*Communs geol. Surv. Namibia*, **12** *(2000), 383-393*

# Constraints on the geomorphological evolution of Namibia from the offshore stratigraphic record

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This paper addresses aspects of the geomorphological evolution of Namibia in the light of recent results of seismic surveying and drilling in the offshore basins. As suggested by Henno Martin in 1976, this offshore data holds important clues for interpreting epeirogenic events onshore Namibia. The main aim in this paper is to correlate significant stratigraphic events offshore with important landscape elements on¬shore. Major depositional systems offshore have been delineated and categorized with respect to terrestrial feeder systems. Major deltaic inputs in the north into the Walvis Basin have also been noted and the inference has been made that supply for these mud-dominated systems was from the erosion of the Etendeka Group basalts. The major stratigraphic surfaces along the marginal basins from South Africa as far north as the Namibe Basin have been correlated and from this, significant along strike variations in depocentres and in sediment calibre in the post-rift have been identified. Recognition of distinct changes in the timing and magnitude of post-rift uplift of the onshore has led to the conclusion that King's early view of a Great Escarpment composed of distinct geomorphic elements with different tectonic and erosional histories is substantially correct. Little evidence was found to support more recent proposals that the Escarpment has its roots in rift flank uplift and fault scarp retreat.

## Introduction

Henno Martin can justifiably be seen as having been ahead of his time in many aspects of his geological and geomorphological thinking. His attempt (Martin, 1976) to link the geodynamic evolution of the offshore and onshore portions of the Namibian continental margin is an ample demonstration of this foresight, since it is only fairly recently that geomorphologists have paid any serious attention to the abundant evidence contained within the offshore stratigraphic record of many passive continental margins that is so critical for any analysis of landscape-forming events on the adjacent continental interiors (Summerfield, 1991; Ollier and Pain, 1997). Equally, offshore stratigraphers have been slow to delve into the geomorphological literature for critical data pertaining to provenance, sediment flux and palaeotopographical controls of major drainage axes. Henno Martin clearly recognized the benefits to be obtained by combining studies offshore with those based onshore but was unfortunately very restricted in the quality and coverage of offshore data available in the 1970's and 1980's.

The aim of this paper is to summarize some of the most important stratigraphic results of recent seismic and drilling campaigns from the Namibian continental margin and to provide some initial thoughts on how these results can be married to existing models for landscape evolution in southwestern Africa. In attempting this, we are conscious that we are merely extending a process initiated by Henno Martin over 25 years ago. This summary is based on over 20,000 line kilometres of multichannel reflection seismic data acquired by the petroleum industry and Namcor over the past decade, tied to 7 wells in the Namibian offshore. We acknowledge here the significant contributions to the understanding of the offshore stratigraphy made by the numerous operating companies who have explored for hydrocarbons and also recently in two comprehensive doctoral theses on the regional geology of the margin (Bagguley, 1997; Clemson, 1997). Space restriction has meant that only a selection of the sources for some of the data used in the interpretations is referred to. Further details will be presented in a subsequent publication on this topic.

## Regional Stratigraphy of the Namibian Margin

The Namibian continental margin consists of a substantial thickness (3-5 km) of mainly clastic post-rift

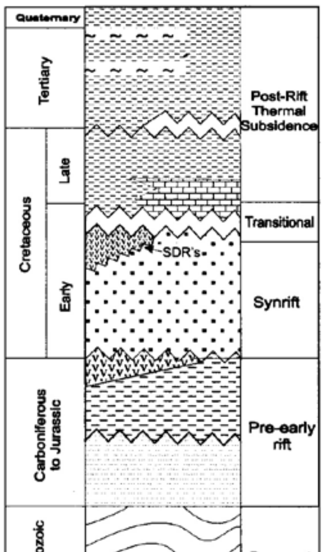


**Figure 1:** Generalised stratigraphy seen in the offshore region of the Namibian continental margin based on the 12 offshore exploration/appraisal wells.

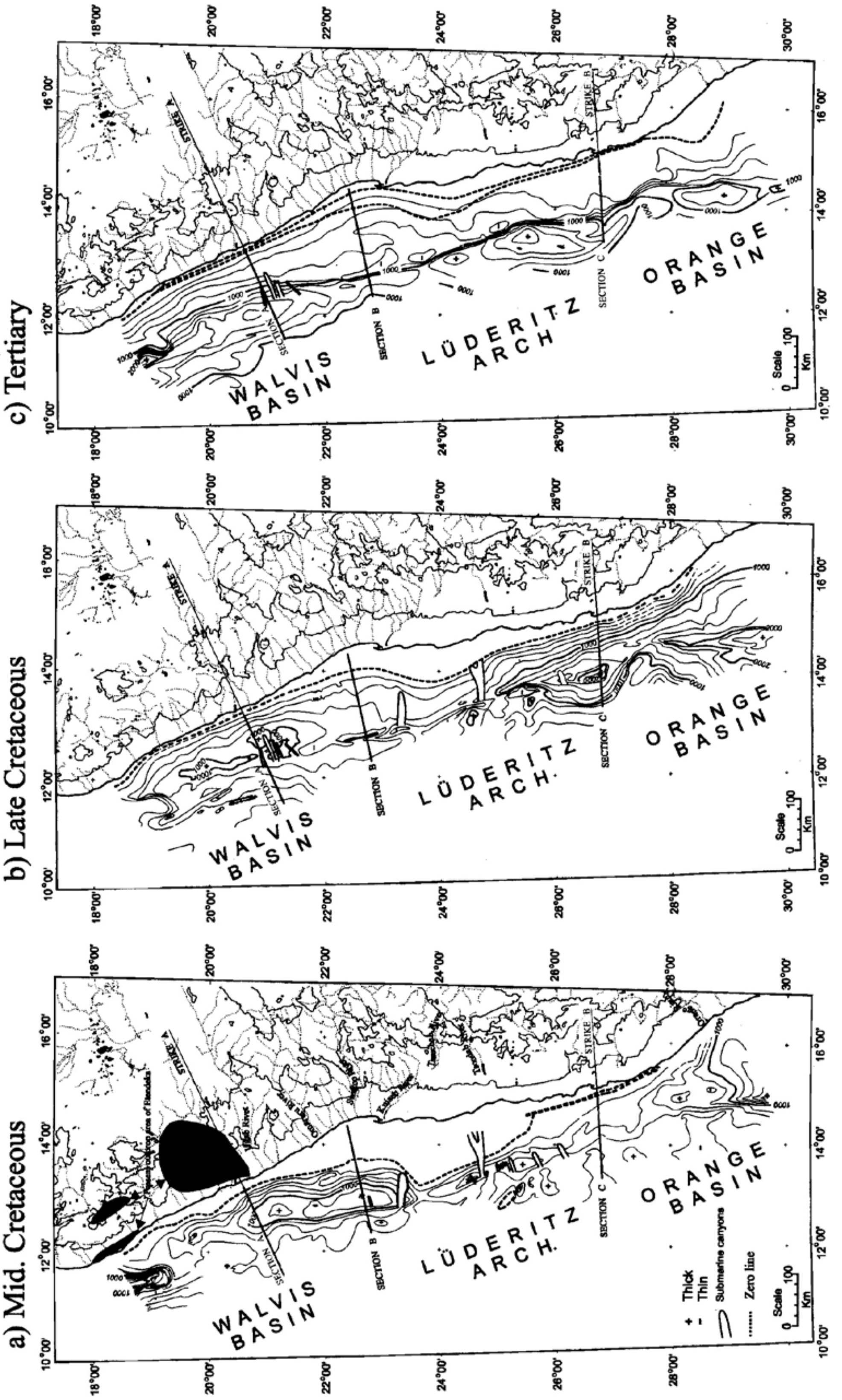


**Figure 2:** Isopach maps of the Namibian continental margin for the three post-rift megasequence intervals. Contours are in 200 m intervals. Locations are given for the geoseismic sections shown in Figure 3 and the reconstructed profiles (strike A and B) shown in Figure 5. Note the migration of the major depocentres along the margin for successive megasequences.

sediments overlying a rifted continental basement (Light *et al.*, (1993) (Fig. 1). The syn-rift sequence has not been calibrated offshore Namibia but is likely to consist of Late Jurassic to Early Cretaceous siliciclastics and volcanics (Clemson, 1997; Clemson *et al.*, 1999). The Namibian margin is regarded by several authors as a classical example of a volcanic margin (Clemson, 1997; Gladczenko *et al.*, 1997) in that the post-rift sequence along the outer portion of the margin overlies a sequence of seaward dipping reflectors (SDR's) that are interpreted to be the result of a huge subaerial basaltic extrusive event associated with break-up. One of the major unknowns in Namibian geology is the seaward extent of the onshore Etendeka flood basalt province and the link, if any, with the offshore SDR province (Clemson, 1997; his fig. 5.42).

The post-rift sequence is fairly well known from offshore drilling. The general stratigraphy is summarized in the form of regional isopach maps and three representative cross-sections through the main depocentres of the Orange and Walvis Basins and the intervening Lüderitz Arch (Figs. 2 and 3). The three isopach maps (Fig. 2) show some important features. Firstly, the general progradation of the post-rift succession from the mid-Cretaceous to the Tertiary with a concomitant seaward migration of the depositions hinge-zone. Secondly, a concentration of much of the offshore sediment volume in the Orange and Walvis Basins with much thinner preserved sequences in the central part of the margin (centred on 24°S). Thirdly, a shift in maximum sediment flux northwards to the Walvis Basin in the Tertiary. Fourthly, the development of numerous submarine canyons in the central and northern sectors. These canyons incised deeply into shelfal sediments during the Late Cretaceous and Early Cenozoic (Bagguley, 1997; Clemson, 1997). The absence of similar canyon systems in the Orange Basin is intriguing, particularly given the degree of shallow marine erosion that took place at around the base Tertiary (see later). A plausible explanation for this was suggested by Clemson (1997) who postulated that canyon development was related to gravitational instability and was not required in the Orange because of the widespread development of growth faults. As will be shown later, this important phase of gravitational instability at the base Tertiary can be linked to longitudinally variable uplift of the margin at this time.

Some of the points discussed above are also well illustrated on the 'geoseismic' cross-sections (Fig. 3). The stratal geometries seen on these cross-sections are taken directly from seismic data and are critically important in interpreting the relative vertical movements of the inner part of the offshore region.

*Section A*

This section is from the centre of the Walvis Basin (location Fig. 2). A thick basal sequence interpreted as Karoo is truncated at an erosional unconformity close to the eastern end of the section. This unconformity has some residual topography and is shown as forming the base of the Etendeka Group, with onlap of Etendeka and subsequent Cretaceous units directly onto the unconformity surface, infilling remnant valleys and hills and younging landward. This relationship is seen along the entire inner margin of the Walvis Basin northwards from 22°S (see also Fig. 4). A prominent valley on this unconformity surface has recently been identified directly offshore from the mouth of the Ugab River and is filled with over 1 000m of probable Etendeka Group rocks. This palaeo-Ugab valley may have been a route for quartz latite flows to reach across into the Parana as required by the trans-Atlantic geochemical correlations of Milner *et al.* (1995).

Above the Etendeka is a seaward thickening wedge of uncalibrated stratigraphy that we interpret as syn-rift and probably consisting of a mixed clastic, volcaniclastic and extrusive succession ranging from Valanginian to Barremian in age. This unit thins convergently to a pinch-out approximately 50km west of the shoreline. It is a structural element recognized along the margin and referred to as the inner half-graben (Clemson, 1997). Its internal geometry is characterized by a divergent suite of reflections with generally high lateral continuity. The convergent geometry is suggestive of rotational subsidence during deposition and the fact that erosional topography is preserved updip of the pinch-out is taken as a sign that the shoreline was at or close to the pinch-out. Overlying this convergent unit, the successive Cretaceous progradational depositional units onlap progressively updip. The geometry of the early onlap units is markedly parallel suggesting that considerable relief was present on the major onlap surface as it was being transgressed. Toplap surfaces within the main Cretaceous progradational system (Albian to Maastrichtian) define useful palaeo-horizontal datums close to sea level and, from their geometry, it is possible to conclude that deltaic progradation throughout the Cretaceous and the Cenozoic has been accompanied by considerable aggradation achieved through rotational subsidence during the post-rift phase of basin development. Toplap surfaces in the latest Cretaceous and Tertiary sequences show little evidence of angular truncation and their geometry is consistent with the persistent rotational subsidence with a hinge line located more or less at the present coastline.

Drilling results indicate that over 90% of the post-rift succession is silty mudstone or mudstone. Shallow marine carbonates are known from the Aptian-Albian in Block 1911 and minor deepwater sandstones are developed at the base Tertiary. Compaction related faults are widely ob-served within the Tertiary and are usually indicative of smectite-rich claystones (Cartwright and Dewhurst, 1998). These are likely to have been derived by erosion of the Etendeka volcanic rocks.

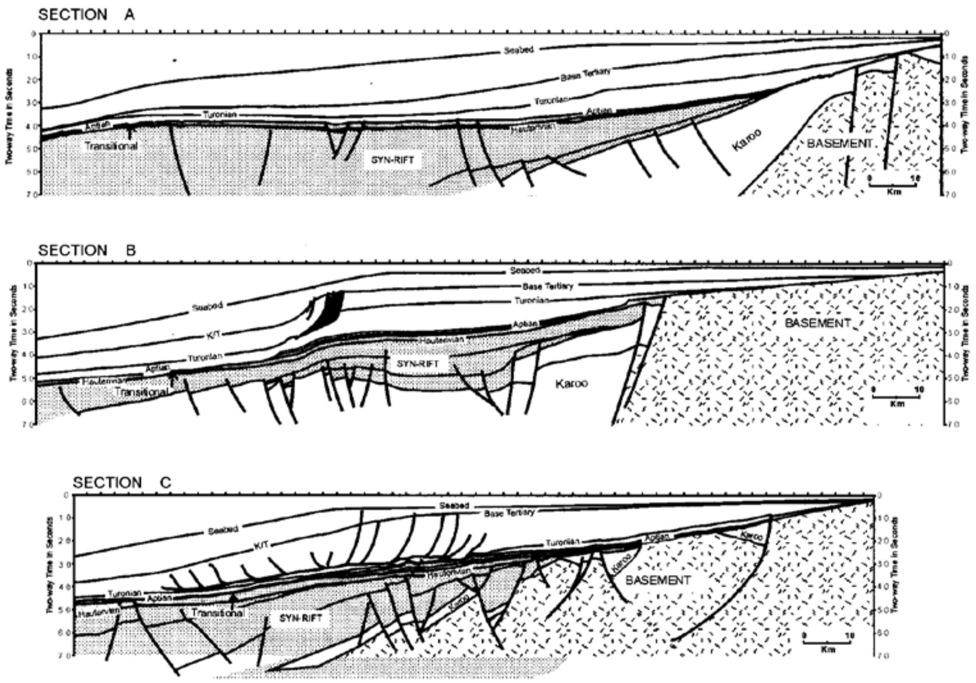


**Figure 3:** Three geoseismic sections illustrating variations in the tectonostratigraphic style of the margin (location in Fig. 2). Note the pronounced hinge zone in Sections A and C and the relatively minor amount of extensional faulting at the hinge zone. On Section B is one of the few examples where shallow basement is juxtaposed with the syn-rift across a major extensional fault.

### *Section B*

This section is located in the southern portion of the Walvis Basin, north of where the Lüderitz Arch is the dominant structural element (Clemson, 1997). The geoseismic section contrasts with section A in several respects. The Karoo Supergroup is interpreted as fault bounded, in contact with the prominent, smooth-topped basement of the Lüderitz Arch. Cretaceous and Tertiary post-rift units thin more gradually towards the coastline and basal onlap is only noticeable in the pre-Turonian. Well defined progradational clinoforms are not recognizable except in the Early Tertiary. Minor growth faults are observable at the Cretaceous shelf break.

The stratal geometries seen in the post-rift on this section are indicative of protracted rotational subsidence with no evidence for significant uplift of the coastal region immediately onshore from this section. Drilling results indicate that much of the Cretaceous post-rift succession consists of coarse sandstone or gravels, probably deposited in a piedmont setting similar to that seen directly onshore today.

### *Section C*

This section is located in the Orange Basin and contrasts markedly with the previous two sections, particularly in the geometry of the post-rift succession close inshore. The Karoo Supergroup is interpreted as being preserved in small half-grabens, but is severely truncated at a markedly angular unconformity. This is probably a compound surface, representing erosion over a prolonged period, and perhaps in excess of a kilometre of Karoo was stripped off prior to Early Cretaceous onlap. This planation left an extremely smooth surface with only a very gentle topographic gradient. Syn- to early post-rift units thin to a pronounced hinge line about 60 km offshore. Barremian to Albian units onlap the major unconformity surface and thin towards a pinch-out close to the current coastline. The bulk of the Orange Delta succession is Turonian to Maastrichtian in age and the top lap surfaces within the progradational clinoforms converge gently to the east, suggestive of rotational subsidence from a hinge line located well onshore, possibly 50-100 km inland from the current coastline. This implies that Cretaceous deltaic deposits were originally widely deposited onshore in this sector of the margin.

A major angular unconformity is recognised along the inner portion of the modem shelf over a distance of about 50 km from the coastline. Early Tertiary units are juxtaposed with Late Cretaceous units at this unconformity, with the degree of truncation increasing coastward. From the angular truncation geometry it is apparent that at least a kilometre of uplift must have occurred at a position close to the present coastline, decreasing to zero at a point about 50 km offshore. Subsidence of the region seaward of this hinge probably continued during this event. Shallow high resolution seismic tied to shallow cores suggests that this uplift occurred in the latest Cretaceous to earliest Tertiary (Maastrichtian to Palaeocene).

Following the shallow marine planation episode associated with the tilting and uplift, subsidence of the margin has resumed, although net Tertiary thicknesses over the shelf region are significantly less than the total accommodation space available. The locus for slope progradation during the Cenozoic shifted seaward of the maximum Cretaceous advance of the delta front. The limited aggradation on the shelf has been attributed to the shallow marine hydrodynamic regime operative from the Eocene onwards (Bluck and Ward, 1997).

In summary, the offshore seismic data shows considerable longitudinal variation in syn-rift stratigraphy and structural style, late rift topography, post-rift subsidence style, and post-rift geodynamic evolution. There is only a limited development of the type of fault-bounded rift margin envisaged, for example, by Gilchrist and Summerfield (1990). The most typical structural configuration is that of a simple rotational hinge, similar to that depicted by King (1962). Significant differences are apparent between the Orange and Walvis Basins. Evidence for a marked phase of uplift at around the base Tertiary is only seen in the Orange Basin. Residual topography at the onset of marine transgression and onlap in the Cretaceous is far more pronounced in the Walvis Basin.

## Significant Unconformities

The following unconformities are recognised on offshore seismic data:-

1. 'Base Karoo' Unconformity
Recognised as top of the effective acoustic basement and mapped along the length of the margin (Clemson *et al.*, 1999). Best seen inshore at shallow travel times (e.g. section C of Fig. 3). Overlying Karoo is usually concordant with the unconformity surface, suggesting a prolonged peneplanation prior to Karoo deposition. There is seismic evidence for extensions of Dwyka valleys identified by Martin (1953) but this may be due to poor acoustic quality.

2. 'Intra-Karoo' Unconformity
Recognised only recently by Clemson (1997) and attributed to a mid-Triassic phase of inversion tectonics. Only seen in the region offshore Cape Cross in the sub-basins associated with the offshore extension of the Omaruru Lineament. The localized nature of this surface means that it is not shown in any of the sections on Fig. 3.

3. 'Base Etendeka' Unconformity
Most clearly seen along the inner margin of the Walvis Basin (e.g. Fig. 4). This unconformity surface has considerable relief, often with the appearance of dip-scarp topography reflecting the truncation geometry of the basement and Karoo. This surface is only confidently identifiable where there are evident remnants of Etendeka with a characteristic reflection character and upper surface topography (e.g. Fig. 4).

4. Mid-Cretaceous Unconformity
This surface is a combination of erosional truncation of underlying units (basement, Karoo, syn-rift, Etendeka Group) and onlap of the Mid-Late Cretaceous marine, coastal and alluvial sedimentary units. It is a smooth surface over almost the entire extent along the margin (e.g. Fig. 3). The development of this unconformity surface is interpreted as largely resulting from shallow marine planation. From the geometry of the onlap in the Walvis Basin it can be inferred that there was a substantial pre-existing topography prior to the initial marine transgression in the Mid-Cretaceous. This contrasts with the onlap geometry in the Orange Basin where there was only a modest gradient for the onlap surface.

5. 'Base Tertiary' Unconformity.
This unconformity is arguably one of the most impressive surfaces in the offshore stratigraphic record and is particularly well developed as a smooth marine planation surface throughout the Orange Basin. As discussed above, this planation event was related to uplift and tilting of the inner part of the southern sector of the margin some time in the latest Cretaceous to earliest Cenozoic. There is no evidence for similar shallow marine planation at this time further north than about 26°S. There are, however, minor hiatuses recorded at approximately the base Tertiary in several of the wells in the Walvis Basin, and an influx of sand into deepwater environments in the late Maastrichtian to early Palaeocene may also be significant. There are also major submarine canyons cut deeply into Late Cretaceous shallow marine and slope units whose incision can be dated at this same period (Fig. 2). These canyons are headless: i.e. they do not connect into incised alluvial valleys anywhere within the coverage of modem seismic data on the present shelf region (Bagguley, 1997; Clemson, 1997). This implies that they were not necessarily cut during an uplift-related relative sea level lowstand affecting the central and northern sectors, although this remains a possibility. It is also possible that they could be related to changes in slope subsidence rates, slope hydrodynamics or even have been triggered climatically.

## Palaeo-drainage and Sediment Supply

Evidence for palaeo-drainage comes from two main sources in the offshore region: (1) the recognition of deltaic progradational geometries, and (2) the recognition of palaeo-valleys and canyons.

### *Orange Delta*

Deltaic progradation commenced in the Orange Basin in the Albian (Brown *et al.*, 1995). The Orange Delta was well established as a major point source depocentre by the Cenomanian, located in its current position. Strike profiles through the Orange Delta do not show any major shifts in depositional axes during the

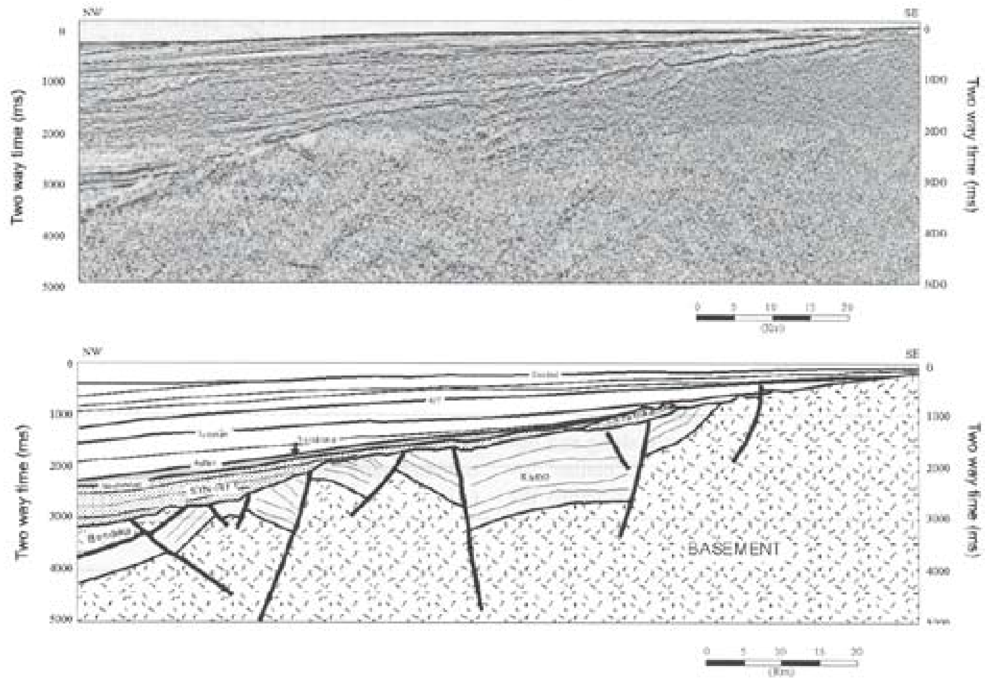


**Figure 4:** Seismic profile (a) and geoseismic section (b) from the Walvis Basin illustrating the nature of the basal and upper Etendeka surfaces in the offshore and the pronounced landward onlap of Cretaceous units.

Mid-Late Cretaceous, although there was an impressive phase of valley or canyon incision in mid-shelf positions in the Turonian, with upwards of 800 m of incision in places. The progradational geometry shows a change from strongly progradational to progradational with strong aggradation at approximately the Coniacian/Santonian transition. This is interpreted as reflecting changes in subsidence with a significant increase in subsidence implied for the latest Cretaceous. A mature and large drainage basin was evidently in place at least by the Santonian, since the sediment flux required to maintain the delta both in position and actively prograding in the face of significant subsidence of the basin was very large, and unlikely to have been supplied by short-headed streams with a linear sourcing mode. This is consistent with the evolution of the Orange River deduced from onshore and coastal studies by Bluck and Ward (1998). The Cretaceous Orange Delta is known from recent drilling to have been mud-dominated and it is estimated that >90% of the sediment supplied by the Orange River was of a muddy calibre. There remains a strong possibility that slope and basin floor fans supplied from the Orange are sand-prone, since the top sets are reasonably sandy, particularly in the Santonian to Maastrichtian.

The absence of any significant incised valley development associated with the major erosion of the inner margin at the base Tertiary is puzzling (N. Pegler, *pers. comm.*, 1998). However, if the marine planation was coeval with the onset of aridification in the Eocene (Ward *et al.*, 1983), reduced discharge combined with fragmented stream patterns on the exposed delta top could have prevented any significant incision occurring along any fixed fluvial axis. The absence of submarine canyons cutting through shelf and slope sediments has been attributed by Clemson (1997) to contemporaneous activity of growth faults during the late Cretaceous and earliest Cenozoic.

Resumption of Orange Delta progradation in the Palaeocene/Eocene was in marked contrast to the Cretaceous style of deposition. An unpublished study with detailed isopachs of individual delta lobes (J. Booth, *pers. comm.*, 1992) shows unequivocally that progradation was achieved in combination with frequent switches of main lobe construction. This progradation was restricted to times of sea level lowstand: during highstands, shelf hydrodynamics prevented any shelf delta construction, and sediment transport of the coarser fractions was dominantly along and onshore directed (Bluck and Ward, 1997). This contest between sediment supply and hydrodynamics was mainly the result of the lack of accommodation space creation in the shelf area through lack of basin subsidence.

### *Lüderitz Delta*

There is some evidence for the development of a separate trunk drainage driving deltaic progradation into the margin at approximately 26°S, close to the position of the modern Tsauchab River. This evidence consists of a discrete isopach maximum located in this area for both the Late Cretaceous and Tertiary intervals (Fig. 2) and the location of several closely spaced Turonian and base Tertiary incised valleys or canyons in this area.

*Walvis 'Delta'*

The post-rift fill of the Walvis Basin differs considerably from that of the Orange Basin in that stratal geometries are dominantly aggradational rather than progradational. The exception to this is in the northern part of the basin, between 19° and 21°S, where impressive progradational clinoforms are seen to dominate the Late Cretaceous and Early Tertiary sequences. Drilling results indicate that this progradational system is a mud-dominated delta, here termed the Walvis Delta. It is not known whether this delta was fed by a single trunk river and, judging from the number of canyons seen at the base Tertiary clustered at about 21°S, it may well have been sourced by an amalgamation of precursors of the modern ephemeral rivers along this stretch of the margin. The Huab/Ugab River axis may have been the main transport route for most of this sediment. The source of most of the mud in the delta is probably the Etendeka volcanics. Late Cretaceous to early Cenozoic shelf carbonates have been interpreted in Block 1911 based on seismic character alone and, if true, these may indicate the onset of aridification. They also support the notion that the feeder rivers for the Walvis Delta were derived from catchments within the Etendeka terrane and not from further afield (continental interior).

An important change in the sediment composition of Late Cretaceous and Tertiary sequences is recognised moving further south in the Walvis Basin. From approximately 20° S, these sequences contain significant proportions of gravels, probably deposited in alluvial sheets similar to those seen today along the fringes of the Great Escarpment. The southerly limit of this 'gravel belt' is not known but, as it broadly coincides with the extent of the major gap in the Great Escarpment at the present day, we suggest that the gravel distribution is a result of enhanced erosion of the Great Escarpment in this area.

## Summary Reconstructions

To summarize many of the points raised in the preceding sections, we have attempted reconstructions of margin evolution coupled to topographic evolution onshore based on depth-converted, interpreted seismic sections linked to topographic profiles calibrated with surface geology. We present two schematic cross-sectional reconstructions whose main object is to capture the link between the offshore stratigraphy and the onshore topography. These two profiles were selected from 14 constructed along the Namibian/South African margin as part of a wider study (Aizawa, in prep.).

*Profile A*

This profile is from the Walvis Basin (Fig. 5A). The profile has been reconstructed in several key stages, each of which is described below:-

*1. Karoo*

Karoo Group sediments are thought to have been deposited in a series of fault-bounded sub-basins with maximum thicknesses >2000m (the Namib Rift of Clemson et at., 1999). This interpretation of the offshore record supports Martin's (1973) suggestions for Karoo basins beneath the shelf or slope of this area. These sediments are shown as being supplied from the ancestral highlands of the Kaokoveld and the glacial valleys described by Martin (1953) may have been principal feeders for this offshore Namib Rift. Note that the topography in the east is not known and if the glacial valleys were partly fjords, the high ground would have been lower than the valley relief implies (Martin, 1953). It seems likely that the thick Karoo rift sequences would have been sourced locally from these highlands. West-dipping normal faults bound the Karoo. No clear evidence for scarp development associated with these Karoo-age faults has been observed, although their reactivation in the Late Jurassic did produce fault scarps >500m in height (Clemson, 1997). The onshore well Toscanini-1 is located close to this profile and proves the fault-controlled thinning of the Karoo in an easterly direction.

*2. Etendeka*

The profile is located close to the maximum preserved thickness of the Etendeka Group, at a value close to 1000m. Similar thicknesses are interpreted directly offshore beyond the limit of erosion of the Etendeka Group in the marginal hinge zone (Fig. 3, section A). Projection of the Top Etendeka inland indicates that the original extent of the flow province may have been >250 km from the present coastline. Preservation of a minor residual topographic gradient (approx. 1°) at the onset of flood volcanism may explain the restriction in the original a real extent of the lavas. Basalts and quartz latites erupted onto a subaerial landscape that was generally highly peneplained but fault scarps that had developed in the Late Jurassic may have been associated with the larger faults bordering the Namib Rift (Clemson, 1997). Some of these faults may have been loci for feeder dyke intrusion. By the end of the extrusive phase, the land surface would probably have been a flat lava plain with a regional elevation substantially above sea level. Subsidence of the inner half-graben (Fig. 3, section A) in the Valanginian and Hauterivian was very rapid (> 1 km/Ma) and this would have tilted the lava plain in a westerly direction across the nascent hinge zone, thus promoting the initiation of a new westerly flowing drainage network. Fluvial transport of erosion products from newly weathered lavas would probably have formed part of the infill of the inner half-graben.

*3. Early to Mid Cretaceous*

The hinge zone became fully established in this interval allowing substantial rotational subsidence towards major, east-dipping, normal faults located some way offshore. Shorelines were probably intermittently posi-

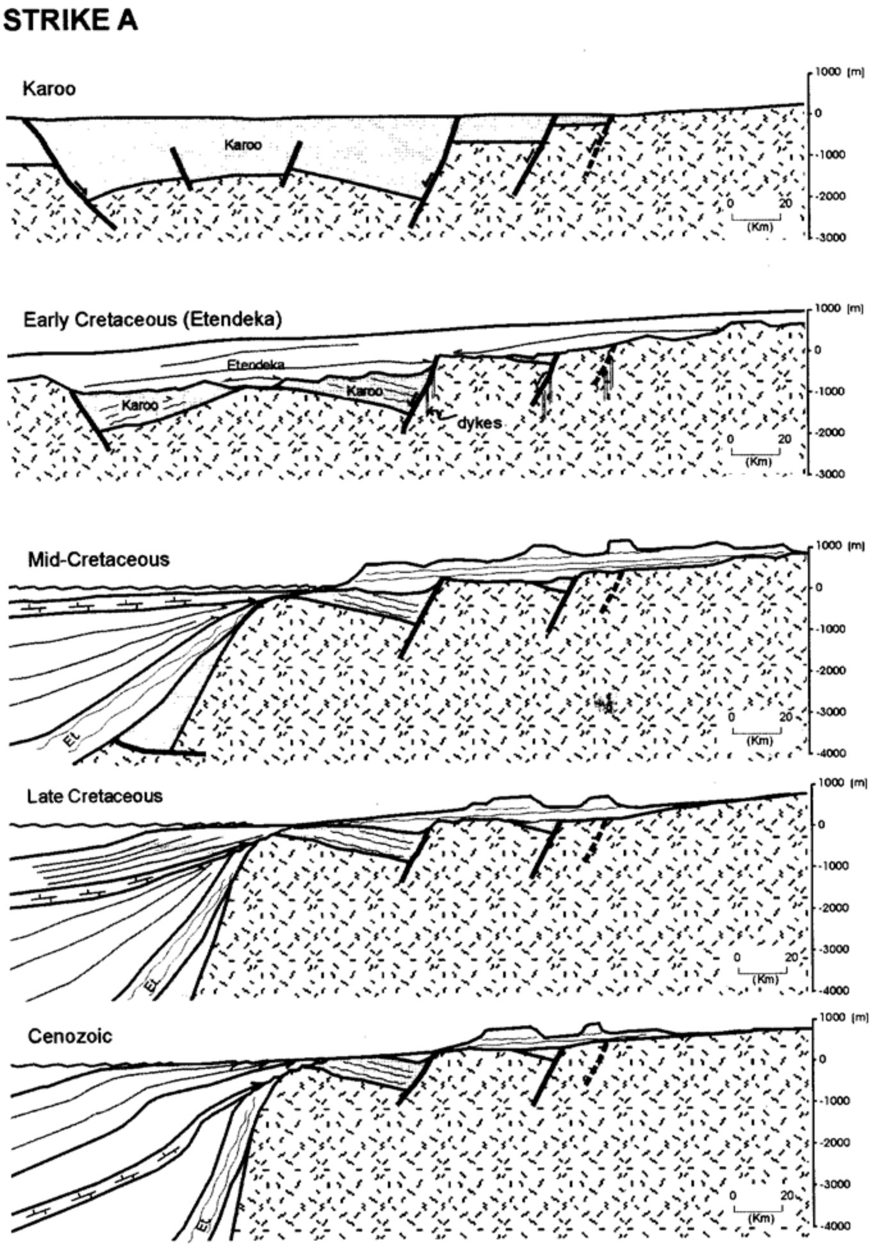


**Figure 5:** Reconstructions of the evolution along two profiles in the Walvis and Orange Basins. For details see text. Locations in Figure 2.

tioned along the hinge zone and shoreline erosion led to the development of a major escarpment. This pre-cursor to the modem Great Escarpment had a relief of at least a kilometre measured from the basal marine onlap of the Albian carbonates to the likely crest of the lava plain. It was not directly related to fault scarps resulting from earlier extension but residual fault scarps may have been component elements of this much larger feature. The scarp was probably several tens of kilometres across judging from the preserved geometry visible on the seismic data (Fig. 4). Humid weathering of the lavas would have led to rapid retreat of this early escarpment. The maximum dips on this feature observable beneath the mid-Cretaceous onlap wedge are ap-proximately 5°. There is no direct evidence for any uplift of the continental interior in this interval, although it should be noted that erosion levels on the escarpment cut through the Etendeka, removing it completely from this hinge area, and reached deeply into Karoo and basement rocks beneath. It is unlikely that such deep erosion could have occurred, however, without some uplift of the continental interior.

*4. Late Cretaceous*

Rotational subsidence continued into the Late Cretaceous but the hinge for this migrated inshore, following the termination of active faulting offshore in the Albian. This led to progressive retreat of the escarpment

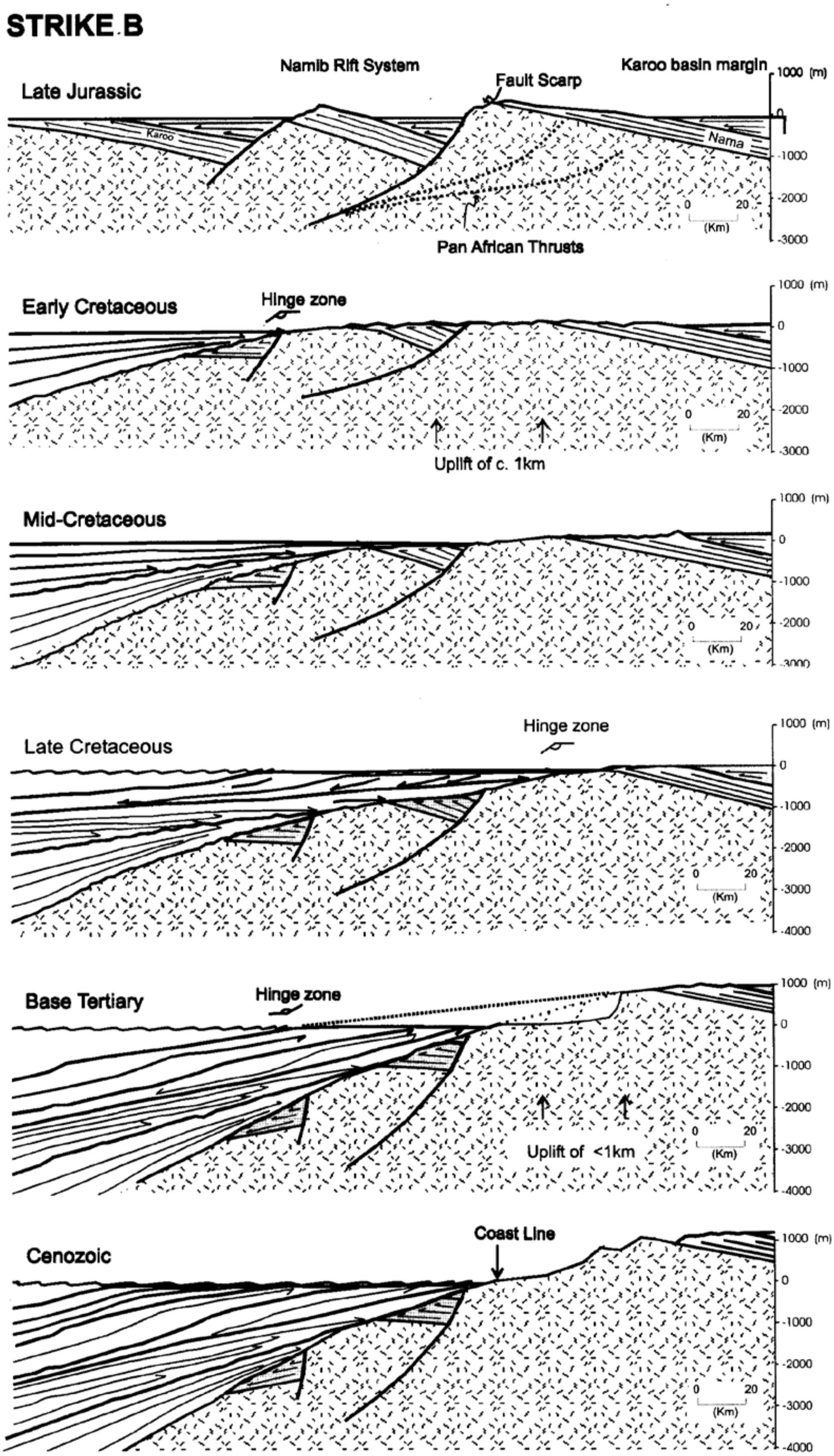


Figure 5: (cont.)

as marine Cretaceous onlap migrated inland. Scarp retreat can be envisaged as primarily a shallow marine erosional process.

*5. Cenozoic*

The hinge for continued subsidence in the Cenozoic was located close to the present shoreline. There is no evidence for uplift and truncation of the updip elements of Cretaceous clinoforms and, hence, nothing to suggest any significant Tertiary uplift along this profile. Global changes in sea level, particularly in the Neogene, would have led to numerous marine incursions and retreats across the coastal plain. Transgressive marine erosion would principally have redistributed sediment in the coastal plain and would not have penetrated far enough updip to lead to any significant additional retreat of the escarpment.

### *Profile B*

This profile (Fig. 5B) is from the northern flank of the Orange Basin (located on Fig. 2). The evolution of this profile is summarized in a series of key stages:¬

*1. Late Jurassic*

Significant amounts of extension occurred mainly through reactivation of west-dipping Pan-African basement thrusts. This produced a set of half-graben basins, mainly thickening to the east. Fairly thick sequences of parallel-bedded strata floor these grabens, and are interpreted as Karoo. Over a kilometre of this Karoo is truncated at the Mid-Cretaceous Unconformity which suggests that cumulative uplift of about a kilometre must have occurred by a combination of footwall uplift during Late Jurassic extension and rift margin uplift during initial break-up. Fault scarps with topographic relief >1 km were probably associated with the major extensional faults.

*2. Early Cretaceous*

Planation of the tilted fault block morphology of the Late Jurassic-Early Cretaceous phase of rifting was probably complete by the Hauterivian/Barremian. A major phase of westward increasing rotational subsidence was initiated with a hinge zone about 100 km offshore and was possibly controlled by landward dipping normal faults located at the western end of the profile. This pronounced tilting west of the hinge zone might have been accompanied by limited uplift inland.

*3. Mid Cretaceous*

Following the initial marine transgression in the ?late Barremian, the hinge for post-rift subsidence progressively migrated eastwards resulting in a major onlap surface. This shallow marine transgressive episode probably re-shaped the planation surface and removed any residual topographic irregularities leaving an almost perfectly smooth unconformity surface.

*4. Late Cretaceous*

Progressive rotational subsidence offshore was matched by sediment flux along the Orange River axis. Late Cretaceous shorelines continued to migrate inland as global sea levels rose and as the hinge for the subsidence also moved eastwards.

*5. Base Tertiary*

A significant uplift event occurred at this time. At least a kilometre of uplift of the continental interior is implied by the truncation geometries of Cretaceous topsets. Shallow marine bevelling was the principal erosional agent and led to the initiation of the Great Escarpment. The hinge separating regions uplifted from regions of continuous subsidence was located approximately 100 km offshore.

*6. Cenozoic*

Progradation resumed in the late Palaeocene to Eocene and continued throughout the Cenozoic. The locus for deposition shifted to beyond the Late Cretaceous shelf edge and most sediment accumulation took place on the slope. The Great Escarpment probably only retreated a few kilometres in this period (Cockburn, 1998) and the almost completely preserved volcanic complexes in the Klinghardt Mts. (dated at 37 Ma, Kröner, 1973) also testifies to the limited erosion of the coastal region during the later Cenozoic.

## Discussion and Concluding Remarks

From these reconstructions it is evident that there are significant differences in the geodynamic and topographic evolution of the northern and southern sectors of the Namibian continental margin. The age and origin of the Great Escarpment is notably different in these two areas, confirming King's (1951) view that the Great Escarpment is an amalgamation of different palaeotopographic elements. Using the classical stratigraphic approach advocated by Henno Martin (1972, 1976) and adopted here, we believe that important constraints can be placed on the geodynamic coupling between offshore subsidence of the margin and onshore uplift/denudational events. This brief contribution is an initial application of this approach and further work will clarify many of these preliminary interpretations.

One of the most important conclusions from this preliminary analysis is that along the greater part of the length of the margin, the dominant structural element is the hinge zone (Light *et al.*, 1993; Clemson, 1997). This forms the critical boundary separating the offshore and onshore morphological elements of the continental margin. Shorelines have evidently migrated seaward and landward of this hinge during the Mesozoic and Cenozoic but the hinge zone has remained as the main fulcrum separating regions of subsidence from regions of stasis or uplift throughout much of the last 130 million years. It is also important to observe that the hinge zone is not defined by significant fault structures along much of its length. The evolution of the margin cannot therefore be related in any simple way to rift-related structural development (Summerfield, 1991) and for much of the margin, the impression gained is that the hinge zone really is just that: a simple region of pronounced bending of the continental lithosphere separating a subsiding oceanic realm from a static or mildly uplifted continental realm. The significance of this hinge zone may well prove to lie in the deeper structure of the crust or upper mantle, and its true significance may only be revealed once the volcanic evolution of the margin is better understood. To close, we can conclude that the evolution of the palaeotopography of the margin is more complex than might be imagined from a cursory examination of present-day topography and much further research will be required before Henno Martin's many predictions can be satisfactorily tested.

**Acknowledgements**

We are grateful to Jon Clemson and Joanne Bagguley for their invaluable thesis contributions on which much of this paper is built. NAMCOR are gratefully acknowledged for logistical support and for permission to publish this paper. We are indebted to NOPEC A/S for permission to include their seismic section reproduced in Figure 4.

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