

Complex rift geometries resulting from inheritance of pre-existing structures: Insights and regional implications from the Barmer Basin rift

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a b s t r a c t

Structural studies of the Barmer Basin in Rajasthan, northwest India, demonstrate the important effect that pre-existing faults can have on the geometries of evolving fault systems at both the outcrop and basin-scale. Outcrop exposures on opposing rift margins reveal two distinct, non-coaxial extensional events. On the eastern rift margin northwest-southeast extension was accommodated on southwest and west-striking faults that form a complex, zig-zag fault network. On the western rift margin northeast-southwest extension was accommodated on northwest-striking faults that form classical extensional geometries.

Combining these outcrop studies with subsurface interpretations demonstrates that northwest-southeast extension preceded northeast-southwest extension. Structures active during the early, previously unrecognised extensional event were variably incorporated into the evolving fault systems during the second. In the study area, an inherited rift-oblique fault transferred extension from the rift margin to a mid-rift fault, rather than linking rift margin fault systems directly. The resultant rift margin accommodation structure has important implications for early sediment routing and depocentre evolution, as well as wider reaching implications for the evolution of the rift basin and West Indian Rift System. The discovery of early rifting in the Barmer Basin supports that extension along the West Indian Rift System was long-lived, multi-event, and likely resulted from far-field plate reorganisations.

1. Introduction

The rifted western and north-western margins of India, comprising the Cambay (Khambhat), Kutch (Kachchh) and Narmada rifts, remain relatively poorly understood, despite many years of study (e.g. Biswas, 1982; Gombos et al., 1995; Dolson et al. in press) and the presence of numerous hydrocarbon discoveries. Situated to the immediate north of the Cambay Basin (Fig. 1a), the Barmer Basin has received very little attention, even though the rift is a significant structure within the West Indian Rift System. The Barmer and Cambay basins are linked by the poorly defined Sanchor sub-basin (Fig. 1a), and together constitute a north-northwest trending rift system that extends for some 600 km into the Indian continent (Compton, 2009). The tectonics, extent, and relationship of the Barmer Basin with the rifted margins remain undocumented. However, the geology of the Barmer Basin rift provides important evidence that contributes to an understanding of the evolution of the West Indian Rift System as a whole. The Barmer Basin is a long (200 km), narrow (<40 km) and deep (6 km), north-northwest trending, low-strain (1.2 b 1.5), failed continental rift in Rajasthan, northwest India (Fig. 1). The Jaisalmer Basin immediately to the north is separated from the Barmer Basin by a basement structural high. The sedimentary

succession in the basin is dominantly Paleocene to Eocene in age, and represents an infilling of accommodation space from fluvial, through lacustrine, to shallow marine-influenced sediments (Sisodia and Singh, 2000; Compton, 2009; Dolson et al. in press). The basin fill overlies rift-basement rocks of the Precambrian Malani Igneous Suite (c.f. Pareek, 1981), and pre-rift sediments of the Mesozoic Lathi and Ghaggar-Hakra formations (Fig. 2) (Sisodia and Singh, 2000). Minor Deccan-related volcanic strata crop out along the eastern rift margin in the Sarnoo (Sarnu[sic]-Dandali Suite) and Tavidar areas (Basu et al., 1993; Roy and Jakhar, 2002; Sen et al., 2012), as well as in the subsurface (Raageshwari Volcanic Formation; Fig. 2). To date, the Barmer Basin has been interpreted as a latest-Cretaceous (Maastrichtian) to mid-Paleogene (Lutetian) rift (Compton, 2009) that opened in response to rifting of the Seychelles microcontinent from the Greater Indian continent near to the Cretaceous-Paleogene boundary (e.g. Collier et al., 2008; Reeves, 2013; Eagles and Hoang, 2014). Similarly, the Cambay (Khambat) Basin is an early Cretaceous to Paleogene, asymmetrical, north-northwest trending rift, containing pre-Deccan (Mesozoic) deposits of unknown thickness (Biswas, 1982, 1987; Gombos et al., 1995). Up to 4 km of Paleogene sediments overlie basin-wide deposits of Deccan volcanics (<2 km) within the Cambay Basin. This study focuses on the detailed structural analysis of key outcrops along the Barmer Basin rift margins, supplemented with subsurface interpretations based on well and seismic data. Certain aspects of the rift structure are comparable to those predicted for transtensional (oblique) rifts (Fig. 1b) (e.g. Withjack and Jamison, 1986; McClay and White, 1995; Clifton et al., 2000; Clifton and Schlische, 2001; McClay et al., 2002; Autin et al., 2013). However, outcrop exposure of two distinct extensional structural regimes on opposing rift shoulders, combined with an atypical rift-scale structure that deviates from conventional extensional margin, accommodation, and transfer zone models as a result of structural inheritance, indicates that rift evolution resulted from two, noncoaxial extensional events (e.g. Keep and McClay, 1997; Bonini et al., 1997; Morley et al., 2007; Henza et al., 2010, 2011). The interpretation of Barmer Basin rift evolution across a prestructured crust robustly explains many poorly understood aspects of the large-scale rift structure (Fig. 1b), and we discuss how the inheritance of pre-existing structures affected depocentre evolution and sediment routing in the study area during early-stage rifting. Subsequently, our findings are up-scaled into the wider context of the west Indian extensional margin.

2. Plate Tectonic Setting

During the multi-stage fragmentation of Gondwana throughout the Mesozoic, the Greater Indian continent became isolated from the African, Antarctic and Australian continents through a series of rifting events involving changes in plate motion, spreading-centre relocations, failed rifting, and mantle plumes (Fig. 3) (e.g. Patriat and Achache, 1984; Storey et al., 1995; Collier et al., 2008; Cande et al., 2010; Cande and Stegman, 2011; Torsvik et al., 2013; Reeves, 2013; Eagles and Hoang, 2014). The West Indian Rift System is the result of this long-lived succession of regional tectonic events. The orientation and configuration of rifts was, in part, controlled by major Precambrian structural grains (Gombos et al., 1995). Mesozoic rift events throughout northwest India are attributed to successive stages of India's northwards drift, accompanied by an anti-clockwise rotation of the Greater Indian continent, and formed a network of failed rift-basins that opened sequentially from north to south (Biswas, 1982, 1987; Gombos et al., 1995; Sheth, 2005a). Rifting was long-lived, possibly beginning as early as the late Triassic Period, and involved multiple rift events that continued into the Paleogene Period (Biswas, 1982; Sharma, 2007). East and west Gondwana separated during the early to middle Jurassic Period, facilitated by opening of the Mozambique and Somali proto-oceans (Fig. 3a) (Reeves & de Wit, 2000; Reeves, 2013).

Relative motion between the Madagascan and Greater Indian (c.f. Ali and Aitchison, 2014) continents may have generated transtension in the region between them during separation (Mascarene Rift of Bastia et al., 2010; Reeves, 2013). Accelerated sea-floor spreading between the Greater Indian and Antarctic continents occurred during the early Cretaceous Period at the expense of rifting in the Somali proto-ocean (Fig. 3b) (Gombos et al., 1995; Reeves & de Wit, 2000; Reeves, 2013). Prior to cessation of rifting in the Somali proto-ocean during the Aptian Age (120 Ma), a period of mutual spreading to the north and south of the Greater Indian continent, combined with a clockwise rotation of the Antarctic continent with respect to the African continent, represents the most likely period during which transtensional rifting occurred between the Greater Indian and Madagascan continents (Bastia et al., 2010; Reeves, 2013). Subsequent to the cessation of spreading in the Somali Basin, little relative motion occurred between the Greater Indian, African, and Madagascan continents, until the Greater Indian continent separated from the Madagascan continent during the Coniacian Age (88 Ma), a rifting event attributed to the Marion Plume (Fig. 3c) (Storey et al., 1995; Reeves, 2013). Thereafter, the Greater Indian continent drifted rapidly northwards (Reeves & de Wit, 2000; Reeves, 2013), with the spreading centre in the Mascarene Basin undergoing three major southwest ridge jumps at 80 Ma, 73.6 Ma and 70 Ma (Torsvik et al., 2013).

The Greater Indian continent was isolated from all fragments of east Gondwana by rifting of the Seychelles microcontinent from northwest India near to the Cretaceous-Paleogene boundary (Fig. 3d) (Collier et al., 2008; Armitage et al., 2010, 2011; Reeves, 2013). Accelerated divergence between the Indian and African continents caused rapid propagation of the Carlsberg Ridge during the Maastrichtian Age (69-65 Ma) (Fig. 3e) (Eagles and Hoang, 2014). The Mascarene Basin (Fig. 3d) was progressively abandoned in favour of short-lived spreading in the Laxmi and Gop basins (Fig. 3e) (Malod et al., 1997; Chaubey et al., 2002; Collier et al., 2008; Yatheesh et al., 2009; Armitage et al., 2011), prior to stabilisation of the Carlsberg Ridge between the Seychelles microcontinent and northwest India during the Danian Age that facilitated successful Seychelles rifting (Cox, 1989; White and McKenzie, 1989; Collier et al., 2008; Armitage et al., 2011; Torsvik et al., 2013; Eagles and Hoang, 2014). A period of contemporaneous spreading along the Carlsberg and Mascarene ridges isolated the Seychelles Plate (Fig. 3e), which rotated rapidly anticlockwise between 64 Ma and 59 Ma, and caused compression along the Amirante Trench (Cande et al., 2010; Eagles and Hoang, 2014). The common assumption of orthogonal rifting between the Seychelles microcontinent and northwest India has been challenged, with some authors (Misra et al., 2014) suggesting oblique rifting based upon outcrop work in the Western Deccan Strike-slip Zone (Fig. 1a inset). Successful separation of the Seychelles microcontinent from the Greater Indian continent was followed by two further jumps of the Carlsberg Ridge at 56 Ma and 41 Ma (Torsvik et al., 2013). Extrusion of the voluminous Deccan Traps (68e60 Ma) was contemporaneous with, and closely associated to rifting of the Seychelles microcontinent from the Greater Indian continent (Cox, 1989; White and McKenzie, 1989; Sheth, 2005a, 2005b, 2007; Collier et al., 2008), with volcanism commonly thought to have instigated rifting (Morgan, 1971; Plummer and Belle, 1995; Sen and Chandrasekharam, 2011). Evidence presented in support of the presence of a mantle plume beneath northwest India at the Cretaceous-Paleogene boundary (Fig. 3d; e.g. Sen and Chandrasekharam, 2011) include: 1) the characteristic trap-and-tail geometry of the Deccan Large Igneous Province and the Lakshadweep-Chagos Ridge (Fig. 1a inset) (White and McKenzie, 1989; Campbell and Griffiths, 1990); 2) radial drainage centred in western India (e.g. Cox, 1989; Rainbird and Ernst, 2001); 3) surface uplift (e.g. Campbell and Griffiths, 1990); 4) rapid extrusion (e.g. Borges et al., 2014) that predated rifting (Hooper et al., 2010); 5) a postulated Cambay triple junction (Sheth and Chandrasekharam, 1997); 6) primitive

Deccan Large Igneous Province geochemistry (Srivastava et al., 2014), and; 7) a southwards age progression of Deccan Trap lavas.

Although widely accepted, a plume origin for the Deccan Traps has been shown to match poorly with many of the features of Deccan Large Igneous Province geology (Sheth, 2005a, 2007). Evidence for post-volcanic uplift - not confined to the Deccan province - with antecedent drainage patterns, long-lived ($\sim 8 \times 10^9$ Ma) eruptions (Sheth and Pande, 2014), pre-Deccan planation surfaces that suggest tectonic stability, a 10° Reunion Mantle Plume palaeolatitude disparity, and a lack of evidence for thinned, sub-Deccan lithosphere, are all inconsistent with the plume-head model (Sheth, 2005a, 2007). Seychelles rifting is also suggested to have resulted from plate reorganisations underway long before the arrival of the Reunion Mantle Plume (Sharma, 2007; Collier et al., 2008) and continued after the main Deccan eruptions (Armitage et al., 2011). Similarly, rather than being formed as part of the Reunion Mantle Plume 'tail,' the Mascarene Plateau (and possibly Lakshadweep-Chagos Ridge) may be underpinned by thinned Proterozoic continental lithosphere that was situated between the Greater Indian and Madagascan continents prior to successful separation (Torsvik et al., 2013). This microcontinent (Mauritia) has since been concealed beneath flood basalts, fragmented by multiple mid-ocean ridge-jumps, and isolated in the Indian Ocean upon establishment of the Central Indian Ridge (Torsvik et al., 2013; Reeves, 2013). A postulated alternative to the plume-head model (e.g. Campbell and Griffiths, 1990) invokes the passive release of fertile lithosphere material, trapped within ancient lithosphere sutures, upon extension, to provide a significant contribution to the voluminous Deccan Trap magmatism (Sheth, 2005b). Similar models involving high mantle fertility beneath Iceland (Foulger et al., 2005; Foulger and Anderson, 2005) and heat accumulation beneath the Karoo Large Igneous Province (Hastie et al., 2014), provide further support for the generation of excessive volcanism during rifting in the absence of a mantle plume. Post India-Seychelles rifting, the Indian peninsula continued to drift northwards, undergoing variable plate-motions (Cande and Stegman, 2011), and directional changes resulting from the initial interactions of the Indian and Eurasian continents (Patriat and Achache, 1984) that collided between 57 Ma and 50 Ma (Green et al., 2008).

3. Rift margin structures

The Barmer Hills are situated along the central section of the western rift margin of the Barmer Basin (Fig. 1b), and are dominated by exposure of the Precambrian Malani Igneous Suite that forms the rift-basement (Fig. 2). This study incorporates and has mapped 10 km of the western rift margin fault system west of Barmer town, where Malani rift-basement rocks are juxtaposed against early syn-rift alluvial fan deposits of the Paleocene Jogmaya Mandir Formation (Fig. 4a). Basin controlling faults are predominantly northwest-striking, northeast-dipping (Fig. 4a and c), enechelon, and anastomosing structures (Fig. 5), with arcuate fault segments that are both hard- and soft-linked. Where hard-linked, offset fault segments are connected by zones of north-northwest to north-striking faults that form a broad series of anastomosing fault splays within the intervening accommodation zone (Fig. 5). The lack of a consistent marker horizon in this sequence precludes determination of displacement from field observations alone. However, adjacent seismic lines suggest displacement on the rift margin fault system is approximately 1 km. The cores of fault zones comprise a spectrum of fault rocks from fault (crush) breccia (Fig. 4b) to fault gouge (Fig. 4c) and are surrounded by brittle damage zones in the adjacent footwall and hanging-wall blocks. Kinematic indicators (slickenlines) are rare, but show predominantly normalsense dip-slip movement towards the northeast and southwest (Fig. 5). Hanging-wall faulting is both syn- and antithetic to the main rift-margin fault, predominantly north-northwest- and northeast-striking, and accommodates significantly less deformation. Dominant extensional fractures are north-northwest trending

(Fig. 5). The Sarnoo Hills are a series of southwest trending ridges situated along the central part of the eastern rift margin of the Barmer Basin (Fig. 1b), covering an area of approximately 3 km². The outcrop is situated in the immediate footwall of the eastern rift margin fault system, and exposes sediments of the Lower Cretaceous Ghaggar-Hakra Formation (Fig. 2) that comprise a series of fluvial sandstone successions interbedded with thick (30 m), red siltstones (Fig. 6). Faulting consists of a complex, zig-zag (e.g. Morley, 1995) fault-network (Fig. 7). West-striking, north-dipping, ridge-dissecting faults are situated between dominant southweststriking, northwest-dipping, ridge-parallel faults that accommodated significantly more deformation. Throw is variable, with southwest-striking faults showing significantly more throw (100 m) than west-striking faults (10 m) (Figs. 8 and 9). Both southwest- and west-striking faults facilitated normal-sense displacement to the northwest (Fig. 7). Fault slip on southweststriking faults is predominantly dip-slip (i.e. slickenline pitch $\approx 90^\circ$); however, average fault slip on west-striking faults displays a significant (15%) component of sinistral oblique-slip (pitch $\approx 75^\circ$; Fig. 4d and e). Extensive small-offset faulting, showing predominantly normal-sense dip-slip movement to the northwest, occurs in the zones of interaction between differing fault trends (Fig. 4f). A further west-southwest fault-set, that is subsidiary to the main southwest-striking block-bounding faults, is present within faulted blocks. Fault zones commonly comprise a thick (1 m) gouge-filled core (Fig. 4d), accompanied by narrow (≈ 5 m) brittle damage zones in the adjacent footwall and hanging-wall blocks. Dominant extensional fractures dip steeply ($\approx 75^\circ$) and are north-northwest trending (Fig. 7).

4. Subsurface structures

In order to relate the structures observed at outcrop to major rift-related faulting, particularly to structures in the Sarnoo Hills where the dominant southwest-striking faults are oblique to the north-northwest rift trend, interpretation of two-dimensional seismic data was conducted (Fig. 10). The ages of modelled subsurface horizons are poorly constrained, and four chronostratigraphical horizons have been interpreted within early basin deposits based on well data, generating three model zones. The seismic data indicate that, as observed at outcrop, large offset, northwest (Barmer Hills) and southwest (Sarnoo Hills) trending faults occur in the subsurface (Fig. 10a). Along the eastern rift margin, two sub-parallel and rift-parallel fault systems accommodated extension, generating terraces adjacent to the eastern margin of the rift (Fig. 10a). Northern and Southern terraces are separated by a major displacement (≈ 3000 m), southwest-striking, northwest-dipping, rift-oblique fault (Major Rift-Oblique Fault; Fig. 10a) that creates a rightwards-step of the terraces. The Southern Terrace constitutes a large, southeast-dipping, rift-internal ramp, resulting from the near complete loss of displacement on the South Eastern Rift-Margin Fault System to the east (Fig. 10a and 11a). Although a consistent 4 km of aggregate extension was accommodated on both fault systems bounding the Southern Terrace (Fig. 11a), a southwards loss of extension on one fault system (Mid-Rift Fault System, fault '9' on Fig. 11a) was coupled with a southwards gain on the other (South Eastern Rift Margin Fault System, fault '8' on Fig. 11a) showing a gradual, left-stepping transfer of displacement. In the north of the model, aggregate extension on fault systems bounding the Northern Terrace (faults '1' & '2' on Fig. 11a) approached 4 km towards the north. It follows that a consistent minimum of 4 km of aggregate extension was accommodated along the modelled length of the eastern rift margin (Fig. 11a); however, two lows in aggregate extension occur at either end of the Major Rift-Oblique Fault (fault '3' on Fig. 11a). Along the western rift margin, extension was accommodated on a single, rift-parallel fault system with extension increasing towards the south (Western Rift Margin Fault System; Fig. 11b).

5. Structural insights into rift evolution

Mapped structures in the Barmer Hills are rift-parallel with enechelon geometries, and form an anastomosing fault system (Fig. 5). The presence of both hard- and soft-linkages between faults suggests evolution from a series of isolated, northweststriking, northeast-dipping fault segments that linked to form a single, through-going fault system by fault-tip propagation, overstep, and subsequent breach of the intervening relay ramps, i.e. an isolated fault growth model (e.g. Peacock and Sanderson, 1994; Cartwright et al., 1995; Cowie et al., 2000; Walsh et al., 2003; Giba et al., 2012). Such relationships signify displacement transfer between faults within an evolving fault system (Gawthorpe and Hurst, 1993), and commonly occur in areas of active extension (e.g. Basin and Range Province, East African Rift System, and Gulf of Suez). Fault kinematic data show predominantly normal-sense dip-slip movement to the northeast, and combined with fault geometries that resemble those predicted to form during orthogonal rifting, are indicative of evolution under a northeast-southwest extensional regime. The juxtaposition of Malani Igneous Suite rocks in the footwalls of major rift margin faults against footwall-derived proximal fan sediments of the Paleocene Jogmaya Mandir Formation in the hanging-walls (Fig. 2), indicates that fault activity was contemporaneous with deposition of the basin fill. It follows that structures in the Barmer Hills were active during the main Paleocene Barmer Basin rift event, during which the majority of subsidence in the rift occurred as a result of northeast-southwest extension. Dominant faults in the Sarnoo Hills are southwest-striking, northwest-dipping, and occur as part of a complex, zig-zag fault network with west-striking, north-dipping faults (Fig. 7). Complex fault networks and zig-zag geometries occur where pre-existing structures interact with the evolving, rift-generated faults (e.g. Morley, 1995; Morley, 1999; Morley et al., 2004; Bellahsen and Daniel, 2005; Henza et al., 2010, 2011). The average 15° component of sinistral oblique-slip of west-striking faults, compared with the normal-sense dip-slip of southwest-striking faults, indicates that the former were non-ideal for extension, and are interpreted as being influenced by pre-existing rift-basement structures. As such, pre-existing west-striking structures acted as discrete, passive (e.g. Morley, 1999) breach-faults, and facilitated displacement transfer between southwest-striking faults that accommodated greater displacement (e.g. Bellahsen and Daniel, 2005). The northwest orientated slip direction on both fault-sets suggests that mutual slipping occurred (e.g. Nieto-Samaniego and Alaniz-Alvarez, 1997). The southwest-strike and northwest-orientated dip-slip of dominant faults indicates evolution under northwest-southeast extension, and is a distinctly different extensional regime to that exposed in the Barmer Hills. The presence of a dominant north-northwest trending extensional fracture set (Fig. 7) however, indicates that the Sarnoo Hills, like the Barmer Hills, underwent a period of northeast-southwest extensional deformation. The data presented from the Sarnoo and Barmer hills demonstrate that fault systems exposed along eastern and western rift margins display significantly different geometries and characteristics, with slip data indicative of evolution under northwest-southeast and northeast-southwest extension respectively. The near-perpendicular relationship of dominant faults on the eastern and western rift margins, in the Sarnoo and Barmer hills (Fig. 1b), attests to these differing extensional regimes. Major rift-parallel faulting in the Barmer Hills is characteristic of that expected to have evolved during the main Barmer Basin rift event. However, southwest-striking rift-oblique faults, and the northwest-southeast extension evident in the Sarnoo Hills, are anomalous, and allude to a previously unrecognised episode of rifting that was near-perpendicular (non-coaxial) to the main Barmer Basin rift event. Insights into the temporal relationships between the two, noncoaxial extensional events evident at outcrop were attained through generation of subsurface sediment thickness [True Vertical Thickness (TVT) or isochore] maps for each zone within our subsurface model (Fig. 12). Thick sedimentary packages at the base of southwest-striking, rift-oblique faults within the earliest rift deposits (zone 3; Fig. 12a), and an absence of activity on rift-parallel fault systems, indicates that activity on southwest-striking,

riftoblique faults, as observed in the Sarnoo Hills, preceded that on northwest-striking, rift-parallel faults, as observed in the Barmer Hills. Rift-parallel faults became active later within early rift deposits (zone 1; Fig. 12c). It follows that northwest-southeast extension preceded northeast-southwest extension; however, the poor age constraints available for the model horizons precludes dating of each extensional event.

6. Structural inheritance

At outcrop in the Sarnoo Hills (Fig. 7), small fault displacements (< 100 m) (Figs. 8 and 9), indicate strain accommodation was relatively minor. Although activity on pre-existing structures may be long-lived throughout rift evolution, it is common for such structures to be active only during the earliest stages of extension, and remain so until a more efficient, rift-ideal fault system is established (Morley et al., 2004). The proximity and sub-parallel orientation of dominant faults in the Sarnoo Hills (southwest-striking) to the Major Rift-Oblique Fault in our subsurface model (Fig. 10a), suggests evolution of the two is closely linked. In the Sarnoo Hills, the preservation of a fault network within which pre-existing structures played a significant role, indicates that structural activity occurred during the earliest stages of northwest-southeast extension. In comparison to the large deformation accommodated on the Major Rift-Oblique Fault adjacent to the outcrop (Fig. 10a), the minor deformation in the Sarnoo Hills suggests that strain localised onto the rift margin fault with continued extension. Upon strain localisation, the Sarnoo Hills would have been situated within a low-strain zone in the immediate footwall of this fault, resulting in cessation of activity on the structural system preserved at outcrop. The complete syn-rift sedimentary succession within the hanging-wall of the Major Rift-Oblique Fault, and its inclusion within the eastern rift margin fault system, indicates that it remained active throughout the evolution of the Barmer Basin, and was inherited during the second, northeast-southwest, Barmer Basin rift event. Incorporation (via inheritance) of the Major Rift-Oblique Fault into the evolving eastern margin fault system facilitated displacement transfer between right-stepping rift margin fault systems to the north and south (Fig. 13). Such a scenario has been described previously, both experimentally (Bellahsen and Daniel, 2005; Henza et al., 2010, 2011) and in nature (McClay and Khalil, 1998; Lezzar et al., 2002; Younes and McClay, 2002; Bellahsen et al., 2006; Whipp et al., 2014). However, the structural geometries and characteristics described here are not in accordance with a model of passive inheritance of a discrete, rift-oblique, pre-existing fault that transferred extension directly between offset rift margin fault systems (Fig. 13d). Significantly, the Southern Terrace (Fig. 10a), comprising a major southeast-dipping, rift-internal ramp, is not predicted by this, or any accepted extensional margin, accommodation or transfer zone models (e.g. Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998), which instead predict a northwest-dipping ramp between two right-stepping, southwest-dipping, synthetic fault systems (Fig. 13c). Importantly, the gradual left-stepping displacement transfer between faults bounding the Southern Terrace (Mid-Rift Fault System and South Eastern Rift Margin Fault System; '8' and '9' on Fig. 11a) is a relationship highly characteristic of soft-linkage between two offset synthetic faults separated by a relay ramp (e.g. Conneally et al., 2014). Such a model fits many of the features of the Southern Terrace in our model. The near complete loss of extension northwards on the South Eastern Rift Margin Fault System ('8' on Fig. 11a), and presence of extensive splays between the Major Rift-Oblique Fault and the Mid-Rift Fault System (Fig. 10a) suggest that, rather than transferring extension between the right-stepping, North and South Eastern Rift Margin Fault Systems directly (e.g. Bellahsen and Daniel, 2005, Fig. 13d), the inherited fault transferred extension onto the Mid-Rift Fault System (Fig. 13a and b). Subsequently, displacement was transferred onto the South Eastern Rift Margin Fault System to the east by soft-linkage with the Mid-Rift Fault System, forming a southeast-dipping relay ramp (Southern Terrace; Fig. 13b). Linkage of the Major Rift-Oblique Fault with

the Mid-Rift Fault System, rather than direct linkage of the North and South Eastern Rift Margin Fault Systems, as proposed, accounts for the numerous splays (Fig. 10a), low in aggregate extension (Fig. 11a), and basinwards thickening sedimentary wedge (Fig. 12c) in the accommodation zone between them (Fig. 13a). The basinwards thickening sedimentary wedge is an unusual tectono-sedimentary relationship, and suggests syn-depositional block-rotations in the accommodation zone between them (Fig. 13a), analogous to that typical of relay ramps. These are all common features of classical accommodation zones (e.g. Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998). This unusual accommodation structure (Fig. 13) illustrates one further example of how extensional fault systems may evolve during rifting within a changing stress-field (e.g. Morley et al., 2007).

7. Discussion

Based on the integration of field-based studies with subsurface interpretations, we show evidence for two different and distinct, non-coaxial extensional events during the early-stage evolution of the Barmer Basin rift, the ages of which are poorly constrained. However, stratigraphical analysis of early syn-rift subsurface deposits (Fig. 12) indicates that northwest extension (event 1) preceded northeast extension (event 2). The effect of structural inheritance is evident at both the outcrop (Fig. 7) and rift (Figs. 10 and 13) scale.

7.1. Oblique vs orthogonal rifting

Some of the observations presented herein could be interpreted to suggest rift evolution under transtensional (oblique) rifting (e.g. Withjack and Jamison, 1986; McClay and White, 1995; Clifton et al., 2000; Clifton and Schlische, 2001; McClay et al., 2002; Autin et al., 2013). Such features include: 1) rift-oblique (NW) extension in the Sarnoo Hills (Fig. 7); 2) rift-oblique faults dominant during early rifting with rift-parallel faults becoming dominant with continued extension (Fig. 12), and; 3) bipolar structural domains in the northern Barmer Basin (rift margin vs mid-rift; Fig. 1b). However, the spatial variation in oblique faulting throughout the rift [i.e. rift-oblique faulting prevalent in the north, but absent in the south (Fig. 1b)], and the incorporation of a rift oblique fault into the eastern rift margin, are inconsistent with such models. The exposure of two distinct extensional structural regimes on the Barmer Basin rift margins (Figs. 5 and 7) that can be correlated with temporally variable sub-rifts in the subsurface (Fig. 12), suggest that rift evolution resulted from two discrete, non-coaxial extensional events (e.g. Keep and McClay, 1997; Bonini et al., 1997; Morley et al., 2007; Henza et al., 2010, 2011), and provides an alternative interpretation to uniaxial transtensional (oblique) rifting. Crucially, the incorporation of a rift-oblique fault into the eastern rift margin (Fig. 13) requires that a rift oblique fault be present prior to rift margin evolution. As such, incorporation of the Major Rift-Oblique Fault into the eastern rift margin, and the long-lived activity of this fault throughout the evolution of the Barmer Basin rift, indicates that: 1) southwest-striking, rift-oblique faults existed prior to the main Barmer Basin rift event (event 2); 2) rift-oblique faults were favourable for reactivation, and; 3) in some cases (such as the Major Rift-Oblique Fault; Fig. 10a), rift-oblique faults were active for the duration of rifting. Further to this, the spatial variation of rift-oblique faulting within the rift (Fig. 1b) can be attributed to the presence or absence of faults generated during event 1, and the favourability of these faults for reactivation during the orthogonal Barmer Basin rift event (event 2). Rift evolution during event 2, over a crust containing spatially variable structures generated during event 1 (a prestructured crust), elucidates structural complications interpreted in the subsurface throughout the rift (Fig. 1b), and provides a robust alternative to transtensional (oblique) rifting.

7.2. Implications of structural inheritance

Pre-existing structures have been shown to have affected the evolution of extension orthogonal fault systems during both extensional events at varying scales (c.f. Section 6 'Structural Inheritance'). At the small (outcrop) scale, characteristics of the fault network exposed in the Sarnoo Hills (Fig. 7) indicates that fault activity occurred during the earliest stages of event 1. We suggest that the complex fault network preserved in the Sarnoo Hills represents a precursory, juvenile fault network from which the more efficient, Major Rift-Oblique Fault in our subsurface model evolved (Fig. 10a). At the rift scale, the structural geometries in our subsurface model differ from that predicted by a model of passive incorporation of a discrete, rift-oblique, pre-existing structure between two right-stepping rift margin fault systems (e.g. Bellahsen and Daniel, 2005, Fig. 13d). These disparities have important implications for early sediment routing and depocentre evolution. Conventional models of linkage between two southwest-dipping, synthetic, right-stepping faults predict formation of a northwest-dipping relay ramp (e.g. Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998), with northwest-orientated sediment inputs, and depocentres towards the centres of each fault segment (Fig. 13c). However, in the east Barmer Basin, activity of the Major Rift-Oblique Fault during event 1 (Fig. 12a and b), and the subsequent incorporation of this fault into the evolving Eastern Rift Margin Fault System during event 2 (Fig. 13a and b), resulted in an early depocentre at the base of the inherited structure (e.g. Bellahsen and Daniel, 2005, Figs. 12b, 13b; 13d), and formation of a southeast-dipping ramp (Fig. 13b). This structure is likely to have directed sediment input towards the southeast rather than to the northwest, as predicted by conventional models.

7.3. Regional context and implications

Early northwest-southeast extension within the Barmer Basin (event 1) was, until now, unrecognised. Poorly constrained subsurface horizon ages preclude accurate dating of this early extensional event. However, placing the northwest-southeast extension observed within the currently understood framework of regional tectonic events (c.f. section 2 'Plate Tectonic Setting') may provide some insights into its origin (Fig. 14). Differential movements between the Greater Indian and Madagascan continents during the separation of east and west Gondwana (Fig. 3a), may have initiated transtension between the two continents (Bastia et al., 2010; Reeves, 2013). Transtension is most likely to have occurred during the early Cretaceous Period as a result of a clockwise rotation of the Antarctic continent relative to the African continent (Reeves, 2013). Importantly, we suggest that the relative plate motions at this time would have been favourable for northwest-southeast extension in the Barmer Basin (event 1; Fig. 14a). As such, the northwest-southeast extension exposed on rift-oblique faults in the Sarnoo Hills (Fig. 7), and the early rift-oblique depocentres (sub-basins) evident in the Barmer Basin subsurface (Fig. 12), may be manifestations of transtension between the Greater Indian and Madagascan continents during the separation of east and west Gondwana (Fig. 3a and 14a) (e.g. Bastia et al., 2010; Reeves, 2013). We speculate that the present day Barmer Basin rift is underlain by an older, Jurassic or Cretaceous rift system orientated northeast-southwest. Equivalent structures may occur in the Kutch (Kachchh) and Cambay basins (e.g. Biswas, 1982; Biswas, 1987; Gombos et al., 1995), and may also be hidden beneath thick Deccan-related volcanics on the broad west Indian continental shelf (Reeves, 2013). After separation of the Greater Indian and Madagascan continents (88 Ma; Storey et al., 1995), relative plate motions (Fig. 3d and e) (c.f. Reeves, 2013) were unlikely to have generated northwest-southeast extension throughout northwest India. The northeast-southwest divergence of the Greater Indian and Madagascan continents, and subsequently the Greater Indian continent and Seychelles microcontinent (Reeves, 2013), suggest the regional extension vector was northeast-southwest orientated (Fig. 14b). This proposed regional extension is sub-parallel to the northeast-southwest (rift-orthogonal) extension inferred to have occurred during the

main Barmer Basin rift event based on exposures in the Barmer Hills (Fig. 5). Placing our observations within the currently understood regional tectonic framework, therefore, suggests the main phase of subsidence in the Barmer Basin and the Barmer Basin rift event (event 2) was likely orthogonal, and is an intracontinental northerly manifestation of attempted rifting in the Gop and Laxmi basins (e.g. Malod et al., 1997; Chaubey et al., 2002; Collier et al., 2008; Yatheesh et al., 2009), and subsequent separation of the Seychelles microcontinent from northwest India (Fig. 14b). The potential for contemporaneous Maastrichtian rifting in the Barmer, Gop, and Laxmi basins may allude to a period of rifting throughout northwest India that pre-dated the main phase of Deccan eruptions (~65 Ma; Chenet et al., 2007). It is likely that early rifting in the Barmer Basin formed a northwest trending, linear series of rifts in conjunction with early rifting in the Cambay Basin to the south (Fig. 14a) (e.g. Biswas, 1982). Rift segments were probably not linked directly, rather formed a linear series of isolated pockets of extension (rift segments), as occurs during the earliest stages of continental-rift evolution (Nelson et al., 1992). A disparity in major rift structural trends at this time, northeast- and northwest-trending in the Barmer and Cambay basins respectively (Fig. 14), may result from an early control of basement structures on rift evolution, as observed in the Permo-Triassic basins of southern Britain (Chadwick and Evans, 1995). As such, we suggest that the Barmer and Cambay basins formed a north-northwest trending series of rifts here termed the Barmer-Cambay Rift System that evolved from at least the early to mid-Cretaceous Period. The Barmer-Cambay Rift System, therefore, is long-lived and mostly resulted from external plate boundary forces generated as the western margin of the Greater Indian continent fragmented during isolation from east Gondwana, and in the wake of the continent's rapid northwards migration throughout Cretaceous and Paleogene times (e.g. Sharma, 2007). The common assumption that the Réunion Mantle Plume triggered rifting throughout west India at the Cretaceous-Paleogene boundary (Morgan, 1971; Plummer and Belle, 1995; Sen and Chandrasekharam, 2011) is not consistent with the interpretation presented herein of early northwest-southeast extension within the Barmer Basin, or the formation of a pre-Deccan Barmer-Cambay Rift System. A mantle-plume origin for the Deccan Traps has been questioned, with many aspects of the Deccan geology inconsistent with that predicted by the plume-head model (Sheth, 2005a, 2005b, 2007), and we suggest that the two non-coaxial episodes of rifting observed within early deposits of the Barmer Basin are better explained by a model of plate reorganisations that initiated long before the arrival of the Réunion Mantle Plume (e.g. Sharma, 2007; Collier et al., 2008). This, combined with a lack of evidence for significant pre-Deccan regional unconformities, and only minor Deccan-age volcanism within the Barmer Basin (Basu et al., 1993; Sen et al., 2012), suggests that rifting did not occur above anomalously hot asthenosphere, despite the rift being situated within the inferred limits of the Réunion plume-head (Fig. 3d) (e.g. Cox, 1989; White and McKenzie, 1989). We suggest models that account for the generation of excessive volcanism during rifting in the absence of a mantle plume (e.g. Foulger et al., 2005; Foulger and Anderson, 2005; Sheth, 2005b; Hastie et al., 2014) should be given consideration as viable alternatives to explain the geology of these regions, rather than a widespread acceptance of the plume-head model that has, in the case of the Deccan, been shown to poorly explain many aspects of the regional geology (Sheth, 2005a, 2007).

8. Conclusions

Outcrop exposure on opposing margins of the Barmer Basin rift reveal two different and distinct, non-coaxial extensional events. Northwest-southeast (Sarnoo Hills) and northeast-southwest (Barmer Hills) extensional regimes are exposed along the eastern and western rift margins respectively. Subsurface interpretations show that activity on southwest-trending (rift-oblique) faults preceded that on northwest-trending (rift-parallel) faults.

It follows that northwest-southeast extension (event 1) preceded northeast-southwest extension (event 2). We suggest early northwest-southeast rifting (event 1) is a manifestation of transtension between the Greater Indian and Madagascan continents during the separation of east and west Gondwana. Equivalent rifts may occur in the Kutch and Cambay basins. In the Sarnoo Hills, discrete, pre-existing rift-basement (W-striking) structures were utilized passively as breach faults within the evolving southwest-striking fault systems during early northwest-southeast extension (event 1). Subsequent incorporation (via inheritance) of a significant rift-oblique fault into the eastern rift margin during the Barmer Basin rift event (event 2; NE-SW) formed an atypical accommodation structure not predicted by conventional models that has important implications for early sediment routing and depocentre evolution. Although certain aspects of the Barmer Basin rift structure have affinities with transtensional (oblique) rifts, rift evolution over a crust containing spatially variable structures generated during early rifting (a pre-structured crust), elucidates structural complications interpreted in the subsurface throughout the rift, and provides a robust alternative to transtensional (oblique) rifting. The longevity of rifting in the Barmer-Cambay rift system, and an apparent lack of large-scale pre-Deccan uplift and excessive volcanism within the Barmer Basin, suggests that rifting in the Barmer Basin was unlikely to have occurred above a plume-head of anomalously hot asthenosphere. As an alternative to plume-induced rifting at the Cretaceous-Paleogene boundary, we suggest that a model of far-field plate reorganisations, that involved long-lived, multi-event Triassic to Paleogene rifting, is more appropriate for the northwest Indian region.

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Figures

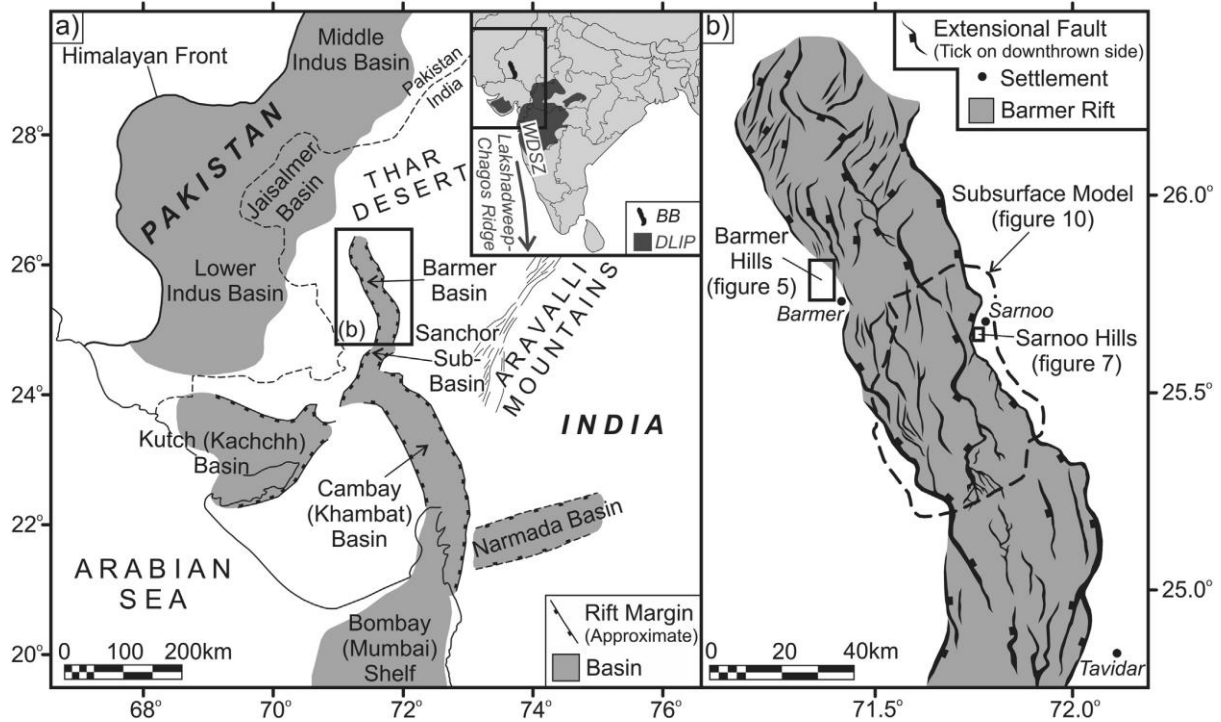


Fig. 1. (a) Northwest Indian basins (location map inset). WDSZ $\frac{1}{4}$ Western Deccan Strike-Slip Zone, BB $\frac{1}{4}$ Barmer Basin, DLIP $\frac{1}{4}$ Deccan Large Igneous Province; (b) Structure map of the Barmer Basin at the Pre-Rift Unconformity horizon. The location of the Sarnoo and Barmer hills, and the extent of the subsurface model included in this study are indicated.

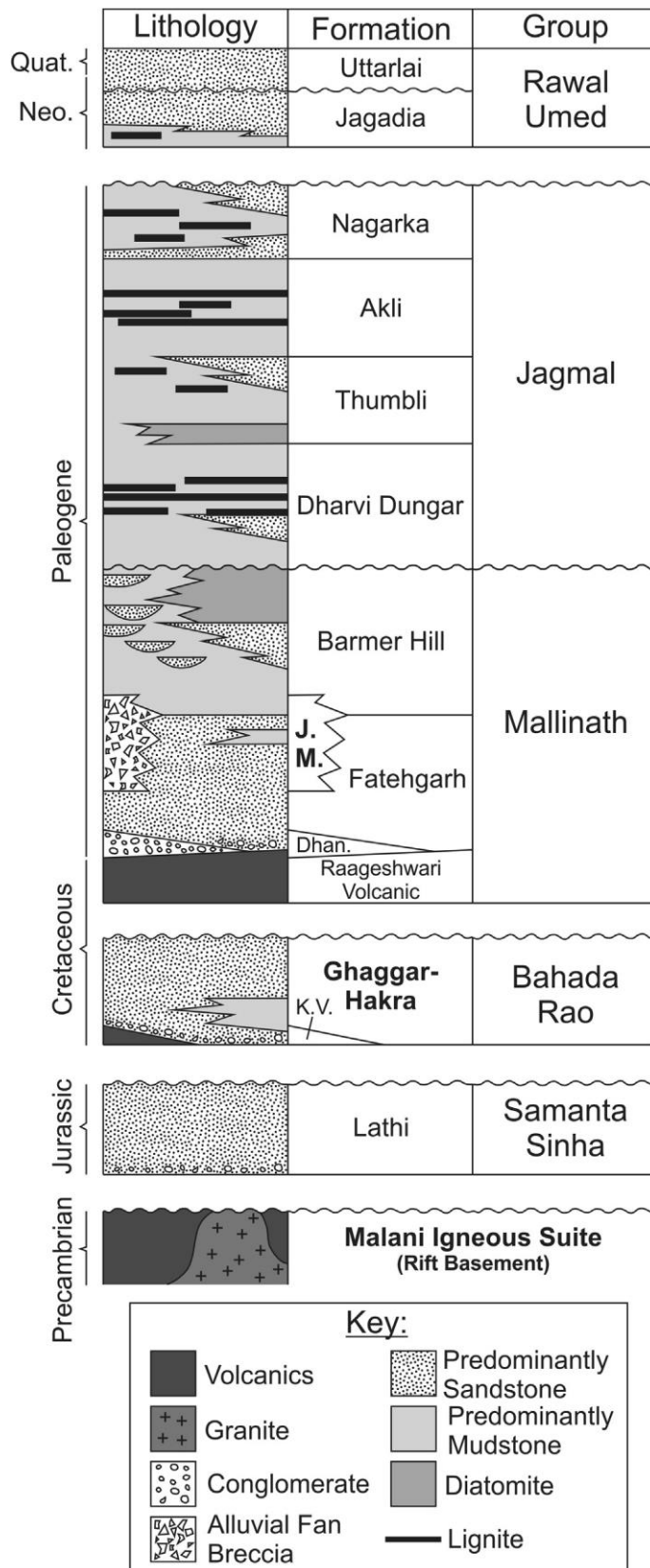


Fig. 2. Stratigraphy of the Barmer Basin. Stratigraphy relevant to this work is highlighted in bold. Quat. ¼ Quaternary; Neo. ¼ Neogene; J.M. ¼ Jogmaya Mandir Formation; Dhan ¼ Dhandlawas Formation; K.V. ¼ Karentia Volcanic Formation.

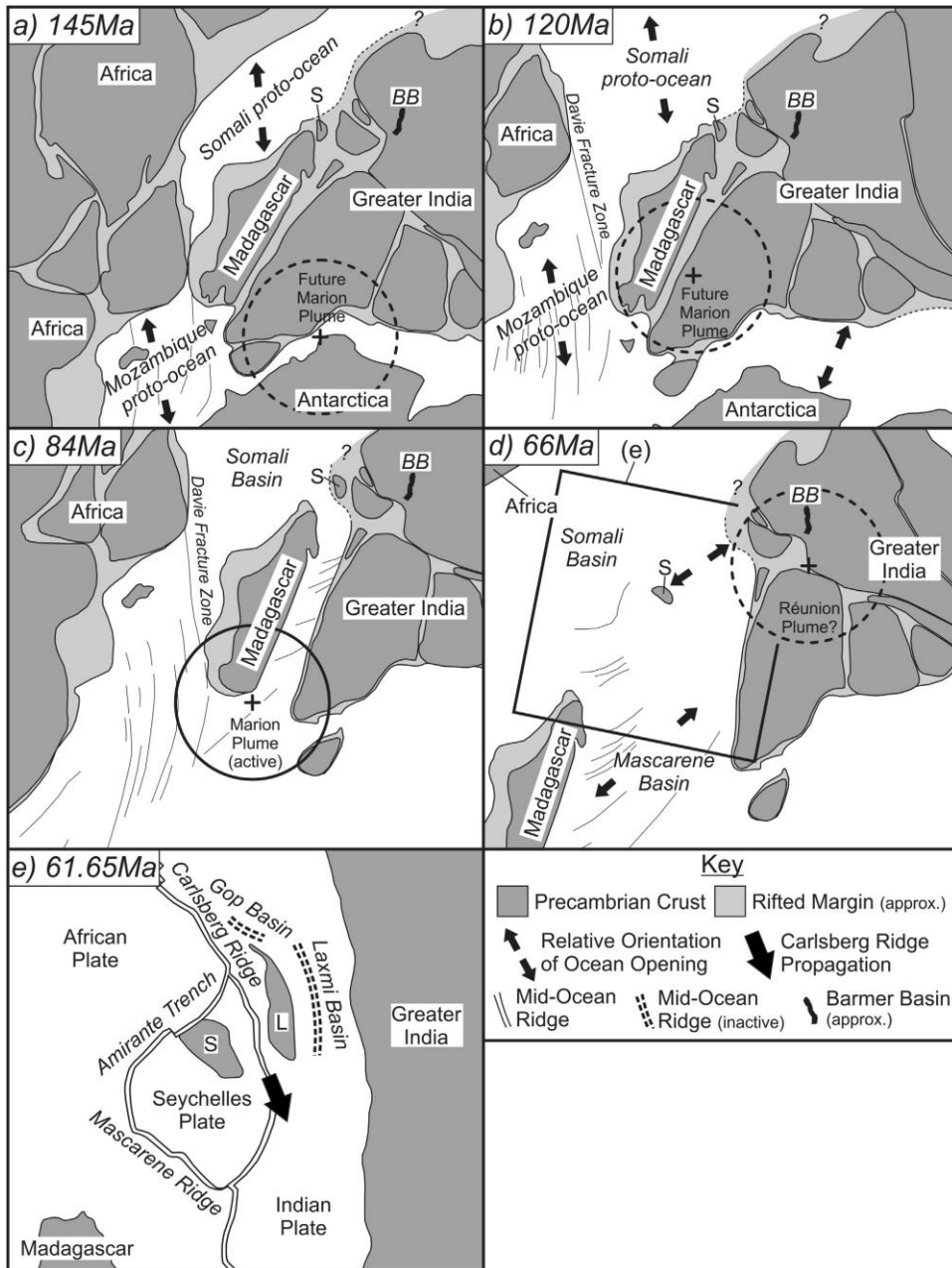


Fig. 3. Paleogeographic reconstructions of the Greater Indian continent during isolation from east Gondwana [after Reeves, 2013 (aed) and Eagles and Hoang, 2014 (e)]. (a) 145 Ma: Opening of the Somali and Mozambique proto-oceans. The Antarctic continent starts to rotate clockwise; (b) 120 Ma: Rifting between the Greater Indian and Antarctic continents at the expense of rifting in the Somali proto-ocean; (c) 84 Ma: Rifting between the Greater Indian and Madagascan continents; (d) 66 Ma: Plate reorganisation between the Greater Indian and African continents; (e) Establishment of the Carlsberg Ridge and separation of the Seychelles microcontinent from northwest India at the expense of spreading in the Gop and Laxmi basins; S $\frac{1}{4}$ Seychelles; L $\frac{1}{4}$ Laxmi Ridge; BB $\frac{1}{4}$ Barmer Basin; Solid plume-head $\frac{1}{4}$ active Marion Plume (c); Dashed plume-head $\frac{1}{4}$ future Marion Plume (a & b) and hypothetical Réunion Plume (d).

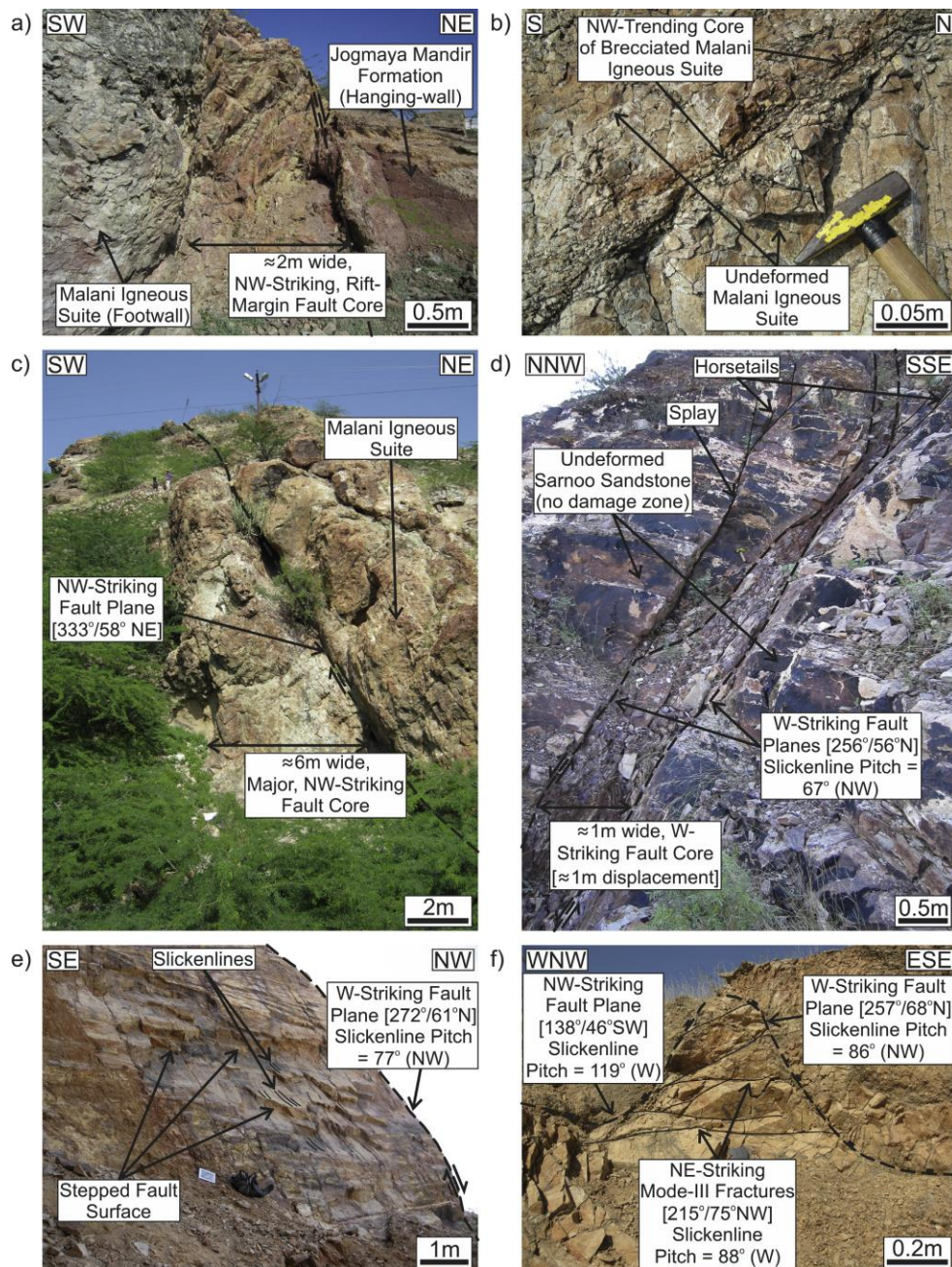


Fig. 4. Field Photographs from the Barmer (a, b, & c) and Sarnoo (d, e, & f) hills (see Fig. 5 and 7 for photograph locations). Fault measurements are recorded as strike/dip/sense and pitch-in-plane is measured from fault strike with the general lineation trend shown in brackets. a) Malani Igneous Suite Rift Basement juxtaposed against footwall-derived alluvial fan sediments of the Paleocene Jogmaya Mandir Formation; b) Tectonic breccia in a narrow (≈ 0.2 m) shear zone within the Malani Igneous Suite (note the lack of fault-gouge); c) NW-striking, NE-dipping fault in the immediate (≈ 100 m) footwall of the western rift margin fault system; d) Gouge-filled W-striking fault core within the Sarnoo Sandstone succession (note the 23° component of sinistral oblique-slip); e) W-striking fault-plane showing 13° component of sinistral-oblique-slip.; f) Zone of interaction between NW- and W-striking faults.

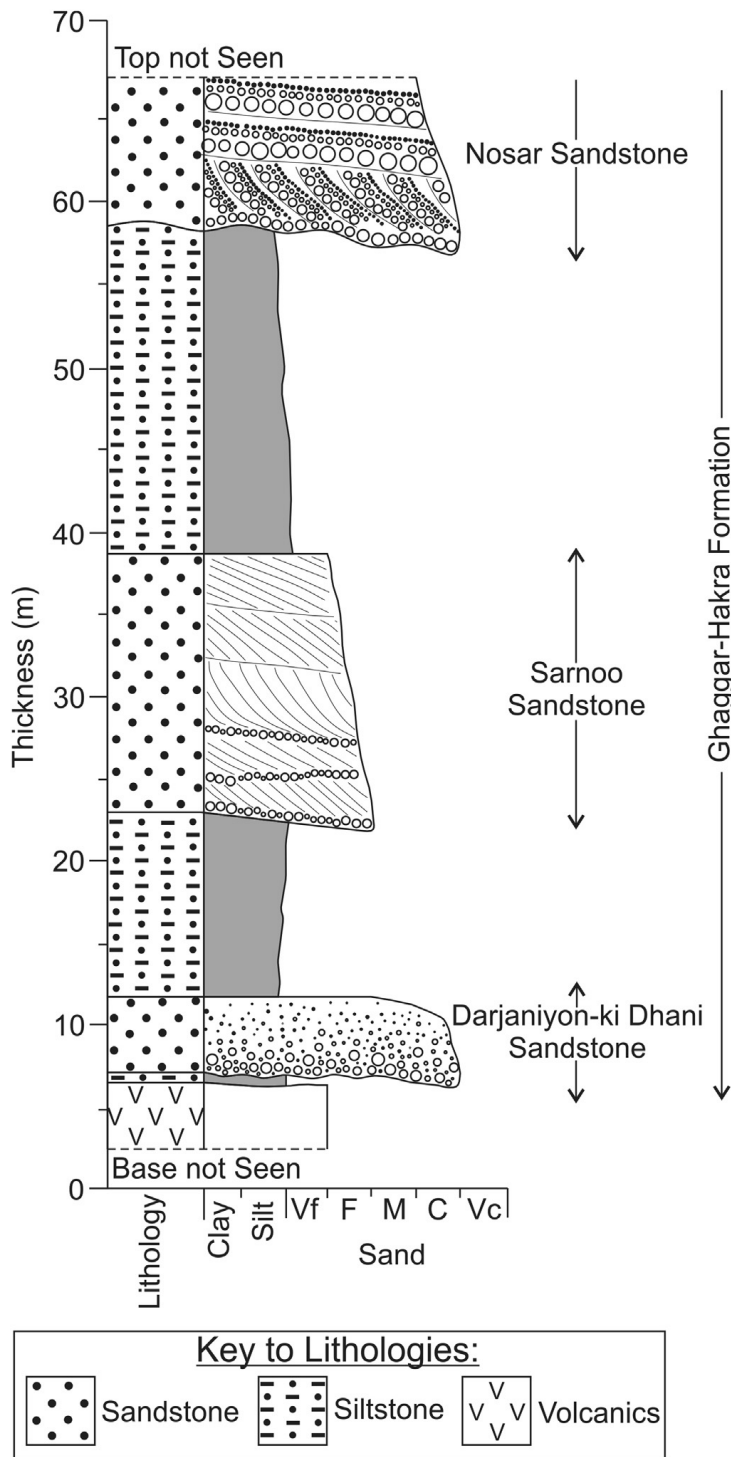


Fig. 6. Generalised sedimentary log through the Ghaggar-Hakra Formation, comprising three distinct sandstone successions, the Nosar sandstone, Sarnoo Sandstone, and Darjaniyon-ki Dhani Sandstone, interbedded with siltstones of the Ghaggar-Hakra Formation. Juxtaposition and offset of sandstone successions were used to estimate fault offset. Vf $\frac{1}{4}$ Very fine; F $\frac{1}{4}$ Fine; M $\frac{1}{4}$ Medium; C $\frac{1}{4}$ Coarse; Vc $\frac{1}{4}$ Very coarse.

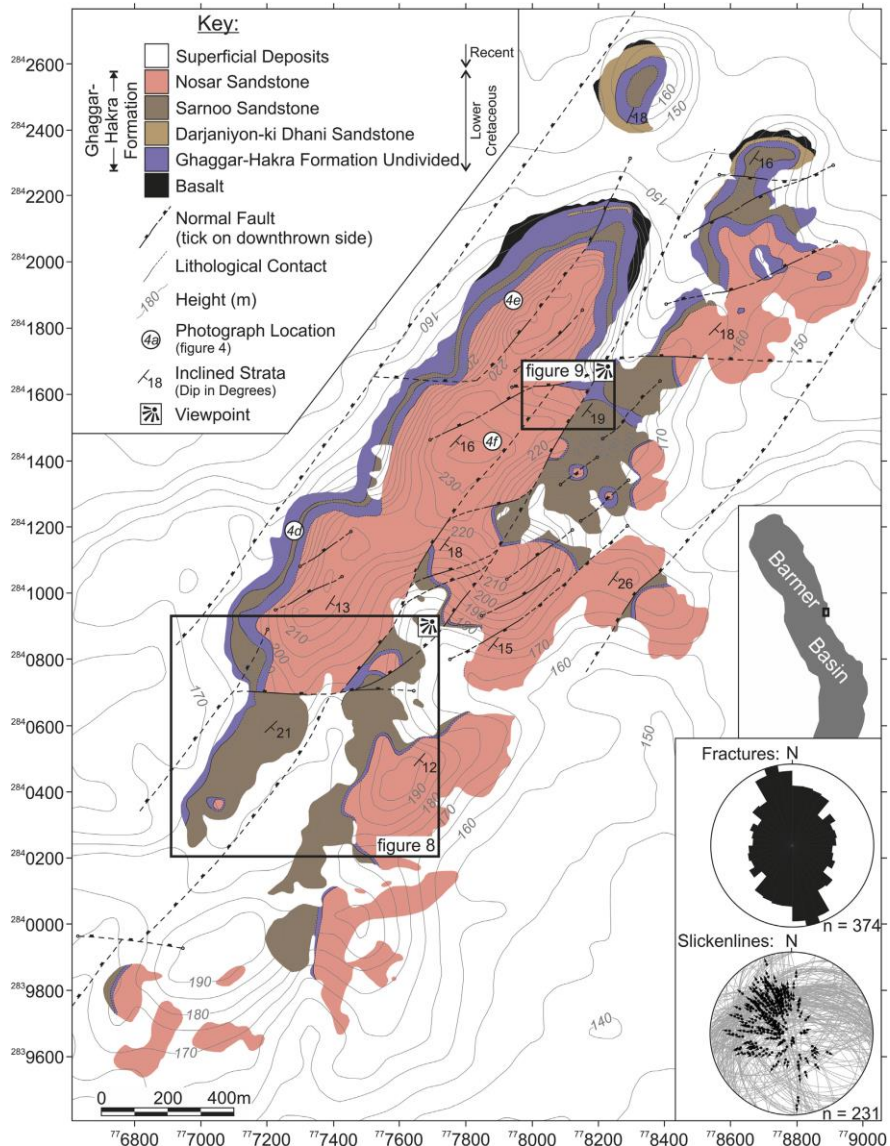


Fig. 7. The Sarnoo Hills, east Barmer rift (location map inset). Topographical contours are at 5 m intervals. Reference grids are UTM zone 42N. Structural data (slickenlines and extensional fractures) are inset and show faulting facilitated NW dip-slip movement and dominant NNW e SSE (rift-parallel) extensional fractures. The locations of photographs in Fig. 4, and the viewpoints and extents of Fig. 8 and 9, are indicated.

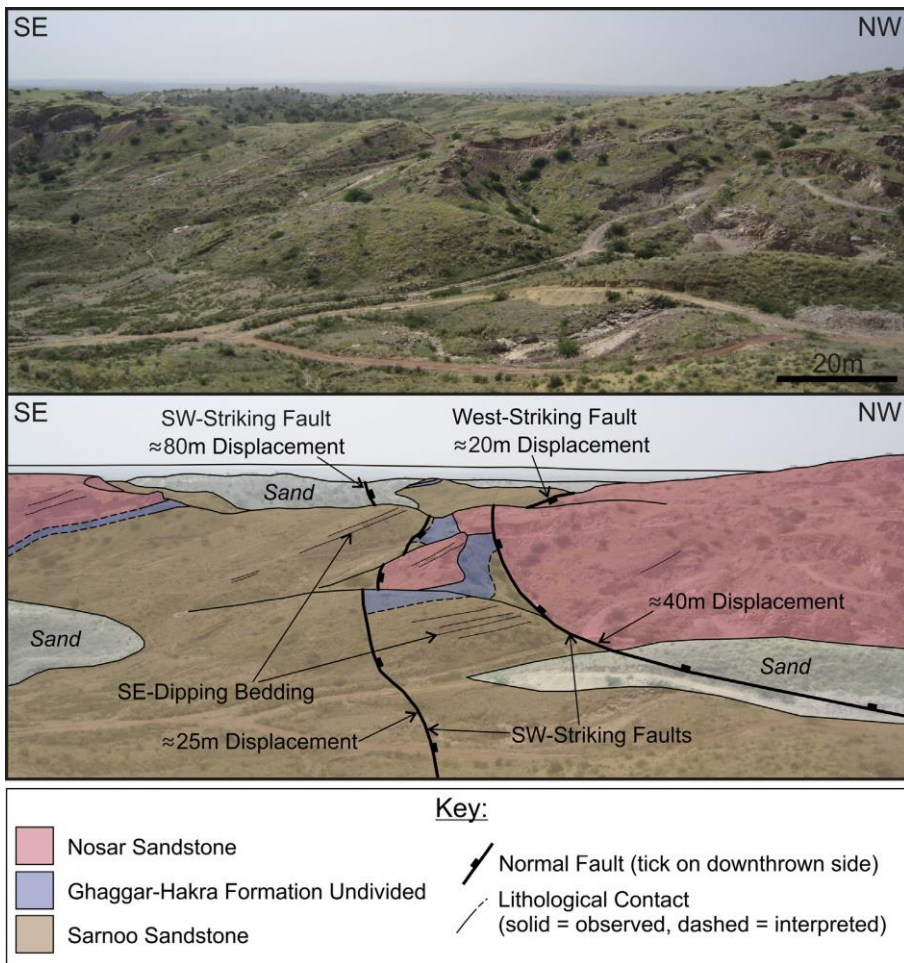


Fig. 8. Landscape interpretation from the south Sarnoo Hills showing a complex fault network in a zig-zag pattern between west- and southwest-striking faults. See Fig. 7 for location.

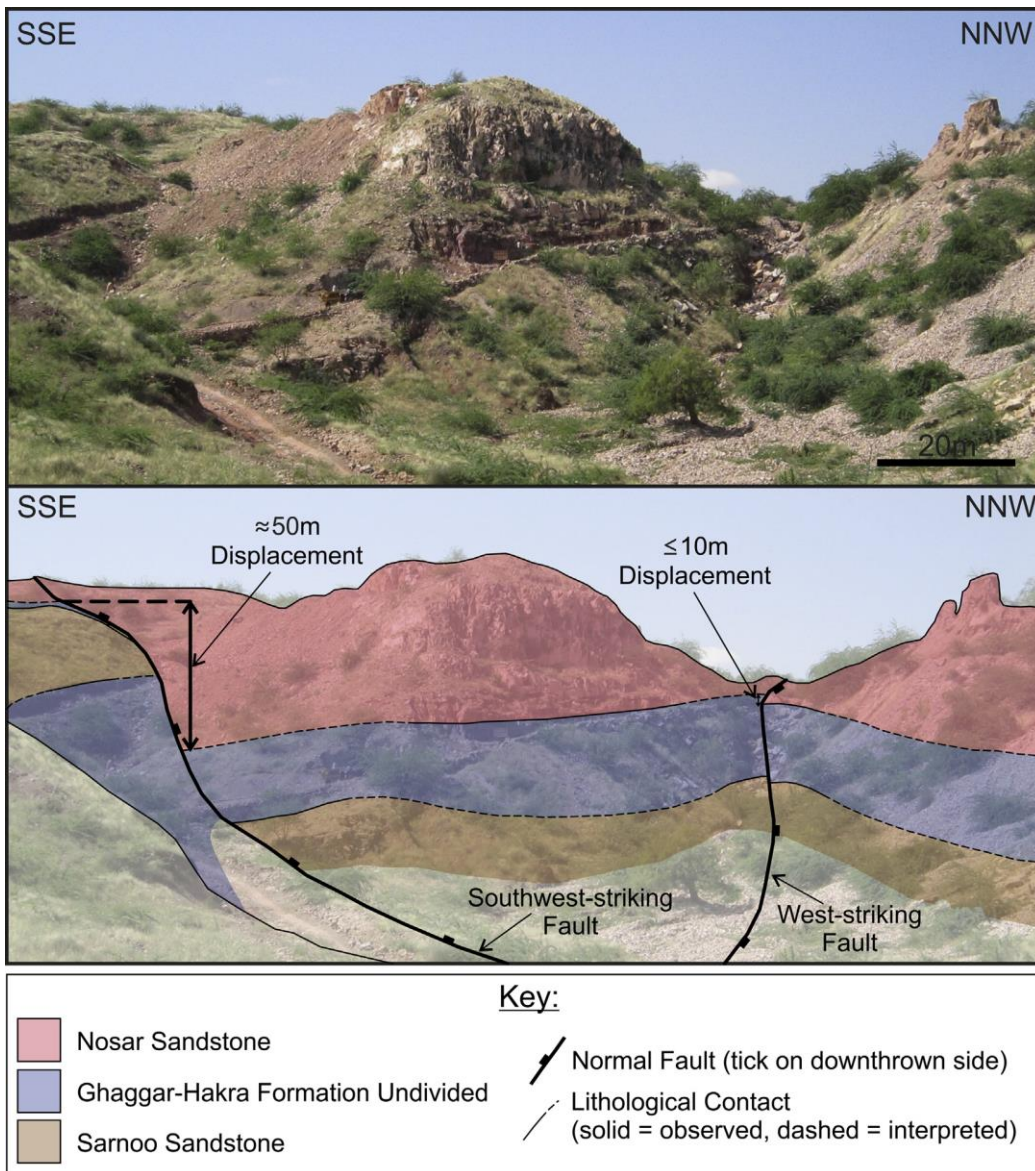


Fig. 9. Variable fault throw between a W-striking fault (≤ 10 m) and a SW-striking fault (≈ 50 m) in the north Sarnoo Hills. See Fig. 7 for location.

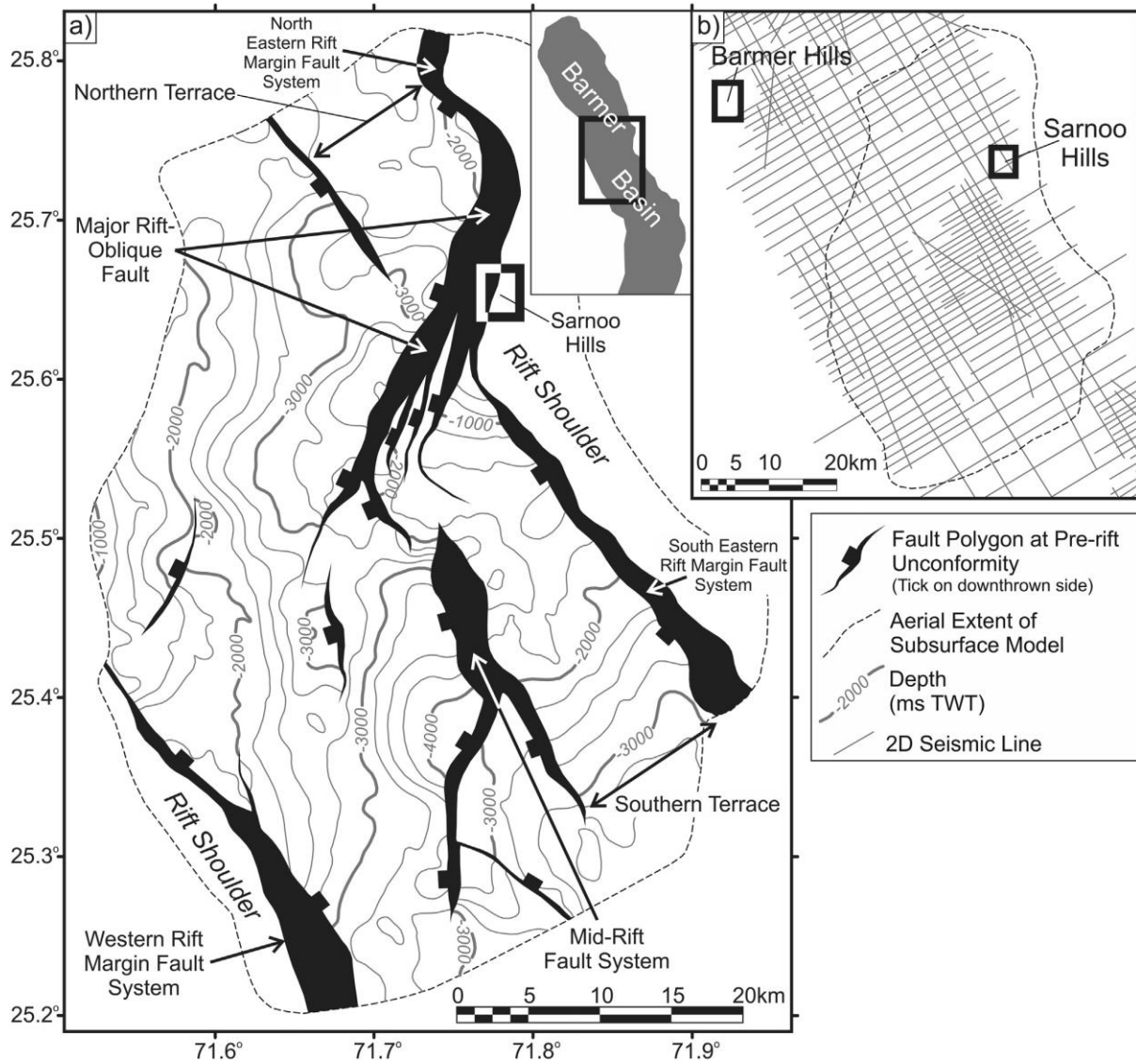


Fig. 10. (a) Time-structure map of the pre-rift unconformity (location map inset). Key structural systems referred to in the text are labelled, and the location of the Sarnoo Hills is shown. (b) 2D seismic dataset used to construct the subsurface model (location map inset). The location of field investigations in the Barmer (Fig. 5) and Sarnoo (Fig. 7) hills are indicated.

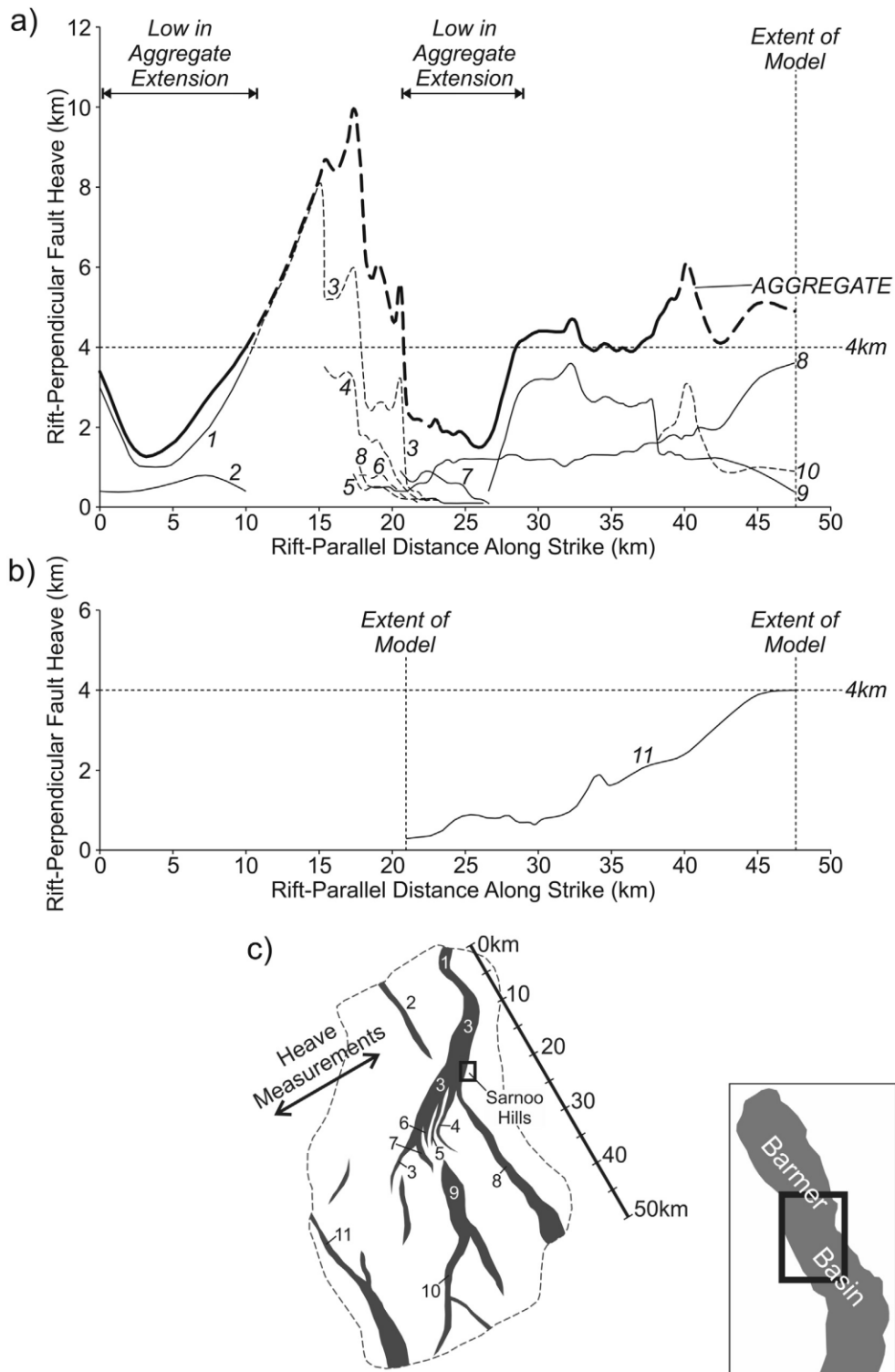


Fig. 11. Subsurface pre-rift unconformity fault heave profiles (location map inset). (a) Faulting along the eastern rift margin. Note the two lows in aggregate extension at either end of the Major Rift-Oblique Fault (fault 3) and the left-stepping displacement transfer between faults 8 & 9; (b) Faulting along the western rift margin; (c) Key to profile labels. The orientation of heave and distance measurements are highlighted.

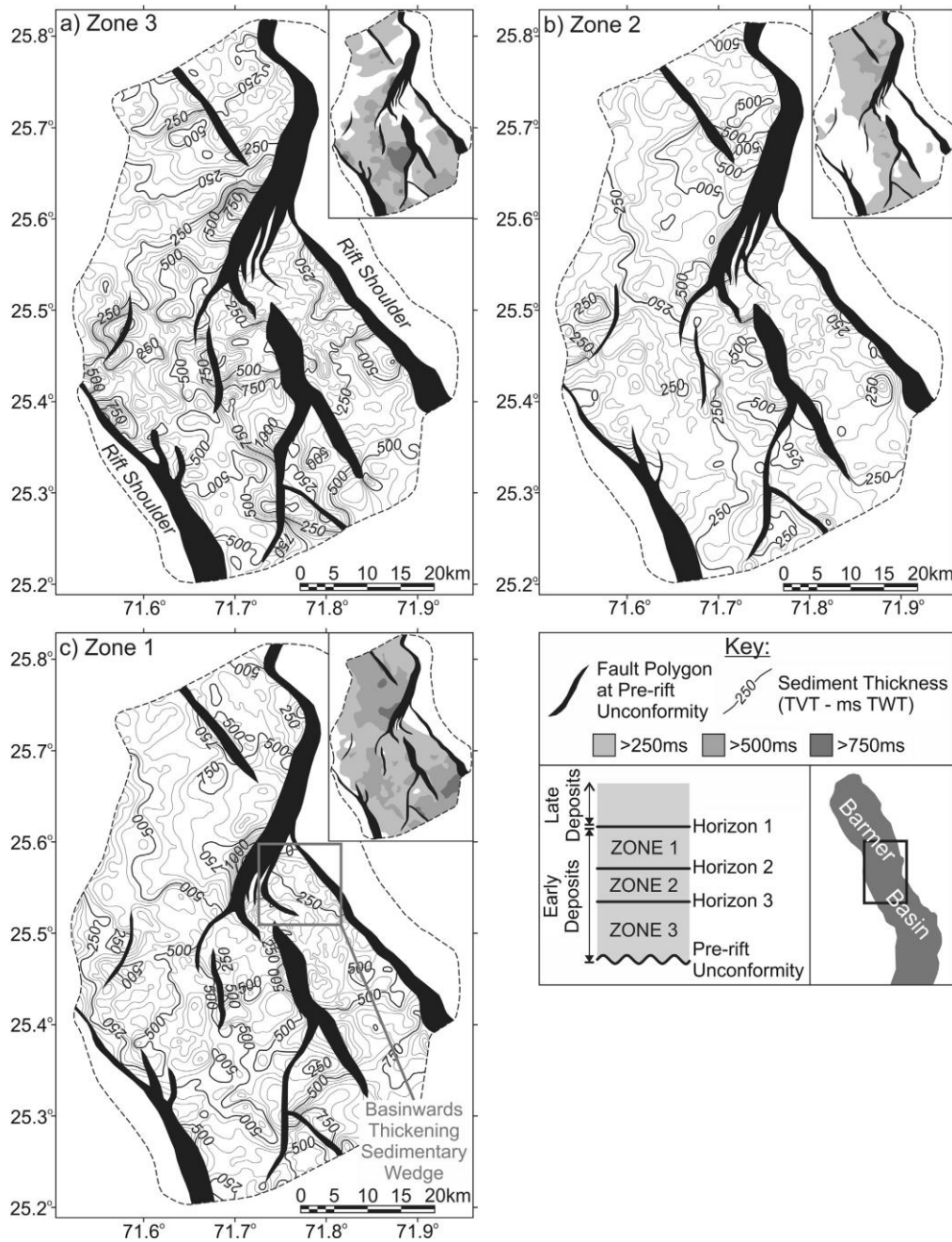


Fig. 12. Contoured subsurface sediment thickness [True Vertical Thickness (TVT) or isochore] maps. Simplified contour maps are shown inset (see key for shading intervals). (a) Zone 3. Thick deposits occur at the base of rift-oblique faults. Minimal activity is evident on rift-parallel fault systems; (b) Zone 2. Thick deposits occur at the base of rift-oblique faults, with little activity on rift-parallel fault systems; (c) Zone 1. Rift-wide deposition. A basinwards thickening sedimentary wedge at the northern end of the Southern Terrace is an important tectono-stratigraphical feature.

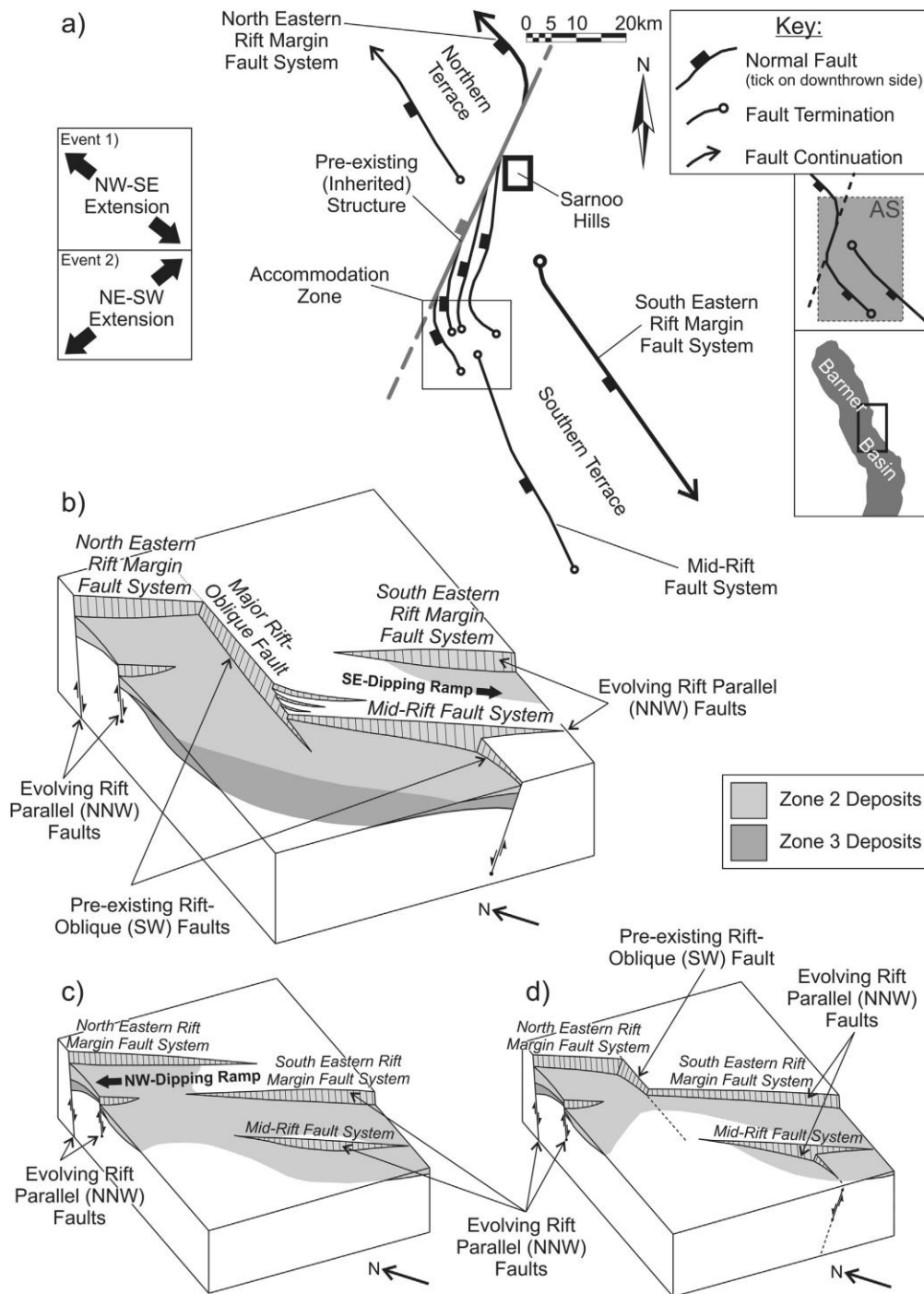


Fig. 13. Subsurface interpretation. Incorporation of a pre-existing, rift-oblique fault (Major Rift-Oblique Fault) into the evolving eastern margin fault system formed an atypical eastern rift margin accommodation structure (AS):(a) Cartoon sketch map (location map and extensional events inset; AS ¼ Accommodation Structure); (b) Block diagram of (a). Note SE-dipping ramp and depocentre at the base of Major Rift-Oblique Fault; (c) Conventional model of linkage between two sub-parallel synthetic faults. Note NW-dipping ramp and depocentres towards the centres of offset fault segments; (d) Passive inheritance of a discrete pre-existing structure as a transfer fault between offset fault systems (e.g. Bellahsen and Daniel, 2005). Note the absence of a ramp, and the depocentre at the base of the Major Rift-Oblique Fault.

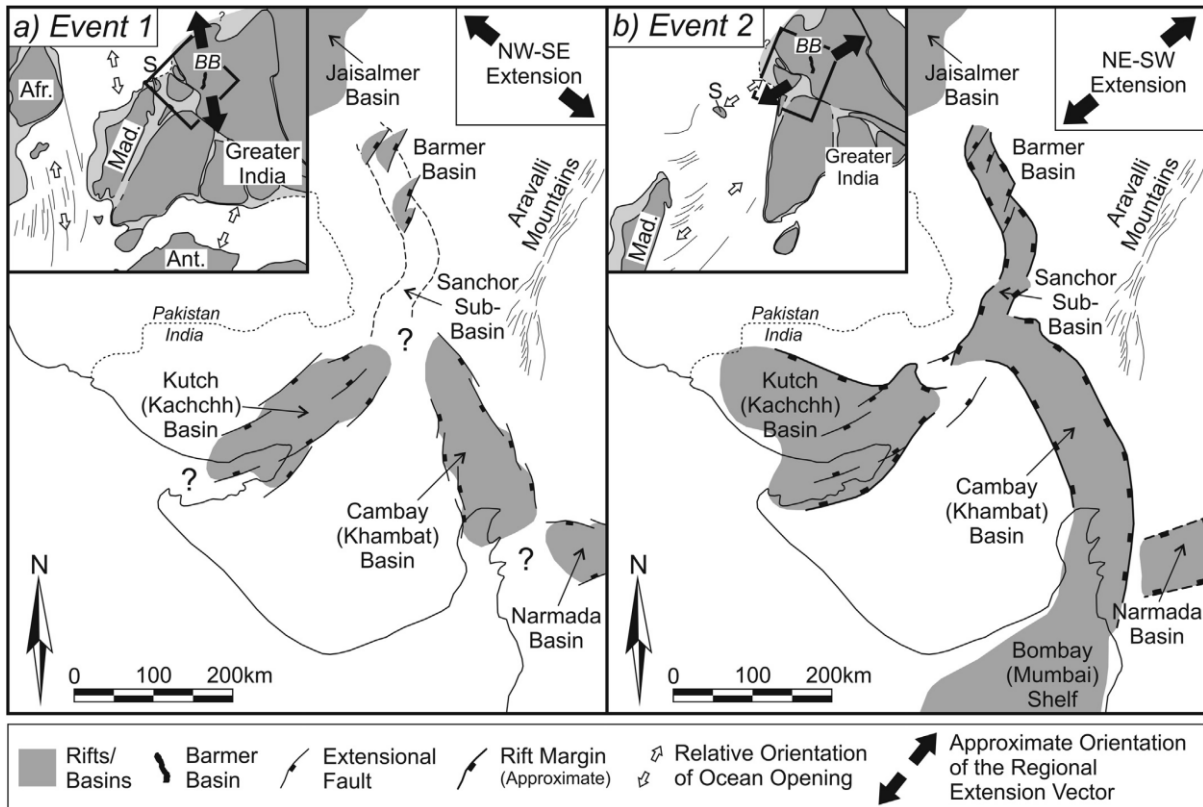


Fig. 14. (a) Event 1. Transtension between the Greater Indian and Madagascan continents during the separation of east and west Gondwana may have generated NW-SE extension throughout northwest India, manifest as rift-oblique faults and depocentres in the Barmer Basin rift. Plate reconstruction at 120 Ma inset (after Reeves, 2013); (b) Event 2. Failed rifting in the Gop and Laxmi basins, and successful rifting of the Seychelles microcontinent in response to plate-boundary reorganisations, generated NE-SW extension throughout northwest India and the majority of subsidence in the Barmer Basin rift. Plate reconstruction at 66 Ma inset (after Reeves, 2013). BB = Barmer Basin, S = Seychelles, Afr. = Africa, Mad. = Madagascar, Ant. = Antarctica.