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Tectonostratigraphic evolution of the Orange Basin, SW Africa

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Abstract: The Orange Basin is a Late Jurassic to present day basin located on the volcanic-rifted passive margin of SW Africa. 2D seismic data and structural restoration techniques were used to develop a tectonostratigraphic model of the basin consisting of a syn-rift and a post-rift megasequences separated by an Early Cretaceous break-up unconformity. The post-rift megasequence is characterised by gravity tectonics where extensional faults transferred displacement downdip into a deep water fold and thrust belt (DWFTB). Gravity gliding tectonics occurred through a combination of cratonic uplift and thermal subsidence and stopped via deltaic progradation and associated differential sedimentary loading.

Keywords: Orange Basin, volcanic-rifted margin, cratonic uplift, thermal subsidence, differential sedimentary loading, gravity tectonics.

The Orange Basin is located in the volcanic-rifted South Atlantic passive margin, extending offshore southern Namibia and South Africa (Fig. 1). The basin contains continental to paralic and marine sediments of Mesozoic to present day age overlying the stretched African continental crust.

General studies of the SW Africa margin evolution and the Orange Basin can be found in Light *et al.* (1993), Bagguley and Prosser (1999), Clemson *et al.* (1999), Gallagher and Brown (1999), Jungslagger (1999b), Menzies *et al.* (2002), Séranne and Anka (2005) and Granado (2006).

Research was focused on the tectonostratigraphic evolution of the Orange Basin and its shale-detached post-rift gravity-driven system (Rowan *et al.*, 2004; Granado, 2006). In similar settings, structural traps are formed by deep water contractional fault-related folding like the Gulf of Mexico and Niger Delta *world class* hydrocarbon provinces (Rowan *et al.*, 2004; Bilotti and Shaw, 2005). As shown by Barton *et al.* (1993) Turonian-age source shales occur in the Orange Basin; these underlie a deep water fold and thrust belt (DWFTB) and the presence of distal turbidite facies of possible reservoir quality (Light *et al.*, 1993; Jungslagger, 1999b; Séranne and Anka, 2005) with associated bright seismic reflectors make this system worth studying.

Structural restoration of a balanced cross section from a regional (ca. 200 km long) 2D seismic line was carried out using *2DMove*™ software so as to unravel the kinematics of the post-rift gravity tectonics (Fig. 2) and particularly its deep water fold belt.

Methods

A 2D time-migrated seismic data grid consisting of 62 seismic lines covering ca. 20,000 km^2 was interpreted in terms of depositional megasequence analysis and structural styles with the aid of a workstation.

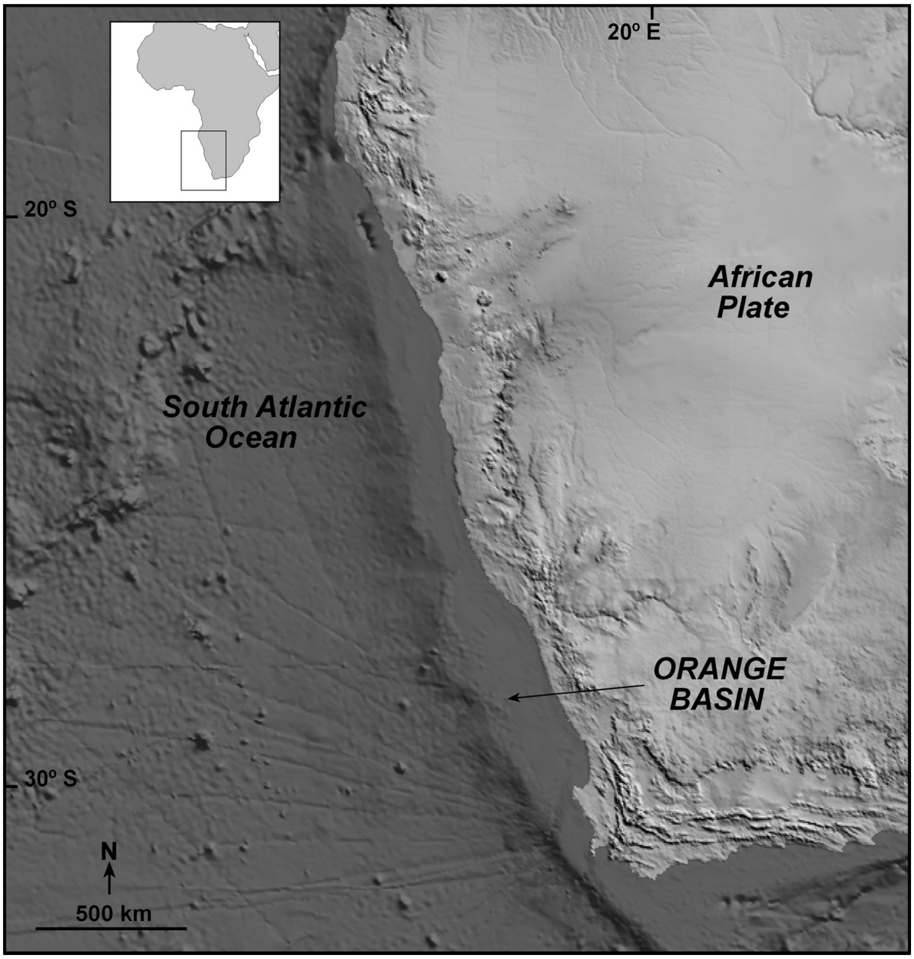

Figure 1. ETOPO2 elevation and bathymetry model showing the location of the Orange Basin. From NOAA, National Geophysical Data Centre (2001).

Syn-rift and post-rift megasequences and major bounding unconformities and structures across the basin were interpreted at this stage (Fig. 2).

A NE-SW-trending seismic line transecting the passive margin normal to the structural trends was imported into Midland Valley's *2DMove™* and a workflow methodology was used to reinterpret when necessary, depth convert, decompact, restore and validate the regional cross section.

Structural restoration was carried out separately for the extensional and the contractional domains of the gravity-driven system. Regional pin lines were inserted where no deformation was recognised, i.e. continental platform and abyssal plain; loose lines were inserted at the ends of the sections being restored (Granado, 2006). Different restoration algorithms were used: *inclined simple shear* or *fault-parallel flow* for listric growth extensional faults; and *line-length unfolding, flexural slip unfolding* and *fault-parallel flow* for thrust faults and associated fault-related folds.

Seismic interpretation

Two contrasting tectono-sedimentary sequences were interpreted from the Orange Basin seismic datasets, these separated by a regional unconformity. The deeper sequence is characterised by landward-dipping growth extensional faults; the upper sequence shows a more complex tectonostratigraphic evolution with quietly deposited strata followed by prograding clinoforms overlain by widespread updip regional growth listric faulting and downdip distal thrusting and folding, followed by further prograding clinoforms and deltaic slope failures (Fig. 2). The deeper section was interpreted as the syn-rift depositional megasequence, as proposed by Light *et al.* (1993) and the upper section as the post-rift depositional megasequence. A summary tectonochronostratigraphic chart is shown in figure 3.

The Late Jurassic to Early Cretaceous Hauterivian syn-rift megasequence (160-130 Ma) was deposited via NE-verging planar growth extensional faulting with syn-tectonic continental sedimentary sequences

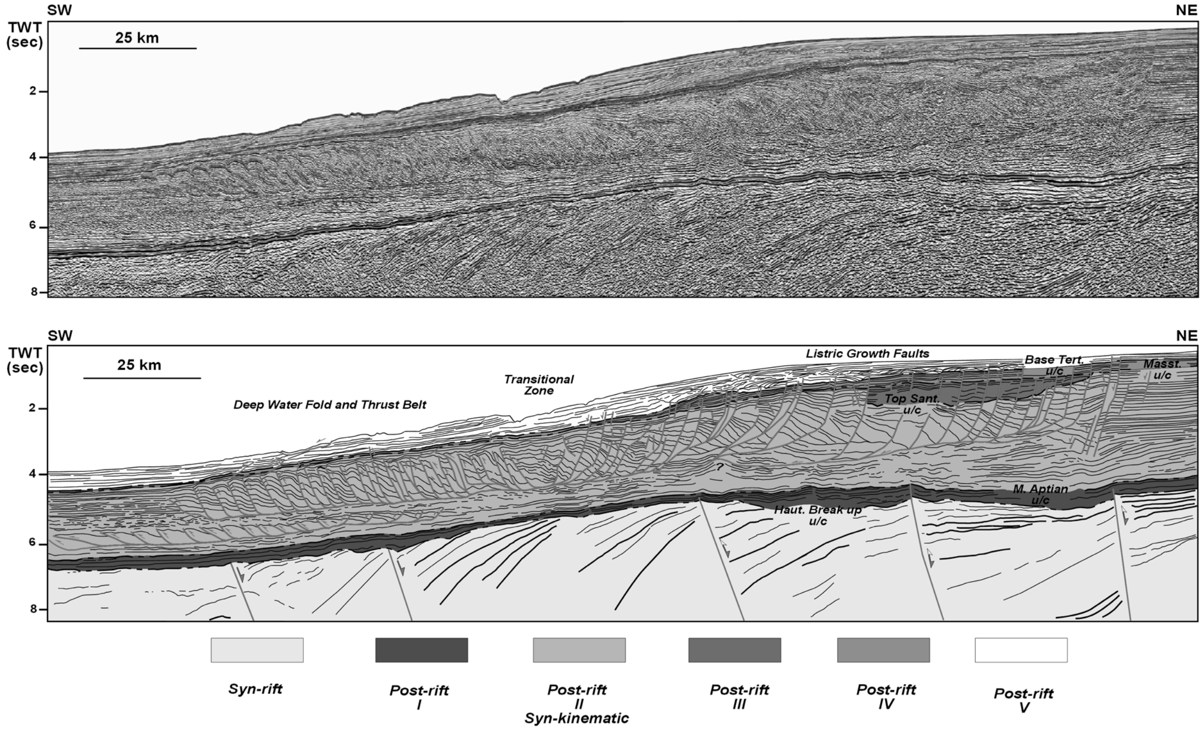

Figure 2. Regional seismic line *vernab_03_063a* and tectonostratigraphic interpretation.

interbedded with high amplitude seismic reflectors (Figs. 2 and 3); these reflectors are interpreted as seaward-dipping seismic reflectors (SDRs), i.e. sub-aerially extruded lava flows typical of volcanic rifted margins (Menzies *et al.*, 2002). Some of the rearmost syn-rift extensional faults show small reverse offsets of reflectors affecting both syn-rift and early post-rift strata but no syn-inversion growth strata were identified. The overlying megasequence is separated by a break-up unconformity of Hauterivian age (130 Ma), hence dating the onset of sea floor spreading.

The Hauterivian (130 Ma) to present-day post-rift megasequence was subdivided in 5 depositional sequences bounded by regional unconformities, named as *depositional sequences I to V*; these sequences show the evolution from the Early Cretaceous Orange Basin deepening to the Late Cretaceous to present day progradation of the Orange River delta through the Coniacian-Campanian (89-75 Ma) gravity tectonics. Extensional, transitional and contractional domains were interpreted for the *Syn-kinematic Depositional Sequence II* (Fig. 2). Regional listric growth extensional faults characterise an extensional domain that soles into a basinward-dipping detachment. Strata within growth fault blocks show high amounts of rotation, heave and throw; up to three different detachments were interpreted in this domain, finally linking basinward into a master detachment.

The extensional domain is downdip-linked to a contractional domain via a structurally complex and poorly imaged transitional zone of ca. 10 km length. The contractional domain fold and thrust belt is formed by an inner and outer fold and thrust belts. The former shows SW-directed imbricate thrust sheets with non-equally spaced thrust faults and two detachments; the outer fold and thrust belt is formed by equally-spaced SW-directed thrust sheets with associated thin growth strata. All thrust sheets terminate in asymmetric SW-verging fault related folds, interpreted in 2D as fault-propagation folds.

Structural restoration

The extensional domain structural restoration yielded 24 km of extension calculated by the interpretation and restoration of syn-kinematic extensional growth sequences (Fig. 4). The contractional domain restoration gave an approximate shortening of 16 km, calculated both by *line length balancing* of a marker seismic reflector and the separation of the pin and loose lines after restoration (Fig. 5). The

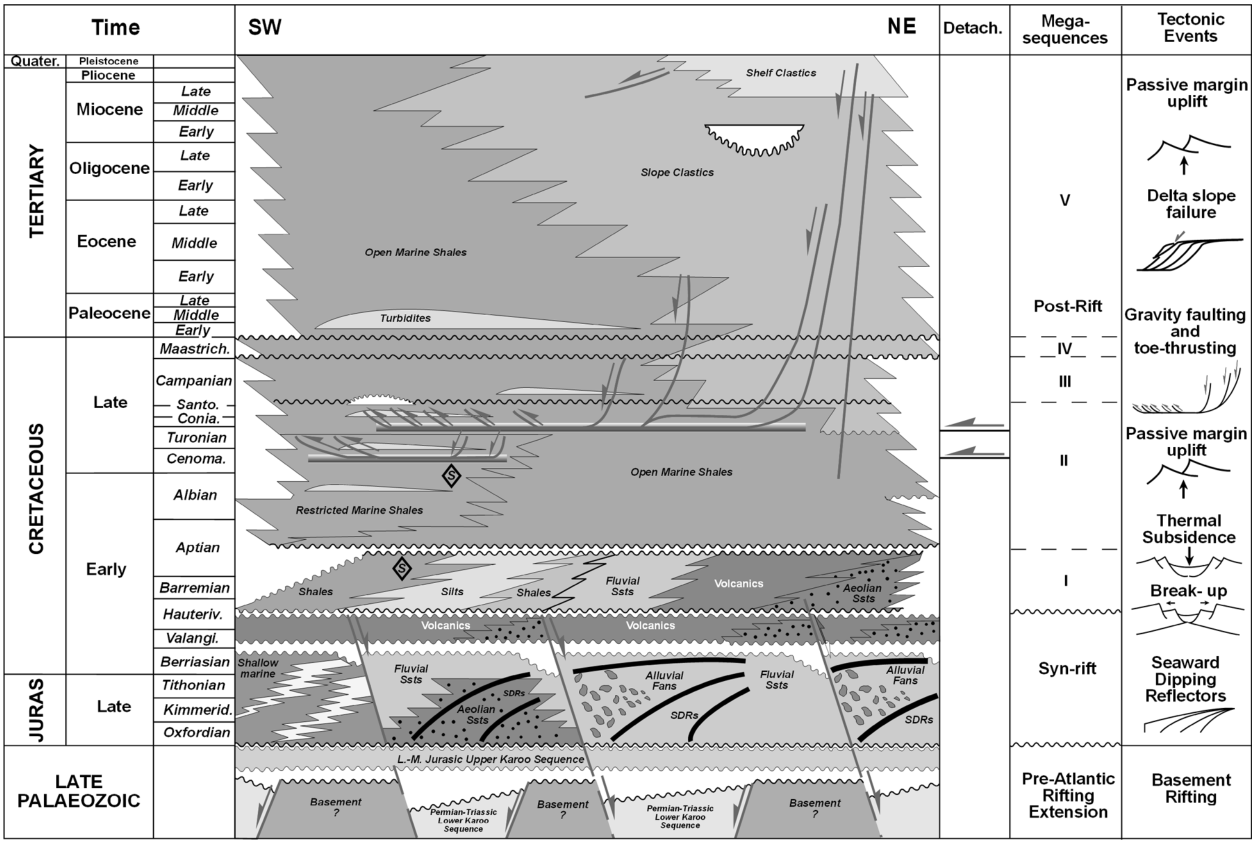

Figure 3. Tectonochronostratigraphic chart of the Orange Basin. S: source rocks. Lithological data from Light *et al.* (1993) and Séranne and Anka (2005). From Granado (2006).

inner fold and thrust belt showed more contraction (9 km) than the outer fold and thrust belt (7 km); this can be appreciated from the more complex structural style of the hinterland belt and the presence of a secondary minor detachment (Fig. 2).

Discussion

The following paragraphs discuss a new tectonostratigraphic model for the Orange Basin in terms of depositional megasequences. It also discusses the structural styles of each megasequence and a comparative study with the also shale-detached Niger Delta gravity-driven system (GDS).

Tectonostratigraphy of the Orange Basin

The Orange Basin shows the typical passive margin evolution represented by the syn-rift and post-rift megasequences. Late Jurassic to Early Cretaceous (160-130 Ma) crustal extension and associated mechanical subsidence explain the extensional fault-controlled syn-rift deposition as seen in many other rift and failed-rift systems (Bosworth *et al.*, 2005 and many others). The presence of SDRs proves the volcanic nature of the Orange Basin rifting (Menzies *et al.*, 2002) and the interplay of volcanism and passive margin evolution.

The Hauterivian break up unconformity (130 Ma) records the onset of sea floor spreading and the progressive deepening of sedimentary facies across the basin (Light *et al.*, 1993).

The post-rift megasequence (130 Ma-Present Day) was divided in 5 depositional sequences bounded by unconformities of regional extent, named *Pre-kinematic (I), Syn-kinematic (II) and Post-kinematic (III-V)*; the sequence II is characterised by gravity-driven tectonics. These sequences were deposited as thermal subsidence occurred through the cooling of the asthenosphere and the underplated igneous material interpreted by Bauer *et al.* (2000).

The syn-rift extensional faults reactivation mentioned earlier had to occur after the deposition of the first post-rift depositional sequence. Basin margin cratonic uplift (Gallagher and Brown, 1999), as well as differential thermal subsidence during the Post-rift stage, can explain the extensional faults inversion.

Structural styles and comparative analysis

The Orange Basin shows contrasting structural styles and kinematic evolution with other west Africa shale-detached GDS, e.g. Niger Delta. The extensional domain is characterised by regional growth extensional faults that transferred displacement through gliding over a regional detachment; the Niger Delta system is characterised by both regional and counter-regional growth extensional faults that transferred displacement down-dip via gravity spreading (Rowan, 2004; Bilotti and Shaw, 2005 and references therein) after the onset of basin subsidence. Both systems have different dimensions also, the Niger Delta being much a larger system (Bilotti and Shaw, 2005; Granado, 2006 and references therein) than the Orange Basin. The absence of counter-regional faults in the Orange Basin implies lower sedimentation rates than those for Niger Delta, also obvious when comparing the dimensions of the extensional (and contractional) growth sections of both.

The Orange Basin fold and thrust belt is characterised by strongly asymmetric, basinward-verging fault-related folds. On the other hand, the Niger Delta shows doubly-vergent structures, triangular zones, and different types of fault-related folds (Corredor *et al.*, 2005). These contrasting structural styles are interpreted according to different detachment strengths (Dahlen *et al.*, 1984); the Orange Basin styles argue in favour of a relatively strong frictional detachment, while Niger Delta shows structural styles related to low strength detachments. Also the detachment is thicker on the Niger Delta DWFTB. All fault-related folds in the Orange Basin were interpreted in 2D as fault-

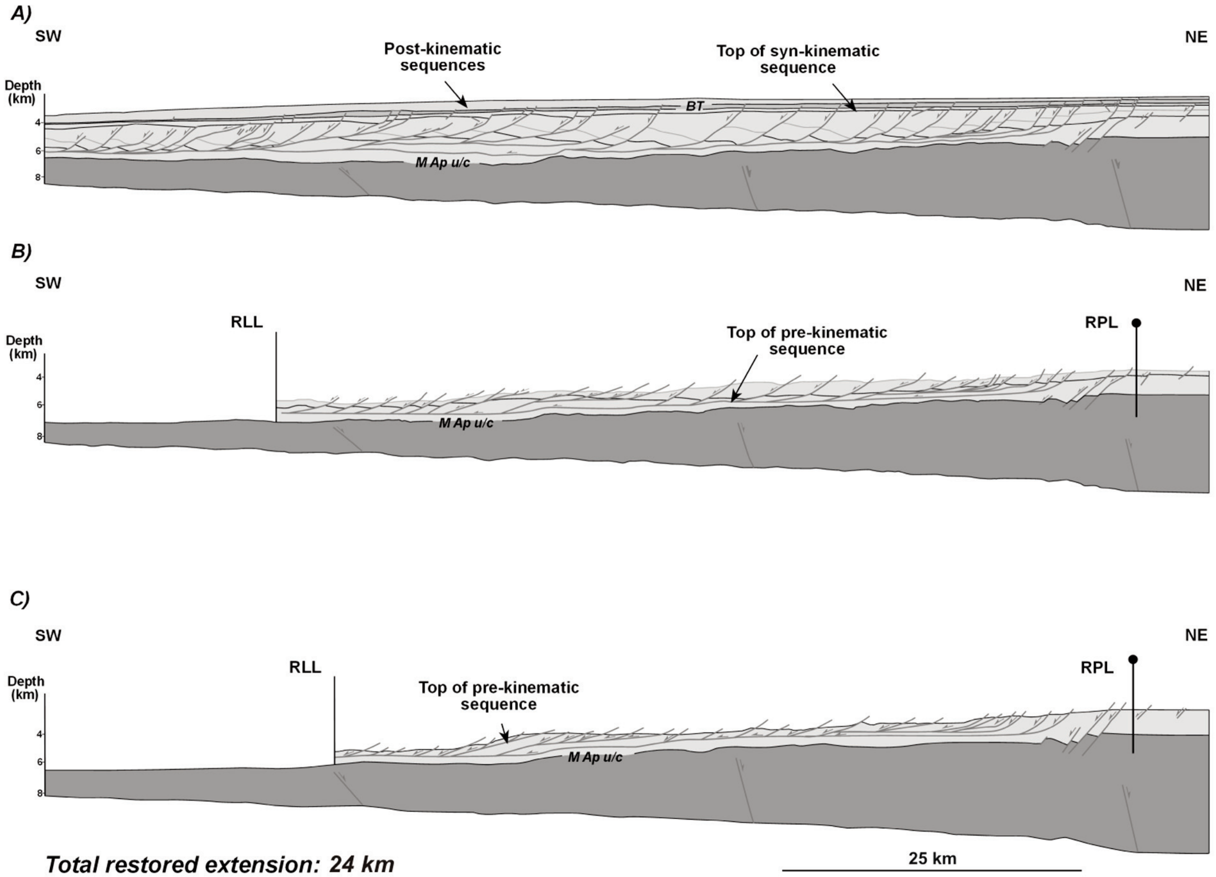

Figure 4. Extensional domain structural restoration. (A) Extensional domain after depth conversion, (B) removal of the post-kinematic sequences III to V and associated decompaction of the sections below, and partial restoration of the growth sequence, (C) pre-deformation state of the section after the restoration of the remaining growth sequence. RLL: regional loose line; RPL: regional pin line; BT: base of Tertiary; M Ap u/c: Middle Aptian unconformity.

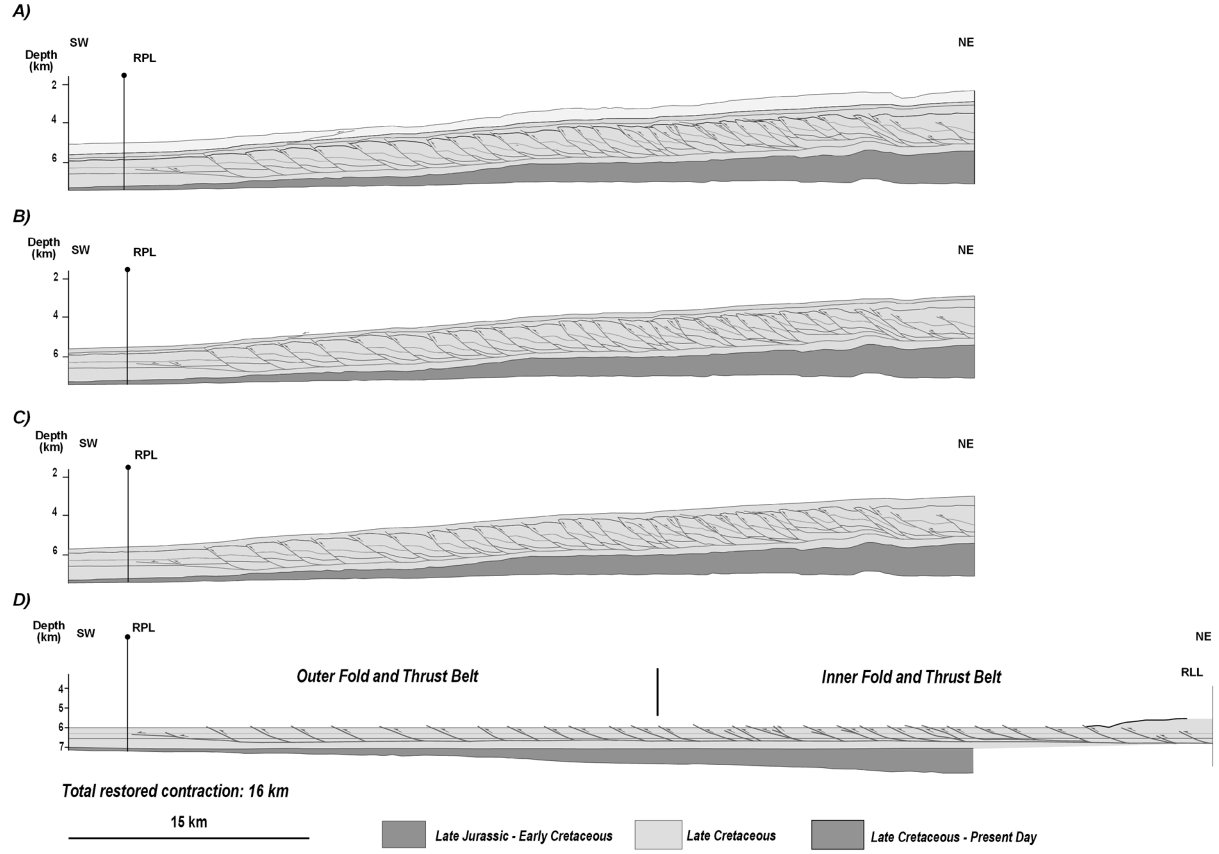

Figure 5. Contractional domain structural restoration. (A) Contractional domain after depth conversion, (B) removal of the post-rift sequence V and associated decompaction of sections below, (C) removal of the post-rift Sequence IV and associated decompaction, (D) removal of the growth sequence and restored section. RLL: regional loose line; RPL: regional pin line.

propagation folds with no hinterland to foreland transition from detachment to fault propagation or shear fault bend folds like in Niger Delta.

The complexly deformed inner fold and thrust belt of the Orange Basin could be seen as an example of out of sequence and/or break-backward thrusting, probably as a reflection of an increased frictional behaviour of the regional detachment. The nature of the transitional domain is also different: in SW Africa is short and consists of listric extensional faults with associated growth packages at the trailing edge, and thrust faults at the leading front of the domain; the West Africa Niger Delta transitional domain is larger and consists of a *"mud diapir"* province (Corredor *et al.*, 2005).

Structural restoration

Structural restoration showed no balance between the two structural domains, with 16 km of contraction and 24 km of extension. Similar results were obtained by Grando (2005) and Vázquez-Meneses (2005) for the Gulf of Mexico in salt-detached and shale-detached GDS, respectively. This could be explained by out-of-plane deformation, layer parallel shortening accompanied by volume loss in the thrust belt, and discrepancies between the location of the seismic line and the direction of tectonic movement (Granado, 2006).

Gravity tectonics

We propose the Orange Basin gravity tectonics was caused by the dramatic basinward tilt produced by the continuous but punctuated SW Africa passive margin uplift shown by Gallagher and Brown (1999) along with the post-rift thermal subsidence aided by the cooling of the igneous underplated material interpreted by Bauer *et al.* (2000).

The controlling mechanisms for the continuous cratonic uplift remains conjectural but could be related with a transient mantle plume associated with rifting (Menzies *et al.*, 2002) and/or due to the margin tilt consequence of the density increase of the cooling underplated igneous material. Gallagher and Brown (1999) showed the SW Africa margin suffering uplift after break-up 130 Ma and being still present today. These authors reported maximum denudation (and hence uplift) occurring at ca. 90-80 Ma from apatite fission tracks analysis. This date coincides with the late *Post-rift Syn-Kinematic Sequence II* and therefore the age of the Orange Basin gravity tectonics. Gravity tectonics seems to have lasted shortly (85-75 Ma) as show by the thin growth strata.

Differential sedimentary loading, as proposed by Rowan *et al.* (2004) as the main triggering mechanism seems to have imposed a minor control on the onset of gravity tectonics, if any on the Namibian Orange Basin. Moreover, deltaic progradation seems to have caped the extensional domain, probably lowering the gravitational potential and stopping the gravity gliding process. This also contrasts with the Niger Delta gravity tectonics where differential sedimentary loading played a major role causing gravity spreading along with the basin subsidence.

Conclusions

The Orange Basin tectonostratigraphy was divided into syn-rift and post-rift depositional megasequences. The syn-rift megasequence shows planar growth extensional faults filled with continental sediments interbedded with volcanic SDRs; the post-rift megasequence is characterised by a gravity-driven deep water fold and thrust belt, and deltaic progradation.

The gravity-driven system consists of an extensional domain that transferred basinward 24 km of extension accommodated by 16 km of contraction through downdip thrusting and fault-propagation folding. The onset of gravity tectonics was due to a combination of punctuated margin uplift and differential thermal subsidence, coming to an end by dramatic deltaic progradation that lowered the margin gravity potential.

The marked asymmetry of fault-related folds, the absence of counter-regional extensional faults, and the seismic characteristics of the detachment, suggest that the fold and thrust belt of the Orange Basin was developed above a frictional and possibly only moderately overpressured detachment.

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