Observed link between folded Seaward Dipping Reflectors (SDRs) and large-scale morphology and architecture of the Early Cretaceous carbonate build-up and platform in the Orange Basin

Anongporn Intawong[1]*, Paolo Esestime[1] and Karyna Rodriguez[1] demonstrate an Early Cretaceous carbonate build-up reef structural closure prospect.

Introduction

The Orange Basin is located in the volcanic-rifted margin of Namibia and South Africa and was formed during the break-up of Gondwana in the Late Jurassic to Early Cretaceous period (e.g. Nurnberg and Muller, 1991; Karner and Driscoll, 1999). Rifting and opening of the Orange Basin is believed to have occurred in an already extended and possibly inverted basement (Clemson et al., 2002). A general tectono-stratigraphic chart of the Orange Basin is presented in Figure 1.

Three major hydrocarbon accumulations have been discovered to date within the Orange Basin; a near shore oilfield A-J and two gas and condensate fields, Kudu and Ibhubesi. The near South African shore A-J oilfield discovered 36 degree API oil in a Hauterivian lacustrine and fluvial sandstone reservoir within a half-graben on the basin's shelf (Crown Energy, 2013). Farther north and more out-board, the Kudu field is situated in the northern part of the Orange Basin in Namibia and has two productive reservoir intervals in aeolian sand dunes of Late Hauterivian or Early Barremain age. The main reservoir is approximately 20 m thick, with high net-to-gross ratio and an average porosity of 15%, mainly secondary porosity generated by the dissolution of widespread calcite cement. These sands are intercalated by flood basalts within the clastic prone Seaward Dipping Reflectors (SDRs) sequence, which have been proven to act as local seals. The Ibhubesi and AF-1 gas fields on the South African Orange basin shelf have reservoirs in Albian channel and fan sandstones displaying good porosities (16-25%), and are tied to anomalously high amplitude seismic reflectors.

Four potential source rocks have been identified in the Orange Basin. These comprise, firstly, localized syn-rift Late Jurassic to Berriasian lacustrine shales (believed to be the source for the A-J Field) and, secondly, Valanginian to Hauterivian lacustrine shales deposited within clastic prone Seaward Dipping Reflectors (SDRs) (believed to be the source for the Kudu field). Highly cracked condensate (oil cracking more than 95%) of lacustrine saline mixed with less mature non-cracked condensate marine derived oil types have been reported from Kudu-4 and -5 condensate samples analysis (Mello et al., 2012).

Thirdly, post-rift Barremian to Aptian restricted marine shales and lastly, high TOC is found along the margin in Cenomanian-Turonian organic-rich open marine shales.

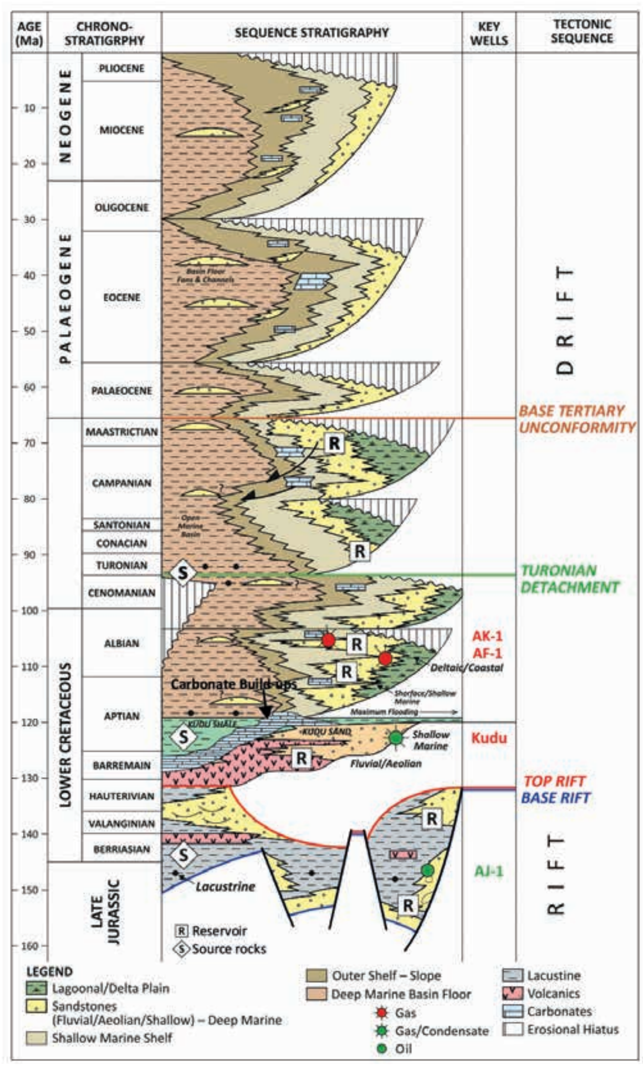

Figure 1 General tectono-stratigraphic chart of the Orange Basin (Modified after HRT, 2011).

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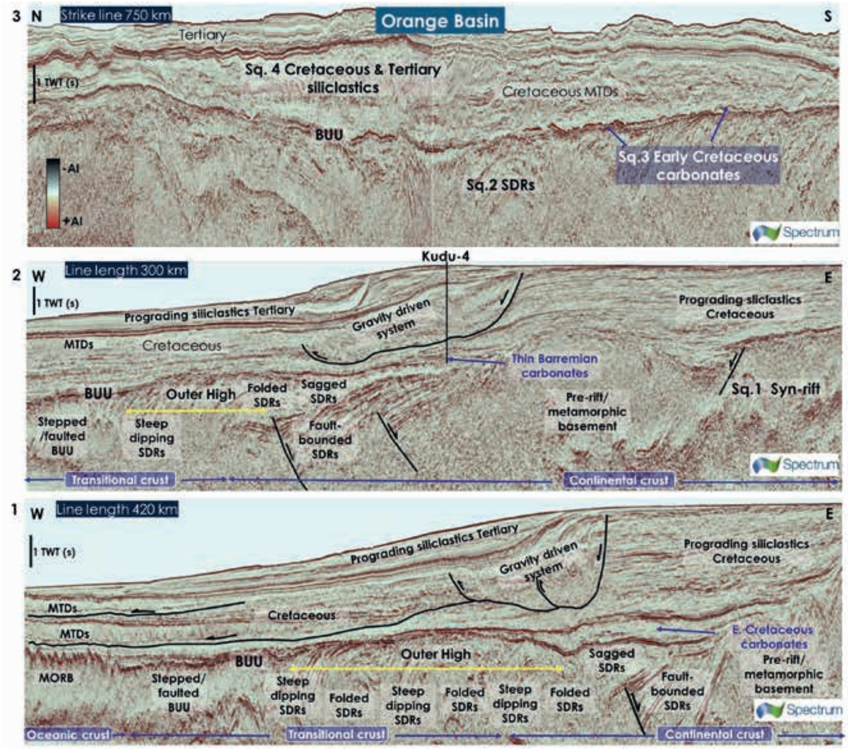


Figure 2 Regional 2D seismic sections demonstrate key geology and basin architecture of the Orange Basin in strike (3) and dip directions (1 and 2). The 2D seismic sections in dip direction display in pseudo depth section (50% water compensation) to highlight a true geomorphology of the section, demonstrating key geology in the southern and northern Orange Basin. The regional 2D seismic sections are located within the black polygons on the post-rift TWT (s) thickness map in Figure 3.

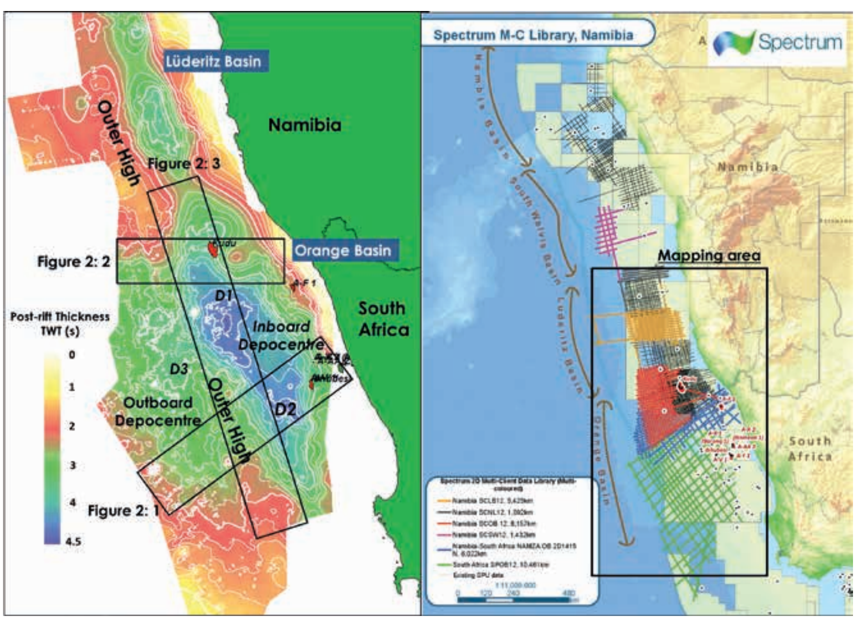


Figure 3 Post-rift thickness map demonstrates the architecture and sedimentary overburden within the Orange Basin. Insert map shows data used for the mapping.

The Barremian to Aptian restricted marine source rocks have been encountered in a number of wells penetrated along the margin including the DSDP 361, South African and Kudu wells, and exploration wells drilled by HRT, with up to 10% TOC. This Barremain-Aptian source rock is also a contributor to the Kudu gas and condensate field and other gas discoveries made on the shelf offshore South Africa. Regional mapping of the Barremian-Aptian source rock based on Spectrum's extensive 2D seismic data in the Namibia and South Africa margin tied to Aptian markers from wells demonstrate the presence of the Aptian source rocks in the Orange Basin (Intawong et al., 2015). The source rock is ubiquitously distributed over the Orange Basin with some variation in thickness over two main depocentres divided by a NW-SE trending Outer High (Intawong et al., 2015). The Cenomanian-Turonian source rock has been penetrated by exploration wells 2012/13-1, 2513/08-1, Kudu and 2515/15-01 with up to 7% TOC. The Cenomanian-Turonian source rock lies below sedimentary gravity driven Mass Transportation Deposits (MTDs), where it may provide a decollement surface accommodating the gravity flow.

Crustal and basin architectures

Below the Break-up Unconformity, similar basement morphology and structural architecture have been observed throughout the Orange Basin (Figure 2). From east to west, we observe a pre-rift metamorphic basement, deformed by a continental half-graben rifting formation. Further outboard there are fault-bounded SDRs with overlying sagged SDRs and outward folded SDRs developed in the continental crust domain. These SDRs are clastic prone deposited in a mixed subaerial and marine depositional environment. The SDRs prograded from the seafloor spreading centre and therefore they are younger seaward.

Younger SDRs subsequently developed with steep dipping, and that created a prominent structural high (the Outer High), a prominent feature established all the way along the Namibia and South Africa margin. This domain has been designated as the 'transitional crust'. The younger SDRs with seaward of the clastic prone SDR's are clastic poor and flood basalt dominated.

In the southern Orange Basin, more than one series of the folded and steeply dipping SDRs have been observed. Up to three series have been identified on Spectrum 2D seismic profiles (Figure 2). Each succession of these remarkable SDR series may be related to a sub-areal ridge jump during early rift spreading.

Outboard of the outer high, and inboard of rugose Mid Ocean Ridge Basalt (MORB) is a cryptic zone where the crustal nature is less understood (Figure 2). We have observed a large area, up to 100 km wide, of stepped/faulted break-up unconformity within this zone (Figure 2).

The Orange Basin's post-rift sedimentary sequence comprises two major depocentres, inboard and outboard sub-basins, divided by the NW-SE trending Outer High (Figure 3). The inboard sub-basin itself contains two depocentres (D1 and D2) located in the north and south of the sub-basin, and it was developed earlier, possibly in Early Barremian period. These sub-basin morphologies later accommodated the deposition of the Aptian source rock.

Mega-sequences

The Orange post-rift sedimentary basin above the break-up unconformity also demonstrates similar key geological features throughout the basin comprising four key sequences, localized continental Late Jurassic to Hauterivian rifting sediments developed along the margin of the basin, SDRs in the transitional crust zone, and post-rift sediments of Early Cretaceous carbonates and Cretaceous to recent siliclastics (Figure 2). The rift-drift

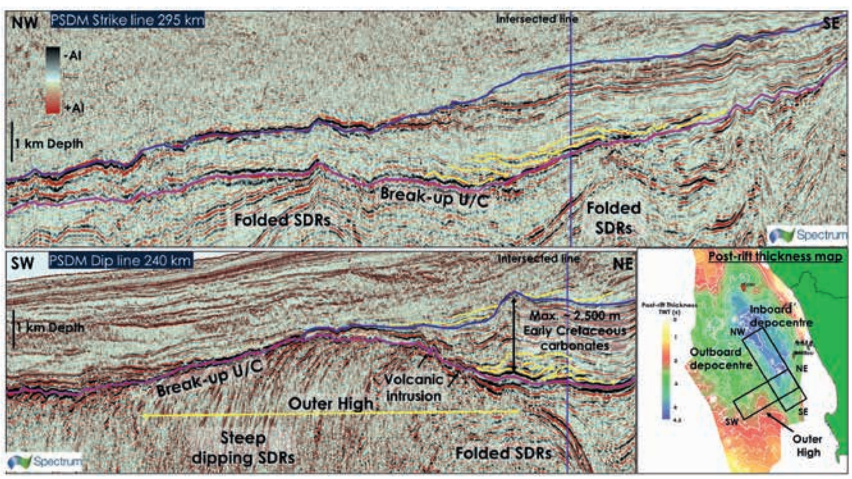


Figure 4 Depth 2D seismic sections in strike and dip directions demonstrate the Early Cretaceous carbonate sequence in the Orange Basin. The 2D seismic sections are located within the black polygons on the post-rift TWT (s) thickness map.

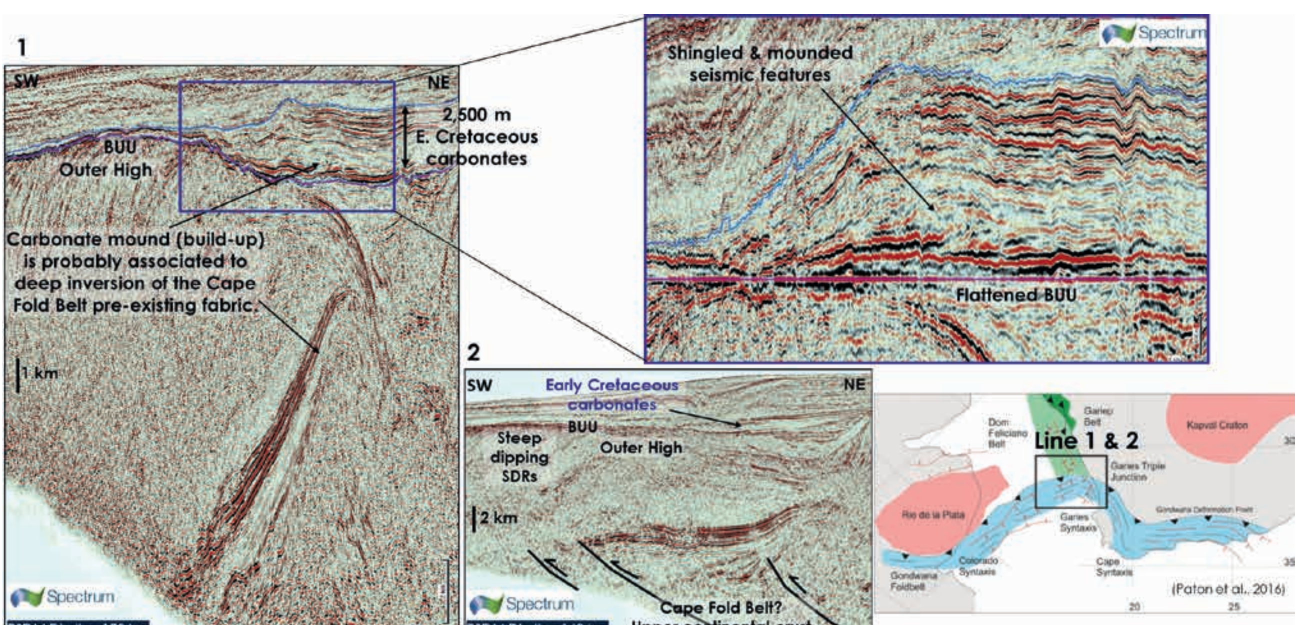


Figure 5 1) A 2D PSDM seismic dip section demonstrates the initial sequence of carbonate build-up showing shingled and mounded seismic features above the break-up unconformity. Example of deep structure of deep seismic reflectors interpreted to be the Cape Fold Belt pre-existing fabric identified in the southern Orange Basin (1 and 2).

transition phase took place in a sub-aerial depositional environment, and that is marked by SDRs.

The later post-rift evolution of the Orange Basin is strongly characterized by the episodic gravitational collapse of the margin in the Late Cretaceous period. The main gravitational collapse structure consists of an up-dip extensional domain that is linked to a down-dip contractional domain, along a basal detachment of possibly over-pressured Cenomanian-Turonian source rock, providing a decollement surface. Beneath the gravitational collapse structures, the Early Cretaceous post-rift section comprises a carbonate build-up and platform, restricted marine shales, and mixed fluvial-deltaic depositional system ranging from the Barremain to Albian period.

Early Cretaceous carbonate sequence

The Early Cretaceous carbonate build-up and platform system is a key sequence in the early sag stage of the Orange Basin formation, especially in the southern and centre part of the basin. The carbonate sequence was developed during marine transgression of the sub-areal SDR flood basalts that form the outer high. This sequence is mostly restricted to the inboard sub-basin, between the hinterland and the present-day outer high. Its morphology and architecture are visibly observed in depth seismic sections. The sequence is also thickening towards the inboard southern sub-basin depocentre (D2) (Figure 4). The carbonate sequence has been identified with maximum thickness of up to 2500 m in the south on Spectrum's 2D seismic section, but it appears to be thinner towards the north (Figure 4). A thin (20-30 m) Barremian limestone interval was found at the Kudu wells 1 to 4, above the Kudu aeolian sand reservoir in SDRs sequence, and below the Late Barremain to Early Aptian Kudu marine shale source rock.

A 400 m carbonate interval was encountered at Moosehead-1 well, above the Outer High of the SDRs sequence. The well is situated at the northern edge of the Orange Basin. The Moosehead carbonate interval is not clearly visible on the 2D seismic section in terms of seismic characterization. A much thicker carbonate sequence displaying better carbonate seismic characteristics including a shingled prograding pattern, mound-shaped build-up and high-relief rimmed platform morphology are commonly recognized in the inboard of the basin (Figure 4). Based on our observation, this carbonate sequence clearly reveals its true geomorphology on the depth seismic section.

First sequence: carbonate build-up

The initial carbonate sequence was generally developed as carbonate build-ups deposited on low-relief SDRs and structural high sequences in shallow water conditions. These build-ups increased in thickness during the early post-rift while the area was only receiving very limited clastic input. This sequence is recognized only inboard of the present-day Outer High as observed on the 2D PSDM strike and dip seismic sections (Figures 2, 4 and 5). Based on our observation, the low-relief SDRs structural highs appear to be associated to the inversion of the fault-bounded SDRs (Figure 2).

Shingled prograding and mound-shaped seismic features are clearly identified on several 2D depth seismic sections (Figures 4 and 5) within this carbonate sequence. The paleo-morphology is interpreted as a gentle shelf, dipping basinward into the main spreading centre. This initial carbonate sequence is probably also associated and controlled by the folded SDRs, which had previously acted as a barrier for preventing the

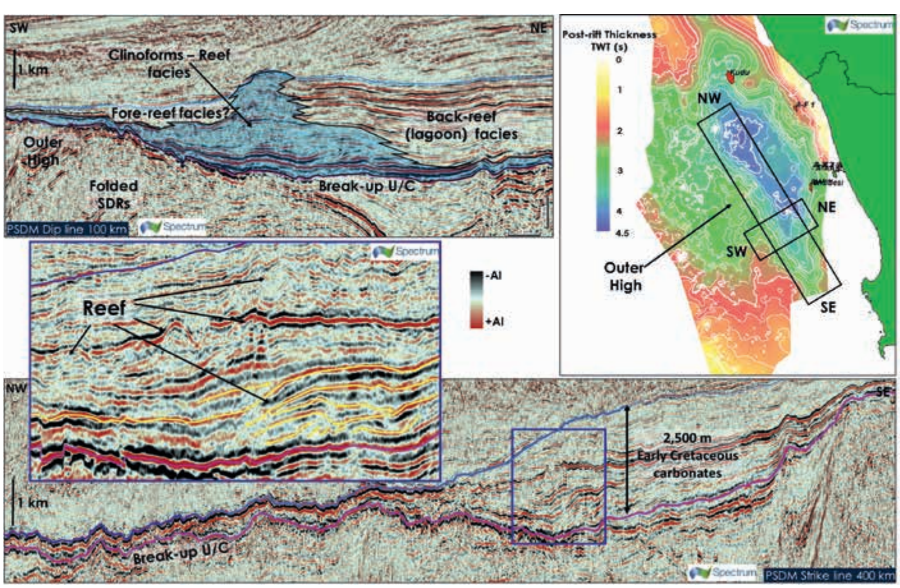


Figure 6 A 2D PSDM seismic dip section shows prograding rimmed shelf platform geometry. Potential reef reservoir facies are identified on the both dip and strike 2D seismic sections. The 2D seismic sections are located within the black polygons on the post-rift TWT (s) thickness map.

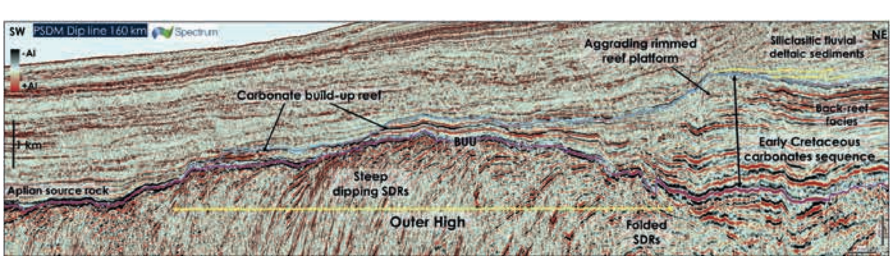


Figure 7 A 2D PSDM seismic dip section demonstrates aggrading platform geometry in the inboard of the basin and carbonate build-up reef deposited on the Outer High representing the latest stage showing the carbonate sequence in the Orange Basin.

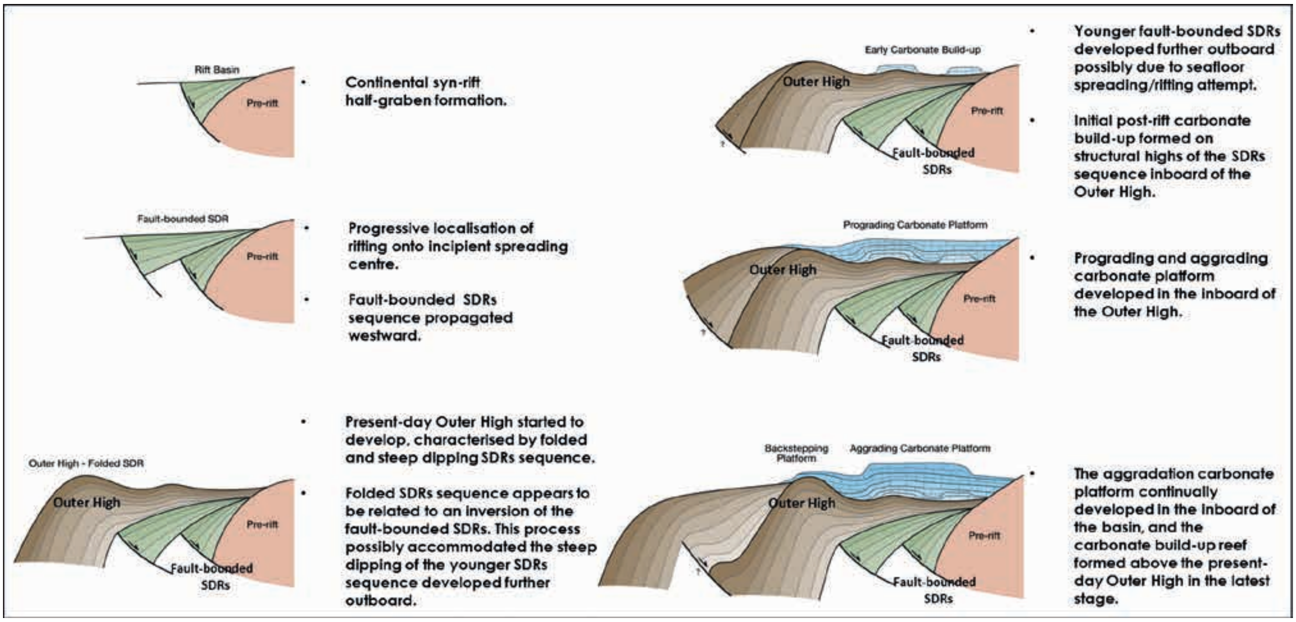


Figure 8 An illustration demonstrates evolution of the Early Cretaceous carbonate sequence and SDRs formation in the Orange Basin.

ocean water getting in to the clastic prone SDR embayment (inboard of the outer high). The paleo-morphological relief of the carbonate progradation is clearly recognized in a dip line oriented SW-NE (perpendicular to the coast), and it can be highlighted by flattening at the break-up unconformity level as presented in Figure 5.

The initial carbonate build-up also appears to be associated to a deep inversion of the deep seismic reflectors interpreted to be the Cape Fold Belt pre-existing fabric. The deep structure possibly controls the geometry of the former outer high which in turn accommodates and controls the carbonate build-up. The deep seismic reflectors are seen only in the southern part of the Orange Basin where the onshore Cape Fold Belt deformation front curved towards the offshore Orange Basin. The Cape Fold Belt was connected to the Colorado Fold Belt of Argentina prior to break-up. This pre-existing fabric also indicates an upper continental crust within this area (Figure 5).

Second sequence: prograding and aggrading rimmed shelf platform

In the second stage of the carbonate development, the carbonates kept up, prograded and aggraded to become rimmed carbonate platforms towards a back reef margin during the rimming stage. Evidence of mound-shaped and clinoform features interpreted to be reef facies are widely recognised in the basin (Figure 6). This reef facies holds a potentially significant reservoir within the basin.

Third sequence: aggrading rimmed platform and carbonate build-up

The carbonates kept up and were dominated by aggradation to become the rimmed shelf platform in the last development stage in the inboard depocentre, while the carbonate build-up with strong seismic reflectors and build-up morphology developed on the present-day outer high (Figure 7). This rimmed shelf platform morphology is clearly visible in most of the depth seismic dip sections, especially in the southern basin (Figures 2, 4, 5, 6 and 7). Well-defined prograding seismic reflectors onlapping on the aggrading carbonate platform representing an influx of fluvial and deltaic siliclastics are also commonly recognized within the basin (Figure 7).

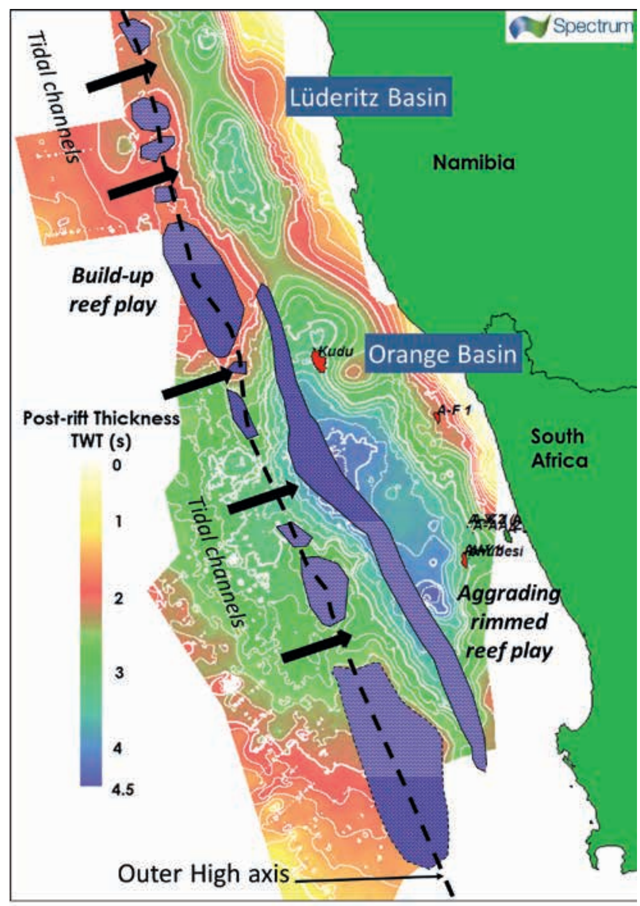
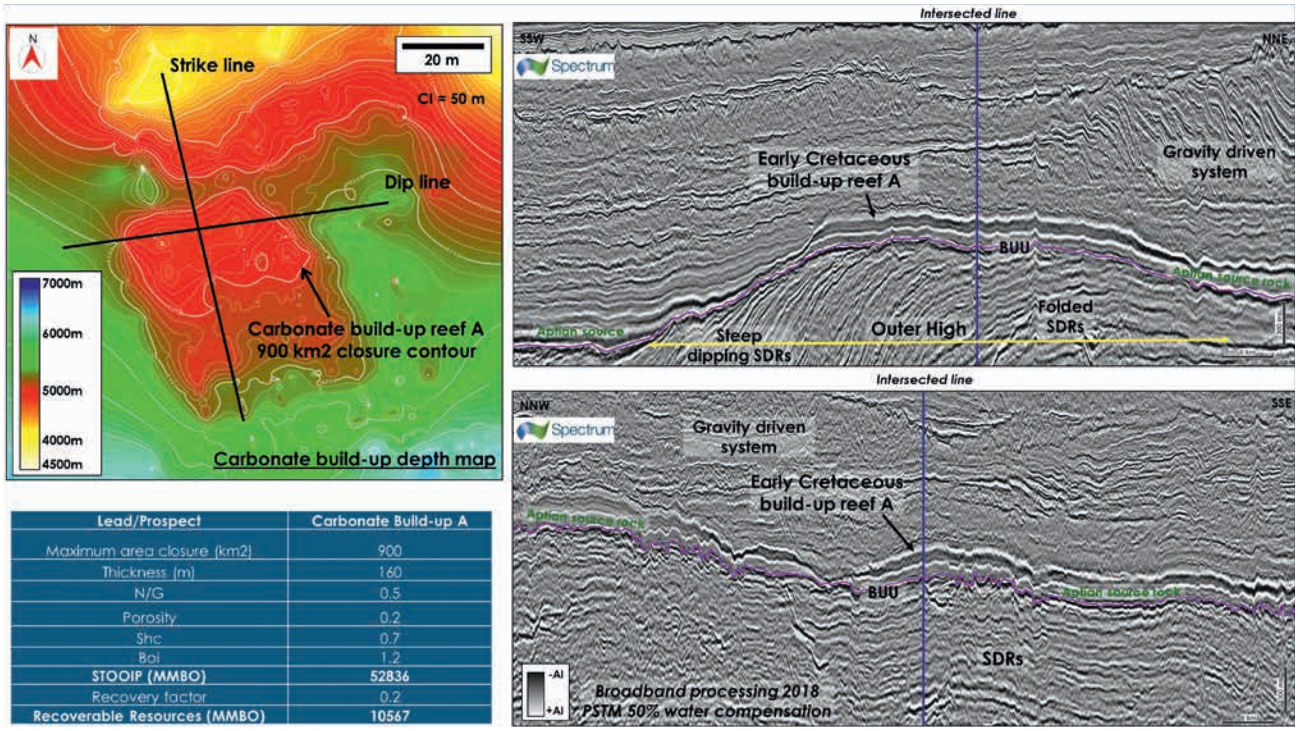


Figure 9 Carbonate build-up and shelf edge reef plays illustration superimposed on the post-rift TWT (s) thickness map.



Lead/Prospect	Carbonate Build-up A
Maximum area closure (km2)	900
Thickness (m)	160
N/G	0.5
Porosity	0.2
Shc	0.7
Boi	1.2
STOOIP (MMBO)	**52836**
Recovery factor	0.2
Recoverable Resources (MMBO)	**10567**

Figure 10 An example of the Early Cretaceous build-up reef prospect showing its potential as a major hydrocarbon play prospect in the Orange Basin.

Evolution of the Early Cretaceous carbonate build-up and platform

Based on our observation, the Early Cretaceous carbonate build-up and platform are strongly associated with the formation of the SDRs sequence. A summary of this relationship and evolution of the carbonate sequence and SDRs formation are illustrated in Figure 8.

Early Cretaceous carbonate play

The Early Cretaceous carbonate build-up and shelf margin reefs hold potential play prospects with significant upside volume in the deep water Orange Basin. The carbonate build-up reefs are possibly developed all the way along the Outer High, and they could offer large structural closures. The carbonate play fairway, both build up and aggrading rimmed reef play within the Orange Basin, is illustrated in Figure 9.

We demonstrate here an Early Cretaceous carbonate build-up reef structural closure prospect, comprising a maximum structural closure of up to 900 km^2 with estimation of STOOIP 52 BBO and recoverable reserve of 10.6 BBO (Figure 10). This carbonate closure could be directly charged by the Aptian restricted marine source rock, which should be in an oil window based on sedimentary overburden above the source rock at this location. This Early Cretaceous build-up reef and shelf edge reef plays certainly have a significant potential as a major hydrocarbon play prospect in the Orange Basin, waiting for the drill bit to prove their prospectivity.

Acknowledgements

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