Cambay), the collision age, the rotation poles used, and the amount of postcollision shortening in Asia.

To test whether flexural effects could result in the formation of the BMU at the distances from the deformation front we have determined, a model is used for the flexure of an elastic plate overlying an inviscid half-space (see Turcotte & Schubert, 2002, for a derivation of the relevant equations). We use a model for the loading of the lateral end of a plate by a vertical line load and assume that there are no along-strike variations in the plate or load, so the model can be constructed along a two-dimensional plane perpendicular to the load (also known as a "broken plate" model and used as standard in this type of tectonic setting; Turcotte & Schubert, 2002). In this study we are concerned with the lateral position of the flexural forebulge, and not the amplitude, so the magnitude of the load plays no role in the analysis, as it has no effect on the length scale of the deformation. The distance between the point of loading and the flexural forebulge, where surface uplift occurs, is shown in Figure 7b. Greater elastic thicknesses result in flexure over a longer wavelength and the formation of a forebulge at greater distances from the deformation front. Our calculations show that an elastic thickness of $>$110 km is required to form the BMU in the northern Barmer Basin by uplift of a flexural forebulge at ~26 Ma. An elastic thickness of $>$190 km is required for this effect to extend to the southern Cambay Basin.

Because of the uncertainties involved in using AFTA and VR data to estimate the date of erosion to form the BMU (Naidu et al., 2017), we also perform calculations using the range of possible ages for the formation of the BMU based upon the paleontological age constraints (see section 3.3.2). Using the youngest possible age for the erosion to form the BMU of 11 Ma (youngest possible age of the Kand Formation), the equivalent elastic thickness estimates are 70 and 125 km. Using the oldest possible age of the Nagarka Formation (40 Ma), the estimates are 160 and 325 km. Comparison of these values to estimates of the elastic thickness of the Indian plate allows us to establish whether a flexural mechanism for the formation of the BMU is plausible, as detailed below.

Numerous attempts have been made to constrain the elastic thickness of the Indian plate using the variation in gravity anomalies, or foreland basin depth, along profiles through the northern Indian subcontinent (e.g., Bilham et al., 2003; Karner & Watts, 1983; Lyon-Caen & Molnar, 1985; Maggi et al., 2000; McKenzie & Fairhead, 1997; Watts & Burov, 2003). These studies obtained estimates of the elastic thickness ranging from $<$40 to $>$100 km, with a poorly constrained upper bound. Jackson et al. (2008) demonstrated that the choice of the location where the flexed plate is broken (i.e., the lateral end of the plate in the models, beneath the load, where a vertical load and bending moment are applied) has a strong control on the resulting estimate of the elastic thickness, for any method involving fitting gravity anomalies or basin geometries along profiles. In India, the location of the plate break is not known from observations, and if this parameter is not fixed in the inversions, then a wide range of elastic thicknesses of greater than ~30 km can fit the data in northern India equally well. Furthermore, Craig and Copley (2014) demonstrated that the combination of the permanent deformation of the flexing plate due to foreland faulting, the unknown yield stress of the lithosphere, and uncertainties regarding the total force transmitted through the lithosphere prevents the elastic thickness from being accurately estimated from profiles through forelands and oceanic outer rises.

An alternative approach to estimate the elastic thickness is to compare the topography and gravity anomalies in the frequency domain. The range of wavelengths over which these two quantities vary in tandem with each other is diagnostic of the elastic thickness of the region (McKenzie & Bowin, 1976; Watts, 2001). Most frequency domain estimates of elastic thicknesses have used the method of Forsyth (1985), which obtains the transfer function between the topography and the Bouguer gravity anomaly. However, McKenzie (2003) argued that in regions where topography has been removed by erosion, this method gives only an upper bound on the elastic thickness. McKenzie et al. (2014) proposed an alternative method, using recently collected satellite gravity data and the transfer function between the free-air gravity anomalies and the topography. They estimated that the elastic thickness in India is 25–32 km. This value is consistent with the estimates constructed using profiles through gravity anomalies or foreland basin depth, as described above, in cases where the "plate break" is not artificially fixed in the inversions (Jackson et al., 2008). Models using elastic thickness estimates in this range are also able to reproduce the observed width of the foreland basin, which is equivalent to the width of the negative gravity anomaly (McKenzie & Fairhead, 1997). For an elastic thickness of 25–32 km, the wavelength of the flexure is too short to have resulted in the formation of the BMU of the NW Indian intraplate basins in a flexural forebulge (Figure 7b).

4.2. The BMU Caused by Mantle Circulation?

With the length scale of flexural effects ruling out Himalayan tectonics as the cause of the BMU in the NW Indian intraplate basins, we must consider alternative mechanisms to explain the unconformity. We note the approximately coeval nature of the unconformity developed in the Himalayan peripheral foreland basin (Figure 1) and suggest that a single cause may explain both the BMU of the NW Indian intraplate basins and the Oligocene unconformity in the Himalayan foreland basin, based on their temporal equivalence. We turn to potential causes that can explain unconformities over regional scales. We describe how subplate mantle circulation can produce the effects we observe. This circulation could be the result of slab break-off beneath the proto-Himalaya, or the ongoing background convection of the mantle, decoupled from shallow tectonics. Presently available information does not allow us to distinguish between these potential causes, but either would represent the production of the BMU as a result of surface uplift due to mantle circulation.

We first examine the background convection of the mantle, unrelated to shallow tectonics. Upwelling in the convecting mantle can result in surface uplift of up to ~2 km, over length scales of up to tens of thousands of kilometers, but has also been observed to have effects on length scales $<$1,000 km and amplitudes of less than 500 m (e.g., Hoggard et al., 2016; Panasyuk & Hager, 2000; Winterbourne et al., 2014) For Rayleigh numbers (10^6–10^8; McKenzie et al., 1974) that correspond to the Earth's mantle, numerical and laboratory experiments (e.g., Larsen & Yuen, 1997; Schubert et al., 2001) suggest that transient temperature anomalies propagate through the convective system and would be expected to produce transient vertical motions at the Earth's surface. Such uplift can result in shallow sedimentary basins and continental margins switching from deposition to erosion, on timescales of hundreds of thousands to tens of millions of years (Burgess et al., 1997; Jones et al., 2012; Meyers et al., 1998; Rudge et al., 2008). A well-documented example of mantle dynamics affecting regional uplift is identified within the North Atlantic, where hot and buoyant material is advected beneath the plates from the Icelandic plume, resulting in a regional unconformity within the stratigraphic record of the Faeroe-Shetland and Porcupine Basins (e.g., White & Lovell, 1997). However, uplift and subsidence related to mantle circulation has been observed globally, not just near large plumes (Hoggard et al., 2016).

Alternatively, processes related to slab break-off have been proposed to explain the Oligocene unconformity within the Himalayan peripheral foreland basin (e.g., Husson et al., 2014; Najman et al., 2004). There are two aspects of this process that may cause uplift: the change in stresses being transmitted through the lithosphere and the flow in the surrounding mantle induced by the sinking of the slab (which would cause subsidence) and its replacement by hot asthenosphere (which would lead to uplift). In the case of changing the stresses being transmitted through the lithosphere, the wavelength of deformation would be comparable to that relating to other forces affecting the flexure of the elastic Indian plate and so is incompatible with the results of this study. However, the large-scale mantle flow that can result from slab break-off can potentially affect much larger regions (e.g., Husson et al., 2014). In this case, the timing of break-off can be used to assess the likelihood that this event led to the arrival of hot, less dense mantle material causing uplift and thus a regional northern Indian unconformity. A range of ages have been proposed for slab break-off events in the India-Asia collision zone (Webb et al., 2017), ranging from 45 Ma (Replumaz et al., 2014) to 25 Ma (Maheo et al., 2002) and as recent as 15 Ma (Husson et al., 2014). This range of suggested ages for slab break-off events are therefore compatible with the formation of the Oligocene unconformity in the peripheral foreland basin and the BMU in the NW Indian Intraplate basins, but a direct causal link is difficult to establish.

With the information we have available, it is therefore not possible to distinguish whether the BMU is directly related to slab break-off or to the background high-Rayleigh-number convection in the mantle, but we conclude that subplate mantle circulation of some form is the likely cause. Husson et al. (2014) also suggested a role for mantle flow in the vertical motions of India and Tibet. Although there is little evidence for the kilometer-scale uplifts and depressions in the Indian plate suggested at the present day by their models, or the gravity anomalies that would be associated with such deflections, their work demonstrates the potential spatial extent and amplitude of vertical surface motions driven by convective circulation.

Our results highlight that correctly understanding the cause of unconformity surfaces requires carefully mapping and correlating their full extent and their potential continuations into adjacent basins. The question then becomes, what controls the extent of such surfaces? The radically different expression of the BMU in terms of the time interval of missing sediments in the various NW Indian intraplate basins shows that the local depositional environment (e.g., basin depth, continental, or marine sedimentation) can play an important role in controlling whether an unconformity is formed, as well as its extent and erosional intensity. This effect limits our ability to know whether the lessening of the BMU southward corresponds to decreasing amounts of uplift or to more pre-uplift accommodation space reducing the effects of the vertical motions. To resolve this question, paleo-water-depth estimates are required. The combination of these effects means that in regions commonly thought to be dominated by the effects of local tectonics, the correct interpretation of unconformity surfaces requires regional-scale mapping of multiple basins; otherwise, the potential overprinting effects of mantle circulation could be misinterpreted.

5. Conclusions

The sedimentary successions of the NW Indian plate intraplate basins are punctuated by a major late Eocene-early Miocene unconformity called the base Miocene unconformity (BMU). We show that the NW Indian intraplate Barmer Basin unconformity is unrelated to Himalayan tectonics. The resumption of deposition post unconformity rules out inversion due to compression associated with India-Asia convergence as a cause, as these compressive forces are still present. The large distance between the NW Indian plate intraplate basins and the Himalayan front excludes flexural effects. The coeval nature of the Himalayan peripheral foreland basin and NW Indian plate intraplate basin unconformities may suggest a common cause. We propose that the unconformity within the Himalayan peripheral foreland basin and NW Indian plate intraplate basins may be a result of mantle circulation, due to either subducting slab break-off or high-Rayleigh-number background convection. Our results suggest that such circulation can produce geological signatures even in regions where collisional tectonics may be expected to dominate and suggests that the interpretation of unconformities rests strongly on mapping out their full extent and coeval structures in adjacent basins.

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