Chapter 12

Post-rift deformation of the North East and South Atlantic margins: are "passive margins" really passive?

DOUGLAS PATON
School of Earth and Environment, University of Leeds, UK

ABSTRACT

There have been many recent advances on understanding the mechanisms and controls on continental lithospheric extension, but most models assume that post-rift thermal subsidence conforms to an exponential decay. This has led to the general use of the term "passive margin" for the resultant margin. This chapter will discuss observations from the North East and South Atlantic margins, which show that such settings are anything but "passive."

The North East Atlantic has a number of rapid subsidence and uplift events that are not accounted for in simple thermal subsidence models and require crust-mantle interactions to explain them. In addition, compressional structures are observed, thus suggesting horizontal shortening generated from ridge-push effects. In the South Atlantic, although less data are available, there is substantial evidence from both onshore and offshore that the margin has undergone significant post-rift deformation. The exact timing of the deformation remains controversial but it is evident that there was deformation in both late Cretaceous and Tertiary times.

Keywords: passive-margin; post-rift subsidence; compressional deformation; uplift

INTRODUCTION

The continental margins of both the North and South Atlantic oceans are universally accepted to be the consequence of crustal thinning and sedimentary-volcanic loading. The process of crustal thinning, and lithospheric stretching, has been extensively studied and documented over the last 30 years with significant advances made to our understanding of the processes and implications. All of these advances still require two fundamental phases in lithospheric stretching, that of rifting followed by thermal subsidence.

From a qualitative perspective, Falvey (1974) proposed that extension in the lithosphere is accommodated through brittle deformation of the crust and plastic flow of the sub-crustal lithosphere and used this to explain the subsidence histories from a number of continental rift basins. McKenzie (1978) proposed a quantitative model of one-dimensional lithospheric stretching that assumes pure shear and uniform stretching of the crust and lithosphere. Upwelling of the asthenosphere was assumed to be passive. The main components and implications of this model are that stretching comprises an initial fault-controlled (rift-related) subsidence, whereby the lithosphere thins vertically and is stretched horizontally by the stretching factor β. The subsequent relaxation of lithospheric isotherms back to their pre-rift status results in thermal subsidence (Fig. 12.1a). The subsidence associated with rifting is considered to be instantaneous whereas the post-rift thermal subsidence decays exponentially with time for approximately 50 Ma until the heat flow of the standard lithosphere reaches 1/e of its original value and subsidence is minimal. For a full discussion on applying the one-dimensional stretching model to basin analysis readers are referred to Busby and Ingersoll (1995) and Allen and Allen (2005).

Tectonics of Sedimentary Basins: Recent Advances, First Edition. Edited by Cathy Busby and Antonio Azor.

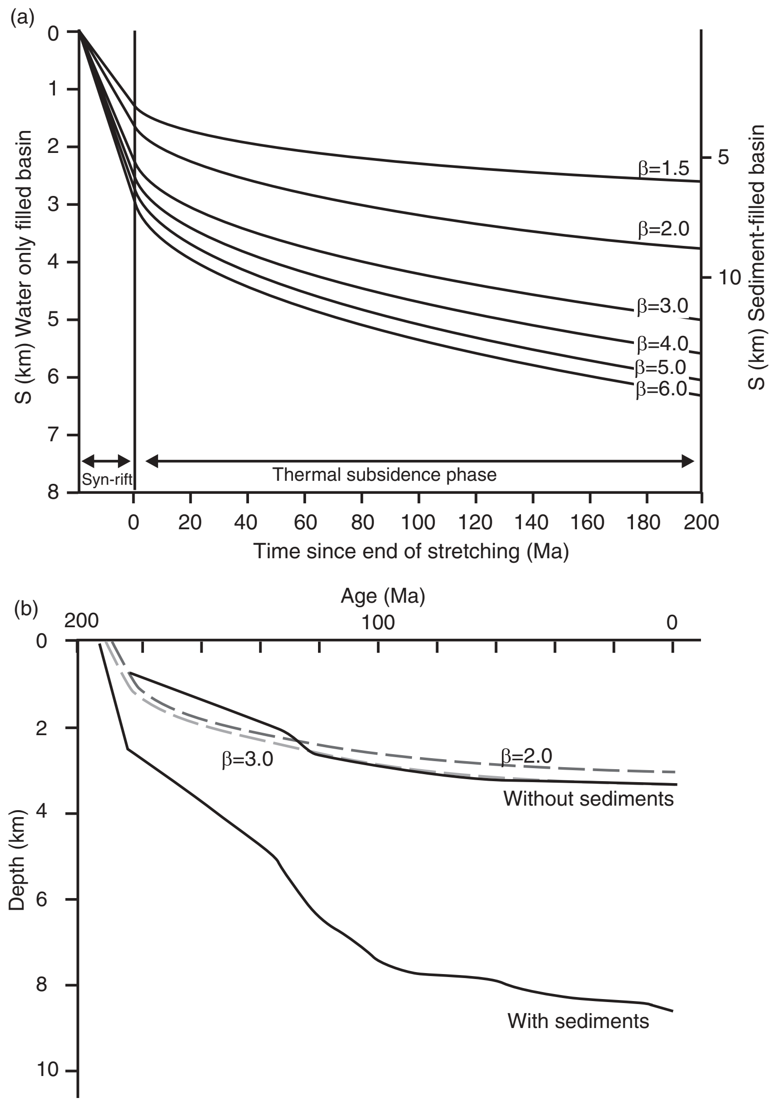

Fig. 12.1. (a) Subsidence curves for differing amounts of extension derived from one-dimensional subsidence models that assume instantaneous rifting followed by exponential decay as a consequence of thermal subsidence. (b) Subsidence analysis of a well on the Nova Scotian margin demonstrates the similarity between modeled (dashed line) and observed subsidence (solid) curves. *Source*: (a) After Sclater et al. (1980). (b) After Keen and Cordsen (1981).

This uniform stretching concept has since been modified and applied to explain the first order subsidence patterns observed in a number of Atlantic-type margin settings including the Bay of Biscay, the eastern Canadian continental margin, the North East US Atlantic coast, and the North Sea (e.g., Steckler and Watts, 1978; Keen and Corsden, 1981; Le Pichon and Sibuet, 1981; Barton and Wood, 1984; Fig. 12.1b).

Subsequently, many models have been proposed that modify the uniform stretching concept to account for observations that are not explained by the simpler models. These modifications include dynamic stretching (including lithospheric strength and viscosity structures), multi-phase rifting, depth dependant stretching, absence of radiogenic heat flow, pure shear stretching, instantaneous stretching and plume induced rifting (Allen and Allen, 2005). In the majority of these models the modifications consider the influence on the rifting stage and generally assume that the thermal subsidence phase is controlled by an exponential decay with time. The margins that result from this thermal subsidence phase are commonly termed as "Atlantic-type" or "passive continental" margins, owing to their type location and the general assumption that they are located overlying attenuated continental crust. They are considered to be "seismically inactive, and, in mature examples, heat flows are near normal" (Allen and

Allen, 2005). Away from oblique spreading or transform faults these settings are assumed to be tectonically quiescent (Miall, 1990) with the exception of "gravity-controlled deformation (salt tectonics, mud diapirism, slumps, slides and listric growth faults in soft sediment)" (Allen and Allen, 2005).

Despite the successful application of the stretching models to explain post-rift subsidence to a first order, a number of observations based upon seismic reflection data, wells and backstripping techniques, from the NW European, eastern North American and the Norwegian margins disagree with model predictions. These departures from the simple models demonstrate episodes of both excessive subsidence and uplift or significantly less subsidence than predicted. As an example, Mutter (1984) estimated there was a deficit of up to 1 km of subsidence compared to model predictions on the Norwegian margin. Over the last decade, with the significant advances in the quality, availability, and coverage of seismic reflection data and exploration wells, the extent to which passive margins do not conform to the simple stretching models has increased. Much of the focus has been on the NW European margin; however, there is increasing evidence of similar features on other "passive" continental margins. The central question this chapter addresses is: are "passive" continental margins really passive? This is answered through a combination of reviewing existing observations and presenting new data analysis from the NW European and South Atlantic margins before discussing possible causes and implications of non-uniform subsidence.

RECOGNITION OF SUBSIDENCE AND UPLIFT

Before addressing the question of post-rift deformation, it is important to consider the data and techniques that are used to quantify uplift and subsidence. Estimation of the magnitude and timing of margin uplift and subsidence have traditionally focused on the offshore components of margins, though a number of recent studies have integrated onshore data with offshore analysis. Most of the techniques estimate the relative motion of rock mass with respect to a datum, which could be a neighboring rock mass (e.g., stratal geometry) or an idealized geotherm (e.g., vitrinite reflectance). Such techniques, therefore, lead to whether the rock mass has subsided or uplifted relative to the datum (for a full discussion on definitions, see England and Molnar, 1990; Corcoran and Doré, 2005).

Thermal analysis

Thermal analysis uses thermal indicators (e.g., vitrinite reflectance and apatite-fission tracks, AFT), within stratigraphic successions to determine the peak paleotemperature of the rock volume. This is then compared to the depth predicted from normal thermal gradients. Vitrinite reflectance is a measurement of the percentage of incident light (usually a wavelength of 546 nm) that is reflected from vitrinite particles within organic-rich components. As the reflective properties of the organic material are related to the amount of heating suffered, the mean vitrinite reflectance is calculated for a representative sample and compared with laboratory data to estimate the paleotemperature (Sweeney and Burnham, 1990). Despite being a commonly used technique in many sedimentary basins, one of its principal limitations is it only records the maximum thermal event, but not multiple events.

Subsidence analysis

Subsidence analysis is based upon determining the magnitude of subsidence of a vertical stratigraphic section through backstripping and decompaction (e.g., Steckler and Watts, 1978), and comparing the resulting values to subsidence curves derived from estimated stretching factors and duration of rifting (McKenzie, 1978; Jarvis and McKenzie, 1980). As outlined above recent modifications of one -dimensional stretching models have been adapted to account for multiple rift events, exhumation and two-dimensions (e.g., Roberts et al., 1998; Rowley and White, 1998). One of the principal limitations of this modeling is the results are largely dependent upon knowing the input parameters with reasonable accuracy, including lithospheric flexure rigidity, stretching factors, palaeo-water depth, compaction factors, and biostratigraphic dating.

Compaction analysis

The burial of sediments during the evolution of a sedimentary basin results in a reduction in porosity so that a comparison of measured porosity with predicted porosity curves can be used to estimate burial depth (Sclater and Christie, 1980). In addition, as the seismic velocity of the rock mass is related to the porosity, variations in seismic velocity can be related to modeled compaction results to indicate burial and exhumation amounts (see Corcoran and Doré, 2005, for detailed references). Limitations of this method are a function of applying generic definitions of porosity against depth curves for standard lithologies and not accounting for variations in lithologies, local lithification, and compaction.

Tectono-stratigraphy

Mapping of seismic reflection terminations and defining basin-wide unconformities are used in tectono-stratigraphic studies to investigate the interaction of eustasy, tectonic subsidence, and thermally controlled margin subsidence at both regional and local scales. The main constraint is the availability and quality of both high-resolution seismic reflection data and biostratigraphic controls from boreholes. A common procedure is to quantify the amount and style of subsidence by determining the relative amount of accommodation space at the time of deposition, or to recognize intervals of uplift and erosion through the identification of reflection terminations. The technique defines a relative sense of motion rather than an absolute magnitude. In near-shore areas, this can be overcome if stratigraphic evidence (e.g., location of shoreline delta systems) can be used as a constraint on paleo-water depth, though this is limited in settings where water depths are difficult to ascertain (Stoker et al., 2005a; Paton et al., 2008).

Onshore geomorphology

The analysis of Atlantic-type margins has been broadly confined to offshore regions. More recently, attention has been paid to the onshore component of such margins using geomorphic evidence. Recent studies (e.g., southern Atlantic margin; Gallagher and Brown, 1999) have used topographic profiles perpendicular to margin strike to show that present-day margin topographies often do not conform to model predictions. These techniques commonly use AFT data.

OBSERVATIONS OF NON-UNIFORM POST-RIFT MARGIN SUBSIDENCE FROM THE NE ATLANTIC

Regional setting

The sedimentary basins that form the NE Atlantic continental margins are the result of discrete episodes of intra-continental rifting from the Permian (~310 Ma) to the Late Cretaceous and early Paleogene (Ziegler, 1988). The NW European component of the margin extends from the Porcupine Basin, offshore Ireland to mid Norway, with a length of approximately 2500 km and a width between <200 km in the Møre Basin and ~500 km across the Vøring margin (Fig. 12.2). Structurally, the margin includes a number of highs separated by deep water basins that formed as a consequence of variations in the amount and timing of lithospheric stretching (Doré et al., 1999). The long duration of rifting prior to oceanic crust formation is reflected in the presence of a number of smaller, older (Permian-Triassic) failed rifts. These failed rift basins are overlain by the more extensive post-rift basins, the ages of which reflect the progressive migration of rift activity towards the NW from the Porcupine and North Sea Basins (Late Jurassic) to the Rockall, Faroe-Shetland, Møre, and Vøring Basins (early to mid-Cretaceous) (Doré et al., 1999).

The final rifting episode was accompanied by significant volumes of igneous eruptions and intrusions in the Paleocene-earliest Eocene (ca. 65–55 Ma) that form the North Atlantic Large Igneous Province and the present-day oceanic margin. The presence of high-velocity lower crustal bodies along the continent-ocean boundary has been interpreted as the product of syn-rift magmatic underplating (Saunders et al., 1997). This interpretation is supported by observations of both sub-aerial volcanism and the presence of seaward-dipping reflectors. Subsequent to the ocean floor initiating event, the margin underwent post-rift thermal subsidence, resulting in the generation of up to 4 km-deep Cenozoic sedimentary basins (e.g., the Rockall Basin; Ceramicola et al., 2005). A number of authors (e.g., Praeg et al., 2005; Doré et al., 2008) have observed episodes of rapid subsidence, tilting, and domal structures that cannot be accounted for in existing models of passive margin evolution. Instead, mechanisms including crust-mantle interactions and far-field stresses have been invoked to explain the observations.

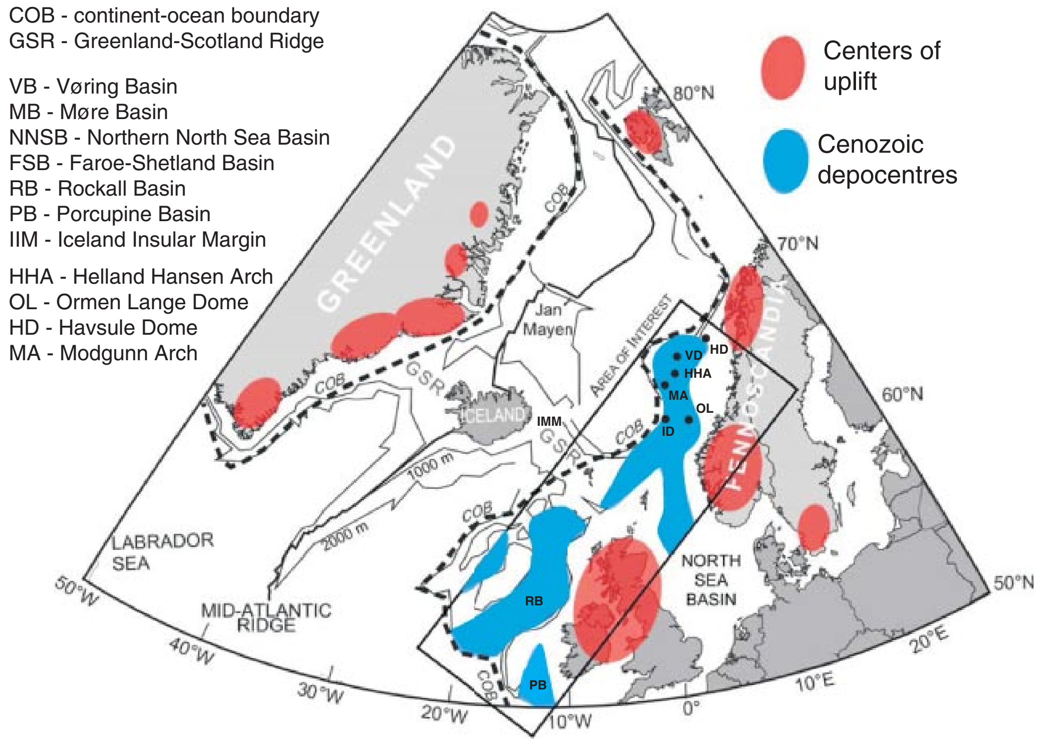

Fig. 12.2. Location of centers of uplift and subsidence in the NE Atlantic, many of which cannot be accounted for by the simple one-dimensional stretching models. *Source*: Modified from Praeg et al. (2005).

Subsidence and uplift

Since the early 1980s, the use of backstripping techniques and comparison of predictions of subsidence with bathymetric observations in both eastern North America and the NW European margin have led to the recognition of deviations from the simple one-dimensional stretching models. Ceramicola et al. (2005) compared restored paleo-depths of the Lower Paleogene unconformity with well data and found significantly greater subsidence than predicted in the Rockall Basin (at least 1.7 km), the Vøring Basin ($>$ 1 km) and the Faroe-Shetland Basin (up to 2.1 km). Tectono-stratigraphic studies of Lower Paleogene-recent subsidence (65.5–0 Ma; Stoker et al., 2005b) conclude that it comprises three regional-scale events: in the Early Cenozoic; Upper Eocene; and intra Pliocene (Fig. 12.3a–b). These discrete events have been attributed to episodes of coupled tilting and sagging. Their relatively brief duration ($<$10 Ma) implies vertical motions of hundreds of m/Ma, which are inconsistent with subsidence rates predicted from lithospheric cooling (Praeg et al., 2005; Stoker et al., 2005b).

When backstripped, basins in the Northern North Sea and Faroe-Shetland areas indicate accelerated subsidence during the Early Cenozoic post-rift episode with an estimated 300–500 m of water loaded subsidence in excess of that predicted by the simple stretching model (Turner and Scrutton, 1993; Hall and White, 1994). Wells in the Faroe-Shetland area suggest this increased subsidence was coincident with a phase of margin uplift ($\sim$100 m) that formed a mid-Paleocene unconformity (Turner and Scrutton, 1993). The margin uplift event is most evident along an elongated zone from Fennoscandia to Scotland, NW England and Ireland with as much as 1.5 km uplift estimated in Fennoscandia (Riis, 1996; Green et al., 2002; Hendriks and Andriessen, 2002). The observations of a coupled basin subsidence-margin uplift episode are in agreement with tectono-stratigraphic studies of the area (Fig. 12.3). These demonstrate rapid subsidence of basinal areas, significant erosional truncation of the margin and deposition of large sediment wedges prograding from the inner margin areas (Stoker et al., 2001; Andersen et al., 2002). Although the event was short-lived ($\sim$5 Ma), it was not completely synchronous,

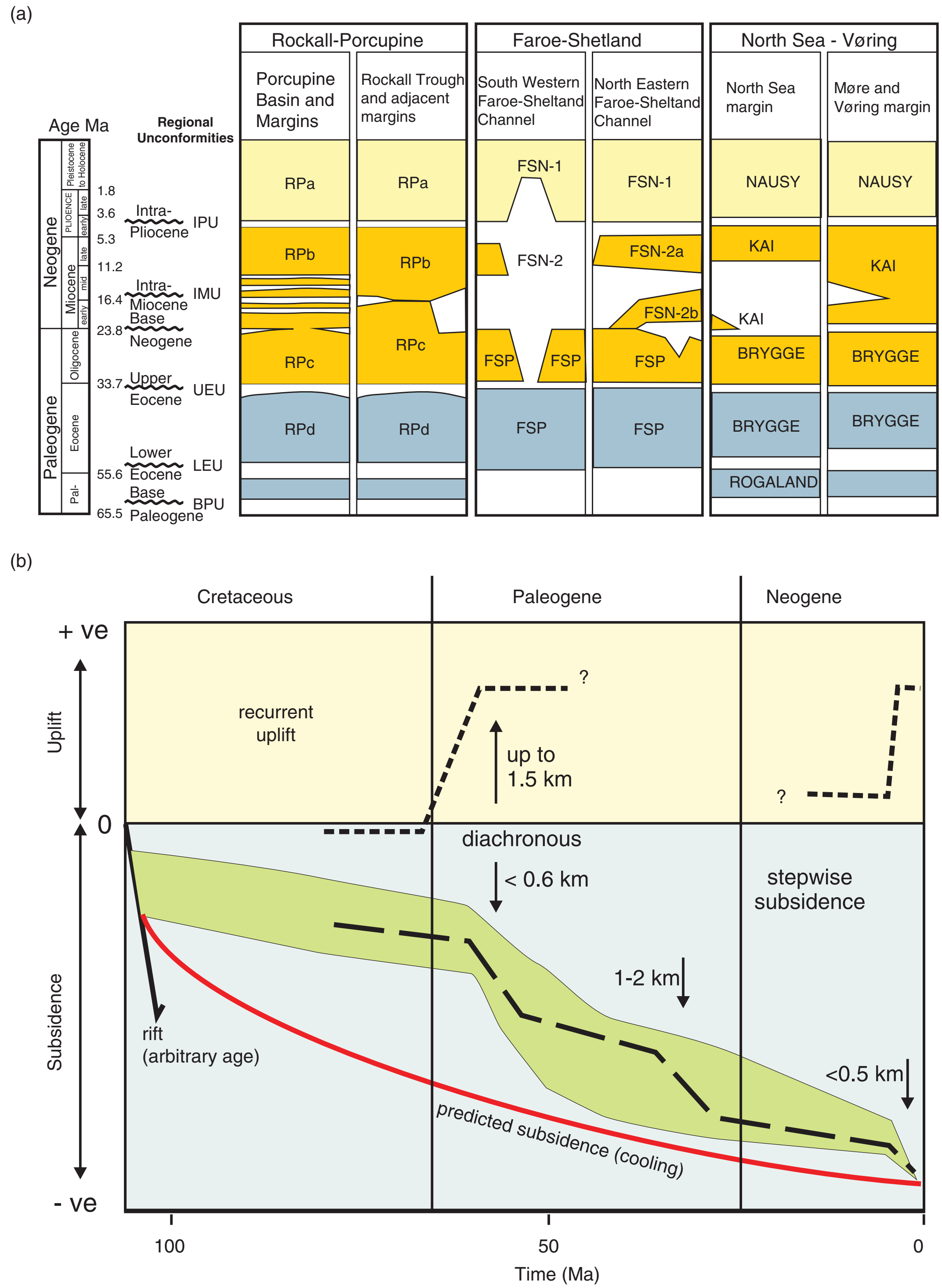

Fig. 12.3. (a) Summary of stratigraphic framework for the NE Atlantic margin. (b) Summary diagram of the discrepancy between observed margin subsidence/uplift and the predicted subsidence curve. The comparison reveals a number of steps of both rapid subsidence and uplift not predicted by simple models. *Source*: After Praeg et al. (2005).

beginning in the Late Paleogene (~55 Ma) in the north (Faroe-Shetlands and Northern North Sea) and occurring later towards the south (Porcupine and Rockall Basins).

The upper Eocene tilting event is evident because the upper Eocene unconformity (UEU; ~33 Ma) represents rapid deepening of the basinal areas (Figs. 12.3a, 12.4). Mid-late Eocene

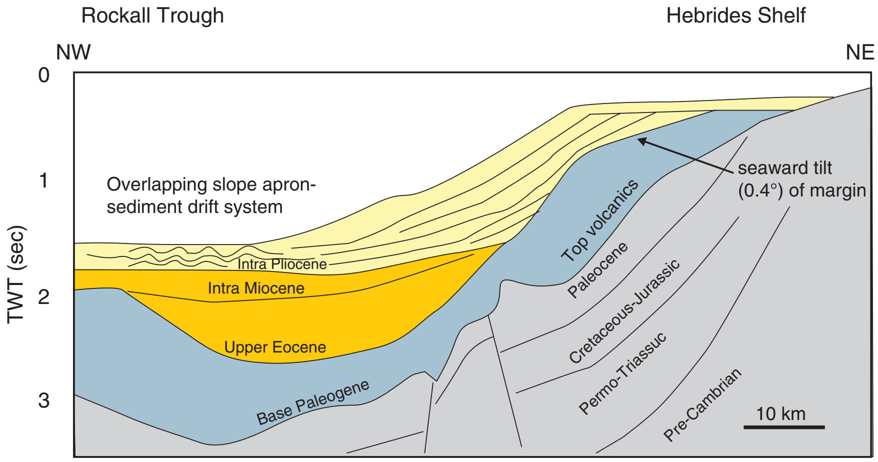

Fig. 12.4. Line drawing of a seismic line across the Rockall trough to illustrate the five regional unconformities, which have been identified and correlated across the NE Atlantic. Striatal architecture of the reflections above and beneath these unconformities reveals episodes of rapid margin subsidence and tilting. *Source*: After Stoker et al. (2005a).

(~33 Ma) shallow-marine conglomerates in the Rockall Basin sit beneath the unconformity, while above the unconformity there are deepwater sediments. The sedimentology, coupled to the depositional geometry, suggest subsidence of up to 700 m in the offshore portion. The proposed tilting is supported by a regional dip of up to 4° of the sub-aerial Paleocene flood basalts, which vary in altitude from 500 m in the inner margin down to greater than 2 km below sea level in the basin floor (Stoker et al., 2005b).

The backstripping of stratigraphy within the Late Cenozoic interval around the North Atlantic records an episode of increased subsidence. This subsidence is also reflected in the deposition of the sedimentary package above the ~4 Ma Intra Pliocene unconformity (Fig. 12.5). Unlike the upper Eocene event that only consisted of basin subsidence, paleo-thermal analysis reveals the Late Cenozoic event included contemporaneous uplift of the margin. Along much of the Fennoscandian margin, AFT data reveal varying amounts of tectonic uplift with up to 1 km in the northern region and 1.5 km in southern Norway (Fig. 12.2). Within the Fennoscandia area, the uplift was most evident from the Pliocene unconformity and the significant truncation of strata beneath it (Riis, 1996). Sections across the area reveal the event resulted in a series of elongated dome features along the coastal margins, which record up to 1.5 km of uplift and that are contemporaneous with up to several hundred meters of basinal subsidence. This km-scale tilting, which has very similar stratal architecture to the early Cenozoic event, resulted in offshore highs (e.g., Faroe banks) and the development of seaward prograding shelf-slope wedges.

Crust–mantle interactions

The Early Cenozoic, Upper Eocene, and Late Cenozoic episode of regional-scale tilting and uplift have been attributed to crustal-mantle interactions. The most obvious interaction is convection-driven deformation, where the emplacement of a mantle plume head below rifting continental lithosphere can result in crustal uplift and concurrent subsidence. Two further mechanisms of crustal-mantle interaction may occur, namely, small-scale convection in the upper mantle during rifting-drifting and reconfiguration of upper mantle flow during plate reorganization (Keen, 1985; Stuevold et al., 1992; King et al., 2002).

Mantle plumes may be responsible for the emplacement of magmatic bodies at mid-lower crustal levels. This causes isostatic uplift of the crustal lithosphere. For instance, underplating of 5 km-thick bodies can account for up to 0.6 km of uplift (Brodie and White, 1994). Although initial models for the Iceland Plume suggested large scale regions of permanent uplift in the order of 2000 m (e.g., White and McKenzie, 1989), recent work concludes plumes may affect a much narrower zone, and the uplift may be more transient as a consequence of temporal fluctuations in plume flow (e.g., Jones et al., 2002). However, some studies suggest that plume models fail

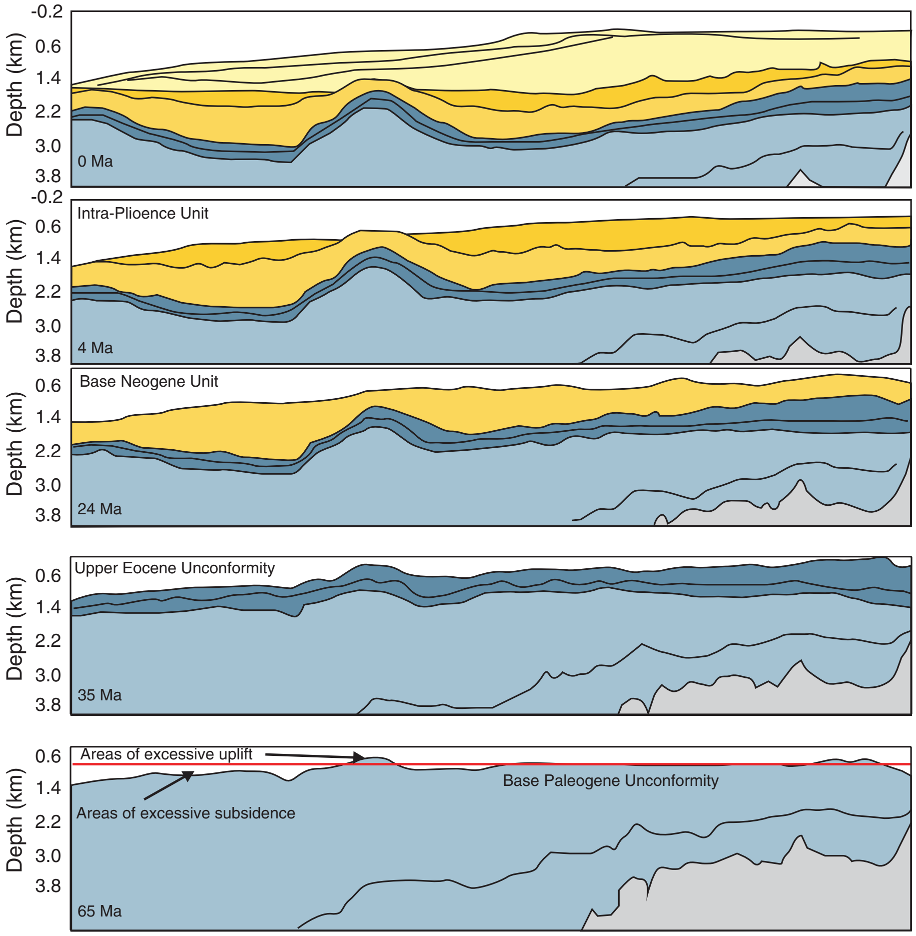

Fig. 12.5. Sequential restoration using backstripping techniques across the Vøring Basin (see location in Fig. 12.2). When model results are compared with known paleo-water depths from well data, a significant subsidence episode is not accounted for from one-dimensional stretching models. *Source*: After Ceramicola et al. (2005).

to explain the observations (Praeg et al., 2005). In the case of the NE Atlantic margin, margin uplift and tilting occurred 50 Ma later than rifting and lasted for only 4 My. Furthermore, the margin also underwent coeval uplift and rapid basin subsidence.

Recent studies have considered mantle-crust interaction through thermo-mechanical numerical modeling (e.g., Keen and Boutilier, 1995) and predict various scales of mantle convection flow. The scale of this flow is dependent upon the lateral thermal gradient - where gradients are greater, as across rifts or continent-ocean boundaries, models predict small-scale cells (~100 km; e.g., Keen, 1985; Keen and Boutilier, 1995; Korenaga and Jordan, 2002). These small-scale mantle circulations are predicted to cause vertical movements on a km-scale, though the actual magnitude is associated with the viscosity of the upper mantle, which remains poorly constrained. Many of the models also predict the resultant mantle flows would not occur as uniform events because the topography at the base of the lithosphere has a significant influence and may result in considerable 3D variations with upwellings and downwellings on a horizontal scale of up to hundreds of kilometers.

In the NE Atlantic, Praeg et al. (2005) attribute the three principal phases of margin deformation to small-scale mantle circulation (Fig. 12.6). The primary mantle-crust interaction during the Paleocene-early Eocene occurred at the central sea-floor spreading axis. Praeg et al. (2005) suggest a secondary mantle flow also operated, which resulted in tilting of the continental margin/basin areas to the east of the continent-ocean boundary. This

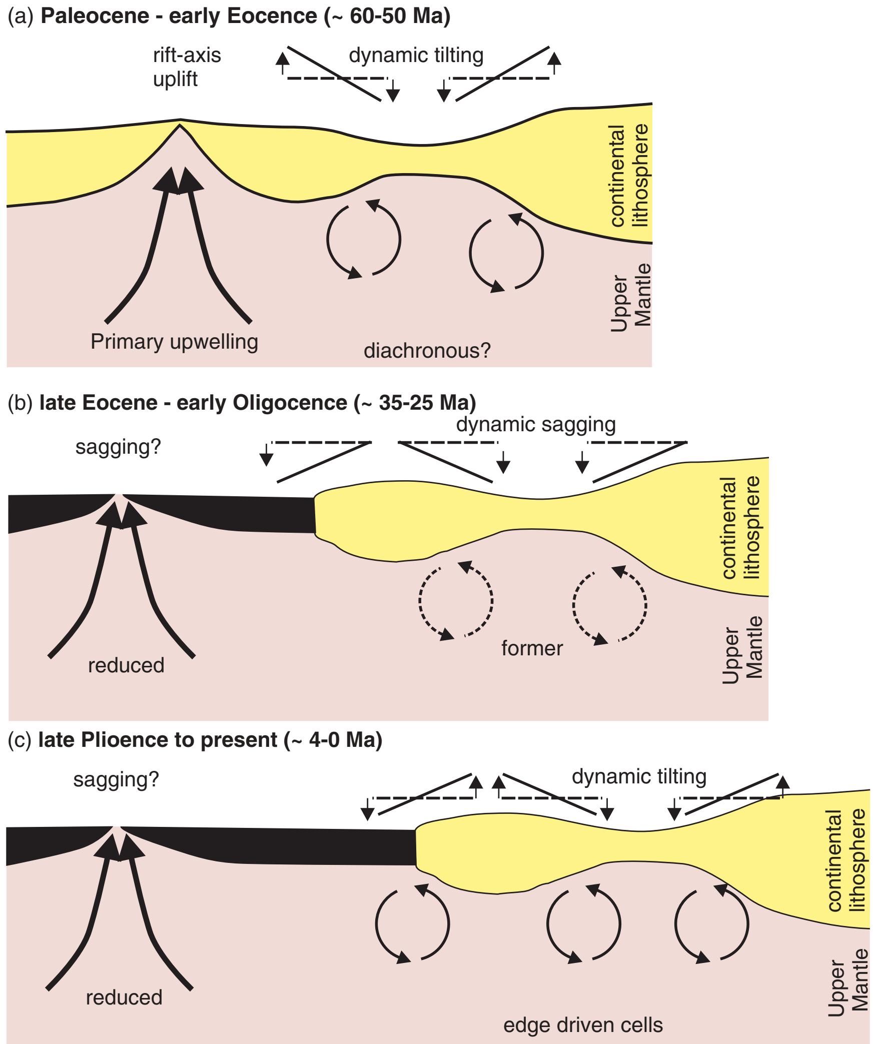

Fig. 12.6. Evolution sketches for the NE Atlantic, in which the episodes of uplift and subsidence are attributed to the interaction of upper mantle convective flow with the continental lithosphere. *Source*: After Praeg et al. (2005).

secondary flow is inferred to have caused both margin uplift and rapid subsidence of the inboard basins. These authors consider this event to be both transient and diachronous, hence explaining the variation in timing from the Faroes (Late Paleocene $>$ 55 Ma) to the Porcupine Basin (early Eocene $<$ 55 Ma). The second phase of post-rift deformation is related to a tectonic-plate reorganization, which resulted in the termination of seafloor spreading between Greenland and Laurentia in the Labrador Sea. As this is coincident with the Upper Eocene margin-scale sag (without evidence of marginal uplift), Praeg et al. (2005) suggest this plate-reorganization switched off the early Eocene small-scale circulations, causing the regional-scale sagging of the margins (Fig. 12.6). The explanation of the early Pliocene to present margin uplift remains more speculative. It may reflect rejuvenation of small-scale mantle cells at the boundary between oceanic and continental lithosphere due either to widening of the NE Atlantic or other global plate reorganizations.

Domal structures

As the NE Atlantic is a magmatic margin, it is not surprising that a number of domes (e.g., the Gjallar Ridge, Vema Dome, and Isak Dome in the mid-Norwegian shelf) have been attributed to magmatic processes during continental break-up (Doré et al.,

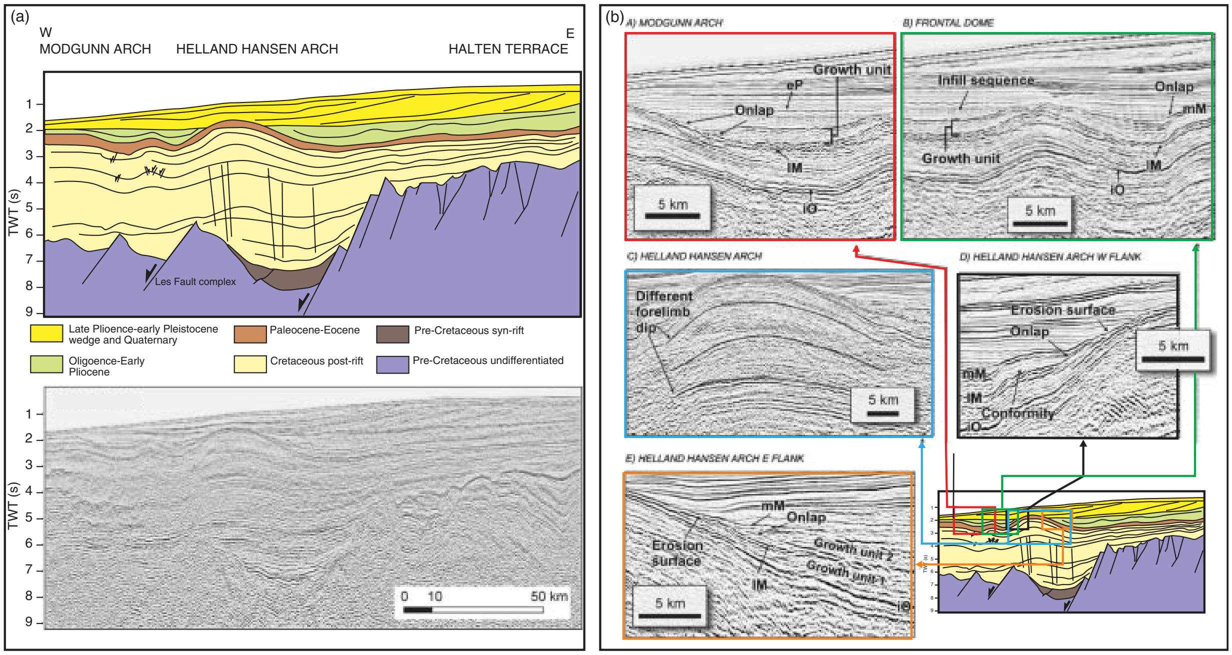

Fig. 12.7. (a) Post-rift folding is evident in the Norwegian margin, as illustrated on these seismic sections across the Helland-Halten Terrace, Hansen Arch and the Modgunn Arch. (b) The timing and geometry of the folding are apparent by the geometry of reflection terminations. *Source*: After Gómez and Vergés (2005).

2008). A number of other domal features, including the Ormen Lange Dome, the Havsule Dome, and the Modgunn Arch (Fig. 12.2) are of post-initial ocean-forming age (early Eocene, 50 Ma, to recent) and cannot, therefore, be related to magmatic events (Fig. 12.2). These structures are characterized by four-way dip closure, broad basin-scale structural inversion and reverse movement on underlying pre-existing normal faults (Doré et al., 2008).

The largest post-break-up domal feature is the Helland Hansen Arch. This is up to 200 km in length and has an amplitude of 500 m (Fig. 12.7a–b). Its location appears to be controlled by the presence of the reactivated Les Fault complex (Brekke, 2000) and is dated as being Mid-Miocene (~14 Ma). This age comes from high-resolution mapping of stratal architecture, tied to the available well data, which reveal the occurrence of a Mid-Miocene (~14 Ma) unconformity and erosion of Oligocene to Early Miocene (~34–20 Ma) strata at the fold hinge (Fig. 12.7b; Gómez and Vergés, 2005). The Mid-Miocene deformation event in the Helland Hansen Arch is seen elsewhere, including the Ormen Lange Dome and the Faroes-Rockall area (Doré et al., 2008, and references therein). Deformation continued until the Early Pliocene (~5 Ma) as the onlapping Mid-Pliocene (~4 Ma) to Early Pliocene (~5 Ma) strata onto the unconformity are themselves folded. The uppermost unit within the Early Pliocene has concordant, parallel reflections that onlap the anticline but do not show folding and have, therefore, been interpreted as post-growth deposition infilling existing bathymetry (Fig. 12.7; Gómez and Vergés, 2005).

Far-field stresses are the main mechanism invoked to explain domal structures such as Ormen Lange. The origin of these stresses are considered to be (1) ridge-push from the North Atlantic spreading centre, (2) orogenic compression from the Alpine-Pyrenean orogenies, or (3) a combination of these.

Doré and Lundin (1996) suggest many of the NE Atlantic domal structures are of a non-volcanic origin, including the largest features of the Helland Hansen Arch and Ormen Lange. They suggest these are associated with the reactivation of pre-existing basement discontinuities during the early Oligocene in response to ridge-push. Subsequent work by Doré et al. (2008), however, argue not only that the mid-Miocene timing of deformation is inconsistent with early Paleogene sea-floor spreading initiation but also that ridge-push force is too small to explain the deformation observed. As an alternative, Doré et al. (2008) suggest the location and timing of these domal structures may be related to the development of the Iceland Insular Margin, which is a 500-km wide plateau located between Iceland and the NE European margin (Fig. 12.2). These authors argue the elevation and extent of the plateau could have generated a greater body force than a spreading ridge. Interestingly, the mid-Miocene timing of the Insular Margin formation is contemporaneous with the timing with the domal structures.

Previously, some workers (e.g., Brekke, 2000) have suggested the Alpine Orogeny, through far-field stresses, was associated with the compression observed in NE Europe. The problem with invoking Alpine compression is that it would require the transmission of stress across the intermediate area, where many basins would have been expected to be susceptible to inversion (e.g., the North Sea); furthermore, no appropriately timed inversion has been observed north of the Alpine compression (Dore et al., 2008).

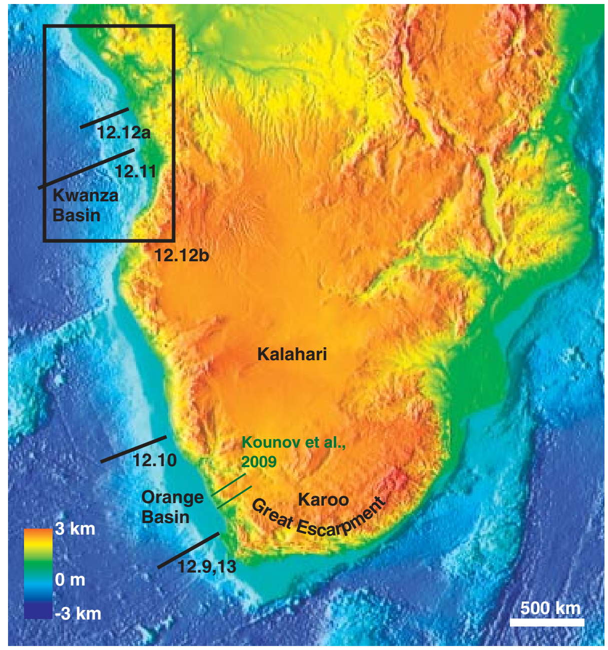

Fig. 12.8. The topography of Southern Africa is dominated by unusually high relief of much of the continent. The most obvious feature is the Great Escarpment.

OBSERVATIONS OF NON-UNIFORM POST-RIFT MARGIN SUBSIDENCE FROM THE SOUTH ATLANTIC

The influence of post-rift deformation on the South Atlantic continental margins is less well documented than in the North Atlantic. This is partly because of the relative scarcity of exploration data, but also because many margin basins contain a significant component of salt that makes it difficult to differentiate salt-driven tectonics and deformation associated with post-rift margin tectonics. Mesozoic rifting of the Gondwana super-continent in southern Africa occurred in two phase: the first ~184 Ma from Durban to Bulge of Africa: and the second from 128 ± 3 Ma from Durban to Guinea Nose when ocean spreading was initiated in the South Atlantic. During continental extension it is likely that flank uplift occurred along the continental margins, and there is a general consensus that any topography, both on the margin and in the interior, was eroded close to sea level resulting in a relatively flat "African surface" by ~100 Ma (Burke and Gunnell, 2008, provide a full discussion on the "African surface"). What remains controversial is the timing of the uplift that caused the present day topography of southern Africa (Fig. 12.8).

Regional-scale uplift

On a continent scale, the African hypsometric curve reflects the highest elevations of a continent with no compressive tectonics, with a modal elevation of 0.4–0.6 km compared to other continents of 0.2–0.5 km (Burke and Gunnell, 2008). The most obvious manifestation of the continental uplift of southern Africa is the Great Escarpment that runs approximately 3000 km parallel to the coast from Namibia on the west coast to the Limpopo River on the east coast. This unusually high topography is not confined to coastal areas, and as the elevation map show a (Fig. 12.8), the high elevation continues across much of the inland part of the landmass. The elevation map also reveals this is not a single continuous surface, but rather the topography comprises five discrete swells (up to 1.5 km above sea level, or a.s.l.) that surround the Kalahari Basin (Partridge and Maud, 1987; Burke and Gunnell, 2008). Stratigraphic evidence also supports the notion of regional uplift as Eocene and Cretaceous marine deposits occur several hundred meters above sea level across much of southern Africa. The key questions in the regional context are when this uplift occurred and what the driving mechanisms were.

A number of studies have considered the magnitude and timing of the uplift of southern Africa using AFT analysis. In one of the initial studies, Gallagher and Brown (1999) suggested pulsed uplift of onshore portions of the South Atlantic margin and attributed them to a mid-Cretaceous age. More recently, Kounov et al. (2009) undertook two traverses perpendicular to the Great Escarpment on the west coast of South Africa to determine the timing of the uplift. From their AFT analysis of the samples they proposed "two discrete phases of cooling, separated by a period of thermal stability" (Kounov et al., 2009). The first phase of cooling (160–138 Ma) was a post-Karoo thermal relaxation event, which was followed by an episode of limited uplift from 138 to 115 Ma. The second phase between 115 and 90 Ma was an episode of accelerated cooling. They discuss the uncertainty in the paleo-geothermal gradient but suggest modeling implies a phase of denudation of 1.5–2.7 km along the coast, which reduces to less than 1 km above the escarpment. This conclusion is supported by other AFT studies both on the Atlantic margin and more generally across Southern Africa. Tinker et al. (2008) used AFT samples from well data within the Karoo basin (Fig. 12.8) and interpreted two episode of increased exhumation with a similar timing of Kounov et al.'s (2009) study.

In contrast, a number of studies including Partridge and Maud (1987), Burke (1996), and Burke and Gunnell (2008) refute the mid-Cretaceous timing of the uplift event and instead attribute the present-day topography to Tertiary age uplift. Burke and Gunnell (2008) agree there was mid-Cretaceous uplift. They also consider that following the Santonian event any associated topography was eroded away prior to Tertiary uplift and basin and swell topography (Burke and Gunnell, 2008). However, their principal disagreement with the AFT data is with a 1 km escarpment elevation and an estimated conductive gradient of 20°C, because surface samples would yield a temperature of 56°C, which is too low to be identifiable by AFT. Therefore, "AFT data do not permit robust discrimination between one-and two stage models." This concern at being able to differentiate more recent uplift was also highlighted by Gallagher and Brown (1999) who state that "most recent (< 20 Ma) chronology is suspect as a consequence of uncertainties in the extrapolation of fission track annealing models to low temperature (<50–60 °C) long timescale (10–100 Ma) scenarios." Kounov et al. (2009), who favor a mid-Cretaceous origin of the present topography, state the samples they modeled were already at temperatures lower than 60 °C by mid-Cretaceous, so any subsequent (i.e., Tertiary) uplift could not be constrained assuming the denudation was less than 2–3 km. Burke and Gunnell (2008) support their hypothesis of a Tertiary age for the present day topography from their analysis of African drainage evolution. This analysis suggests significant changes in topographic and drainage divides associated with elevation reflect the initiation of the basin and swell topography 30 Ma (Burke and Wells, 1989; Faure and Lange, 1991).

The timing of the present topography, and hence margin uplift, remains controversial. A consequence of onshore denudation uplift is an input of sediment into the offshore continental margin basins; therefore, an important place to test the timing of margin uplift in the South Atlantic is in these basins.

South African and Namibian margin uplift

Along South Africa's Atlantic margin, offshore evidence of margin deformation comes from tectono-stratigraphic studies coupled to thermal-burial history, which reveal the margin has been associated with long term stable subsidence during much of the post-rift episode. This subsidence results in a considerable thickness (4 km) of sediment deposited onto the continental slope area. This sediment has concordant reflections, indicating uniform subsidence across the 120 km-wide margin (Fig. 12.9). The stratal architecture of the margin is considered to be a consequence of the interplay between uniform thermal subsidence and eustatic variations, resulting in a combination of generally aggrading and prograding packages with occasional maximum flooding surfaces (Brown et al., 1995). Paton et al. (2008) note the Cretaceous package is remarkably undeformed in comparison to many other margins. They attribute this to uniform subsidence with an absence of a suitable early post-rift detachment horizon (the Orange Basin was also too far south for deposition of salt during the Aptian (112 Ma)). It also reflects an absence of deformation prior to the late Cretaceous. The only deformation is

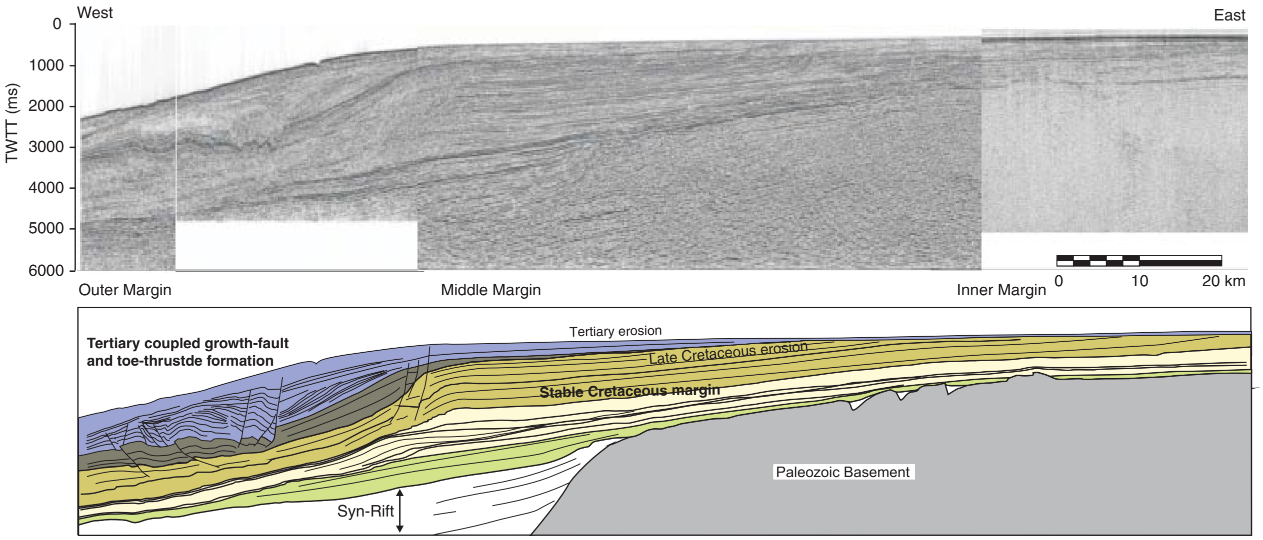

Fig. 12.9. Seismic profile and interpretation across the Orange Basin in South. This study reveals a uniform margin subsidence with the majority of sediment accumulation on the inner margin throughout the Cretaceous. At the end of the Cretaceous, there is up to 1 km of uplift and erosion of the inner margin and the subsequent switching of deposition to the outer margin in the Tertiary. *Source*: Modified from Paton et al. (2008).

limited to small-scale (< 100 m) faulting that occurred through slope-failure of the shelf margin break.

Tectono-stratigraphic studies (Paton et al., 2008) demonstrate a significant change in the location of deposition at the end of the Cretaceous (Maastrichtian, 67 Ma). Deposition rapidly switched westward from the middle shelf area of the Cretaceous slope-break resulting in the deposition of a slope fan system (Fig. 12.9). This switch in deposition is accompanied by the development of a significant erosional unconformity across much of the middle and inner margin. Structural restorations of the unconformity reveal a differential amount of uplift and erosion ranging from 0 m at the slope-break up to at least 800 m in the near shore area. In addition to the late Cretaceous erosion, there is evidence of significant erosion of the end Cretaceous reflection indicating the section was subjected to a later, Tertiary phase of uplift. The magnitude of uplift in the Tertiary is difficult to quantify because of the very thin Tertiary sediment on the inner and middle margin. Heat flow analysis of well data and modeling of vitrinite reflectance can be used to reveal there has to have been up to 800 m of uplift, but cannot differentiate between late Cretaceous and Tertiary uplift (Fig. 12.9). Despite the thin Tertiary sequence across the inshore area there is a significant thickness on the outboard portion. This suggests substantial Tertiary sediment supply, which may be attributed to onshore uplift. The unconformity and erosional truncation associated with the Tertiary uplift is mappable further north in the Orange Basin, while the Cretaceous uplift appears to be more areally limited.

The Namibian margin, which is located to the north of the South African Orange Basin, has been less well studied in the context of post-rift margin deformation. Despite this, the reflection geometry of the Cretaceous and Tertiary margin packages are very similar to that of South Africa (Fig. 12.10). Seismic sections in the southern Namibian basins also reveal both a late Cretaceous and an intra-Tertiary unconformity.

Angolan and Congo margin uplift

A number of studies to the north of the South African and Namibian basins provide evidence for more extensive regional-uplift and tilting along the South Atlantic margin, in particular the Kwanza Basin of Angloa (e.g., Hudec and Jackson, 2004; Jackson et al., 2005; Walford and White, 2005; Al-Hajri et al., 2009). The Kwanza Basin, which is located in the centre of the Angolan continental margin, formed during Neocomian (145–131 Ma) rifting. The early post-rift basin was dominated by the deposition of Aptian-Albian evaporites that may have reached thicknesses > 1 km. Such a large evaporite

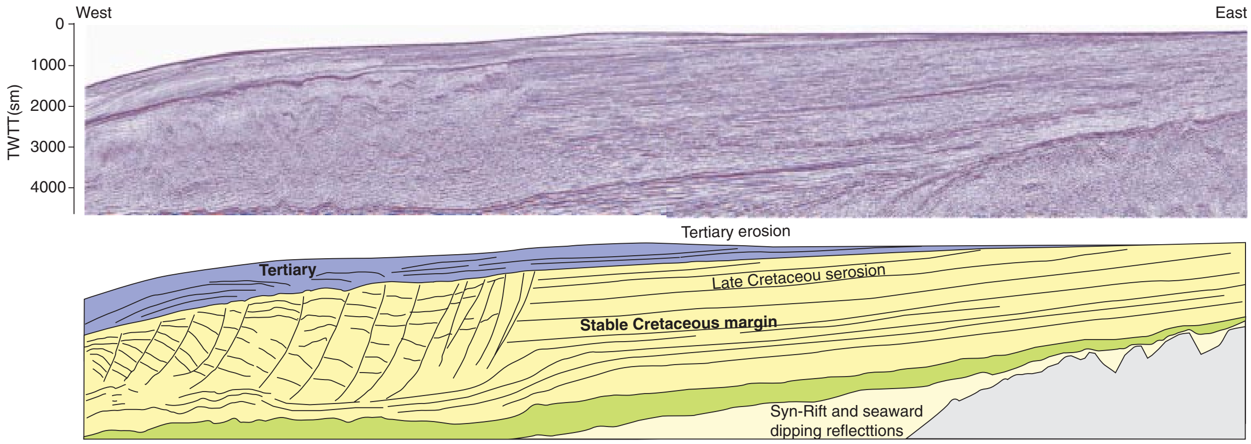

Fig. 12.10. Seismic profile and interpretation of offshore Namibia. Despite being ~500 km north of the profile in Figure 12.9, the margin geometry is very similar and illustrates both late Cretaceous and Tertiary uplift events.

thickness, coupled to differential thermal subsidence and sediment loading, typically sets up gravity driven margin instability. Hudec and Jackson (2004) present a detailed analysis of a 375-km long section across the basin. Their section (Fig. 12.11a) captures many of the structural styles associated with salt driven, gravity collapse of continental margins. This includes (from landward to seaward): outcrop of Precambrian basement; a wedge shaped domain that exhibits erosional truncation of previously dipping reflections; a fold-thrust belt containing thrust folds and buckle folds; potential salt turtles; extensionally driven rafts; salt dominated areas that are expressed as diapiars, salt-plateaus and nappes; and a relatively undeformed abyssal plain. Hudec and Jackson (2004) also undertook a structural restoration of the section (Fig. 12.11b–d) and concluded that thermal subsidence driven salt tectonics played a role but that additional post-rift margin uplift events had to be invoked to explain all the observations. The first phase of deformation (Aptian-Albian, 121–99 Ma), which has been attributed to thermal subsidence, resulted in tilting of the basin seaward with the development of the updip extensional systems. After a period of quiescence, Hudec and Jackson (2004) recognized a relatively short period of deformation in the form of basement uplift of the outer Kwanza Basin during the Campanian (75 Ma). Interestingly, they suggest there may be an association with the basement reactivation of in the inner Kwanza Basin in the Santonian (ca. 84 Ma). Their final phase of deformation, during the Miocene (24 Ma), only had a few hundred meters of uplift but resulted in significant remobilization of the gravity slide.

In the inner Kwanza basin the Tertiary uplift is very evident and seismic reflection terminations suggest two significant unconformities of Oligocene (ca. 30–35 Ma) and Pliocene (3.5–1.8 Ma age) (Fig. 12.12; Jackson et al., 2005; Al-Hajri et al., 2009). The amount of denudation associated with the Pliocene unconformity is constrained from estimating the thickness of eroded strata in depth-converted sections, and is approximately 1.6 km. The denudation associated with the older Oligocene (ca. 30–35 Ma) unconformity is harder to constrain. Cramez and Jackson (2000) used seismic reflection terminations to document the uplift and estimated 150 m of erosion, though the occurrence of shelf margin clinoforms within the eroded package makes this quantification problematic. In contrast, Walford and White (2005), using stacking velocity analysis of seismic reflection profiles, proposed the late Neogene (Plioence, 3.5–1.8 Ma) event accounts for 0.5–1.5 km of erosion whilst the Oligocene unconformity could have been associated with as much as 2.5 km of denudation. This approach was extended across the margin by Al-Hajri et al. (2009) whose quantification of post-Pliocene denudation agrees with Cramez and Jackson (2000). Al-Hajri et al. (2009) concluded there was 500 m of denudation in the Congo delta and 1 km in the Kwanza Basin that demonstrates the significant lateral variation in uplift (Fig. 12.12).

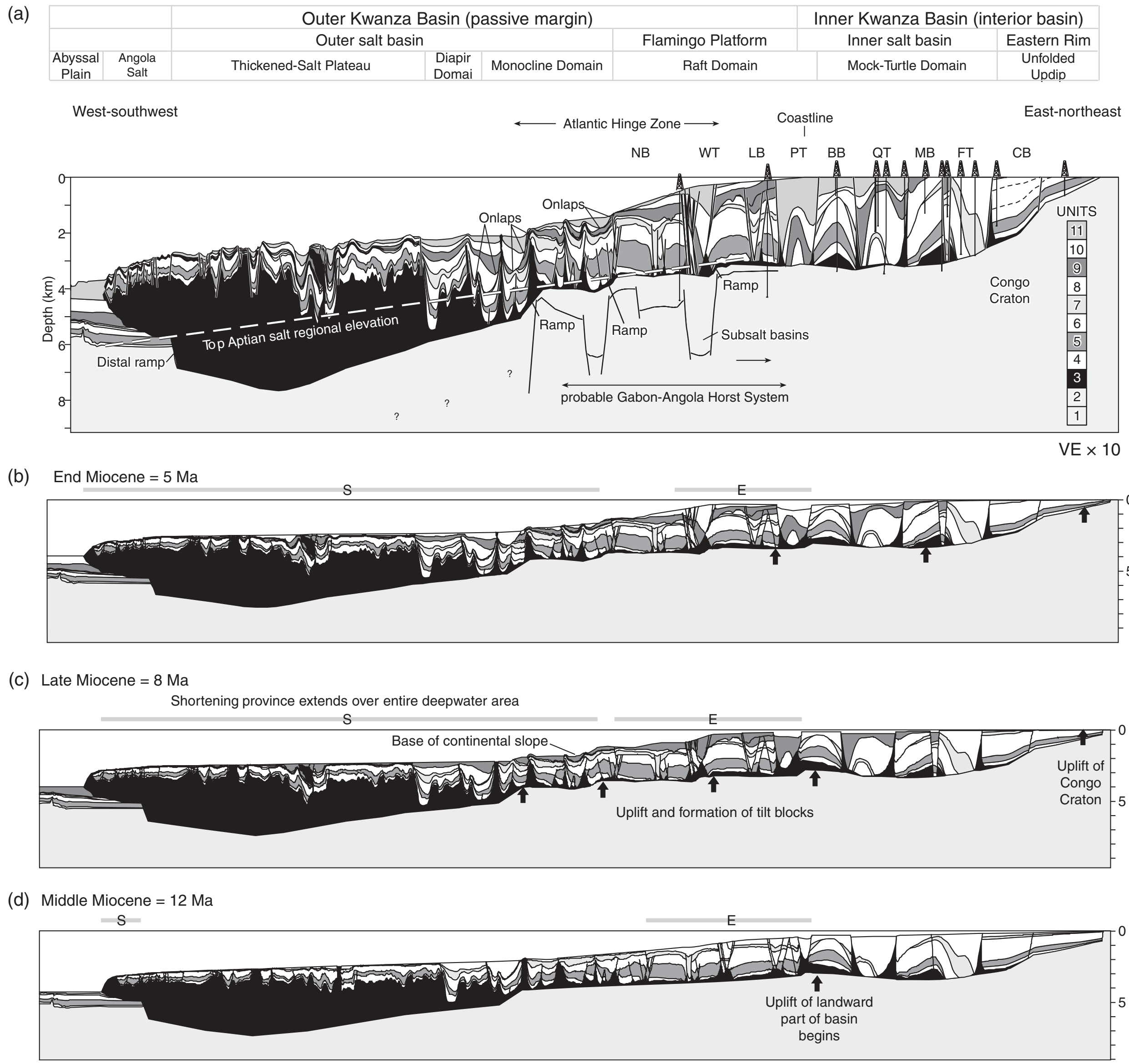

Fig. 12.11. (a) Structural profile across the Kwanza Basin showing some of the main features associated with salt driven tectonics and margin instability. (b) Restorations of seismic profile in (a). The restorations illustrate that the observed deformation can not be accounted simply by salt tectonics and that additional tectonic deformation is required (Hudec and Jackson, 1994).

Mechanisms and timing of uplift

In comparison to the NW European margin, post-rift margin deformation in the South Atlantic is relatively poorly documented and understood. Despite the controversy regarding the timing of uplift, the majority of authors agree that, given the regional scale of the phenomenon, it is a dynamic response to vertical stress at the base of the lithosphere. Seismic tomography methods show a low-velocity zone in the sublithosphere beneath southern Africa and free-gravity anomalies support the notion that the lithosphere in the area is underlain with a superswell (Nyblade and Robinson, 1994; Burke, 1996; Lithgow-Bertelloni & Silver, 1998; Gurnis et al., 2000). It is generally agreed that the superswell has resulted in the present day topography. The timing of the uplift, as discussed, and hence the timing of initiation of the superswell remain controversial.

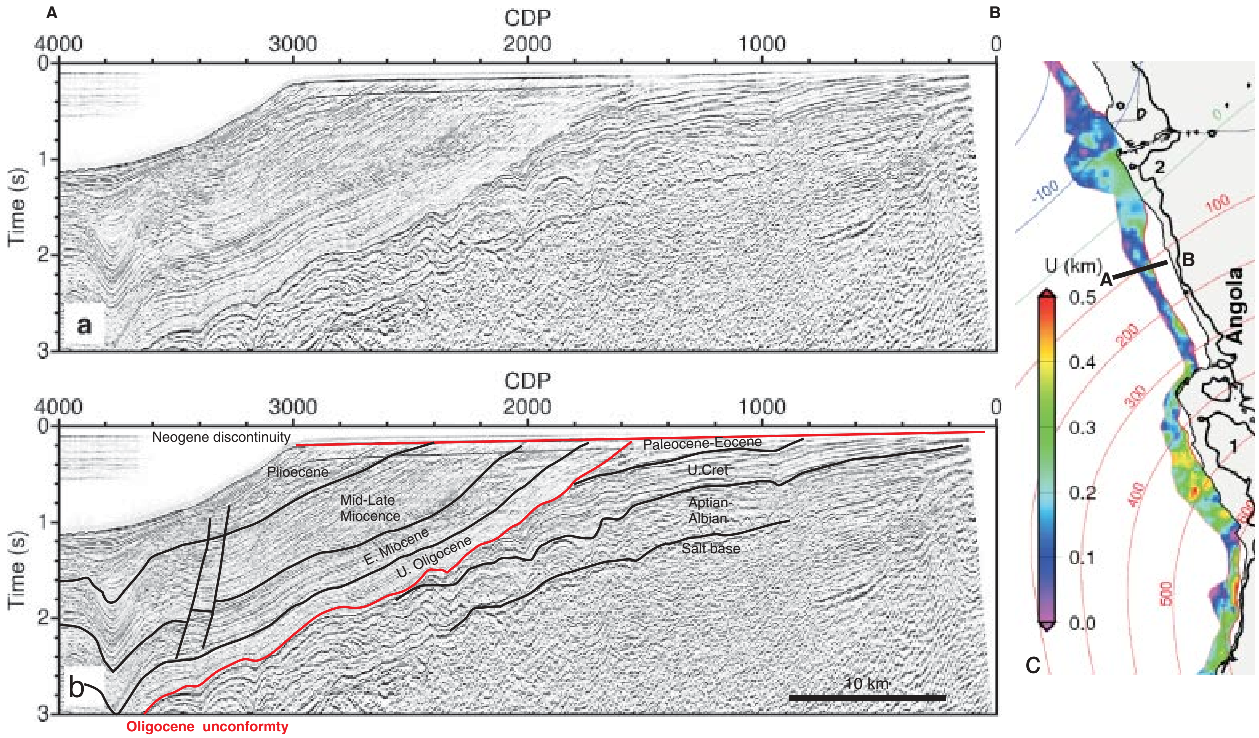

Fig. 12.12. (a) Seismic reflection profile from the Angolan margin. (b) Interpretation of section calibrated to region well information that highlights at least two episodes of uplift of the margin with > 1.6 km of erosion. (c) Calculated uplift (U) and denudation (D) of the Angolan margin derived from root mean square velocity profiles. Solid black and colored circles are location of profiles used. *Source*: After Al-Hajri et al. (2009).

Authors who argue the present day uplift is a consequence of the Mid-Cretaceous event cite evidence in both onshore AFT data and observed unconformities in the offshore. Tinker et al. (2008) relate the uplift to the superswell and also discuss the coincidence in timing between the uplift and the formation of large mafic igneous provinces and kimberlite activity across southern Africa. These authors do not rule out Tertiary uplift but they suggest it is minor and not sufficiently significant to be reflected in AFT data.

The alternative view is that the present topography is related to Tertiary uplift (e.g., Burke and Gunnell, 2005; Al-Hajri et al., 2009). The Oligocene age of the first unconformity suggests the initiation of the superplume may have been at 30–35 Ma. Burke and Gunnell (2005) do not rule out the existence of an earlier uplift event, but disagree it relates to the present day topography. Rather, the Mid-Cretaceous event is attributed to far-field stress systems associated with either the Santonian (~84 Ma) arc-collision on the coast of Arabia or with plate reorganisation attributed to changes in plate rotation poles (Nürnberg and Müller, 1991; Guiraud and Bosworth, 1997).

CONCLUSIONS AND IMPLICATIONS

The assumption that divergent, continental margins are tectonically quiescent during the post-rift, thermal subsidence phase does not agree with recent observations. Examples have been presented from both the NE and South Atlantic margins that there is substantial evidence for episodes of uplift, erosion and subsidence that are inconsistent with the subsidence predicted from exponential thermal decay models. These episodes include regional-scale uplift and tilting of Norway, South Africa, Namibia, and Angola margins and may be of relatively short wavelength (100 km) and short duration (<5 My). In the NE Atlantic, there is evidence of more limited uplift events resulting in structural domes, such as Helland Henson and Orman Lange.

Since a single mechanism cannot explain all the observations, it remains controversial what controls them. A number of mechanisms have been invoked, such as plate reorganization, mantle

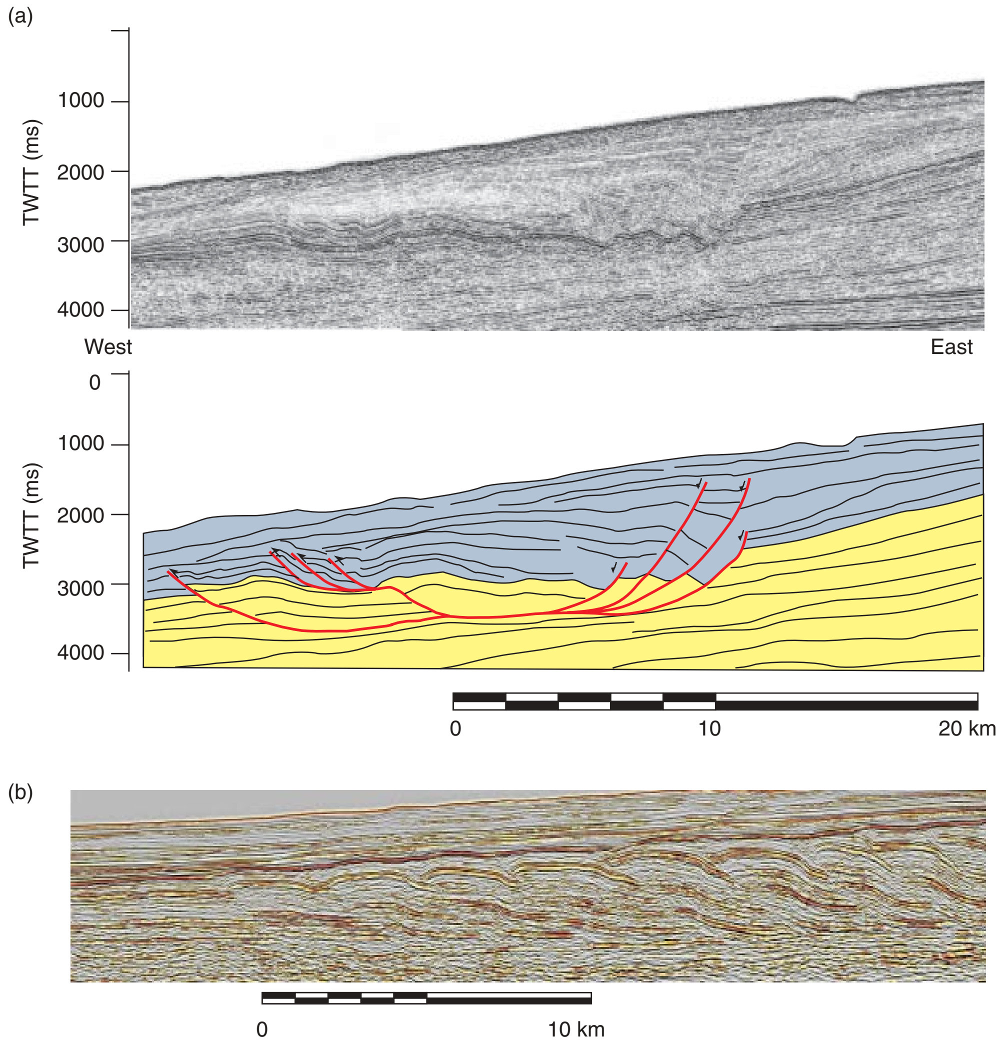

Fig. 12.13. (a) A rapid transition in sedimentation in the Orange Basin during the Tertiary results in margin instability and establishment of a coupled growth-fault and toe-thrust system. This switch in sedimentation is a consequence of post-rift tectonic deformation. (b) Offshore Namibia has a similar toe-thrust system and this seismic profile reveals some exceptionally imaged imbricates within the thrust system. *Source*: (a) Modified from Paton et al. (2008). (b) Butler and Paton (2010); seismic image has been made available through the Virtual Seismic Atlas, www.seismicatlas.org.

plume induced uplift, compressive forces either from far-field stress or ridge-push, and upper mantle convection. Regardless of the mechanisms, the implications of these features are significant and control many aspects of margin evolution, including sedimentology, structure, and hydrocarbon prospectivity.

As discussed in the NE Atlantic, episodes of deformation have a significant influence on the variation of margin water depth profile. The shallow water clastic sediments of the Paleocene (Stoker et al., 2005b) form a prograding package into the available accommodation space. As a consequence of margin deformation, there is a very rapid transition from proximal, shallow marine sedimentary facies to deep water distal sedimentation. In the Orange Basin of the South Atlantic, the episode of margin tilting results in the rapid switching of the location of sedimentation from the inner to the outer margin. One direct consequence of this transition is that the relatively stable margin of the Cretaceous changes to an unstable margin in the Tertiary (Fig. 12.13). This instability results in the establishment of a deep-water fold-thrust-belt, which comprises inboard normal growth faults that are coupled to down-dip toe-thrust faults (Fig. 12.13; e.g., Butler and Paton, 2010).

Margin deformation may have other consequences, such as alterations to ocean currents. In the case of the NE Atlantic, Stoker et al. (2005b) describe how rapid changes in margin bathymetry alter the location of deep water contourite deposits and transport pathways. The associated margin uplift can also have an influence on basin evolution by forming emergent highs, from which localized sediment sources may be established. It has even been suggested that the uplifted domal features in the NE Atlantic were sites of localization of ice-caps during the last glacial maxima (Eyles, 1996).

The interaction of tectonics/uplift and climate has also been discussed in southern Africa (Burke and Gunnell, 2008) with much of it centered on the timing of uplift.

With respect to hydrocarbon potential, the post-rift deformation has implications for all aspects of the hydrocarbon systems, such as deposition of source, reservoir and seal intervals, generation of suitable traps and timing of maturation. In the NW European shelf, post-rift deformation areas form some of the most attractive exploration targets. In areas where structural inversion occurred, simple four way closures with little internal deformation, coupled with the presence of sand-prone Paleocene turbidites, form suitable hydrocarbon plays. Such targets are further improved by the presence of adjacent deeply buried source intervals. The principal limitation is the timing of migration with respect to the timing of the structural inversion and trap formation (Lundin and Doré, 2002). In the South Atlantic, these uplift events increase the gravity potential of margin instability, which, in turn, contributes to the formation of deep-water fold-and-thrust-belts. These locations are becoming increasingly attractive areas for hydrocarbon exploration as ultra-deep water settings become more economically viable (White et al., 2003).

An often overlooked component of these systems is the influence of overburden deposition on the degree of maturation of the underlying source intervals. Given the fact that many of these basins are in the post-rift phase, where the heat flow spike associated with rifting is likely to have a relatively insignificant influence, the main control on the thermal regime of the source rock interval is the amount of burial. In the Orange Basin, there is a rapid change in the location of sediment accumulation with an increase in overburden thickness on the middle margin throughout the Cretaceous and little accumulation on the outer margin. Hydrocarbon system modeling of the margin reveals that this variation in overburden has resulted in nearly 100% transformation ratio (Tr) of organic matter to hydrocarbons in the middle margin. In contrast, the outer margin has a Tr of ∼0%. Following the End Cretaceous margin deformation, deposition switched to the outer margin resulting in an increase in Tr from ∼0% to 65%. In addition to the degree of transformation, the establishment of the distal toe-thrust system in the Tertiary may provide local structural traps for the hydrocarbons generated by the switch in overburden (Paton et al., 2007).

In conclusion, it is evident that although Atlantic-type continental margin settings may have episodes of tectonic quiescence during which they are "passive." they are very susceptible to changes in either far-field stress or crustal-mantle interactions. As Hudec and Jackson (2004) suggest, "Some passive margins may remain delicately balanced in metastability over long periods, until a small change makes them unstable."

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