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Interaction of crustal heterogeneity and lithospheric process in determining passive margin architecture on the Southern Namibian margin

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Abstract: The influence of pre-rift crustal heterogeneity and structure upon the evolution of a continental rift and its subsequent passive margin is explored. The absence of thick Aptian salts in the Namibian South Atlantic allows imaging of sufficient resolution to distinguish different pre-rift basement seismic facies. Aspects of pre-rift basement geometry have been characterized which are then compared with the geometries of Cretaceous rift basin structure, and of subsequent post-rift margin architectural elements. Half-graben depocentres migrate westward within the continental syn-rift phase, at the same time as basin bounding faults become established as hard-linked arrays with lengths of approximately 100 km. The rift-drift transition phase, marked by Seaward Dipping Reflectors, gives way to the early post-rift progradation of clastics off the Namibian coast. In the Late Cretaceous, these shelf clastics are much thicker in the south, reflecting the dominance of the newly formed Orange River catchment as the main sediment entry point on the South African/Namibian margin. Tertiary clastics largely bypass the pre-existing shelf area, revealing a marked basinwards shift in sedimentation. Post-rift megasequence thicknesses do not vary simply according to the location of syn-rift half-grabens and thinned continental crust. Rather, the Namibian margin exemplifies margins influenced by a complex interplay of crustal thinning, pre-rift basement heterogeneity, volcanic bodies and transient dynamic uplift events on the evolution of lithospheric strain and depositional architectures.

Keywords: South Atlantic, Lithospheric Stretching, Passive Margin, Basement Heterogeneity

Introduction

The South Atlantic passive margin provides an exceptional region to study the mechanisms involved in lithospheric stretching, continental break-up and margin development (Hirsch et al. 2007; Heine, et al. 2013; Pernon-Pinvidic et al. 2013; Sibuet & Tucholke, 2014). But despite a recent focus on the evolution of passive margins, and the South Atlantic in particular (Blaich et al. 2011; Franke et al. 2013; Moulin et al. 2013), fundamental questions remain unanswered with regards to the degree that crustal heterogeneity controls passive margin formation, and the influence this structure may have on early margin accommodation space and on the development of oceanic transform segmentation. Addressing these questions is important not just for improving our understanding of lithospheric processes but also in constraining our knowledge of the petroleum system within such settings. This arises, for example, from spatial and temporal variations in lithospheric thickness across a margin and along its strike influencing heat flux both in the syn-rift phase and during post-rift thermal relaxation. Source rock maturation histories are therefore sensitive to variations in the underlying lithospheric structural and thermal evolution (e.g. Beglinger et al. 2012; Paton et al. 2008).

In this study we focus on the Namibian margin for two reasons. Firstly it provides an opportunity to investigate the temporal evolution of a margin from rift initiation through break-up and seafloor spreading into full passive margin development. Secondly, as it is located to the south of the Walvis Ridge it is not complicated by the presence of salt. Therefore we can establish the architecture of the post-rift margin without either having to account for salt tectonics or being constrained by poor sub-salt imaging of the syn-rift.

This study sets out to test a base case hypothesis, that although the configuration of passive margins are dominated by syn-rift structures and often by post-rift deformation, e.g. gravitational collapse, the pre-rift configuration plays an often poorly understood role in defining structure and evolution of such basins.

Regional Setting

The West African margin is closely associated with the grain of the Proterozoic to early Palaeozoic Pan-African fold belt along much of its length (Fig. 1; Clemson 1997) and the onshore part is dominated by the broadly N-S trending Neoproterozoic Gariep Belt (Coward 1981; Miller 1983). As a consequence of limited well data in the offshore, and the absence of significant Palaeozoic onshore outcrops, the stratigraphy of the post Pan-African basement is uncertain on the Namibian margin. It is generally considered that the basement is overlain by a Carboniferous-Permian stratigraphy associated with the Karoo foreland basin (Maslanyj et al. 1992; Light et al. 1993). This is subsequently overlain by deposits associated with the early stages of continental rifting, although again the timing of this is poorly constrained. Clemson (1997) proposed that the early rift portion comprises Triassic to mid-Jurassic Karoo sediments that were deposited in a major rift basin along much of the present day passive margin. Regardless of the timing of this phase of rift initiation, there is a consensus that the Pan-African fabrics played an important role in the subsequent South Atlantic rift phase along the margin (e.g. Uchupi 1989; Maslanyi et al. 1992). A significant rift onset unconformity has been identified in a number of previous seismic reflection studies (e.g. Gerrard and Smith 1982; Light et al. 1993) and has been attributed to the initiation of the main South Atlantic rift phase in the Late Jurassic.

The basin fill of the main rift phase (Fig. 2), which has in parts been penetrated by boreholes in the South African part of the Orange basin, comprises continental clastics (fluvial claystones, sandstones and pebble beds) and claystones interbedded with volcaniclastics and volcanics (McMillan 2003), passing into significant thicknesses of volcanics towards the top. Light et al. (1993) recognised a number of intra-syn-rift sequences with distinct seismic facies and also noted a marked variation in dip across the margin, with westward dips to the west of a structural “hinge line” and eastward dips to its east. Of particular note is the development of a seaward dipping reflection (SDR) complex that developed in the west just prior to continental break-up (Gladczenko et al. 1997). The timing of break-up is constrained by the M4 magnetic anomaly (126.5 Ma), indicating an Early Cretaceous age (Numberg & Muller 1991) or more specifically a Barremian age according to the Walker et al. (2012) timescale.

The break-up unconformity, which sits above the seaward dipping reflector package, is overlain across most of the basin by a Barremian-early Aptian package, which denotes marine inundation of much of the continental margin and has been considered part of the transition phase (Light et al. 1993). This package is important for the presence of organic-rich source rocks. An unconformity at the top of the transition phase marks the development of the main post-rift phase (Fig. 2), which is represented by a thick succession of Cretaceous and Tertiary age sediments that have a number of internal unconformities. These unconformities in the northern Orange basin in Southern Namibia, and the correlatable unconformities in the South African portion of the Orange Basin, have a variety of horizon names but are consistent in identifying the key basinwide events (Emery 1975; Gerrard and Smith 1982; Light et al. 1993; Brown 1995; Paton et al. 2008). The early part of the post-rift stratigraphy consists of an Aptian-Turonian progradational succession that consists of deltaic and fluvio-marginal deposits that exceed 3500 m in thickness in the inner part of the margin. The deposition of this package was punctuated in the Cenomanian and Turonian with organic-rich shales, which form significant, basinwide and correlatable reflections (Light et al. 1993; Brown et al. 1995). The top of the Cretaceous is identifiable with an additional basinwide unconformity and marks a major shift from deposition on the inner margin towards sediment accumulation predominantly on the outer margin during the Tertiary.

Data and methods

This study combines 2D reflection data from four surveys (ECL-89, SN-1996, GNA-1997 and Vernob-2003) that were acquired between 1998 and 2003. The data cover the northern parts of the Orange Basin in southern Namibia and in this study we utilise PSTM data that had a maximum recording time of between 5 and 7 seconds two-way travel time. The lines in the southern area of the data set intersect the Kudu gas field (wells Kudu 9A-1, 9A-2 and 9A-3) and these have been used to provide age and lithological constraints for the seismic interpretation. A megasequence approach has been taken for the interpretation of the data based upon identification of regional and local unconformities using reflection termination, cut-offs and onlap relationships with the sequence stratigraphic system based upon Muntingh & Brown (1993) (Figure 1 for location of Lines A, B and C shown as Figures 3a, 3b and 3c respectively).

Megasequence Architecture

Pre-rift

The reflection character of the intra-basement pre-rift in the offshore data is highly variable and is consistent with the complex Gariep Belt that is directly onshore of the study area. In places, continuous high amplitude reflections are evident and are demonstrably beneath the divergent reflections that are indicative of the main rift phase (Fig. 4). Given the presence of abundant mid-crustal reflectivity and of west-dipping and folded reflections in the eastern Namibian margin, these are likely to be imaging portions of the nearshore Gariep Belt. This is in contrast to the well imaged, concordant reflections that have been inferred to be Karoo sediments identified on other parts of the Namibian margin (e.g. Clemson 1997). Elsewhere the basement is much more akin to a transparent acoustic basement with no internal reflectivity or character and this seismic facies is present along much of the margin (Fig. 3). This transparent acoustic basement forms a 30 km wide continuous zone that trends approximately North-South. The feature is often referred to as the hinge line (e.g. Light et al. 1993), which implies a discrete fulcrum and by association conveys a kinematic process. In this study we will discuss the nature of this zone, but prefer to call it the Kudu Basement Ridge (Fig. 3) to differentiate between the feature and its origin.

Syn-rift megasequence (MSB1 to MSB2)

Although not penetrated by boreholes in this area, the syn-rift intervals are identifiable from divergence of reflections in a half-graben geometry; the fault locations and timings are mapped and constrained from the termination of these divergent reflections. Of particular note for this interval is the spatial distribution of faulting across the Kudu Basement Ridge that separates the basin into two distinct structural domains (Fig. 3).

To the east of the basement ridge small wedge-shaped half-grabens with typical widths of between 5 and 12 km are present and are consistently controlled by west-dipping normal faults (Fig. 4). The geometry of the rift basin fill, which is predominantly contained within the lower syn-rift interval, is dominated by low to medium amplitudes and semi-continuous reflectivity, and the controlling faults reveal a highly asymmetric system with faults which possibly decolle onto a more regionally correlatable west dipping crustal reflection within the pre-rift/basement sequence. The internal seismic character of the rift basins is consistent with the style of deposition typical of early continental rift basins, with isolated depocentres that are likely to be fluvial-dominated with occasional lacustrine basin fill (e.g. Gawthorpe & Leeder 2000). Comparable syn-rift intervals have been identified and penetrated to the south in well A-J1 in the South African Orange Basin (Jungslager 1999).

The basins to the west of the basement ridge are also characterised by a divergent reflection geometry but these reflectors onlap onto the basement ridge to the east and thicken towards the west, and are controlled by east-dipping normal faults. In the type sections Figs. 3 a and b, three diverging packages are imaged and each of them is bounded by an east-dipping fault. These western faults are more widely spaced than those to the east of the Kudu Basement Ridge, with half-graben widths of up to 50 km although it is likely that smaller faults that were active early in the syn-rift phase are also present but not resolved seismically. The seismic character of the basin fill to the west of the basement ridge is divided into a lower and upper package. The lower package, which is similar to that to the east of the ridge, is also noticeably different as it consists of higher amplitude, more continuous reflections. The early syn-rift interval, which is present on the east and west of the basement high, has a variable amplitude and semi-continuous reflectivity, while the later syn-rift interval shows divergence into the western normal faults but reflections are not cross-cut by the eastern faults, indicating that the late syn-rift faulting progressively migrated towards the west.

The isochron maps of the lower syn-rift interval (Fig. 6a) reveal that sedimentation is controlled by NNW-SSE trending fault systems that are separated by the Kudu Basement Ridge (Fig. 6). The continuity of areas of sediment accumulation allows us to correlate faults between seismic lines. Discrete faults and associated depocentres are evident, typically 20-30 km in length, typical of fault segments in early rift systems (Gupta et al. 1998; Ebinger et al. 1999; Cowie et al. 2000). This is the deepest resolvable syn-rift interval and faults, or linked fault arrays, show lateral continuities of between 20 and 100 km; again this is comparable to other rift systems. Three areas are also evident where fault traces abruptly terminate and are offset from neighbouring arrays (Fig. 6a). These correspond either to transfer/accommodation zones (Morley 1990) or conceivably represent later strike slip faults that dissect the rift basin. In contrast, the isochron map for the upper syn-rift interval (Fig. 6b) reveals a significant reorganisation of the rift system. The inboard faults are not present as they have switched off and accommodation space is focussed progressively onto the outboard faults. Fault arrays and associated isochron “thicks” are more continuous, indicating that the western fault sets had by this stage evolved into hard-linked rift segments of approximately 100 km in length. The transfer zones are also more clearly apparent at this time.

Transitional megasequences (MSB2 to MSB4)

The lower part of the megasequence above MSB2 is enigmatic (MSB2 to MSB2a; Fig. 5). It sits beneath a seaward dipping reflector package and shows a thickness increase to the west across the margin but there is no evidence, at least in the current data, of significant faulting. This observation therefore disagrees with previously understanding of the system but our current data set is not extensive enough to define its geometry. Further analysis should be undertaken on subsequent data sets to determine whether the package is, or is not, fault controlled.

The transitional phase (MSB2a to MSB4), as a whole, encompasses the transition from the syn-rift interval into the demonstrable passive margin megasequences, and here we divide it into a lower transition megasequence and an upper transition megasequence (Fig. 5). The lower transition megasequence only occurs west of the basement high and is characterised by onlap onto either the uppermost reflection of the syn-rift or onto the basement/pre-rift ridge to the east. The megasquence (MSB2-3), which is the deepest penetrated by the Kudu wells (Bagguley, 1997; Schmidt, 2004), is of Hauterivian-Barremian age and consists of interbedded volcanic and fluvial strata that form the main clastic reservoir interval for the area. The upper part of this megasequence is characterised by high amplitude reflections with a fanning, west-dipping geometry that corresponds to Seaward Dipping Reflections typical of volcanic passive margins (e.g. Franke 2013). In plan view the lower transition megasequence thickens noticeably to the west where there is the lateral transition into the SDRs (Fig. 6c). It is evident that seismically resolvable faulting has switched off by this stage and the accumulation of volcanics was being controlled by accommodation space outboard of the main early continental rift system.

The upper transition megasequence (delineated by MSB3-4) overlies the SDRs, is best developed west of the basement high and is Barremian-early Aptian in age. It is dominated by high amplitiude and laterally continuous reflections that overstep the Kudu Basement Ridge and which are shallowly truncated by the bounding reflection at the top of the package. This interval contains the organic rich source rock encountered in the Kudu well and is a consequence of the restricted marine environment and the major flooding event during the early Aptian in which the regionally important black shale was deposited (Serranne & Anka 2005).

There is a distinct pattern of variation in thickness of this upper package (Fig. 6d), in contrast to the lower transition megasequence. For much of the margin the unit is noticeably thin and is often condensed to be below seismic resolution. Towards the north there is a clear thickening into the basin forming an elliptical geometry which is bound on the east by the Kudu Basement Ridge.

Cretaceous megasequences (MSB4 to MSB6)

The two post-rift Cretaceous megasequences, which have a thickness of up to 4 km, account for most of the stratigraphy in both the inner and outer parts of the passive margin. The Cretaceous post-rift megasequences are bound by the MSB4 surface (mid-Aptian) at the base, showing some erosional truncation of the underlying Transitional package, and by the MSB6 horizon at the top.

The lower of the two Cretaceous post-rift megasequences (MSB4-5) comprises the first broadly progradational unit of the margin. It progressively onlaps onto the top of the syn-rift and onto basement to the east (Fig. 3c). The westward-prograding clinoform geometry typically has a “height” (in two-way-travel time) of approximately 100 ms (Fig. 3b), the steepest slope of which is inferred to represent a pro-delta (outer-shelf) to slope mudstone facies transition. The package thins downdip to the west where it becomes condensed, and in places is not seismically resolvable. The MSB5 horizon, at the top of this lower post-rift package, is defined by a high amplitude reflection that is correlatable across the entire basin and corresponds to the end-Cenomanian maximum flooding surface.

The progradation of the MSB4-5 megasequence towards the west marks the development of an established coastline or shelf-break and the migration of that coastline basinward; the Kudu wells indicate this is a mainly shallow marine interval. The megasequence thickness is greater in the south (Fig. 3a) compared to the middle or the north of the study area (Figs. 3b and c). This reflects that there was a dominant sediment input point for the basin in a similar location to the present day Orange River, to the south of the basin (Fig. 6e).

The overlying package (MSB5-6) is dominated by an aggradational to progradational architecture and the progressive development of a bathymetric break in slope of up to 800 ms. In the middle part of the margin it is noticeable that the package is dominated by continuous, high amplitude and concordant reflections over a length scale of at least 80 km across the margin. The sedimentology of this megasequence is dominated by claystones, as documented in the Kudu wells. In contrast, the geometry of the outer margin is markedly different. In the southern part of the basin the upper part of the megasequence is dominated by gravity collapse structures (Fig. 3a); the up-dip extensional domain and the associated down-dip compressional domain are clearly imaged and have been described in detail elsewhere (Butler & Paton 2008; Dalton et al. 2015; Dalton et al. *in press*).

The timing of the upper horizon (MSB 6) is diachronous across the margin, having a subcrop of Maastrichtian age (67 Ma) stratigraphy in the inner margin and early Tertiary (53-65 Ma) stratigraphy in the outer margin (as constrained by the Kudu wells (Bagguley 1997; Schmidt 2004). This diachroneity is a consequence of a varying degree of erosion at the top of the Cretaceous megasequence as shown by the erosional truncation of its uppermost reflections. In the outer margin there is no erosion, with concordant reflections throughout the Cretaceous and Tertiary megasequences. This is also the case at the break in slope of the Cretaceous margin. To the east of this, however, there is a progressive increase in erosion toward the inner shelf and the amount of erosion may be calculated by projecting the geometry of the underlying stratigraphy from the position at which erosion begins (Paton et al. 2008 for method). This indicates a variable degree of erosion along 200 km of the Namibian margin, with a maximum of approximately 800 m of section lost by erosion at the end-Cretaceous.

A south to north reduction in interval thickness is also evident in the Turonian- Maastrichtian megasequence (Figs. 3 a-c) but is less pronounced than in the preceding megasequence, with a much more uniform distribution of sediment. It is only in the most northern part of the basin that significant thinning is apparent and this corresponds to a northward progradation of the package. The thinning that is evident in the isochron map in the inner margin is a reflection of the uppermost Cretaceous-earliest Tertiary erosion rather than deposition (Fig. 6e).

Tertiary megasequence (MSB6-Sea Bed)

The seismic character and geometry of the Tertiary megasequence (MSB6-sea bed) varies significantly both across and along the margin. In the inner part of the margin the megasequence is very thin and characterised by medium to high amplitude, continuous, sub-parallel to parallel reflections that downlap onto the base-Tertiary unconformity. The most eastern part of the megasequence has undergone tilting and erosional truncation at the seabed where it is in places entirely absent.

For most of the southern area (Fig. 3a) the megasequence shallowly progrades and where the underlying base-Tertiary unconformity forms a break of slope the Tertiary megasequence forms a shelf margin system. Within the megasequence there is a correlatable horizon that is characterised by erosional truncation below and onlap and downlap above, and divides the Tertiary into two packages. This horizon corresponds to the SCB-B surface of Weigelt & Uenzelmann-Neben (2004) and is inferred to be of Middle Miocene age. This horizon separates two wedges both of which prograde from the underlying break in slope towards the west.

Stratigraphic data from the Kudu wells show that most of the Tertiary sediments are dominated by claystones and siltstones, with interbedded sandstone. On the shelf, the Tertiary sediments are very thin and characterised by high amplitude, parallel and continuous reflections which are interpreted to represent the presence of interbedded calcareous sandstones and shelly limestones (Gerrard & Smith 1982).

The internal architecture of the Tertiary megasequence along most of the margin is broadly similar with a relatively thin package, probably representing significant sediment bypass of the shelf above the base Tertiary unconformity (Figs. 3a-c). A rapid thickening towards the west, beyond the shelf break, is also evident along the margin and the location of this is controlled by the geometry of the base-Tertiary unconformity that mimics the Late Cretaceous break in slope.

The most outboard part of the basin is dominated by downlap onto the more distal portion of the base-Tertiary unconformity. Despite the westward switch in location of sediment accumulation during the Early Tertiary (Fig. 6f), the margin is remarkably undeformed with very little faulting and no significant gravity collapse structures that are so characteristic of the underlying Late Cretaceous megasequence.

Development of the Namibian part of the Orange Basin

The Orange Basin of Southern Namibia preserves an exceptional record of the development of a continental margin from rifting through to the present day. We now present a summary of the development of the margin and consider both its spatial and temporal development (Figs. 7 and 8).

The Late Jurassic to Early Cretaceous early rift phase shows distributed extension with a number of relatively long north-south trending normal fault sets (Fig. 8a). The onshore Gariep Belt structures converge with depth onto a west-dipping crustal deformation zone (Gray et al. 2008) which when extrapolated offshore can explain the west-dipping, mid-crustal reflections that are observed. The early rift faults, at least those east of the Kudu Basement Ridge, also appear to converge onto this zone, suggesting that this basement heterogeneity localised the deformation, at least during the early rift phase (Figs. 7a and 8a). This early evolution of a rift system corresponds well with equivalent histories documented in many rift systems that were at least partly controlled by crustal heterogeneity (Clemson, 1997). The Kudu Basement Ridge, as discussed, is an interesting feature as it separates two pre-rift basement zones of more continuous reflection character but has little internal character itself. We interpret this to represent a Precambrian granitoid body around which the Pan-African deformation of the Gariep Belt is localised. The shape and scale of this feature consistent with other similar bodies along the southern African margin, such as the Cape Granites. From the perspective of continental rifting, it appears to have acted to localise stress at its edges and so influenced where the rift system developed and its spatial geometry.

The exact configuration of the main rift system is relatively poorly constrained given the widely spaced 2D seismic dataset that is available over much of the study area, but geometrically it resembles many rift systems with normal faults that show segmentation along their length. Comparisons with fault growth models, such as those developed by Gupta et al. (1998) and Cowie et al. (2000) appear to be appropriate.

As the rift evolved, there was a marked migration of the system towards the incipient spreading centre in the west, while the system in the east progressively switched off (Fig. 5). The end of the rift phase is characterised by an erosion event in the east and by the widespread development of the two packages within the transition phase. The lower transitional megasequence includes the emplacement of SDRs as well as the extrusion of more extensive volcanics across the basin that cap the syn-rift half-graben fills. The distribution of volcanics is often associated with lower crustal bodies (Hirsch et al. 2010). As these bodies are considered to be emplaced at the time of rifting it is likely that these lower crustal bodies represent the remnants of the magma chambers that fed the surface volcanics. The end of the SDR package is marked by the onset of the upper transition megasequence which includes the main organic source rock unit, suggesting rapid basin deepening and anoxic conditions. As seen in Fig. 3a, there is a significant thickness variation of this upper transitional unit, with the greatest thickness occurring immediately to the west of the Kudu Basement Ridge. This is likely to be a consequence of where post-rift thermal subsidence was greatest at this earliest stage of break-up.

Throughout the syn-rift and transitional phases of the Namibian margin there is relatively little variation along the 200 km of the margin (Fig. 8a). The Late Cretaceous package, by contrast, exhibits significant variation (Fig. 8b). The lower portion is dominated throughout by the progradation of the shelf margin clinoforms and by the development of a clastics-dominated margin sequence. The sediment input at this stage is obviously determined by its provenance, but at this stage it is most likely to be have been derived from the erosion of the remnant rift margin and proximal continental sequences.

To the south of the study area, in the South African portion of the Orange Basin, the Aptian clastic shallow marine succession was sourced from a number of smaller river systems along the margin (Paton et al. 2008). This results in a relatively uniform deposition of this mainly deltaic package along much of the margin to the south of the Orange River. In contrast, on the Southern Namibian margin the isochron map for this interval (encompassed by Fig. 6e) conforms much more to a single entry point for deposition, with the location of the source being very close to the present day Orange River delta. This is in agreement with previous studies that propose the evolution of the Oliphants drainage system into the Orange system during the Albian (e.g. Dingle & Hendry, 1984). The sedimentology of the package in the Kudu wells confirms that it is a clastics-dominated shallow marine sequence. The result is a radial distribution of the clastic shallow marine deltaics to the north and west. In the north this is represented by a very thin, and most likely highly condensed, sequence that can be interpreted as the transition from pro-delta to distal shelf deposits.

In contrast, the Late Cretaceous megasequence is much more extensively developed both across and along the Namibian margin (Figs. 7d and 8b). Only in the most distal, north-western part of the margin are accumulations of limited thickness (equivalent to 200 ms TWT or less). The progradational geometry of the MSB4-5 megasequence is replaced initially by a much more aggradational geometry, but then becoming more progradational again in the later stages of the Late Cretaceous MSB5-6 megasequence (e.g. Fig. 3c). This change in depositional geometry is coincident with a dramatic change from a coarser clastics-dominated system to a claystone-dominated system. A similar relationship between geometry and sedimentology is also observed in the southern Orange Basin (Paton et al. 2008). The abrupt switch in sediment grade is considered to reflect the emergence of the Orange River catchment area capturing, eroding and draining the Karoo Basin over much of southern Africa. Despite significant sediment accumulation in the Late Cretaceous the concordant reflections of the inner margin imply uniform subsidence across much of the margin, over an area at least 100 km in width and 300 km in length. The Late Cretaceous shelf was remarkably stable apart from small normal faults with throws equivalent to reflector offsets on the order of 50-80 ms TWT. The end of the Turonian-Maastrichtian megasequence is marked by the erosional event that is most evident in the south (Fig. 3a) but which also extends towards the north (Fig. 3b); this is equivalent to a similarly aged erosion event in the southern portion of the Orange Basin (Paton et al. 2008).

A comparison of the Cretaceous post-rift and Tertiary post-rift isochron maps (Figs. 6e and f) reveals the abrupt reorganisation of the shelf depositional system. The relatively thin (200 ms TWT) Tertiary megasequence of the middle margin likely reflects modest subsidence post-erosion, but also represents the significant bypass of sediments across a shelf that is 100 km wide, leading to deposition in the available accommodation space that lay outboard of the inherited Cretaceous shelf break. The lateral variation along the Tertiary continental slope is a reflection of the switching of the Bengula current that redistributes sediments from south to north along the margin (Weiglt & Uenzelmann-Neben 2004).

Discussion

What controls fault evolution from continental rift to drift stages?

A number of studies have documented the influence of crustal heterogeneity upon the evolution of passive margins (Ring 1994; Schumacher 2002; Korme et al. 2004). In this part of the South Atlantic the role of the Pan-African basement fabric being utilised by Mesozoic extension has been discussed previously (Light et al. 1993; Clemson 1997), and in particular the inheritance of Gariep Belt fabrics as a control on the north-south structural trend (Frimmel et al. 1996; Halbich & Alchin 1995). While our study agrees with this for the nearshore portion of the margin, we propose that an alternative explanation of the Kudu Basement Ridge, especially given its transparent internal character, is that it is a Precambrian granitoid body. This is supported by the ridge being directly along trend of the granite bodies contained within the onshore Gariep Belt (Fig. 1). This would suggest that rifting to the west of this basement high may not have reactivated pre-existing fabric on through-going structures, and therefore caution must be applied before extrapolating basement fabric as continuous to the more distal parts of the basin margin.

In addition to affecting the location of the subsequent rift structure, our results suggest that the pre-existing crustal heterogeneity influences the evolution of the rift faults. A significant number of studies have documented the nature in which faults grow and interact with sedimentary basin fill, through field observations (e.g. Cartwright et al. 1995; Dawers & Anders 1995), analogue and numerical models (e.g. Gupta et al. 1998; Marchal et al. 1998; Cowie et al. 2000; McClay et al. 2002), and subsurface seismic studies at a variety of scales from regional 2D to high resolution 3D data (e.g. Morley 1999; Dawers & Underhill 2000; Contreras et al. 2000; McLeod et al. 2000; McLeod et al. 2002). Given the caveat that we cannot clearly map the earliest fault development, we present evidence of smaller faults growing and linking to form larger structures. These early faults do not show evidence of significant en-echelon patterns as predicted by numerical and analogue models (e.g. Cowie et al. 2000; McClay et al. 2000). Even accounting for the line spacing of the available data, we would expect such a spatial geometry to be evident in our data; therefore we propose that the absence of en-echelon faults is because the inheritance of basin fabric itself plays a role in modifying the nature of how the faults grow and interact (Walsh et al. 2002;

Paton 2006). It has been documented within the Cape Fold Belt of South Africa that the basement fabric can result in the co-linear development of normal faults and we invoke a similar process here (after Paton 2006). The faults that we do observe are evident as having length scales of up to 30 km in the early syn-rift, but these had coalesced by the late syn-rift into linked segments of up to 100 km; again these observations are consistent with normal fault developments in southern Africa (Paton et al. 2006). However, what we propose is that there are significant offsets in fault locations on a wavelength of 100 km, and that these steps are accommodated through accommodation zones or strike-slip faults, which would be akin to continental transfer faults (Bosworth, 1985).

Numerical models of rift evolution show that as lithospheric stretching approaches incipient break-up strain should progressively localise towards the spreading centre. Huismans and Beaumont (2013) predicted that during a rift stage distributed strain, and hence a wide rift basin, would progressively localise onto the rift axis. Although previous studies have demonstrated that this may happen during the continental rift phase (e.g. Skogseid 2001), this study suggests that this is the case throughout much of the rift history and into the oceanic spreading phase.

Segmentation and margin evolution

The segmentation of passive margin basins has been much discussed, and clearly plays a significant role in the tectonic evolution of the South Atlantic (Clemson et al. 1997; Franke et al. 2007). Of note is the correspondence between segment boundaries and onshore structural lineaments, specifically with the well-established trends of Damara fold belt and Gariep structures, (e.g. Clemson et al. 1997; Corner 1983; Holzförster et al. 1999; Stollhofen et al. 2000; Corner et al. 2002). Koopman et al. (2014) provides further insights into the role of segmentation in the evolution of the Orange Basin, including discussion of how these formed propagation barriers to the northward progression of seafloor spreading, and they associated these features with onshore structures, e.g. Cape Cross. On the conjugate margin in Argentina and Uruguay, Stica et al. (2014) outline how these segments play a fundamental role in ocean spreading and margin development, as well as influencing plate reconstructions (e.g. Moulin et al. 2013; Numberg & Muller 1991; Heine et al. 2013). Although there is evidence that not all onshore structures control offshore transfer zones, for example on the northern Norwegian margin (Tsikala et al. 2001), there is broad agreement that pre-existing structures can influence the location of fracture zones (e.g. Lister et al. 1986; Sitca 2014). A point recognised by Sitca (2014) is that no studies to date can relate the first evolution with break up segmentation. Clemson et al. (1997) discuss the importance of segmentation for the development of the passive margin along the entire Namibian basin. Our results agree with their conclusion, but in addition demonstrate for the first time that some rift segments will become inactive as a function of how faults grow and interact, but that where continental transform faults may have formed major structures they do remain significant features during the post-rift phase and into the oceanic domain.

Continuity of post-rift megasequences and thermal subsidence

Our mapping of the rift architecture, and hence the level of the top pre-rift surface, shows that is it very variable, both along and across the margin, with half grabens interspersed with basement highs (Fig. 8). When compared with the South African portion of the Orange Basin the variability increases and is a reflection of the presence of the Cape Fold Belt reactivation that cross-cuts the north-south trending Atlantic rift system (Paton et al. this volume). The results of this study, in conjuction with Paton et al. (this volume) reflects significant variations in the extent to which the upper crust has been stretched along the margin. Yet there is remarkable continuity of post-rift megasequences along the 1000 km length of the Orange Basin. The early post-rift fill (MSB4-5) is dominated by margin-derived clastic deposits prograding westward into the ocean basin, having been sourced from a number of smaller fluvial systems. Sediment thicknesses are broadly comparable throughout the Aptian-Albian, suggesting erosion rates of the hinterland were similar along its length. The Cenomanian sees the development of the Orange

River as the dominant sediment entry point (Jungslager, 1999) and because there were no significant ocean current systems at the time, there is a broad symmetry in its deposits to its north (Namibia) and south (South Africa). Stratigraphic successions are almost identical and have remarkably similar thicknesses, except in the furthest north beyond the edge of the Orange River system.

The geometry and accommodation space created along a passive margin should be a function of crustal thinning (McKenzie 1978; Steckler & Watts 1978). It would be expected that areas with greatest extension should correspond to areas of greatest post-rift thermal subsidence, at least during the earlier phase of the post-rift period. Yet the observations from the combined South African-Namibian Orange Basin (this study and Paton et al. 2008) demonstrate that the earliest post-rift phase shows little thickness variation along the 1000 km margin regardless of the rift architecture on which it sits. This is strong evidence that the magnitude of upper crustal extension does not always correspond to that of the lower crust, as is invoked by depth-dependant stretching models (e.g. Huisman and Beaumont 2011).

Conclusion

Using the Southern Namibian margin as an example, we have demonstrated that rift evolution and subsequent passive margin architecture are the products of a complex interplay of lithospheric processes and crustal heterogeneity. The latter plays a role in influencing the dimensions and style of fault evolution and in establishing the position of cross-cutting structures. We also highlight the role of pre-rift granitic bodies in influencing the location of deformation.

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Figure captions

Figure 1 – Regional map of the Namibian South Atlantic margin (namcor.com.na). This study focuses on the northern part of the Orange Basin, which includes the Kudu Field. The position of illustrated seismic sections are indicated.

Figure 2 – Tectono-stratigraphic scheme for the Namibian continental margin, with megasequence boundaries (MSB1-MSB6) identified in this study. Previous nomenclature of Brown et al. (1995) for key seismic reflections is included for comparison, from 1At1 to 22At1. Geologic timescale is from Walker et al. (2012).

Figure 3 – Regional east-west sections across the Namibian Orange Basin. a) this section, which is in the south, is taken as the type section and shows the Kudu Basement Ridge, the syn-rift and transition phase, and the Cretaceous and Tertiary post-rift sequences. b) and c) are to the north of Section (a) and show how the basin changes configuration towards the north (Figure 1 for location).

Figure 4 – This section (and its interpretation on the lower panel) is located to the east of the Kudu Basement Ridge and shows reflectivity within the crust. This corresponds to the offshore equivalent to the Gariep Belt and shows how Mesozoic faulting reactivates pre-existing heterogeneity (Figure 1 for location).

Figure 5 – This section (and its interpretation on the lower panel) is located to the west of the Kudu Basement Ridge. It shows the transition from continental crust through the volcanic syn-rift sequence and seaward dipping reflections into ocean crust (Figure 1 for location).

Figure 6 – Isopach maps of the main tectono-stratigraphic intervals in the study area. a) The deposition of the lower syn-rift is controlled by a number of north-south trending normal faults on both side of the Kudu Basement Ridge that are interpreted here as being dissected by SW-NE trending transform faults. b) In contrast the upper syn-rift interval is controlled by fewer faults in the west of the basin, indicating localisation of strain towards the incipient spreading centre. The continued localisation of accommodation space towards the west is reflected in the lower transition phase c) whereas accommodation space dramatically reorganises in the upper transition phase (d). The change in post-rift thickness variations between a single point source in the south in the Cretaceous (e), compared with bypass deposition in the outer margin (f) is evident.

Figure 7 – Cartoon evolution of the Namibian margin showing the progressive evolution of the syn-rift, transition phase and the post-rift deposition.

Figure 8 – 3D cartoon to show the variation through time at the end of the Transition phase (MSB4), the end Cretaceous (MSB6) and Present day in the margin geometry based upon the three sections in Figure 3.

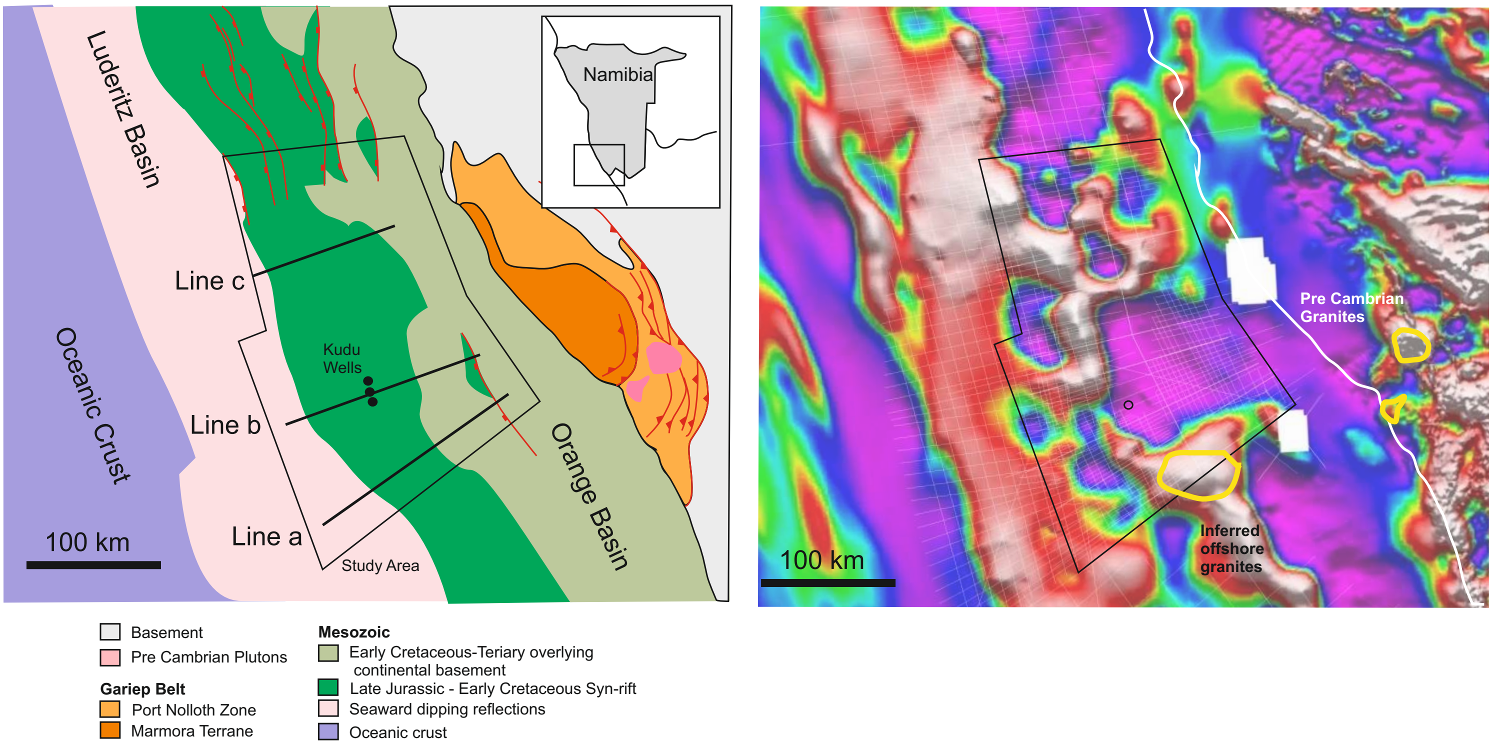
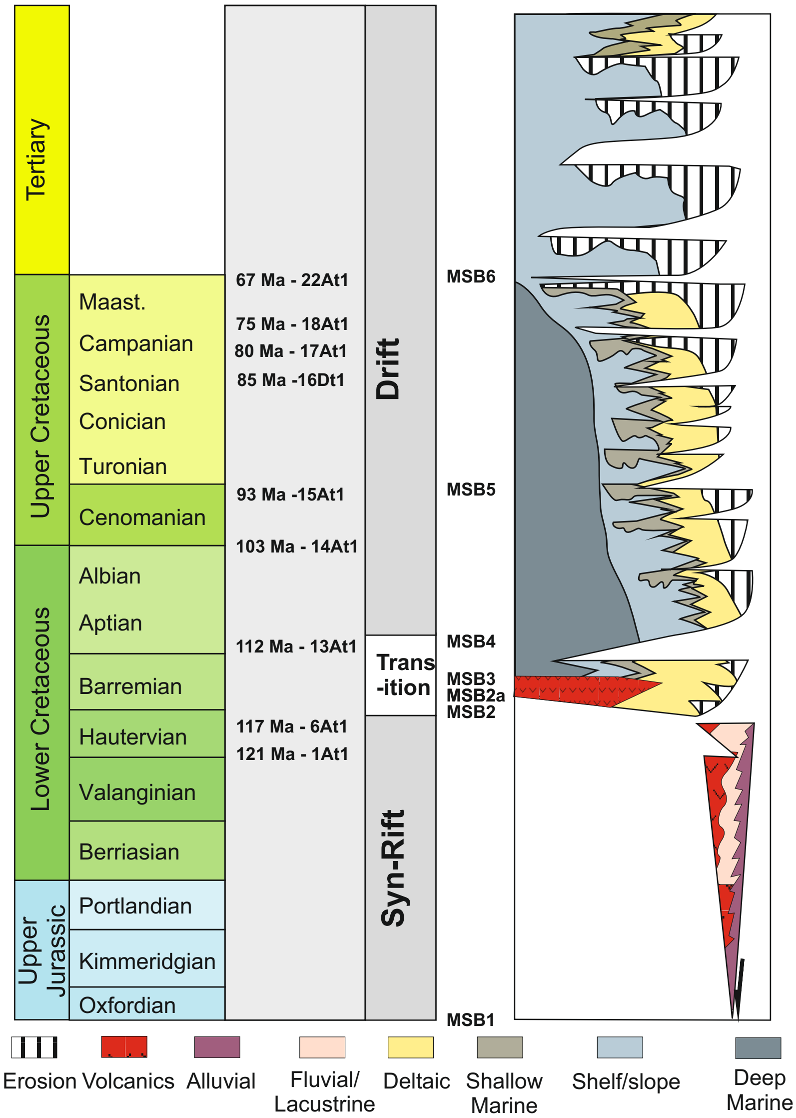

Luderitz Basin
Oceanic Crust
Line c
Line b
Line a
Kudu
Wells
Study Area
Orange Basin
Namibia
100 km
Pre Cambrian
Granites
Inferred
offshore
granites
100 km
Basement
Pre Cambrian Plutons
Gariep Belt
Port Nolloth Zone
Marmora Terrane
Mesozoic
Early Cretaceous-Teriary overlying
continental basement
Late Jurassic - Early Cretaceous Syn-rift
Seaward dipping reflections
Oceanic crust

Figure 2


Tertiary
Upper Cretaceous
Lower Cretaceous
Upper Jurassic
Maast.
Campanian
Santonian
Conician
Turonian
Cenomanian
Albian
Aptian
Barremian
Hautervian
Valanginian
Berriasian
Portlandian
Kimmeridgian
Oxfordian
67 Ma - 22At1
75 Ma - 18At1
80 Ma - 17At1
85 Ma -16Dt1
93 Ma -15At1
103 Ma - 14At1
112 Ma - 13At1
117 Ma - 6At1
121 Ma - 1At1
Drift
Trans -ition
Syn-Rift
MSB6
MSB5
MSB4
MSB3
MSB2a
MSB2
MSB1
Erosion
Volcanics
Alluvial
Fluvial/ Lacustrine
Deltaic
Shallow Marine
Shelf/slope
Deep Marine

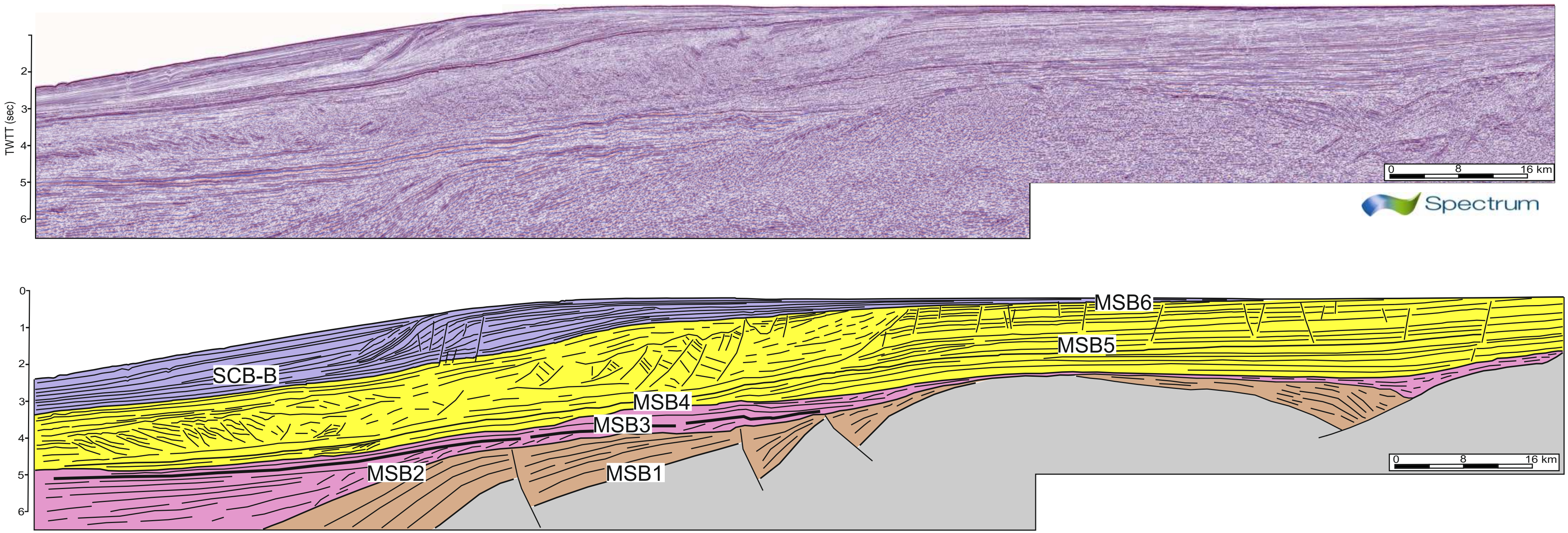

TWTT (sec)
2
3
4
5
6
0
8
16 km
Spectrum
0
1
2
3
4
5
6
MSB6
MSB5
SCB-B
MSB4
MSB3
MSB2
MSB1
0
8
16 km

Figure 3a

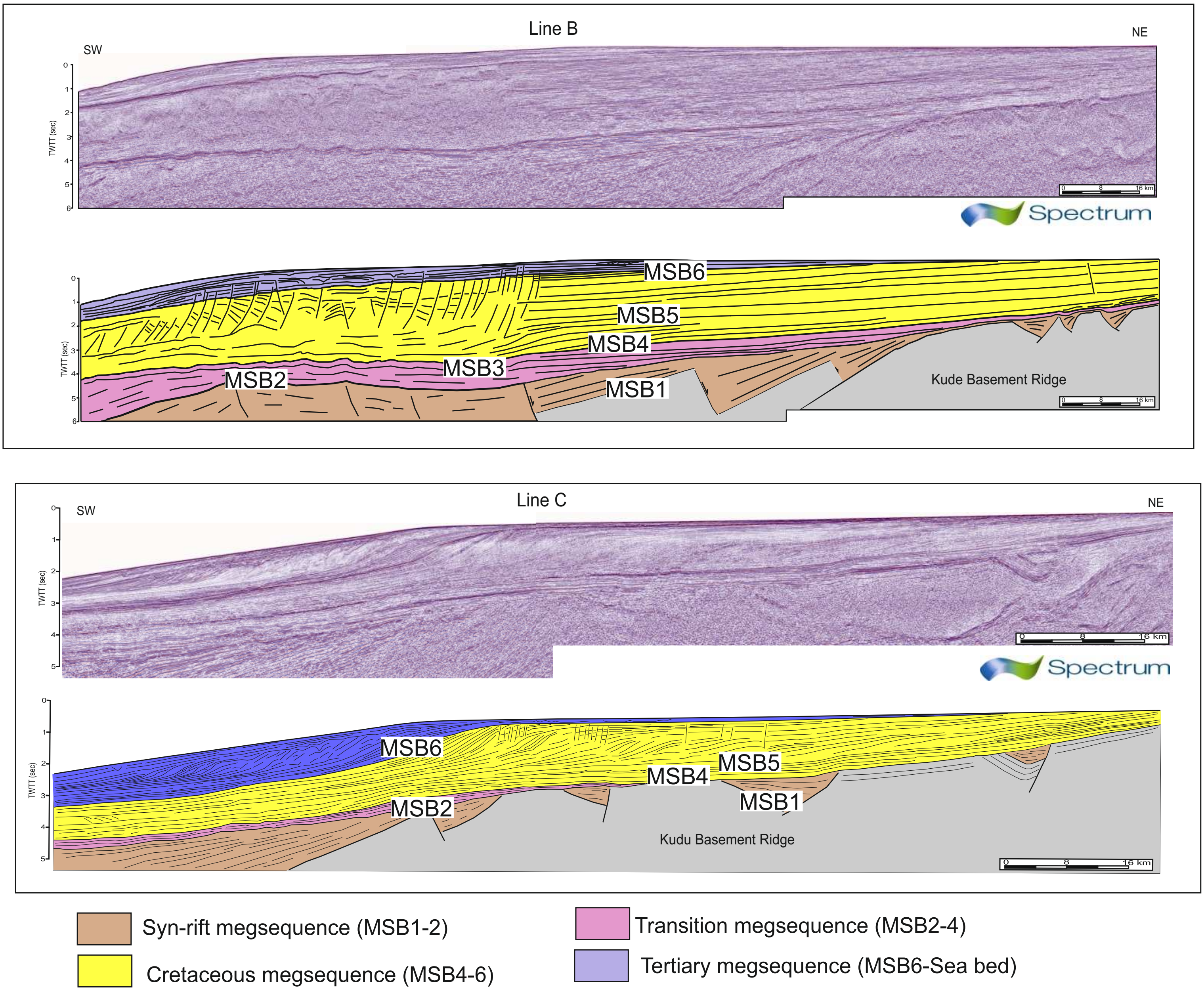
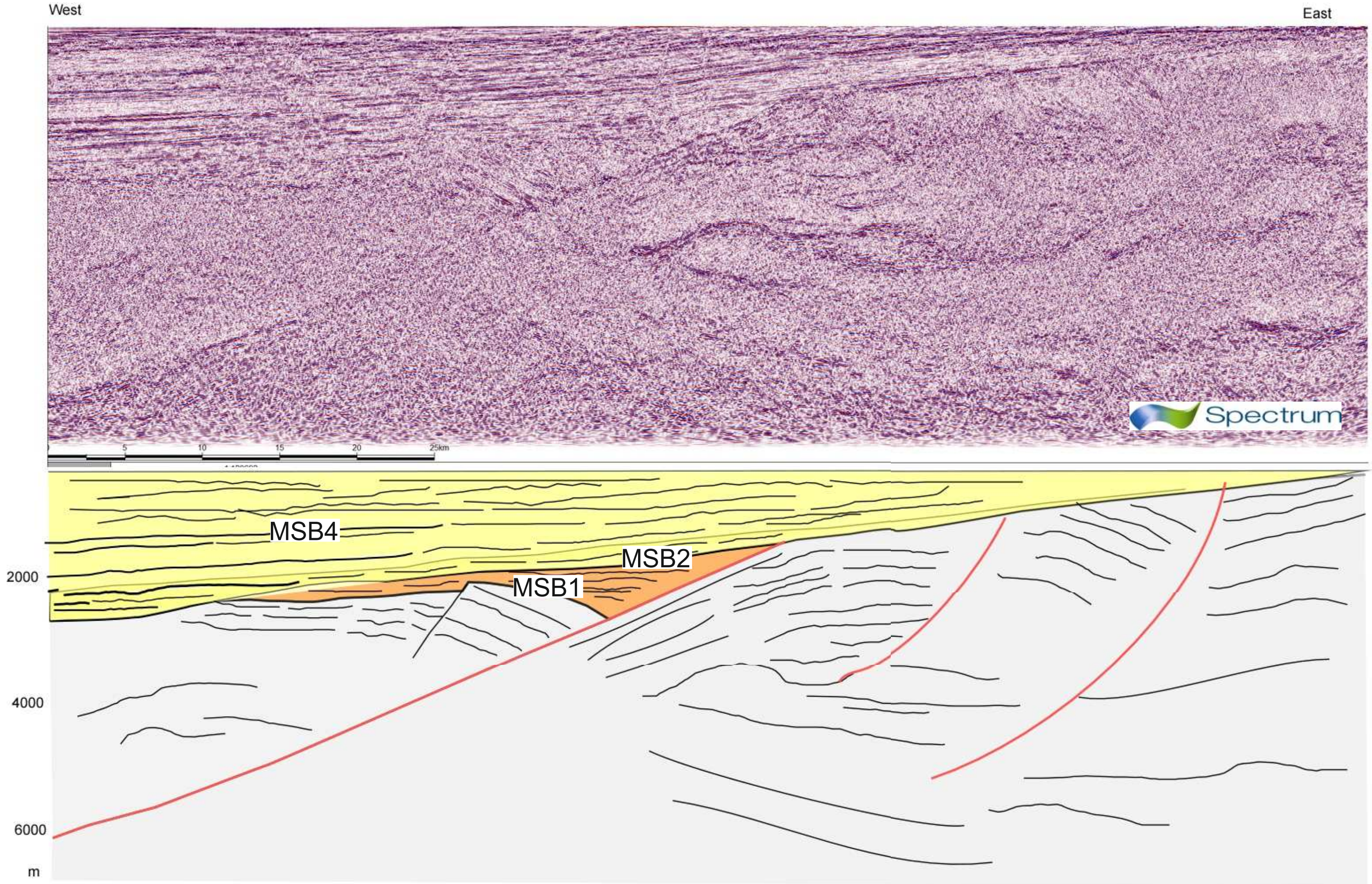


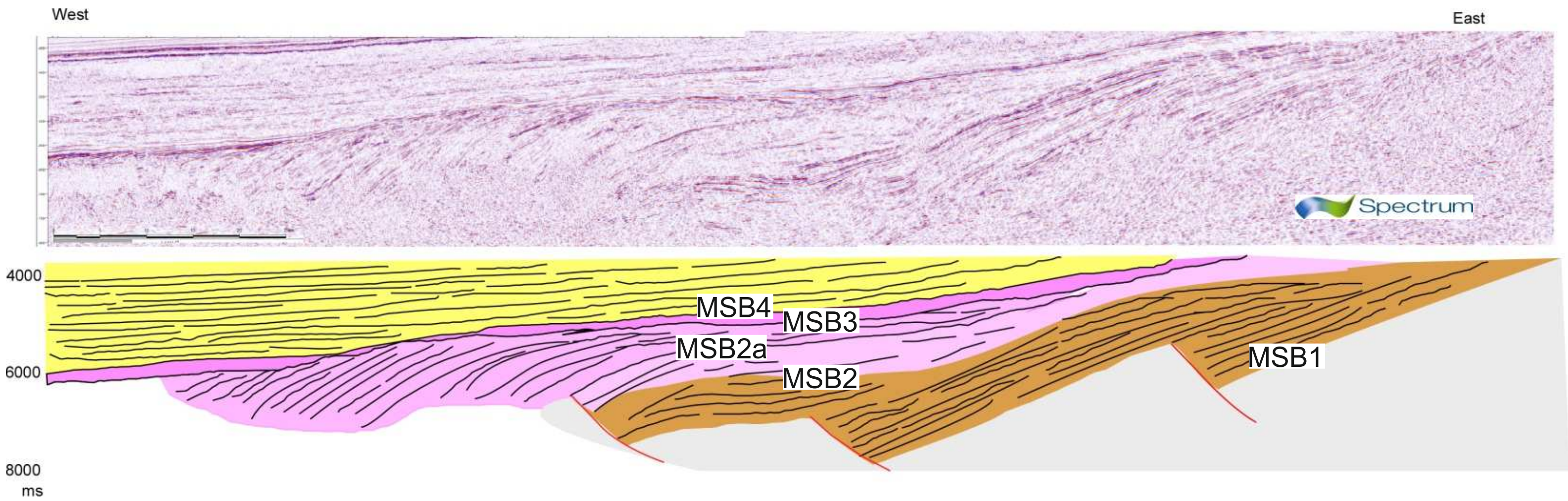
Figure 3b and c

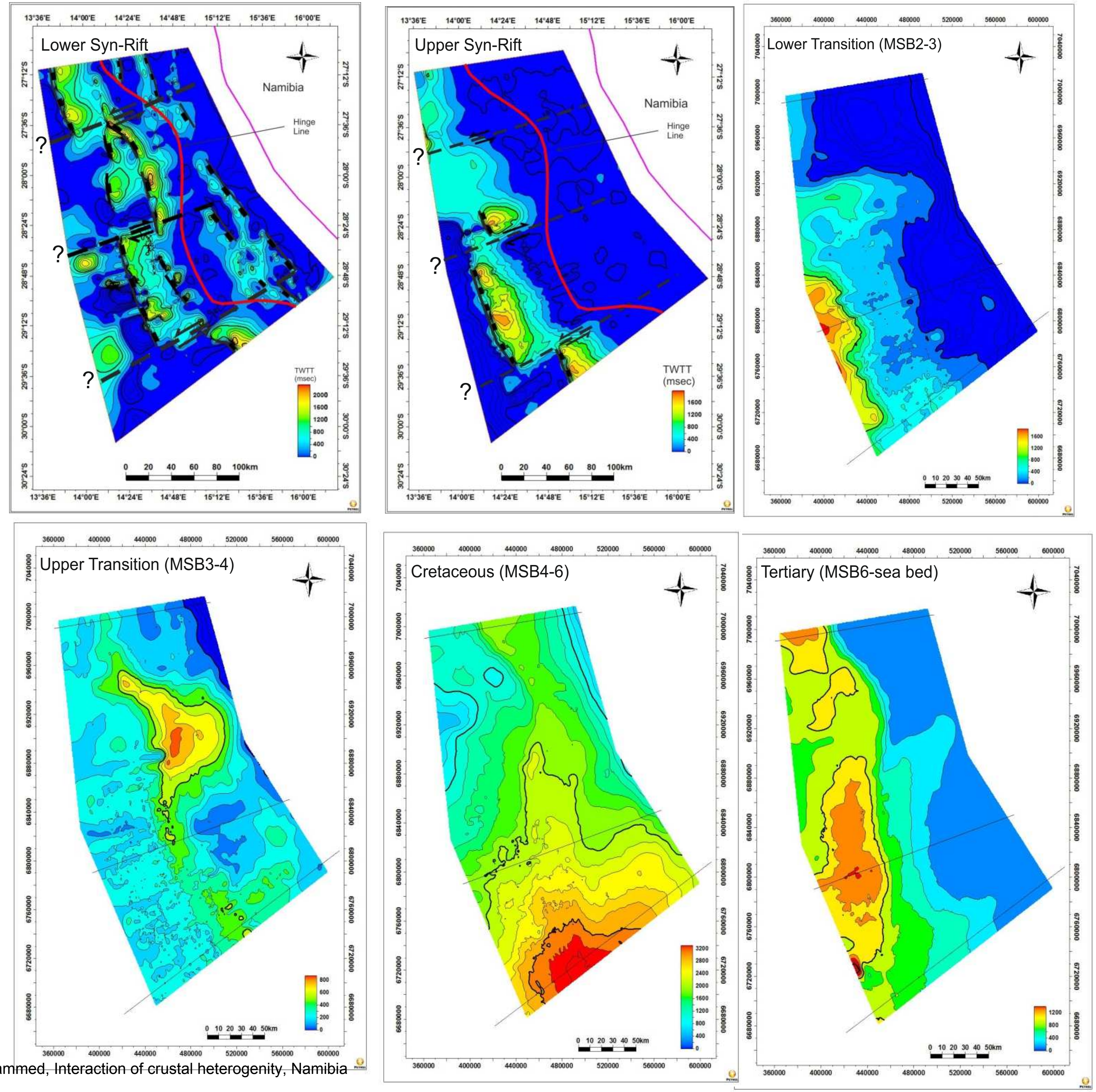
Figure 4



West
East
Spectrum
5
10
15
20
25km
MSB4
MSB2
MSB1
2000
4000
6000
m

Figure 5


West
East
Spectrum
4000
6000
8000
ms
MSB4
MSB3
MSB2a
MSB2
MSB1



Mohammed, Interaction of crustal heterogenity, Namibia

Figure 6

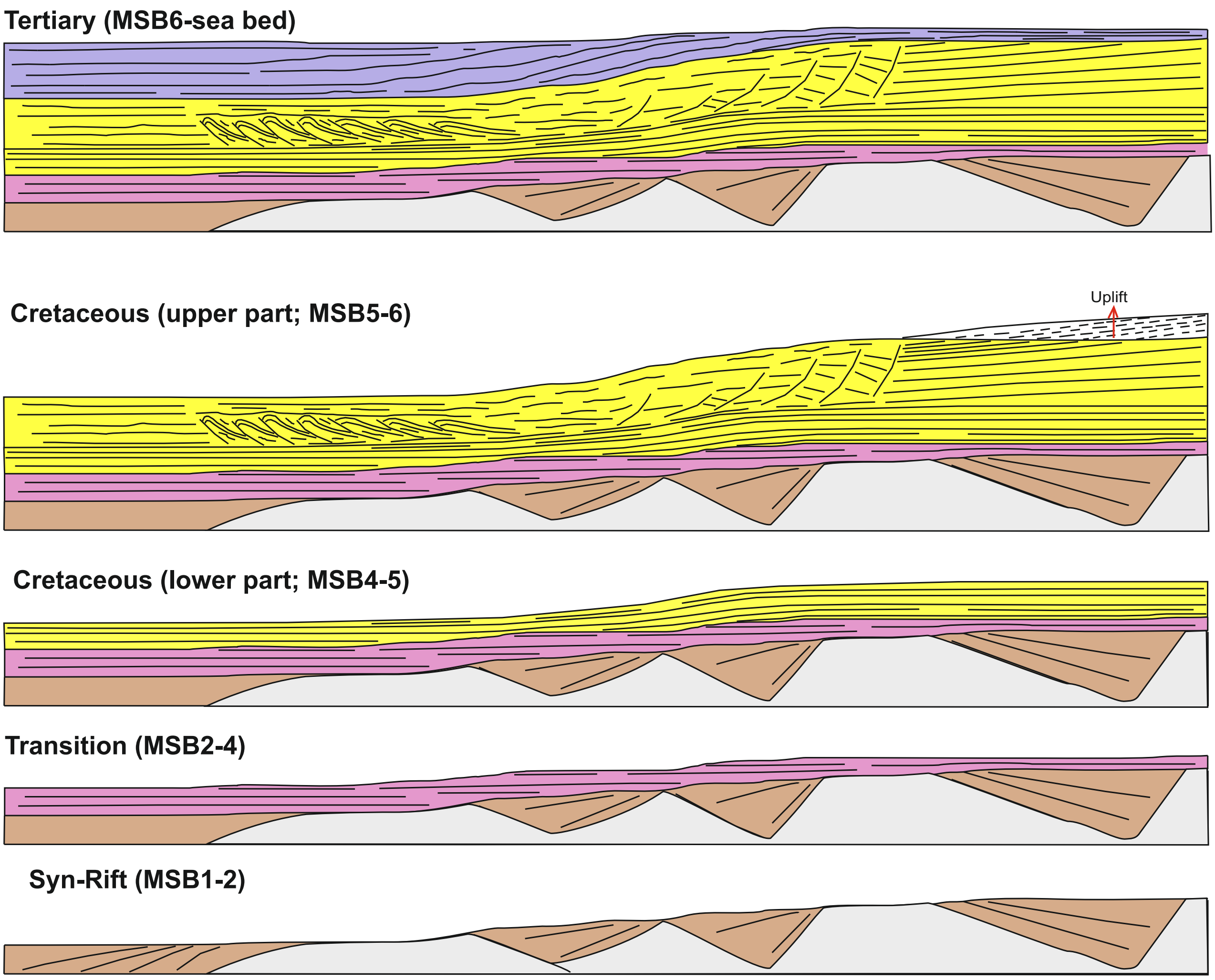

Tertiary (MSB6-sea bed)
Cretaceous (upper part; MSB5-6)
Uplift
Cretaceous (lower part; MSB4-5)
Transition (MSB2-4)
Syn-Rift (MSB1-2)

Figure 7

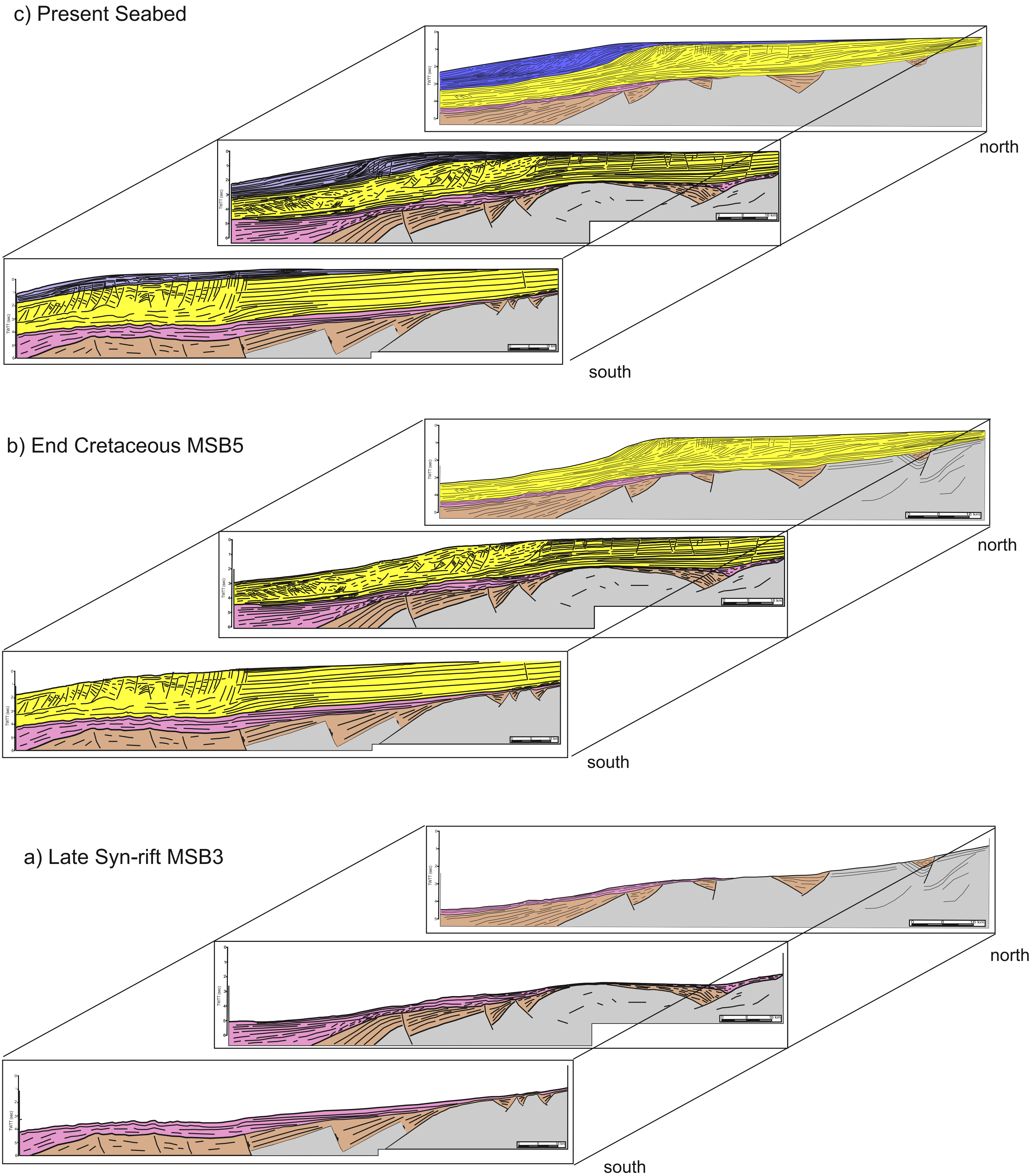


Figure 8 Mohammed, Interaction of crustal heterogenity, Namibia