

Structural Inheritance in the Barmer Basin, India: its influence on early-stage rift evolution and structural geometries*

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Abstract

Pre-existing structures have long been known to affect the evolution of rifts and influence their structural geometries. Consequently, structural inheritance can play an important role in defining all aspects of hydrocarbon systems within extensional sedimentary basins. In this work we describe the characteristics and effects of structural inheritance upon the development of the Barmer Basin, India, and we discuss the implications of this in the wider context of extensional basin evolution.

Working across two scales of investigation we combine targeted field mapping with sub-surface seismic interpretation to construct a structural model that focuses on the early basin fill local to the field area and shows how early-stage rifting was accommodated. We find evidence for multiple episodes of rifting, with structural inheritance influencing both. The effect of pre-existing structures during each rift-episode varied.

At the small-scale, an early extensional event was accommodated by localised reactivation of pre-existing, extension-oblique structures acting in combination with the evolving rift-structures. At the basin-scale, the structures generated during this early episode of rifting were variably utilised during a subsequent episode of rifting. Significantly, a large-offset (≥ 3 km), rift-oblique structure was incorporated into the evolving eastern margin fault system and facilitated displacement transfer between offset fault-systems to its north and south, generating a complex accommodation structure between two oblique (120°) structures. This type of accommodation zone is significantly different in geometry to classical accommodation zone models between two sub-parallel structures as it transfers displacement through extensive block-rotations and fault splays.

Our results show the important affect that pre-existing crustal structures have on the structural geometries generated during early-stage rifting. The structural relationships described here do not fit with 'classical' extensional margin or accommodation zone models and, as a result, early depocentre location and linkage in the Barmer Basin deviated from accepted models of depocentre evolution. We find that structural inheritance may manifest itself as small-scale (sub-seismic) structural complexities that can compartmentalise a reservoir, detrimental to its quality, or at the basin-scale, control early sediment routing and depositional systems that are key for understanding all petroleum plays.

Introduction

It is well known that pre-existing structures inherent in the crust effect the evolution of rift basins and influence the structural geometries produced during rifting (e.g. Chadwick and Evans, 1995; Morley, 1995; Lezzar et al., 2002; Morley et al., 2004; Autin et al., 2013). The effects of such structures may be highly variable, both between and within rift-systems. The Barmer Basin rift, situated in northwest India ([Figure 1a](#)), is an excellent natural laboratory, with outcrop and subsurface datasets, to demonstrate the affect that structural inheritance has had on continental rift evolution across numerous scales of investigation.

The rifted north-western margin of India, active since the Mesozoic Era, is poorly understood despite many hydrocarbon discoveries (Biswas, 1982; Gombos et al., 1995). Onshore rift basins within the West Indian Rift System (WIRS) include the Kachchh (Kutch), Cambay, and Narmada basins. The Barmer Basin is the most northerly rift within the WIRS ([Figure 1a](#)) and is a long, narrow, and deep (200 km, < 40 km, and ≤ 6 km respectively), low strain ($1.2 \leq \beta \leq 1.5$), failed continental rift, that is linked with the Cambay Basin to the south via the poorly defined Sanchor Sub-Basin. The Barmer Basin is separated from the Jaisalmer Basin to the north by a basement structural high, the Devikot Ridge ([Figure 1a](#)). Together, the Barmer and Cambay basins form a north-northwest trending rift system that extends some 600 km into the Indian Craton.

The main phase of extension within the Barmer Basin occurred between the late Cretaceous (Maastrichtian) and mid-Eocene (Lutetian). Rift onset was contemporaneous with separation of the Seychelles microcontinent from western India (70-62Ma; Collier et al., 2008; Armitage et al., 2010; Armitage et al., 2011), and the main phase of Deccan extrusions (65Ma; Chenet et al., 2007). Although Seychelles rifting and the Deccan extrusions were closely related (Collier et al., 2008), the cause of extension throughout northwest India at this time is poorly understood. It is commonly assumed that extension resulted from the impact of the Réunion mantle plume beneath the Indian peninsular as the latter drifted rapidly northwards (e.g. Morgan, 1971; Plummer and Belle, 1995). However, Seychelles rifting has been suggested to have resulted from external plate boundary forces (Sheth, 2005a; Collier et al., 2008), and many aspects of the Deccan geology have been shown to be inconsistent with plume activity, being more typical of deep-seated rifting (Sheth, 2005a; Sheth, 2005b; Sheth, 2007).

This work combines detailed field investigations from opposing rift shoulders of the Barmer Basin ([Figure 1b](#)) with associated subsurface interpretations, to assess how pre-existing structures influenced and complicated rift evolution. Field evidence supports the presence of two, non-coaxial extensional events, with structural inheritance evident during both. Rift-oblique structures generated during the first extensional event were variably incorporated into the evolving rift-parallel fault systems during the second. Significantly, the incorporation of a pre-existing, rift-oblique fault into the evolving eastern rift margin generated an unorthodox accommodation structure. The findings reported here are applicable to all continental rifts where accommodation zones separate rift-segments during early-stage rift evolution, and exert a primary control on depocentre evolution and sediment routing.

Rift Margin Structures

To compare the evolution of rift-parallel and rift-oblique faults apparent on the current subsurface structural model ([Figure 1b](#)), field work was conducted along rift-parallel and rift-oblique sections of the rift margin. Exposures in the Barmer Basin are sparse (<1% by area), but a large series of hills situated along the western rift margin (the Barmer Hills) are dominated by exposure of rift-basement belonging to the Precambrian Malani Igneous Suite (c.f. Pareek, 1981), and a series of northeast-trending ridges, situated on a prominent 'kink' in the eastern rift margin (the Sarnoo Hills; [Figure 1b](#)), expose pre-rift sediments of Lower Cretaceous age (the Ghaggar-Hakra Formation).

Faults in the Barmer Hills are northwest-striking, northeast-dipping (*Trend 1*; [Table 1](#)), rift-parallel, and both hard and soft linked ([Figure 2](#)). Dominant fractures are northwest-southeast (rift-parallel), and fault slip is predominantly northeast-southwest ([Figure 2](#)). The juxtaposition of fan sediments of Paleocene age, derived from the uplifted Malani rift-basement footwall, against the rift-margin fault indicates that faulting occurred during the main phase of rifting. Structures in the Barmer Hills, therefore, were active under northeast-southwest extension during the Paleocene Epoch.

Dominant faults in the Sarnoo Hills are southwest-striking, northwest-dipping (*Trend 2*; [Table 1](#)) and form a zig-zag fault network with west-striking, north-dipping faults (*Trend 3*; [Figure 3](#)). As observed in the Barmer Hills fractures are approximately rift-parallel. Dominant trend 2 faults experienced near pure normal slip, with average slickenline pitch measurements of 87°, and trend 3 faults exhibited a 15° component of sinistral oblique slip (75° avg. slickenline pitch). Fault slip is predominantly towards the northwest ([Figure 3](#)), and this combined with the orientation of dominant trend 2 faults, indicates that the Sarnoo Hills fault network was active under northwest-southeast extension.

In summary, two near-perpendicular, non-coaxial extensional events are evident at outcrop on opposing rift-margins of the Barmer Basin. Northeast-southwest extension is evident on rift-parallel faults in the Barmer Hills, and northwest-southeast extension is evident on rift-oblique faults in the Sarnoo Hills ([Figure 4](#)).

Structural Inheritance in the Sarnoo Hills

Zig-zag fault networks, as observed in the Sarnoo Hills, are a fundamental pattern of extensional faults, and may arise from non-plane strain or from the inheritance of pre-existing fabrics (Morley, 1995). Based on the non-ideal, oblique orientation of trend 3 faults ([Table 1](#)) to the northwest-southeast extensional event evident in the Sarnoo Hills, and the average 15° component of sinistral oblique slip experienced by these faults, trend 3 faults are interpreted to have been influenced by pre-existing rift-basement faults. By comparison, the near pure normal slip experienced by dominant trend 2 faults, suggests evolution in a near-ideal orientation to the extension direction. Upon northwest-southeast extension, sections of pre-existing rift-basement faults were incorporated into the evolving, extension-ideal (trend 2) fault systems, and acted passively as breach faults (e.g. Bellahsen and Daniel, 2005). With continued extension strain localised onto the rift margin fault immediately adjacent to the outcrop and rendered the juvenile fault network preserved in the Sarnoo Hills inactive.

Subsurface Structures

Within the north-northwest trending Barmer Basin, northwest-southeast extension ([Figure 3](#)), is anomalous. In order to understand the relationship between the two non-coaxial extensional events evident at outcrop ([Figure 4](#)), the investigation was extended into the subsurface. Subsurface interpretations focused on the prominent ‘kink’ in the eastern rift margin and on the Sarnoo Hills ([Figure 1b](#)), with four, poorly age-constrained stratigraphical horizons interpreted within early syn-rift deposits ([Figure 5](#)). The rift is asymmetrical in the central section of the model, and is increasingly symmetrical southwards. As at outcrop, faults are both rift-parallel and rift-oblique ([Figure 6](#)), and eastern rift margin fault systems in the north and south of the model (*Faults F1 and F3*; [Figure 6](#)) are separated by a rift-oblique fault (*Fault F2*). Fault F2 is immediately adjacent and sub-parallel to dominant trend 2 faults in the Sarnoo Hills ([Figure 6](#)), suggesting the two are genetically linked. Numerous splays occur at the southern end of fault F2, and a large, southeast-dipping, rift-internal ramp is situated adjacent to fault F3 in the south of the model ([Figure 6](#)).

Sediment thickness (isochore) maps demonstrate that early depocentres were situated at the base of rift-oblique faults (zones 3 and 2; [Figure 7](#)), and that rift-parallel faults became active later during rift-evolution (zone 1; [Figure 7](#)). As structural activity on rift-oblique faults preceded that on rift-parallel faults, northwest-southeast extension (Sarnoo Hills) must have preceded the main northeast-southwest Barmer rift event (Barmer Hills).

Eastern Rift-Margin Accommodation Structure

Conventional models of linkage predict development of a northwest-dipping relay-ramp between faults F1 and F3 (e.g. Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998). In natural datasets, minima in aggregate extension occur in relay zones between fault segments where strain is accommodated through block-rotations and sub-seismic faulting. Rather than a low in aggregate extension between faults F1 and F3 (10-17 km along rift-strike; [Figure 8](#)), aggregate extension is at a maximum, and extension minima occur at either end of fault F2 ([Figure 8](#)). This, along with an extension-length profile comparable to that expected for an isolated fault (i.e. maximum extension at its centre decreasing towards the tips) suggests that fault F2 evolved as an isolated fault, rather than as a secondary breach fault between faults F1 and F3, and linked with faults F1 and F4 at its tips.

South of fault F2, extension is partitioned between faults F3 and F4 in a manner characteristic of soft-linkage ([Figure 8](#); c.f. Conneally et al., 2014). The near complete loss of extension on fault F3 northwards towards fault F2 indicates that strain was increasingly accommodated on fault F4 to the west, highlighting a left-stepping transfer of displacement. Seismic-stratigraphical relationships indicating a basinwards rotation of the southeast-dipping, rift-internal ramp adjacent to fault F3 ([Figure 6](#)), further support a transfer of displacement between faults F3 and F4 (c.f. Walsh et al., 1999).

The proximity and sub-parallel orientation of fault F2 ([Figure 6](#)) to dominant trend 2 faults in the Sarnoo Hills ([Figure 3](#)), suggests that fault F2 evolved during northwest-southeast extension. Sediment thickness (isochore) maps indicate that northwest-southeast extension preceded northeast-southwest extension ([Figure 7](#)). Hence, at the onset of northeast-southwest extension, fault F2 was inherent in the crust. The complete syn-rift succession in the hanging-wall of fault F2 indicates it was active throughout the duration of rifting, and was not by-passed or cross-cut by the evolving rift-parallel fault systems. Linkage at the tips of fault F2 ([Figure 8](#)), and the significant left-stepping displacement transfer between faults F3 and F4 to the south ([Figure 8](#) and [Figure 9](#)), indicate that fault F2 transferred displacement from fault F1 to the north, onto fault F4 to the south, rather than linking right-stepping rift-

margin faults (Faults F1 and F3) to the north and south directly (e.g. Bellahsen and Daniel, 2005; [Figure 10](#)). The left-stepping transfer of extension between faults F3 and F4 was accommodated by soft-linkage, and formation of the southeast-dipping, rift-internal relay-ramp ([Figure 6](#)). Along the central eastern rift margin of the Barmer Basin, therefore, inheritance of a pre-existing, rift-oblique fault within the evolving rift-margin, indirectly linked rift-margin fault systems to the north and south during early-stage rifting, and formed an unorthodox accommodation structure ([Figure 10](#)).

Conclusions

Field investigations combined with subsurface interpretations ([Figure 1b](#)) highlight that a previously unrecognised northwest-southeast extension preceded the main northeast-southwest Barmer Basin rift event. In the Sarnoo Hills, pre-existing, west-striking, north-dipping faults (*Trend 3*) were utilized passively as breach faults between the evolving, extension ideal, southwest-striking faults (*Trend 2*) during early northwest-southeast extension ([Figure 3](#); e.g. Bellahsen and Daniel, 2005). With continued extension, strain localised onto a southwest-striking, rift-oblique fault immediately adjacent to the outcrop (*Fault F2*; [Figure 6](#)), rendering the Sarnoo Hills fault network inactive. Subsequently, upon northeast-southwest extension, this rift-oblique fault was inherent in the crust and became incorporated within the evolving eastern rift margin. Extension was transferred from the rift-margin fault system to the north (Fault F1) onto a mid-rift fault system to the south (*Fault 4*; [Figure 10](#)), rather than directly between rift margin fault systems (*Faults F1 and F3*; e.g. Bellahsen and Daniel, 2005). Noteworthy differences exist between the unconventional accommodation structure presented, and classical models of linkage between two right-stepping faults (e.g. Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998), most notably the formation of a southeast- rather than northwest-dipping relay ramp ([Figure 11](#)).

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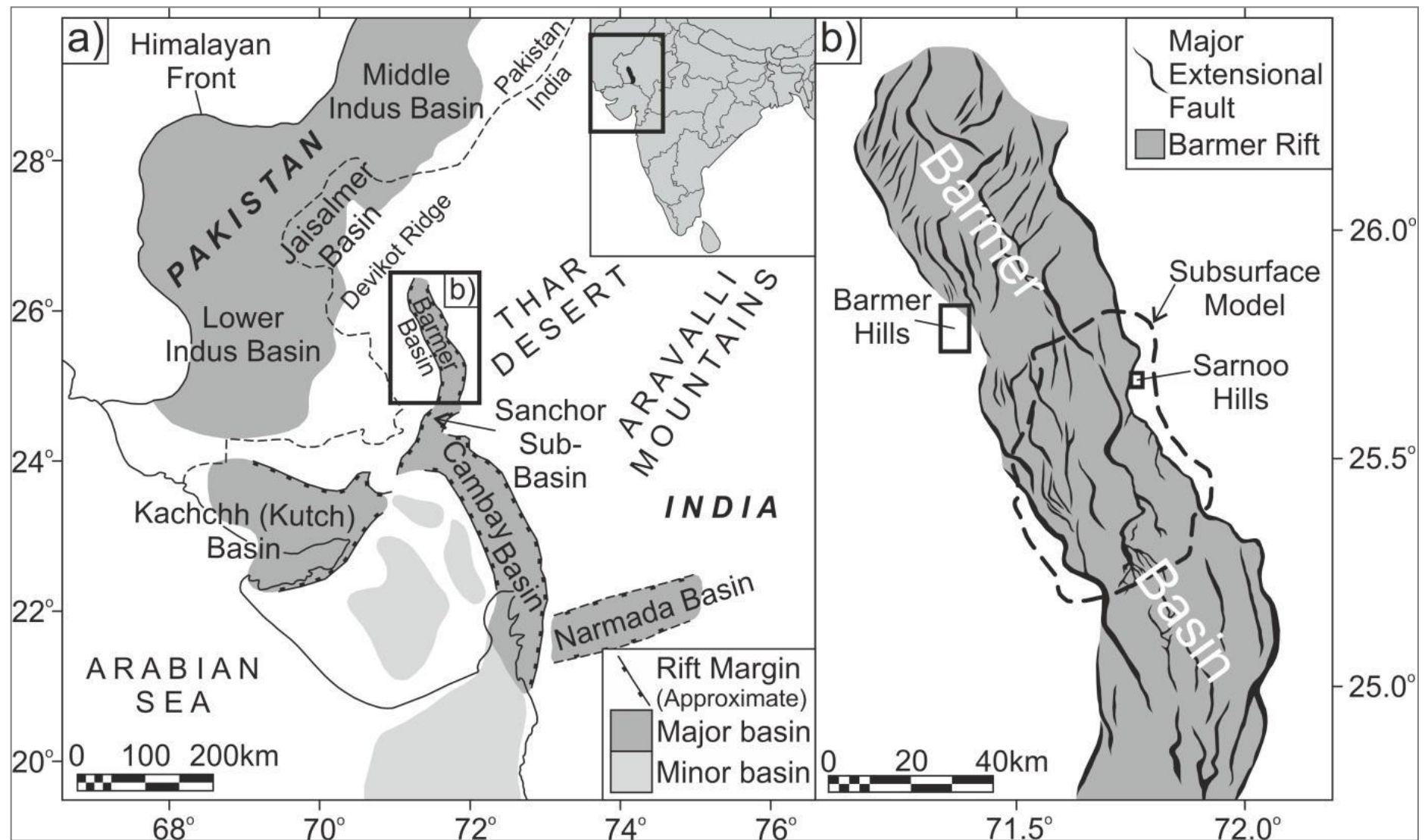


Figure 1. (a) Onshore rift basins of northwest India (see inset for location within India); (b) Current basin-wide structural interpretation based on subsurface data alone (for location see a). The Barmer and Sarnoo hills were the focus of field work, the findings of which were complemented with subsurface interpretations (model area dashed).

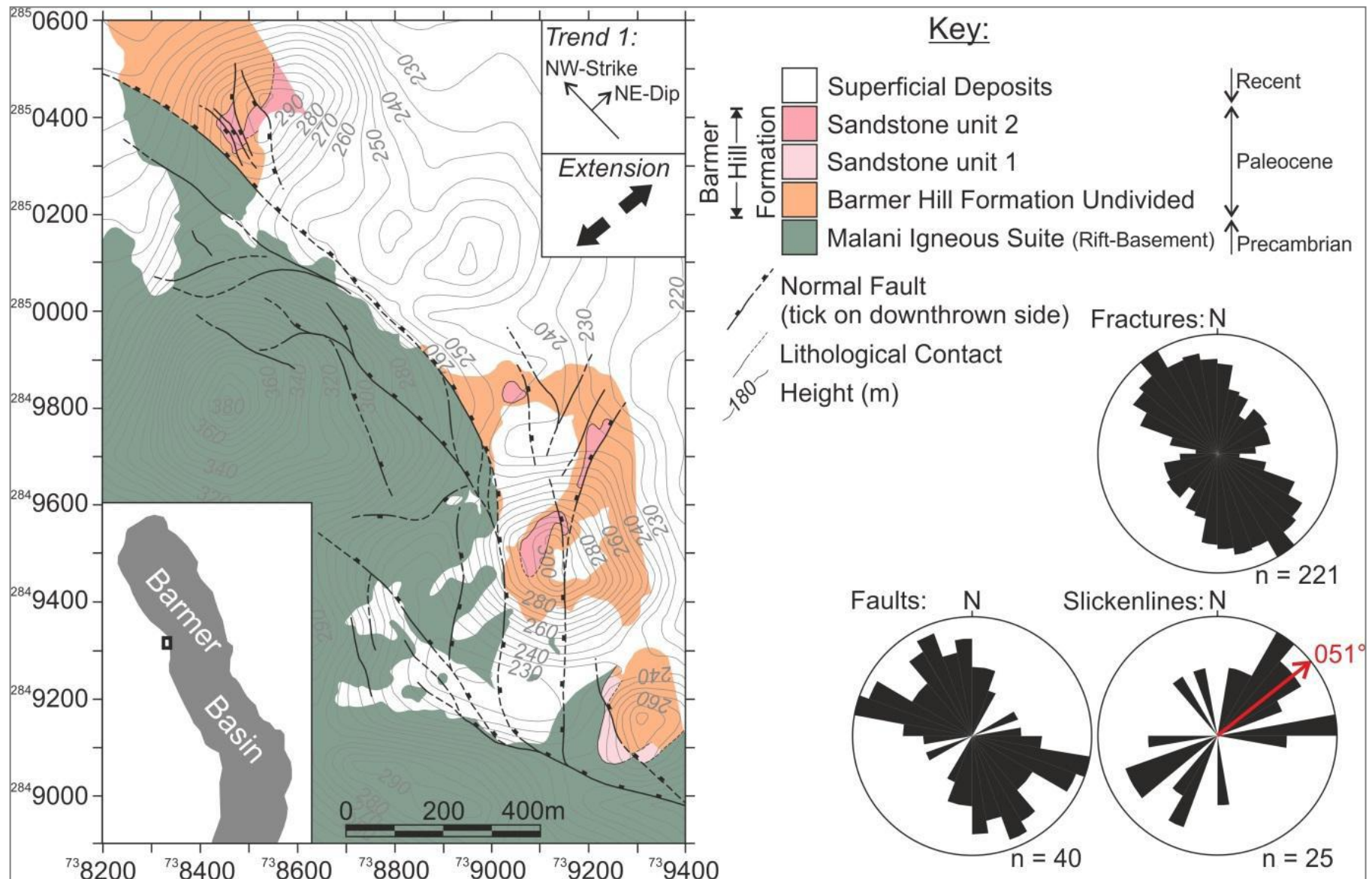


Figure 2. The Barmer Hills are situated on the western rift margin of the Barmer Basin (location map inset). Topographical contours are at 5 m intervals and coordinates are UTM zone 42N. Dominant faults are northwest-striking, northeast-dipping (Trend 1), dominant fractures are northwest-southeast (rift parallel), and fault slip is approximately northeast-southwest (see stereonets).

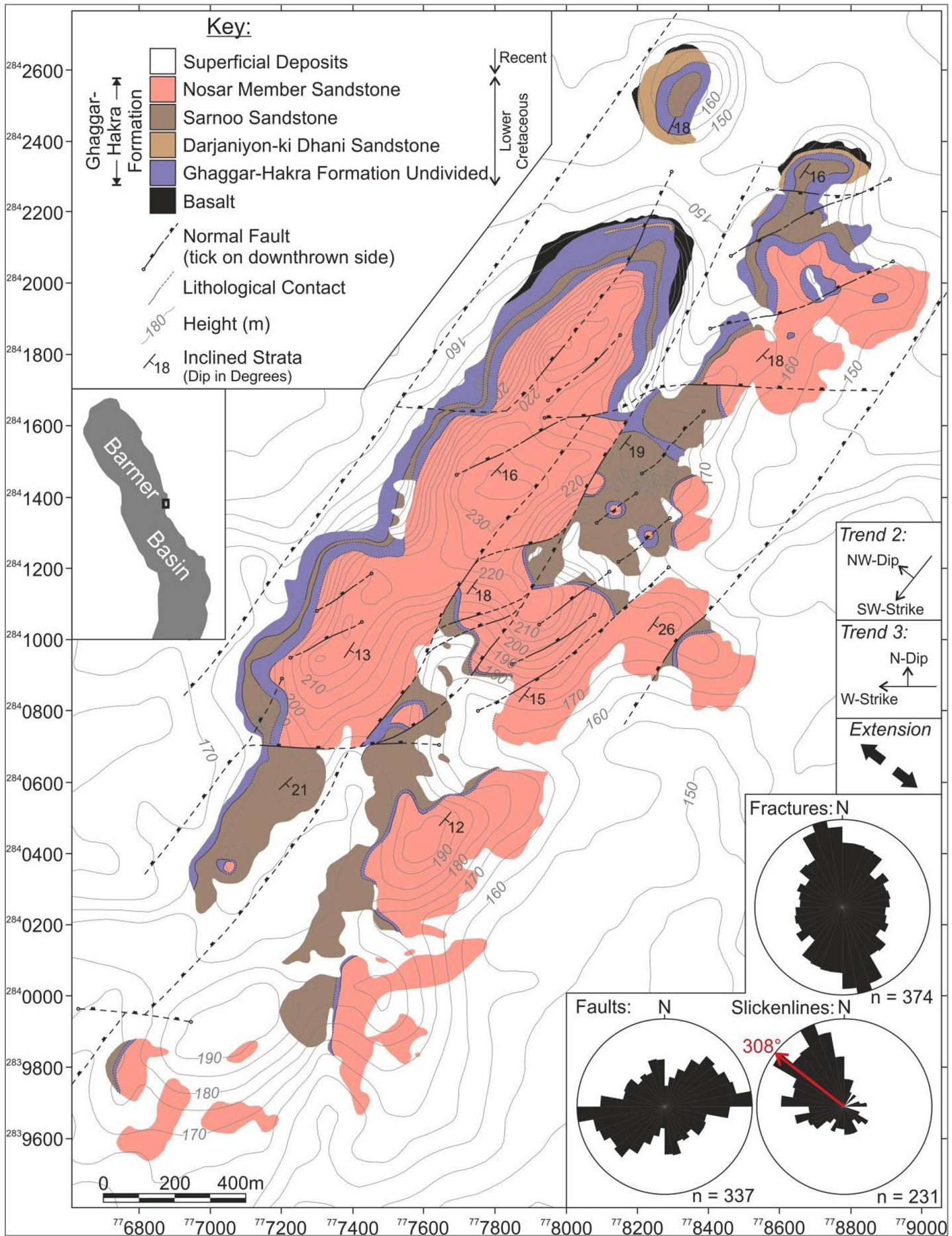


Figure 3. The Sarnoo Hills are situated on a prominent ‘kink’ in the eastern rift margin of the Barmer Basin (location map inset). Topographical contours are at 5 m intervals and coordinates are UTM zone 42N. Dominant faults are southwest-striking, northwest-dipping (Trend 2) and form a zig-zag fault network with west-striking, north-dipping faults (Trend 3). Dominant fractures are northwest-southeast (rift-parallel), and fault slip is almost exclusively towards the northwest (see stereonets).

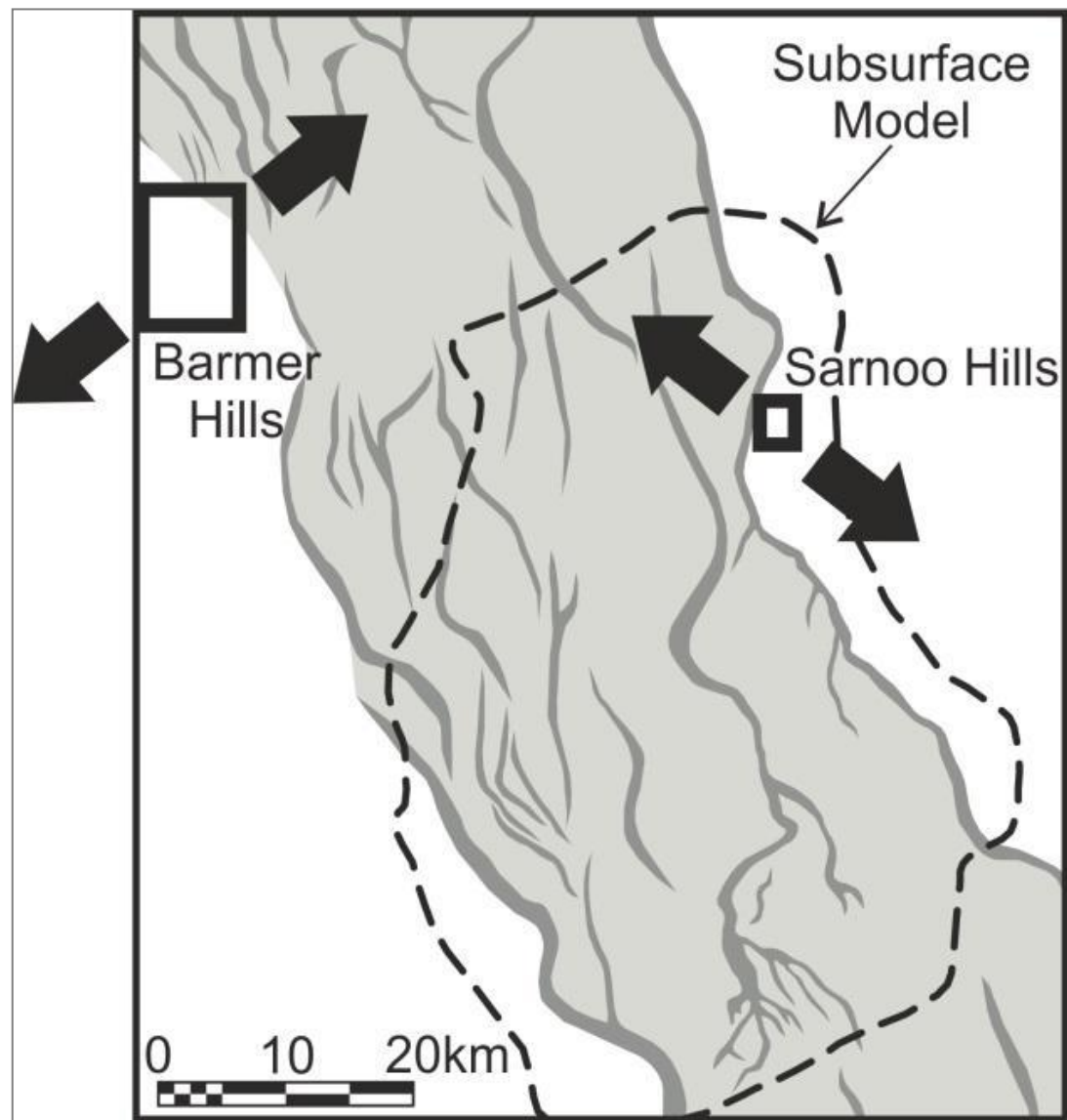


Figure 4. Two, non-coaxial extensional events are evident at outcrop on opposing rift shoulders of the Barmer Basin; northeast-southwest Paleocene extension in the Barmer Hills, and a previously unrecognised northwest-southeast extension in the Sarnoo Hills.

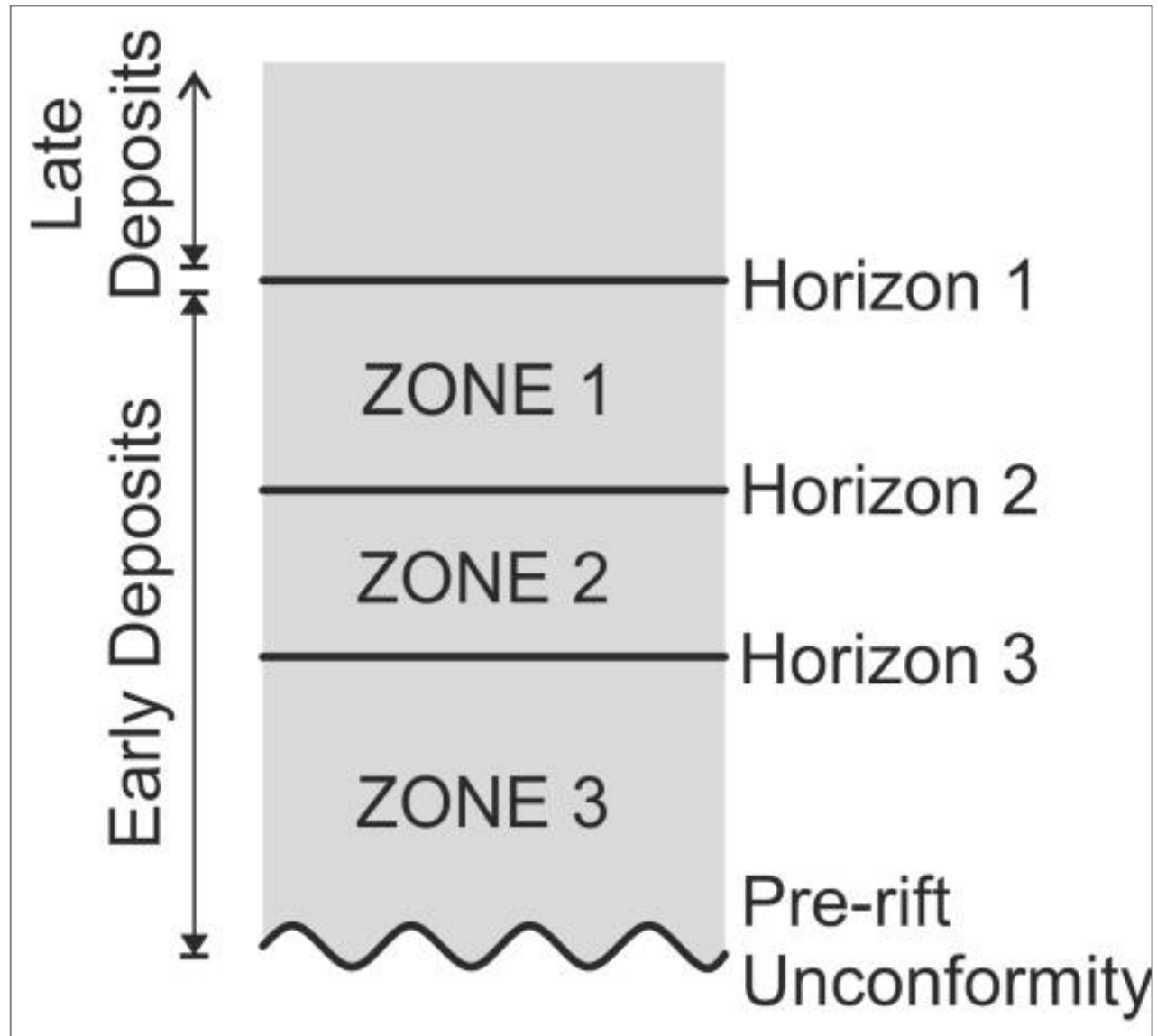


Figure 5. Four poorly age-constrained stratigraphical horizons were interpreted within early syn-rift deposits (youngest = Horizon 1, oldest = Pre-rift unconformity) generating three zones within the model.

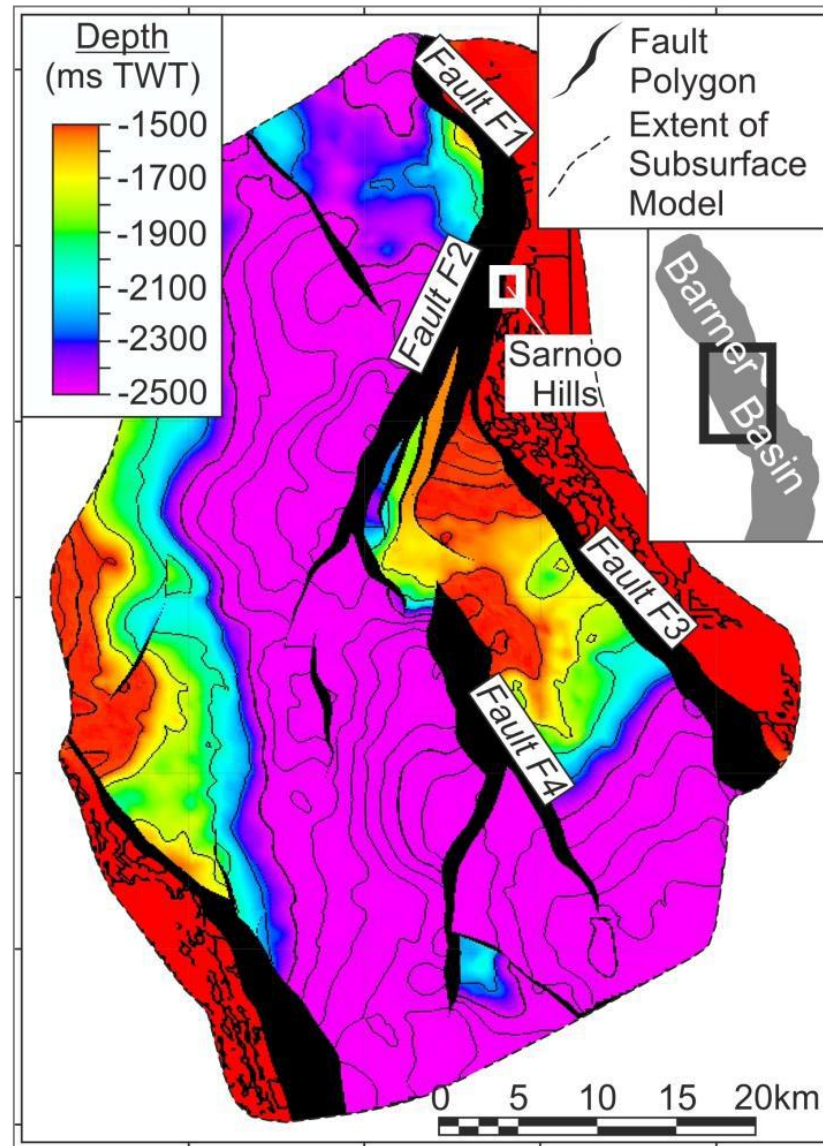


Figure 6. Present day topography of the pre-rift unconformity with fault polygons overlain (location map inset). The model has been simplified to display the major structures. As observed at outcrop, rift parallel- and rift-oblique faults are interpreted.

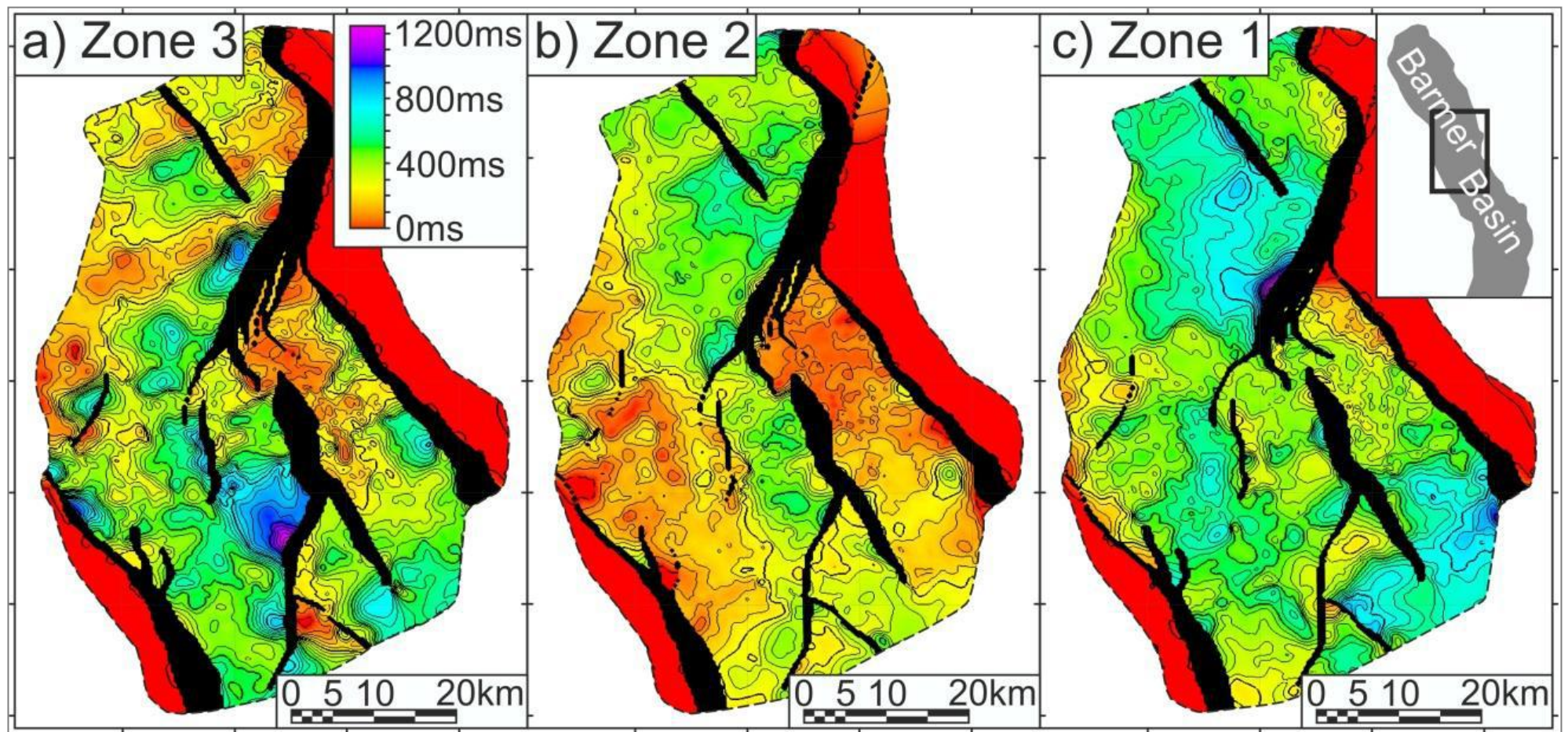


Figure 7. Contoured sediment thickness (isochore) maps of each zone within the subsurface model (location map and key inset); (a) and (b) Zone 3 and Zone 2. Depocentres are situated at the base of rift-oblique faults, with little activity on rift-parallel faults; (c) Zone 1. Depocentres are situated at the base of rift-parallel faults, alongside continued activity on some sections of rift-oblique faults. Activity on rift-oblique faults preceded activity on rift-parallel faults, indicating that northwest-southeast extension (Sarnoo Hills) preceded northeast-southwest extension (Barmer Hills).

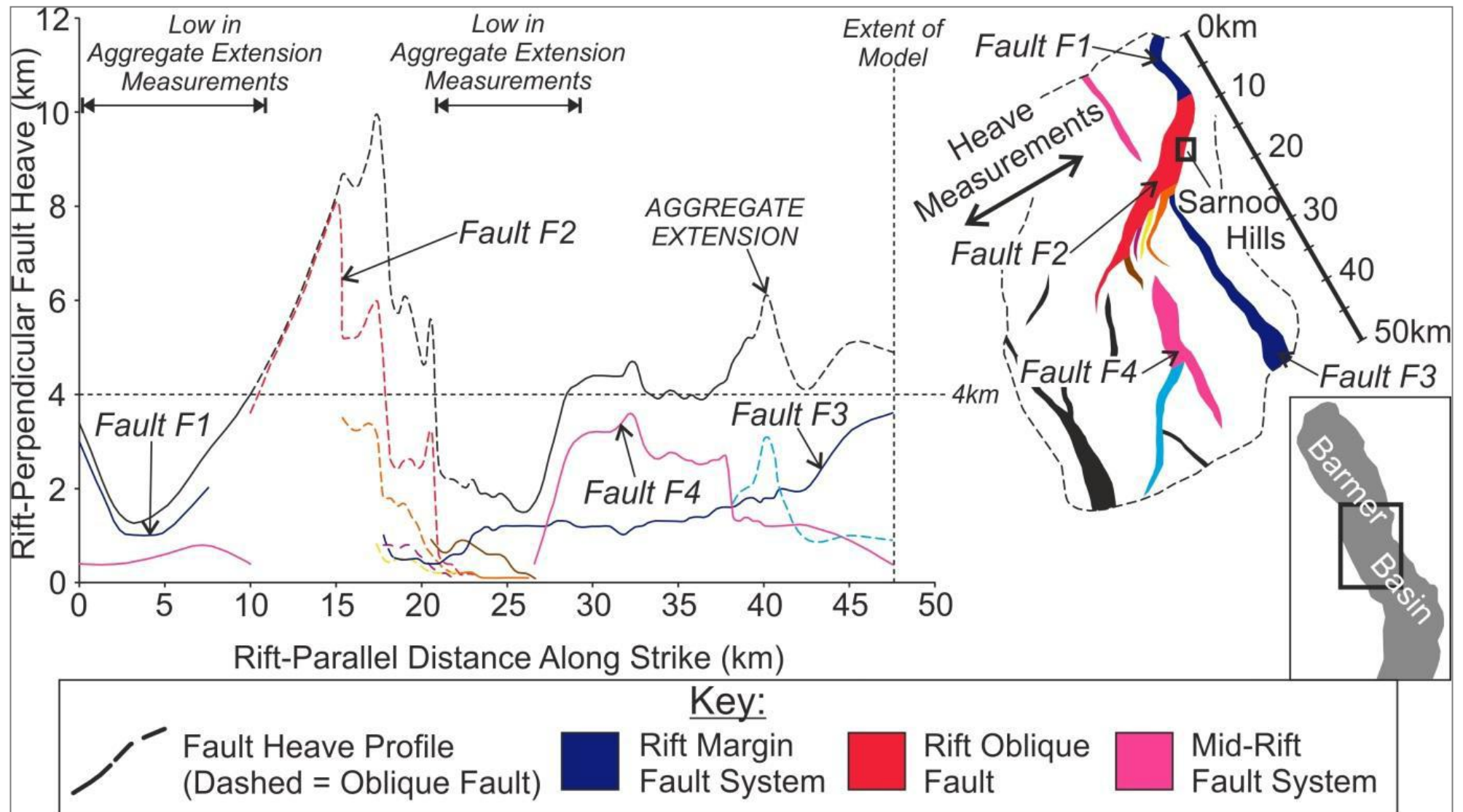


Figure 8. Fault heave profiles used to investigate strain partitioning during the main northeast-southwest Barmer rift event (Barmer Hills; [Figure 2](#)). Fault heave was measured perpendicular to the trend of the rift, and approximately parallel to the extension direction. This technique does not account for extension during the earlier, non-coaxial northwest-southeast extensional event (Sarnoo Hills; [Figure 3](#)) and, therefore, fault heave on structures active during northwest-southeast extension are overestimated (dashed profiles). Fault heave profiles were constructed from the subsurface model.

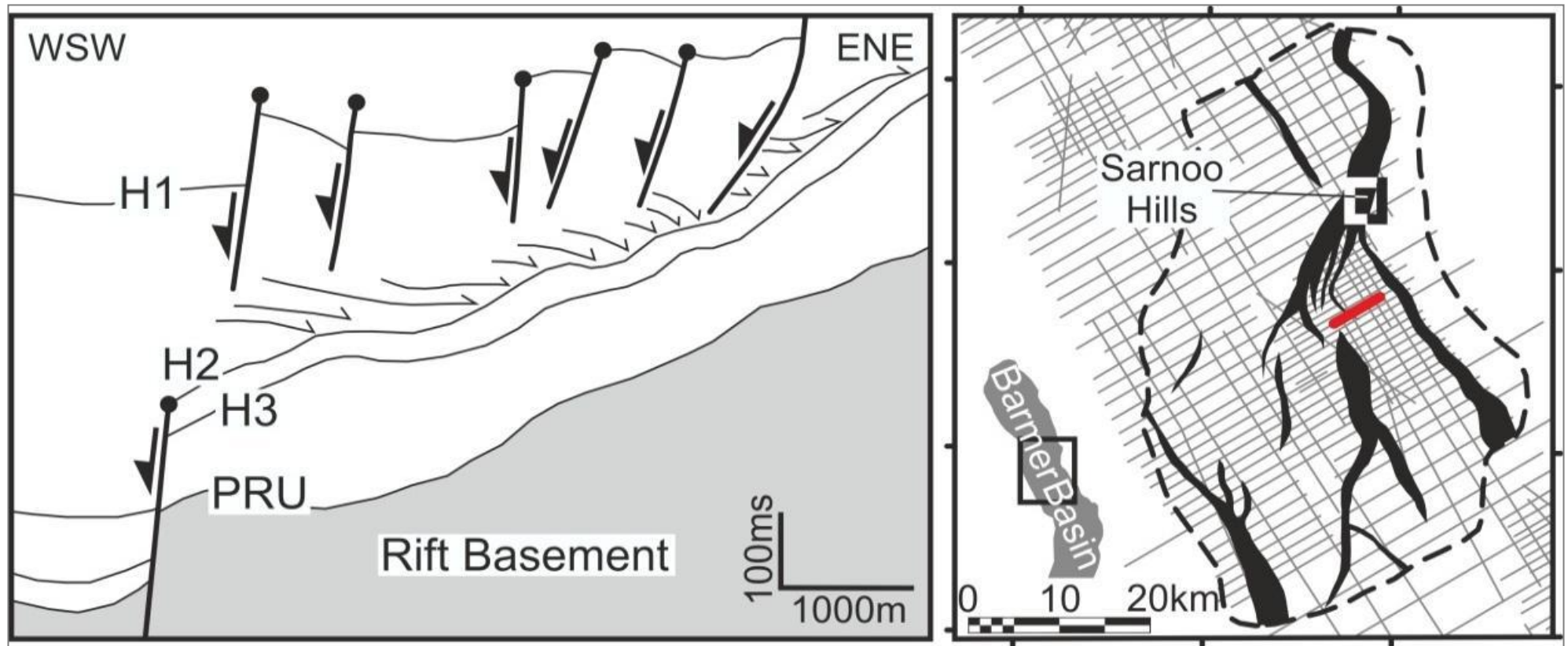


Figure 9. Unusual seismic stratigraphical relationships encountered at the northern end of the rift-internal, southeast-dipping ramp situated adjacent to Fault F3, showing a basinwards thickening sedimentary wedge that onlaps towards the rift margin (location of section shown in red).

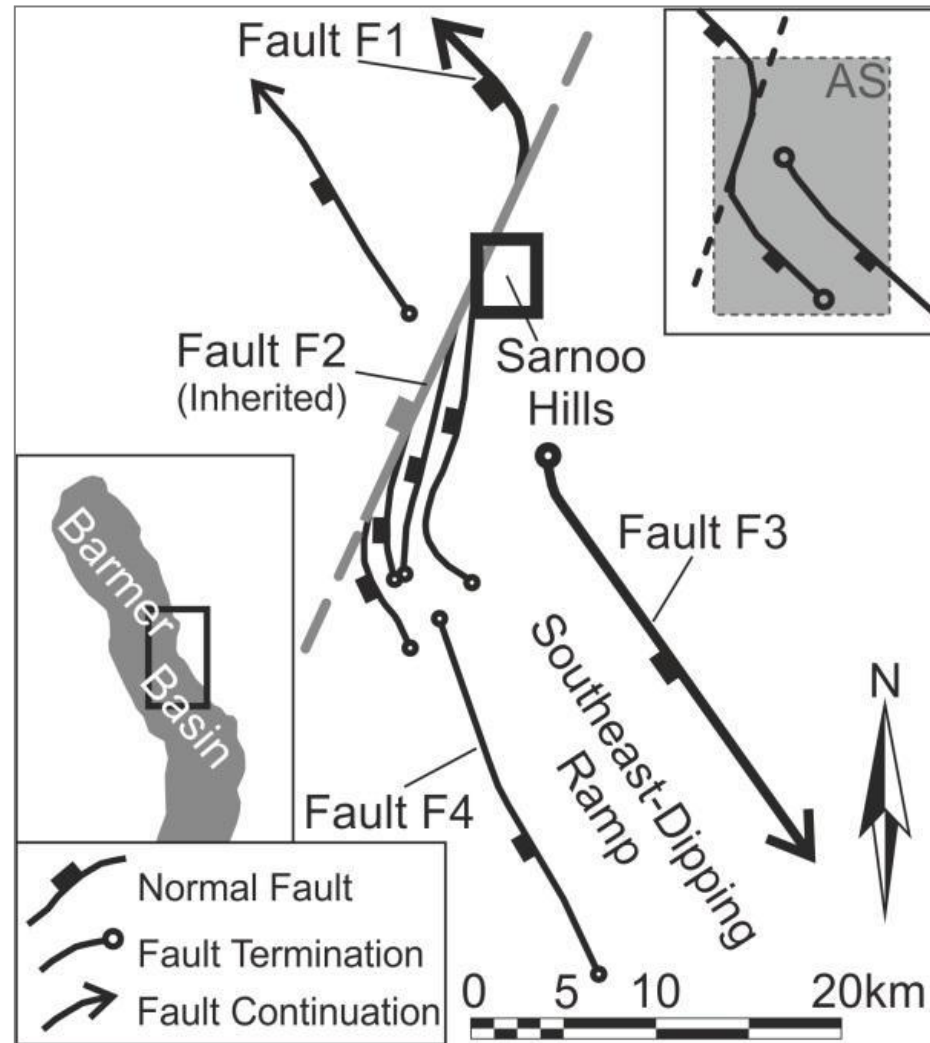


Figure 10. Incorporation of a pre-existing, rift-oblique fault (Fault F2) that was active during early northwest-southeast extension (Sarnoo Hills; [Figure 3](#)), into the evolving eastern rift margin fault system during the main Barmer rift event (Barmer Hills; [Figure 2](#)), formed an unorthodox eastern rift margin accommodation structure. Rather than directly linking right-stepping rift margin faults systems to the north and south directly (Faults F1 and F3), the inherited rift-oblique fault (Fault F2) transferred extension to a mid-rift fault system (Fault F4), that subsequently soft-linked with the rift margin fault system to its east (Fault F3) and formed a southeast-dipping, rift-internal relay ramp (simplified cartoon sketch and location map inset; AS = Accommodation Structure).

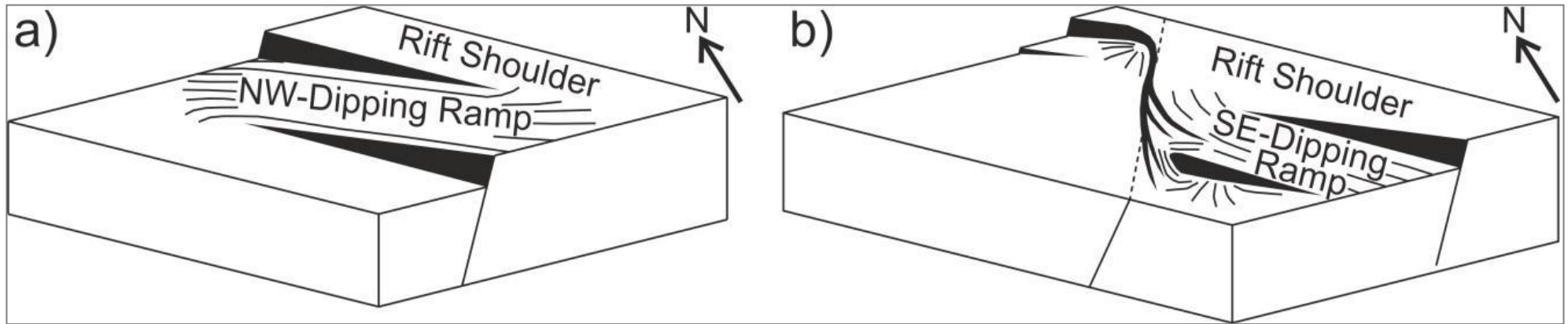


Figure 11. Cartoon sketch diagrams of a conventional model of (soft) linkage between two synthetic, right-stepping faults that form a northwest-dipping relay ramp (a) (e.g. Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998), and the unorthodox accommodation structure from the eastern rift margin of the Barmer Basin (b), that formed a southeast-dipping relay ramp due to the incorporation (via inheritance) of a pre-existing, rift-oblique fault into the evolving rift margin.

Name	Description	Location
<i>Trend 1</i>	Northwest-striking, northeast-dipping faults	Exposed in the Barmer Hills (Figure 2)
<i>Trend 2</i>	Southwest-striking, northwest-dipping faults	Dominant fault trend in the Sarnoo Hills (Figure 3)
<i>Trend 3</i>	West-striking, north-dipping faults	Exposed in the Sarnoo Hills (Figure 3)
<i>Fault F1</i>	South-southeast-striking, west-southwest-dipping (rift-parallel) eastern rift margin fault	Situated in the north of the subsurface model (Figure 6)
<i>Fault F2</i>	Southwest-striking, northwest-dipping (rift-oblique) rift-margin fault	Situated in the central section of the subsurface model (Figure 6)
<i>Fault F3</i>	South-southeast-striking, west-southwest-dipping (rift-parallel) eastern rift margin fault	Situated in the south of the subsurface model (Figure 6)
<i>Fault F4</i>	South-southeast-striking, west-southwest-dipping (rift-parallel) mid-rift fault system	Situated in the south of the subsurface model (Figure 6)

Table 1. Definitions of terms used in the text.