Raft tectonics in the Kwanza Basin, Angola*

Bernard Duval and Carlos Cramez
Total CFP, Cedex 47, 92069 Paris-La-Défense, France

and M. P. A Jackson
Applied Geodynamics Laboratory, Bureau of Economic Geology, The University of Texas at Austin, Austin, TX 78713, USA

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Raft tectonics (*tectonique en radeaux*) allows the extreme thin-skinned extension of overburden over a décollement of thin salt or other evaporites. Rafts are allochthonous fault blocks no longer in mutual contact. In the Kwanza Basin, the type area for raft tectonics, Jurassic–Lower Cretaceous rift fill was succeeded by a cratonic Aptian lowstand progradational wedge. At about 119 Ma, the Massive Salt capped this wedge just before the South Atlantic Ocean began opening. Active spreading caused a eustatic sea level rise and the accumulation of transgressive systems tract carbonates. About 200 km of downdip space for extension on the tilted continental margin was created, mainly by the glide of allochthonous rafts onto fresh oceanic crust. At about 110 Ma, the overburden began to extend when only a few 100 m thick, forming many small, tilted, phase 1 rafts. These older rafts were yoked together by Upper Cretaceous sedimentation before rupturing into huge, non-rotated glide blocks during phase 2 rafting from 55 to 10 Ma. Tertiary sediments accumulated asymmetrically in strike-parallel depocentres created by deep, widening grabens between phase 2 rafts. These sediments rest directly on salt or subsalt strata with a tectonic jump of 60–90 Ma. Strain rates for both phases of rafting varied from 2×10^{-16} to 3×10^{-16} s^{-1}.

Keywords: Kwanza Basin, Angola; salt tectonics; extension tectonics; raft tectonics

Introduction

Raft tectonics was first recognized as a distinctive structural style in the Kwanza (formerly Cuanza) Basin of Angola, south-western Africa. In the early 1970s exploration geologists from Total and Petrofina coined the term *tectonics en radeaux* (Burollet, 1975), from which *raft tectonics* (Jackson and Cramez, 1989) is a direct translation. At present, the concept of raft tectonics is hardly known by most academic structural geologists, even those well versed with other aspects of salt tectonics. Aspects of raft tectonics have become familiar to petroleum geologists working on both margins of the South Atlantic, but few people appear to appreciate the massive amounts of thin-skinned extension inherent in this style of deformation. For example, the crucial role of extension controlling the salt tectonics of Angola and Gabon was not recognized by Baumgartner and van Andel (1971), Brink (1974) Brice *et al.* (1982) or Logar *et al.* (1983). Burollet (1975) rightly deduced that extension had formed the asymmetric depocentres between rafts in Angola, but even he depicted symmetrical depocentres formed without extension in his explanatory cartoon (his figure 2).

Our paper has two aims: first, to introduce and document raft tectonics by describing its regional setting and showing representative seismic examples; and second, to address the most important mechanical problem to be solved to explain how and why rafting operates.

Raft tectonics is the most extreme form of thin-skinned extension (*Figure 1*). In places, the overburden becomes stretched to two or three times its original length by normal faulting, but the basement remains the same length. When allochthonous fault blocks separate so far that they are no longer in mutual contact, they are termed rafts. With less extension, fault blocks still in contact can be termed prerafts. Prodigious extension of the overburden over a non-deforming basement is enabled by an intervening ductile, weak, décollement layer, typically consisting of thin evaporites or shale. In the widening gaps between the gliding rafts, younger sediments accumulate as trough-like depocentres.

Stretching results from gravity gliding or from gravity spreading. Gravity gliding is the translation of fault blocks down a gentle slope, driven by the downslope shear stress component of gravity on a tilted mass. Gravity spreading is the vertical collapse and lateral spreading of a rock mass under gravity. Both mechanisms require the creation of immense amounts of lateral space into which the overburden can expand during stretching (left side of *Figure 1*). To explain how this lateral space is created is a central problem in raft tectonics. As raft tectonics represents the most expanded form of thin-skinned extension, the space problem is equally extreme.

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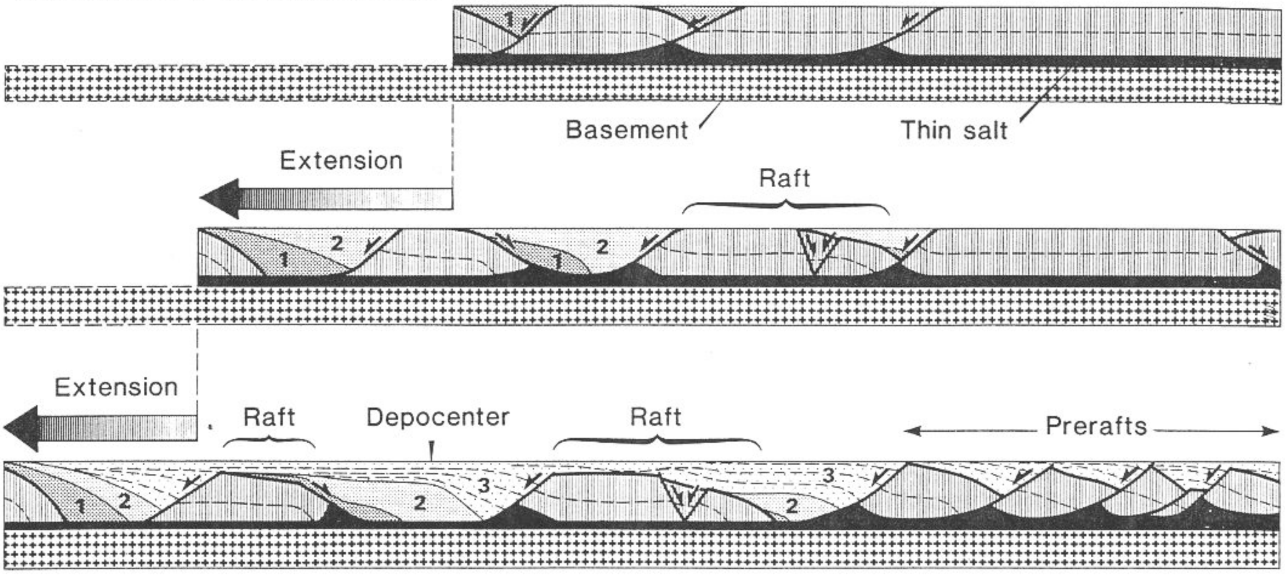


Figure 1 Processes of raft tectonics during thin-skinned extension (adapted from Jackson and Talbot, 1991). Prerafts remain in mutual contact and hanging walls rest on their original footwalls after faulting. In contrast, rafts separate so far that they are no longer in mutual contact and hanging walls no longer rest on their original footwalls. The basement remains the same length throughout. Weak rocks other than salt could act as the décollement layer

Tectonic setting of rafting in the Kwanza Basin

The type area for raft tectonics is the western divergent continental margin of Africa. Best known from Angola and Gabon, these structures are also well developed in the subsurface of the Campos Basin off Brazil, on the edges of the Nordkapp Basin north of Norway, in the eastern Mediterranean Basin and in the Alabama sector of the Gulf Coast. Quaternary examples of raft tectonics have bathymetric expression on the floor of the Red Sea off Sudan.

All our examples are taken from the type area in the Kwanza Basin, Angola (*Figure 2*). The basin, 314 km long and 4 km deep, contains sediments of Cretaceous

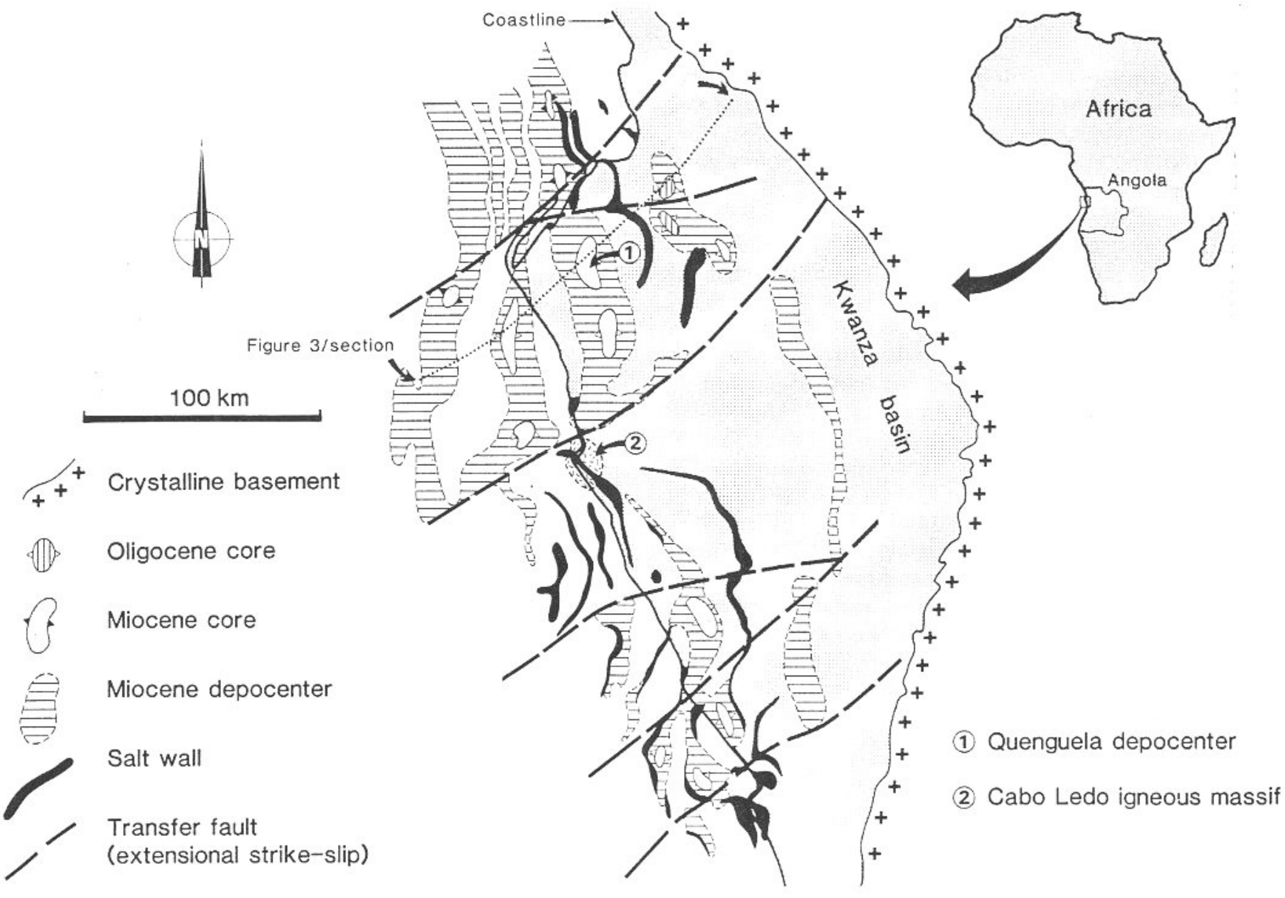


Figure 2 Map of the Kwanza Basin showing principal tectonic features and line of section for *Figure 3*

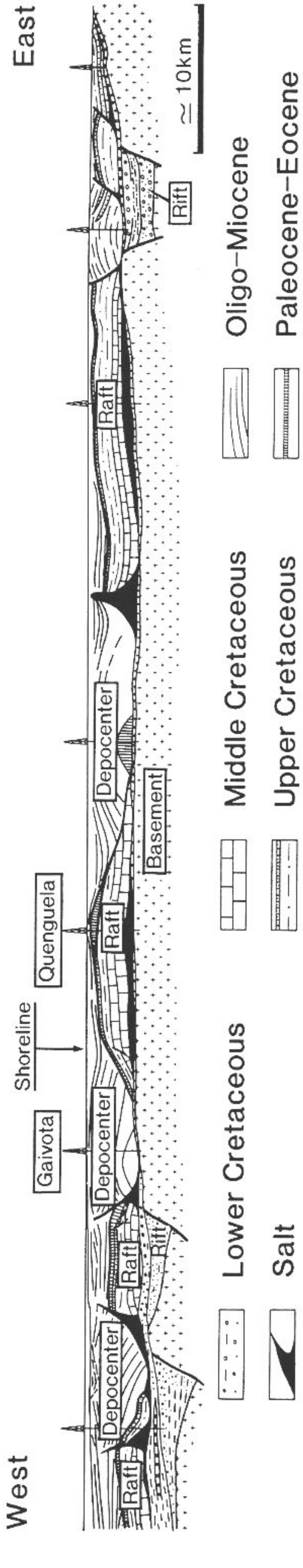


Figure 3 Regional cross-section through the Kwanza Basin with no vertical exaggeration. Location shown in *Figure 2*

to mid-Tertiary age (Brognon and Verrier, 1966). Regional extension created a characteristic assemblage of strike-parallel and dip-parallel structures. Strike-parallel structures are narrow but many kilometres long, following the strike of continental margins or other regional tectonic features on the slope or shelf. In this group are strike-parallel, elongated grabens filled with turtle structure depocentres and sporadically flanked by diapiric walls (*Figure 2*). The width of these depocentres is roughly proportional to the amount of extension from place to place. Moreover, the age of the oldest sediments in their cores (differentiated on *Figure 2*) indicates the time when rafting began in that particular depocentre. Dip-parallel transfer faults offset all these structures, allowing differential amounts of extension on each side of the transfer faults.

Figure 3 is a regional cross-section across the Kwanza Basin, including the location of wells used to confirm the seismic interpretation. Jurassic to Lower Cretaceous basins of rifted lithosphere are unconformably overlain by undeformed Lower Cretaceous strata. These, in turn, are conformably overlain by a presently thin layer of lower Aptian salt, known as the Massive Salt. Relict salt walls rising from this layer are sporadically preserved at the ends of rafts comprising Middle to Upper Cretaceous strata. The rafts are separated by Tertiary depocentres bounded by

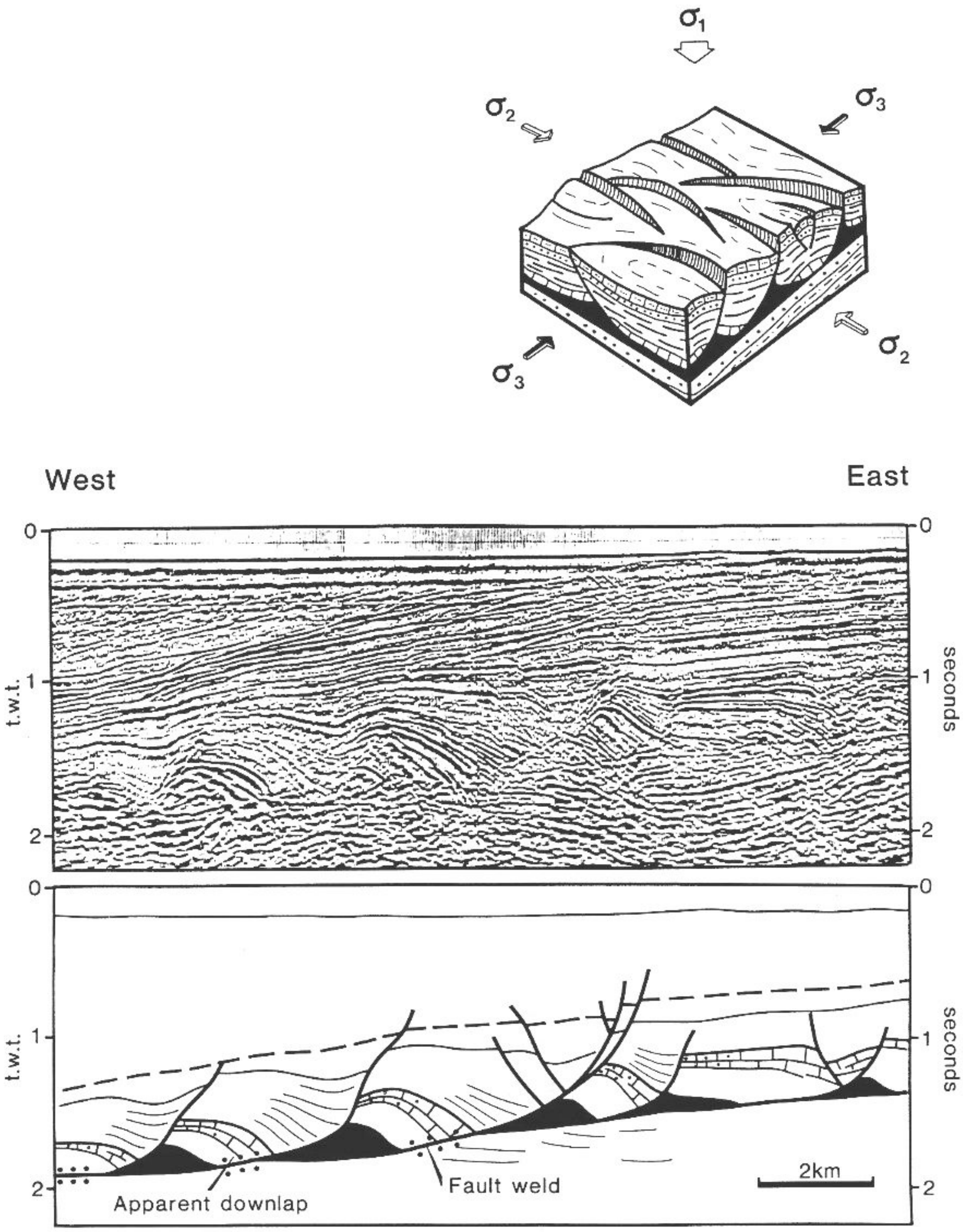


Figure 4 Interpreted and uninterpreted seismic profiles illustrating salt rollers formed by phase 1 rafting in the Kwanza Basin; extension has produced both rafts and prerafts. The block diagram illustrates the relationship between principal stresses and strain

normal faults and relict salt walls. Between rafts, the Tertiary depocentres rest directly on the pre-salt, Lower Cretaceous strata. Because the Cretaceous overburden has been rafted off, the structural discontinuity joins Tertiary strata to salt or subsalt strata, representing an age jump of 60–90 Ma. This discontinuity, produced by the removal of intervening salt, can be termed a primary salt weld (Jackson and Cramez, 1989) or, where it is known to have undergone slip or simple shear, a fault weld (Hossack and McGuinness, 1990).

Rafting requires a specific stress field. The regional σ_1 maximum effective stress is subvertical; σ_3 is subhorizontal and oriented downslope (east–west); σ_2 is oriented parallel to the regional strike (north–south). The same regional stress field can account for the grabens, growth faults, depocentres, rafts and salt walls.

Seismic examples of raft tectonics

Each of the following examples shows an uninterpreted seismic section and an interpreted section, both in two-way travel time.

Figure 4 illustrates the early stages of the process when the Middle to Upper Cretaceous overburden was segmented into prerafts (right side), then into rafts (left side). The rafts are underlain by salt rollers and are bounded by growth faults, most of them listric. In map view, as shown schematically in the block diagram in *Figure 4*, the growth faults form anastomosing relays. The salt rollers are separated by fault welds. During extension, the rafts tilted clockwise in the opposite direction to the regional dip to the left and west. Faulting and tilting began in the Middle Cretaceous about 115 Ma ago, recorded in the lowermost overburden layer where reflectors diverge towards the growth faults. Thus extension began early under thin overburden less than 500 m thick.

Figure 5 shows a large raft 22 km long. The base of this gliding block is concordant with the thin salt décollement. We contend later that salt probably flowed downdip from beneath all the rafts, again creating a fault weld where the raft rests directly on the pre-salt strata. The ends of the raft are marked by triangular salt structures. If sections like this are restored back in time, these salt structures can be seen as relics of formerly larger salt walls. The raft consists of Cretaceous rocks, but it only became a structural entity in the Early Tertiary when rafting began, recorded by the age of the depocentre core. The raft is mostly intact, but normal faults are developed where the raft arches over a relict salt pillow. A turtle structure anticline is prominent in the right hand depocentre.

An important point about raft tectonics is that it occurs on more than one scale. *Figure 5* shows Tertiary rafting on a large scale. For reasons that will shortly be obvious, we call this phase 2 rafting. *Figure 6* also shows phase 2 rafting. The heavy line at the top of the Upper Cretaceous layer demarcates the top of a large 25 km long raft. This large raft is itself built of smaller, older rafts that ruptured in the Middle to Upper Cretaceous, a separation we refer to as phase 1 rafting. The age of the internal phase 1 rafting can be inferred from the divergence of reflectors in the layers with the brick pattern. Most of the older, smaller, phase 1 faults dip to the west; this caused these older rafts to rotate clockwise. However, a listric growth fault of phase 1 dips eastward in the centre of the section. This faulted when sediments slumped to the right off the clockwise rotating raft below, which had locally reversed the regional dip. From a detailed correlation of reflectors in the profile, we deduce that this early episode of phase 1 extension occurred roughly simultaneously along the length of the larger raft.

The larger rafts of phase 2 formed by amalgamation of the phase 1 rafts (*Figure 7*). The phase 1 rafts consolidated when they were yoked together by the overlying Upper Cretaceous units (stippled), which were themselves later extended during phase 2 rafting. On a regional scale, the age of the cores of depocentres between the major phase 2 rafts are oldest downdip and youngest updip. This indicates that major rafting began downdip and progressed updip during the Tertiary. Thus phase 1 rafting appears to have been synchronous within individual phase 2 rafts, whereas phase 2 rafting migrated diachronously up the regional dip. The map of Brognon and Verrier (1966; their figure 9) shows the eastern limit of regional salt deformation migrating 35–75 km updip over a period of 60 Ma. This duration includes the Late Cretaceous phase 1 rafting, so this early extension, too, may have been diachronous on a regional scale.

The thickness of underlying salt greatly influenced the structural style of rafting (*Figure 7*). During phase 1 rafting, the salt was relatively thick because the rafts were thin (about 0.5 s two-way travel time). Salt was probably also thicker in an absolute sense; we think that much salt flowed downdip during extension — a process which would thin it farther updip, as shown speculatively in *Figure 7*. The phase 1 rafts were thus able to rotate significantly as they sank into thick salt, isolating asymmetric salt rollers below them. The base of these tilted rafts is discordant. In contrast, during phase 2 rafting, the salt was relatively thinner because these younger rafts were twice as thick (about 1 s two-way travel time); the salt was probably actually thinner as well because of the inferred downdip flow of salt. Thus the phase 2 rafts could not sink and rotate into the relatively thin salt remaining at that stage; the blocky rafts simply glided concordantly by translation over the thin salt décollement without rotating.

Figure 7 illustrates intense faulting on the updip ends of the phase 2 rafts. This faulting accompanied extreme rollover rotation, distortion and subsidence of the original hanging wall cut-off on the major fault along which the phase 2 rafts separated. The original hanging wall comes to rest on the subhorizontal fault weld.

The next diagrams focus on the strucural geometry of the depocentres between the major rafts. In *Figure 8*, the depocentre has welded discordantly onto the pre-salt strata. The core of the depocentre is Eocene, which is also present in reduced thickness on the top of the Cretaceous rafts. The depocentre is strongly asymmetric. Most of the subsidence has occurred along the right-hand growth fault, causing a prominant rollover of the regional dip. Faults on the left side of the Tertiary depocentre formed as accommodation structures where downbending of strata began.

Figure 9 shows a more highly evolved depocentre. This depocentre looks superficially like a symmetrical turtle structure because it is anticlinal. However, it is not a true turtle structure. Arching was produced by

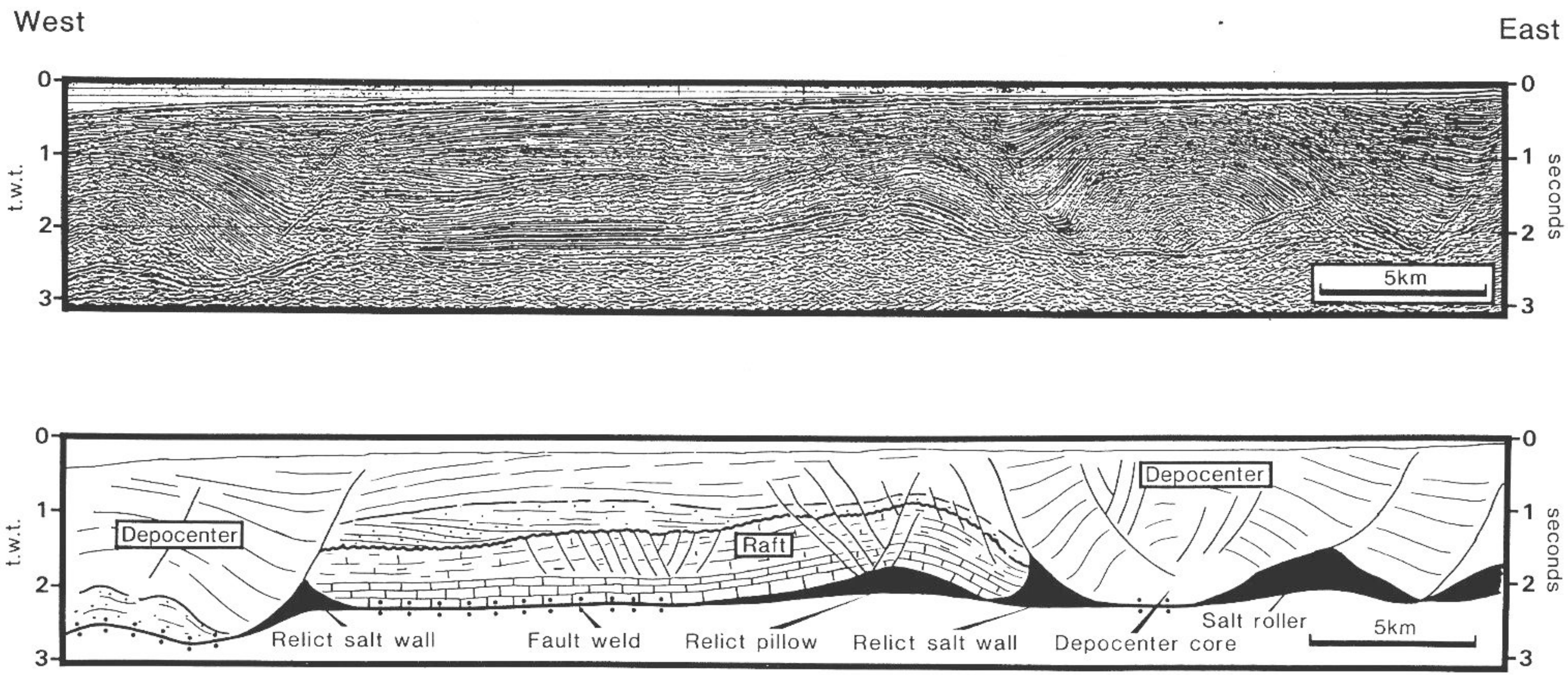


Figure 5 Interpreted and uninterpreted seismic profiles of a large phase 2 raft separated by relict salt walls from adjacent Tertiary depocentres in the Kwanza Basin. Crestal faults developed where the raft was arched over a relict salt pillow

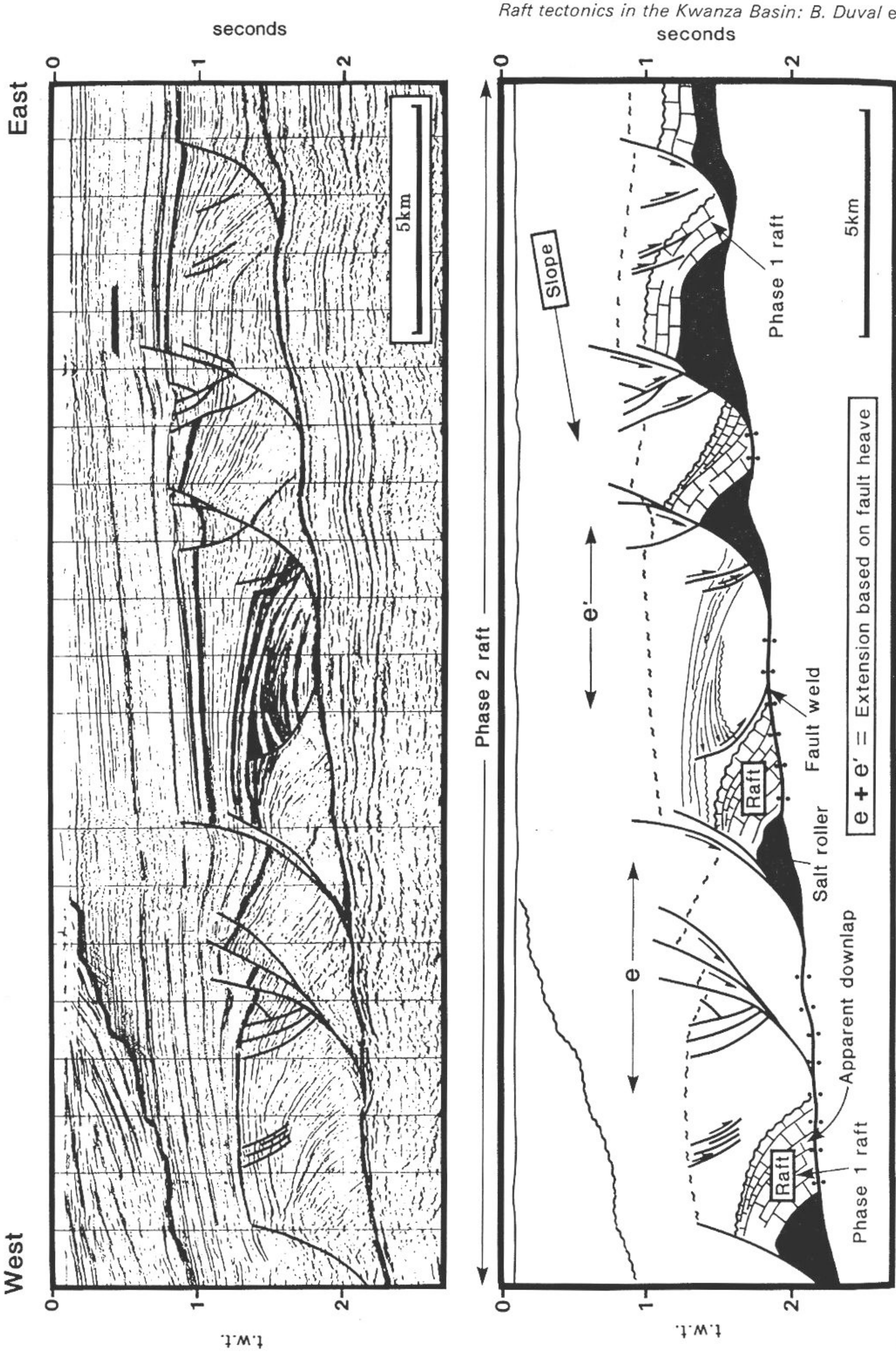


Figure 6 Interpreted seismic profile from the Kwanza Basin showing phase 1 (Upper Cretaceous) rafts yoked into a large phase 2 raft (Lower Tertiary), which spans the whole seismic section and whose top is marked by a heavy broken line

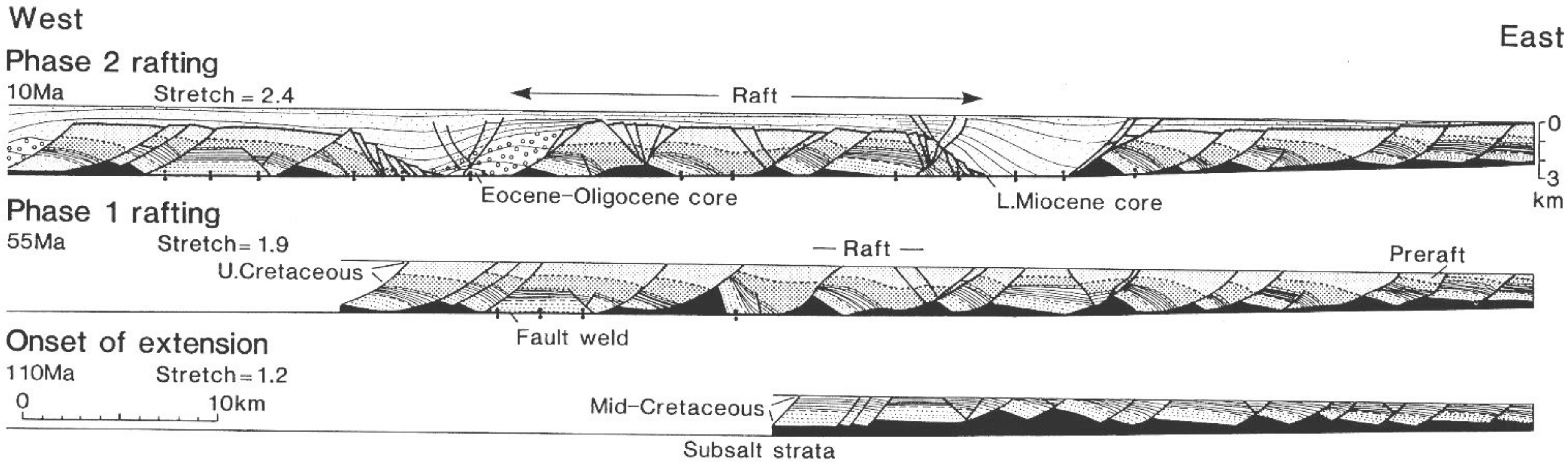


Figure 7 Composite cross-sections showing the two phases of rafting. After an early stage of extension (110 – 80 Ma, lower section), continued stretching forms phase 1 rafts, which were then yoked together (80 – 55 Ma, middle section) and subsequently ruptured by phase 2 rafting (55 – 10 Ma, upper section). Strain rates for phases 1 and 2 are calculated to have been 3×10^{-16} and $2 \times 10^{-16}\ s^{-1}$, respectively — almost identical. The sections, which are area balanced with no vertical exaggeration, were compiled by synthesizing data from several Kwanza seismic lines. The original thickness of salt is not accurately known

growth faulting as two relict salt walls on its flanks diverged and reduced in area as the salt moved downdip or out of the plane of section. Nor is the structure actually symmetrical. Initially the landward (right) growth fault was active, then the seaward (left) fault was active. This is indicated by the fact that the landward diverging reflectors on the right are overlain by the seaward diverging reflectors on the left. *Figure 7* shows the diachronous formation of asymmetrical phase 2 depocentres: the basinward (left hand) depocentre began forming in the Eocene–Oligocene before the landward one in the Lower Miocene.

As a result of their arched form, several of these structures have been successfully drilled, such as the Quenguela oil field, an antiformal depocentre in the onshore Kwanza Basin (*Figures 2* and *3*). This depocentre is tightly constrained by well control (Logar *et al.*, 1983). It also neatly illustrates how an extension dominated style of tectonics has sweeping effects in palinspastic reconstruction (*Figure 10*). As in *Figure 9*, the divergence in the depocentre is asymmetrical, with the landward side subsiding before the seaward side.

On the left of *Figure 10* is a published reconstruction from Masson (1972), who assumed no regional extension (stretch = S = 1 constantly). This paper daringly recognized that significant amounts of salt could be lost from a section. Masson's reconstruction required a massive loss of salt, mostly between 17 and 11 Ma. Altogether 77% of the salt area must disappear in this reconstruction. However, in ignoring the effects of regional extension, the reconstruction ran into two obstacles. First, the stippled Cretaceous units (initial overburden) must be progressively and severely trimmed in length from 70 to 17 Ma to make them fit the final geometry. Second, the section requires that a diapir active for nearly 30 Ma should inexplicably reverse its rise and transform into a dramatically deepening trough over only 2 Ma; to invoke dissolution is unconvincing, given the long duration of salt at the surface without subsiding, the rapid onset of deepening and the continued subsidence after the salt was deeply buried.

On the right is an alternative reconstruction, which is area balanced and includes the effects of compaction. The section was reconstructed from the opposite premise to that of Masson (1972). It allows a maximum of extension (stretch >3) commensurate with minimum salt loss (only 24% is lost). Without an accurate regional line across the entire basin, we cannot determine the actual extension in the Quenguela area. However, we think that the radically different interpretation on the right is more realistic than that on the left for the following reasons. No trimming of the Cretaceous units is necessary. Furthermore, the rapid development of an active depocentre above an active diapir can easily be explained as a function of regional extension. The diapir began to sag as it continued to be stretched by regional extension after the salt supply from the substratum was restricted or depleted (Vendeville and Jackson, 1992).

Creation of lateral space for raft tectonics

Our introduction alluded to the acute problem of creating lateral space to accommodate this extreme form of thin-skinned extension. The size of the required space can be crudely estimated from *Figure 7*, assuming that the extension in this 80 km long composite section approximates the style and amount of extension throughout the Kwanza Basin. *Figure 7* depicts 39 km of extension to reach the final length of 80 km by 10 Ma. The width of the well known part of the basin shown in *Figure 2* is 250 km. The seaward limit of the Kwanza Basin is uncertain; we have assumed a full width of 440 km based on the seaward limit of salt structures here, which corresponds to the base of the continental slope (Rabinowitz, 1982). The corresponding amounts of extension for basin widths of 250 and 440 km are 120 and 210 km, respectively. Thus the total amount of lateral space required to accommodate raft tectonics across the whole Kwanza Basin is approximately 200 km.

If both the pre-salt strata and the post-salt strata were stretched at the same time, there would be no space problem for the overburden. However, rifting had ended before the salt accumulated and before rafting began, as we discuss later in this section. Hence the nature of the space problem is schematically illustrated in *Figure 1*, which shows extreme extension across a basement unchanged in length. Resolving this severe space problem is difficult. The critical structures that might accommodate updip extension are located downdip where they tend to be partly obscured by the overlying, seaward thickening terrace wedge. These distal regions are also less well explored because of their greater water depths.

Three mechanisms appear to create space for lateral stretching. The most commonly invoked explanation is to balance the zone of extension updip with a downdip zone of shortening in the form of a fold and thrust belt (*Figure 11*); both extension and shortening are thin-skinned, with decoupling over the salt. This mechanism is one of the cornerstones for balancing cross-sections and is so familiar it need not be elaborated upon. This mechanism has operated locally in the Kwanza Basin wherever seaward movement has been obstructed by basement uplifts, such as the Cabo Ledo igneous massif (*Figure 2*). These uplifts provide a local buttress against which the sliding overburden piles up as folds and thrusts. As fold and thrust belts are only locally present, this mechanism cannot have created space for extension throughout most of the Kwanza Basin.

A more unusual explanation is the displacement of allochthonous salt (*Figure 12*). Initially thick salt accumulates seaward of the overburden. This thickening of the salt could be primary, or it could be due to the flow of salt from beneath the extending overburden to accumulate as a frontal bulge, partly by downdip flow of salt under gravity and partly by squeezing out from beneath the foundering fault blocks of overburden. From this frontal bulge of salt allochthonous salt sheets are most likely to arise. The removal of salt from its original source to a higher stratigraphic level creates space for lateral expansion of overburden sandwiched between the autochthonous and allochthonous levels. This vertical transfer of salt vacates space into which rafts can spread laterally. How likely is this mechanism? Cross-section restorations in the northern Gulf of Mexico suggest that space for extension has indeed been created in this way (Diegel and Cook, 1990; Hossack and McGuinness, 1990). Allochthonous salt sheets are also known in some distal

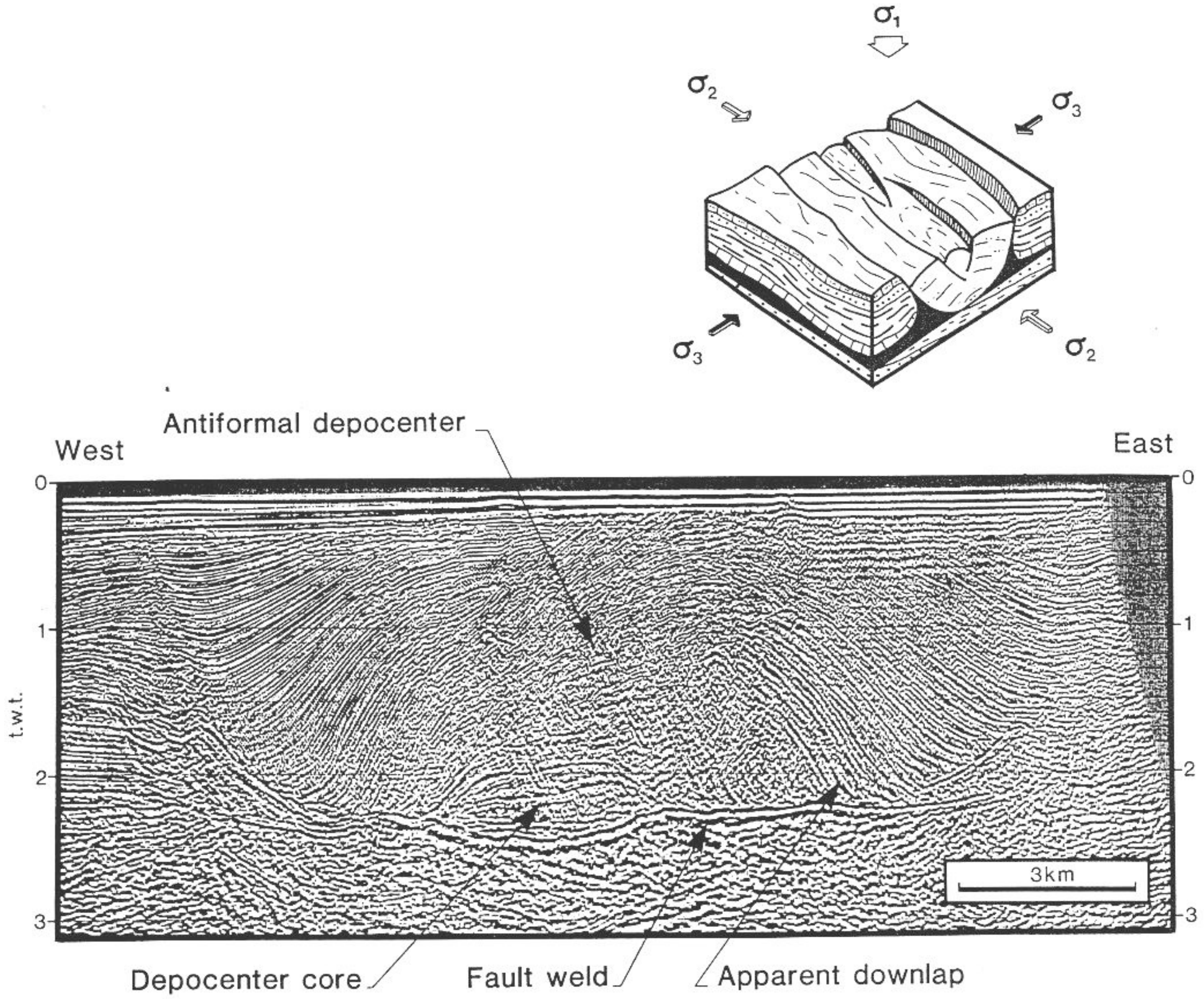


Figure 9 Seismic profile of an antiformal depocentre in a graben that opened during phase 2 rafting in the Kwanza Basin. Initially the right hand fault was the more active, then the left hand fault slipped faster. The block diagram illustrates the relationship between principal stresses and strain

areas of the Kwanza Basin, so this mechanism could contribute locally to creating lateral space. However, allochthonous sheets are not everywhere present on the seaward margin of the rafts, and it seems doubtful that this process, alone or in combination with seaward folding and thrusting, could create the necessary 200 km of space for extreme extension.

Sequence stratigraphy and the role of oceanic crust in creating space

A third explanation is the generation of oceanic crust. To our knowledge, this mechanism has not previously been proposed. We discuss this mechanism by first establishing when sea-floor spreading began off Angola. Then we use sequence stratigraphy to reconstruct the early history of the Kwanza Basin, when rafting began. After describing how space is generated by sea-floor spreading, we compare the rates of sea-floor spreading and rafting to check if space was created fast enough to accommodate the extension.

Most authorities on the plate-tectonics of the South Atlantic Ocean believe that the southern part of this ocean, south of the Rio Grande–Walvis fracture zone, began to open before the northern part of the South Atlantic Ocean. As so many papers have been published on this subject, we tried a statistical approach to bracket the timing of ocean opening from the following radiometric, palaeomagnetic and palaeontological data: Larson and Ladd (1973), Scrutton and Dingle (1976), Norton and Sclater (1979), Rabinowitz and LaBreque (1979), Barron and Harrison (1980), Freeth (1980), Veevers *et al.* (1980), Martin *et al.* (1981), Rabinowitz (1982), Sclater *et al.* (1981), Smith *et al.* (1981), Gerrard and Smith (1982), Harland *et al.* (1982), Emery and Uchupi (1984), Uliana *et al.* (1989) and Kooi and Cloetingh (1989). We took the mid-point between these workers' bracketing dates for ocean opening, averaged the mid-points and calculated the fiducial limits for 95% confidence levels. Calculated this way, the age bracket for the start of sea-floor spreading in the southern South Atlantic Ocean was 131 – 123 Ma; for the northern South

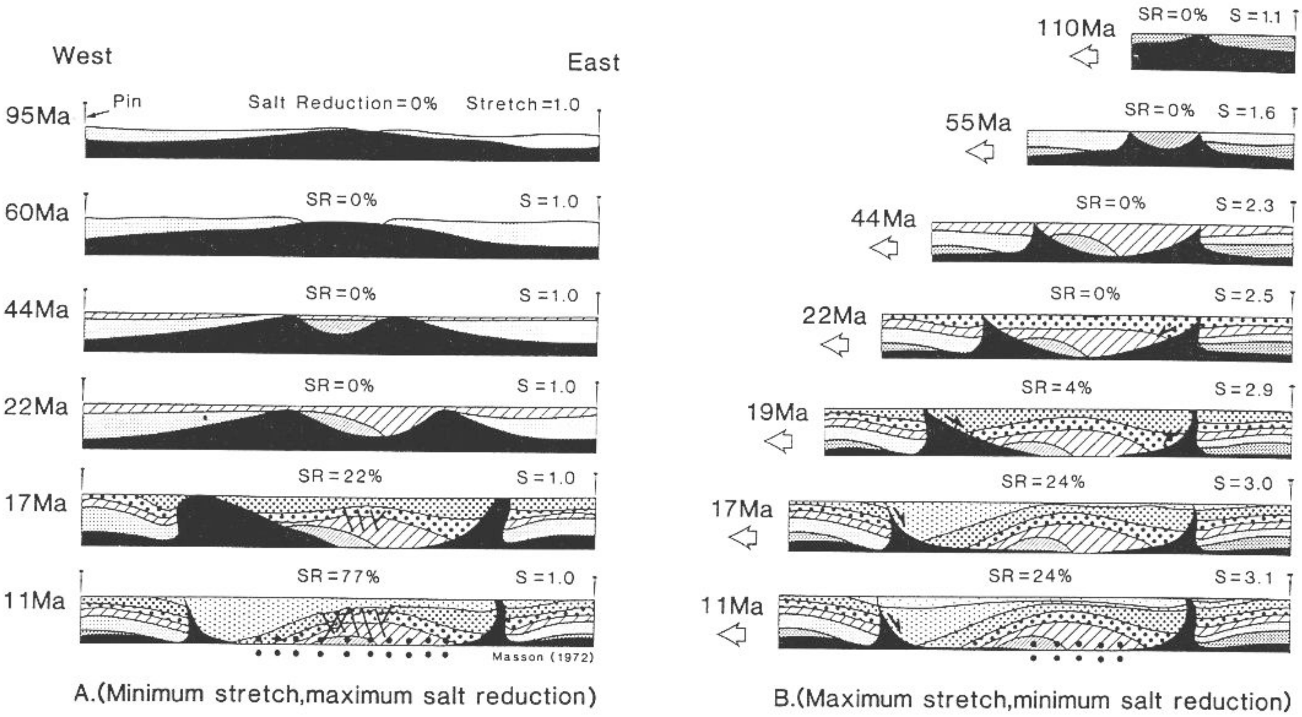


Figure 10 Two cross-sectional restorations of the Quenguela graben, Kwanza Basin, illustrating the difficulty of estimating the local amount of extension associated with salt tectonics. (A) Reconstruction by Masson (1972), which assumes no regional extension (stretch = 1) and considerable reduction of salt area (77%). (B) Our computer reconstruction, using *Restore* [developed by Schultz-Ela and Duncan (1991)], which assumes the maximum amount of regional extension (stretch = 3.1) commensurate with minimum loss of salt (24%). This balanced restoration also includes the effects of decompaction. The amount of extension at the earliest stage (110 Ma) is uncertain because the fine scale structure is not revealed

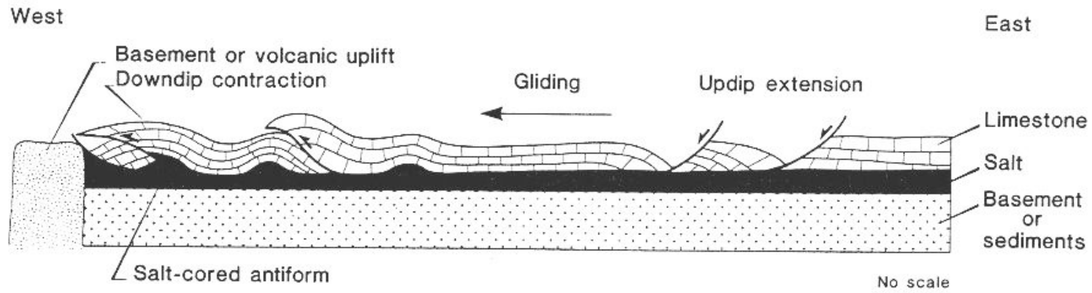


Figure 11 Creation of lateral space for raft tectonics by the formation of a downdip fold and thrust belt

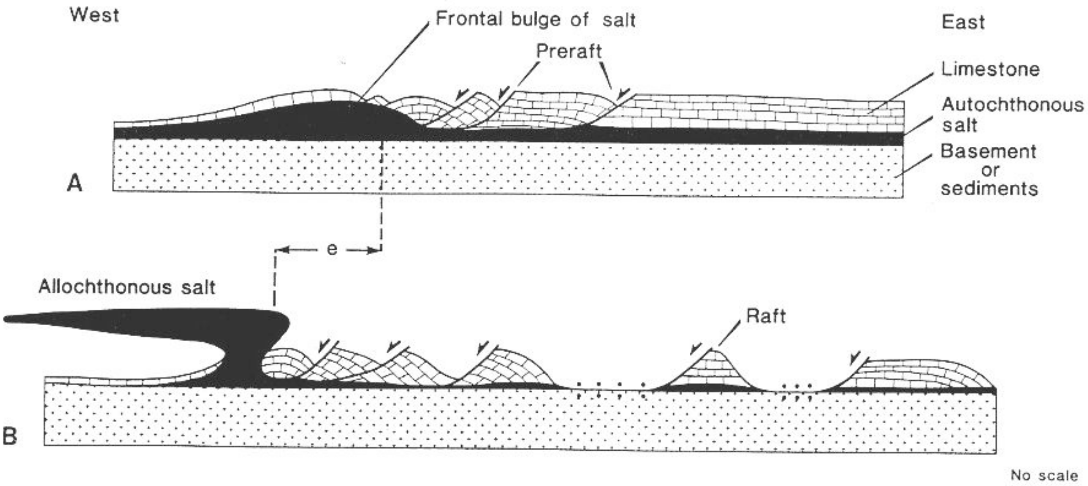
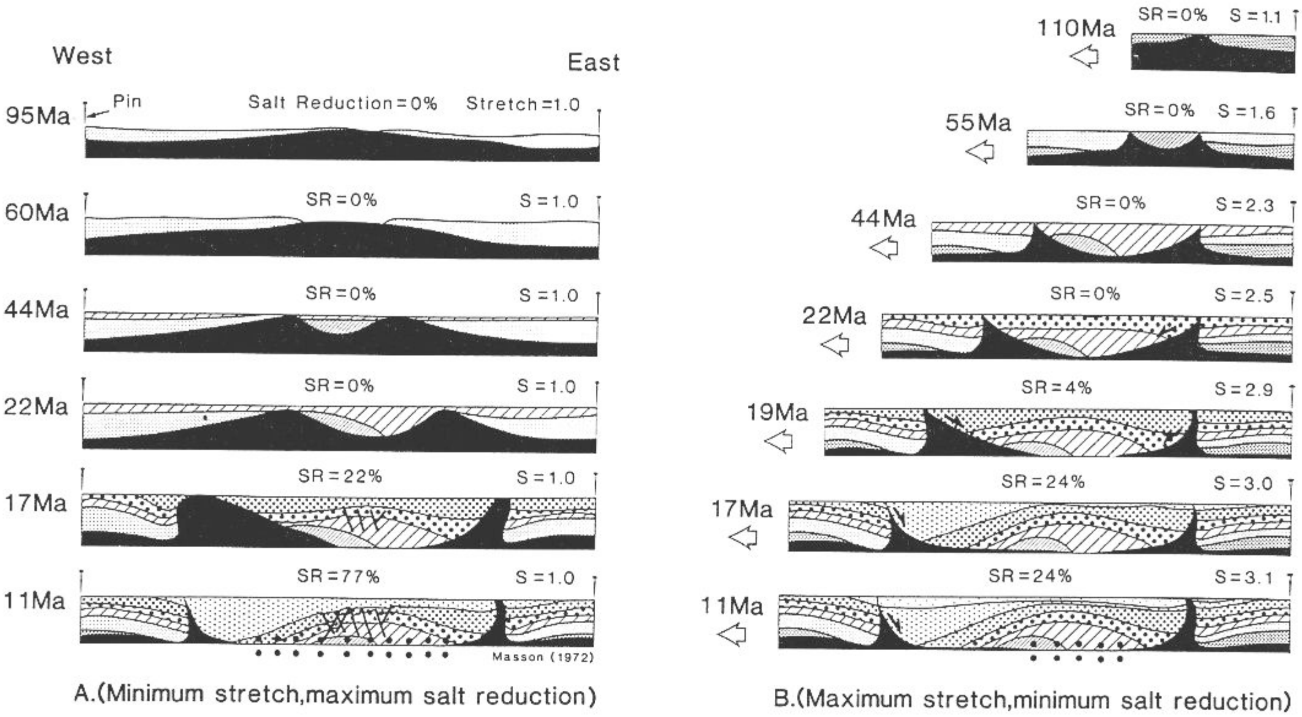


Figure 12 Creation of lateral space for raft tectonics by the displacement of autochthonous salt into an allochthonous salt tongue emplaced at higher stratigraphic levels



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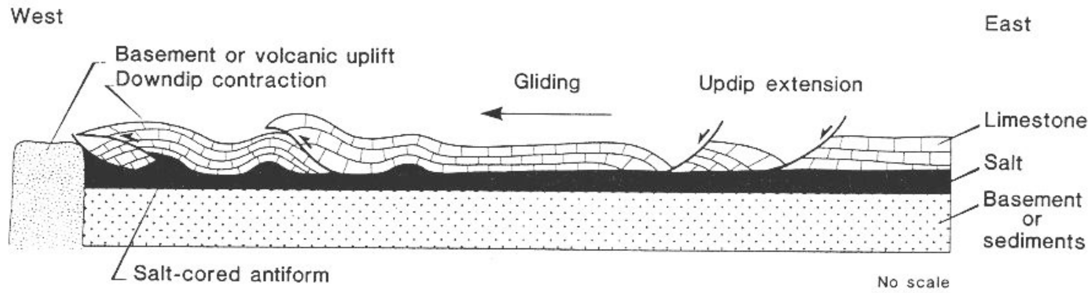

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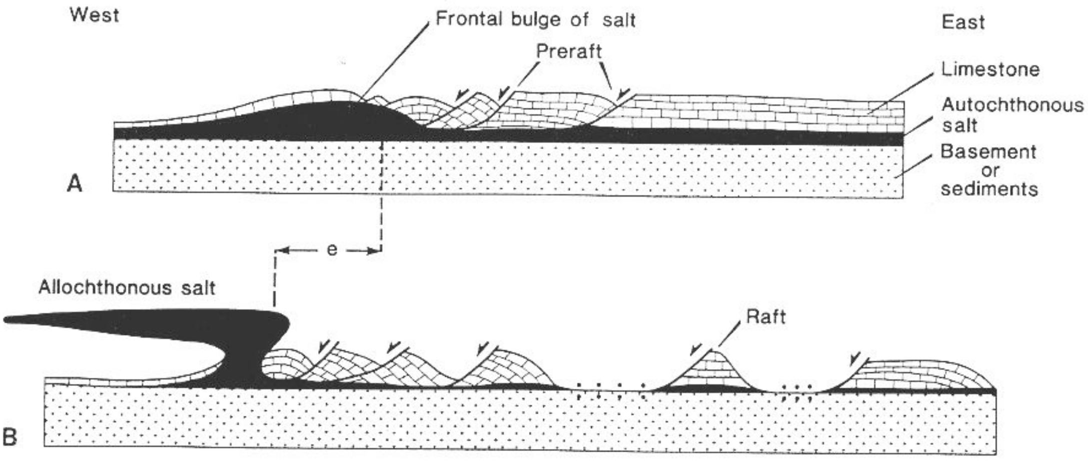

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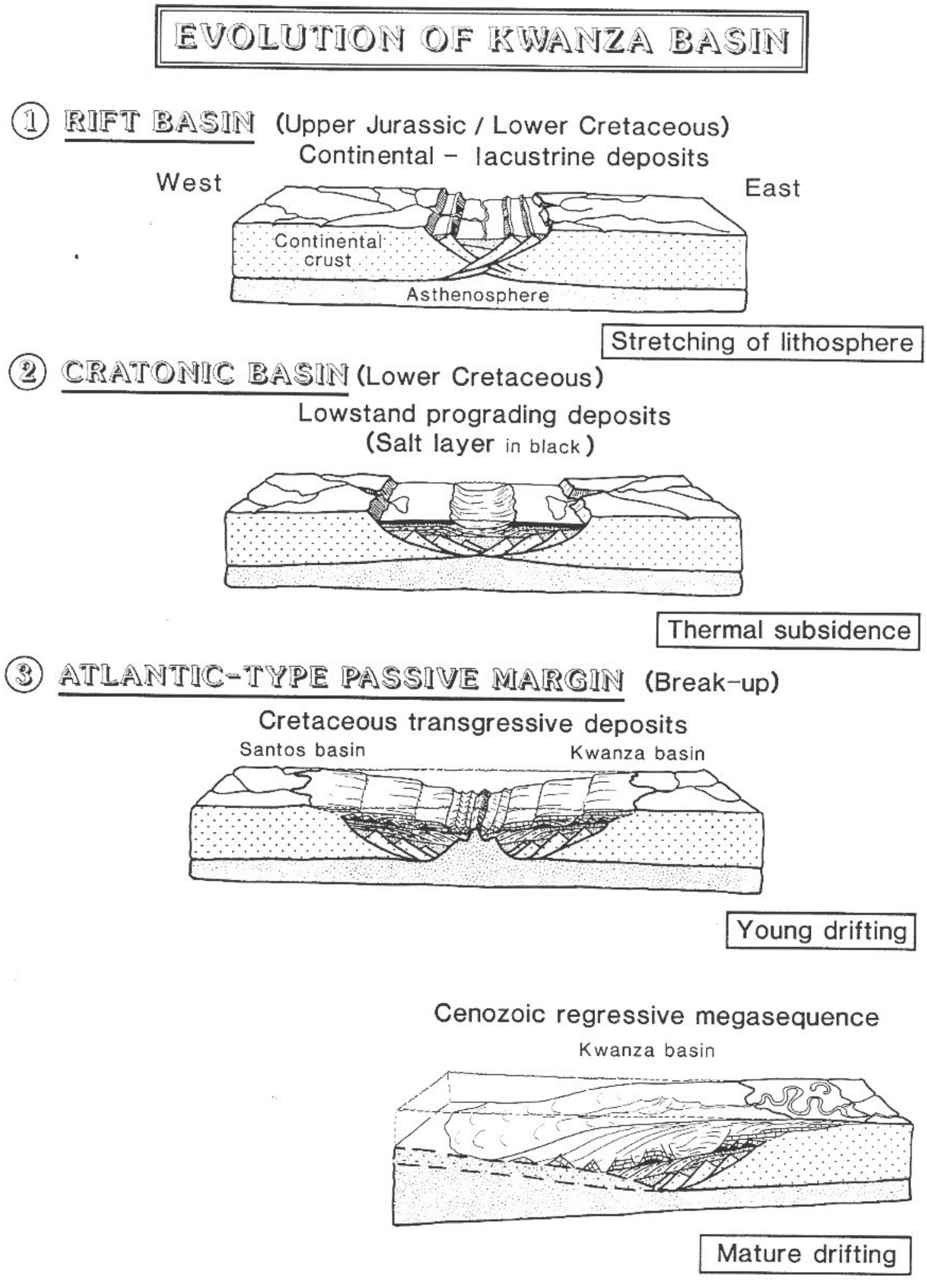

Figure 14 Evolution of the Kwanza Basin of Angola (right-hand side) and the Santos (or Campos) Basin of Brazil (left-hand side) during the rifting of Gondwana and later opening of the South Atlantic Ocean. The block diagrams are schematic and not to scale

space would have been created when lateral support for the salt's overburden was removed as the cratonic basin was split by fresh oceanic crust. Before sea-floor spreading started, the Massive Salt extended across the cratonic basin. *Figure 15* (upper panel) shows the salt split by a spreading ridge of oceanic crust. *Figure 15* (centre) depicts the beginning of extension of the overburden as it glides or spreads across the widening expanse of fresh oceanic crust. This requires a thin décollement layer, which could consist either of Upper Cretaceous marine clay accumulated on oceanic crust or of salt. The thin décollement layer would have stretched together with its overburden across the oceanic crust.

Was space created fast enough by sea-floor spreading to accommodate the extension due to rafting? Yes. We can estimate the rate of extension during rafting from *Figure 7*. The strain rate here during phase 1 and phase 2 rafting was about 2×10^{-16} s^{-1}. For both phases of rafting, the basinward edge of the 80 km long slab extended at about 0.4 mm yr^{-1}. Over the full basin width of 440 km, this extension rate is equivalent to 2 mm yr^{-1}. This is much slower than the unilateral rate of sea-floor spreading beween Africa and the mid-Atlantic ridge. Based on the map of the world's oceanic crust by Sclater *et al.* (1981), the unilateral spreading rate adjacent to the Kwanza Basin is 33 mm yr^{-1} for the period 125 – 110 Ma and 22 mm yr^{-1} for the period 125 – 65 Ma. Accordingly, the creation of oceanic crust created space extremely efficiently — about ten times faster than was required to accommodate Angolan raft tectonics.

Conclusions

(1) During extreme thin-skinned extension over a décollement of salt or other evaporites, allochthonous normal fault blocks separate into rafts that are no longer in contact with each other. This process is known as raft tectonics. The Kwanza Basin has been the type area for raft tectonics since this structural style was recognized there in the early 1970s.

(2) In the combined Kwanza–Campos precursor basin, Jurassic–Lower Cretaceous basins in rifted lithosphere were succeeded by a cooling induced, flexural, cratonic basin filled with an Aptian lowstand progradational wedge capped by the Massive Salt. Sea-floor spreading of the South Atlantic probably began during or just after the evaporites accumulated from 118 to 115 Ma. The active mid-ocean ridge bulged, causing eustatic rise and accumulation of transgressive systems tract carbonates above the salt on the tilted continental margin.

(3) The transgressive carbonate overburden began to stretch in the Middle to Late Cretaceous around 110 Ma, when the overburden was only a few hundred metres thick. This extension formed many small, tilted, phase 1 rafts over relatively thick salt. These older rafts were then yoked together by further Upper Cretaceous sedimentation.

(4) From the Early to Middle Tertiary, the thickened overburden ruptured into 10 – 20 km long, non-rotated, blocky rafts that moved concordantly over relatively thin salt during phase 2 rafting. Tertiary sediments accumulated asymmetrically in strike-parallel depocentres created by deep, widening grabens between phase 2 rafts. These sediments rest directly on salt or subsalt strata, with a tectonically induced age jump of 60 – 90 Ma. Most salt walls flanking the rafts subsided into relict salt ridges and were buried during phase 2 rafting.

(5) About 200 km of lateral space was needed to accommodate the two phases of rafting. Extension updip took place by gravity gliding and spreading into space created by opening of the South Atlantic Ocean. Strain rates for both phases of rafting are estimated to be between 2×10^{-16} and 3×10^{-16} s^{-1}. The extension rate for rafting across the entire Kwanza Basin was about 2 mm yr^{-1} — a rate that was easily accommodated by the oceanic spreading

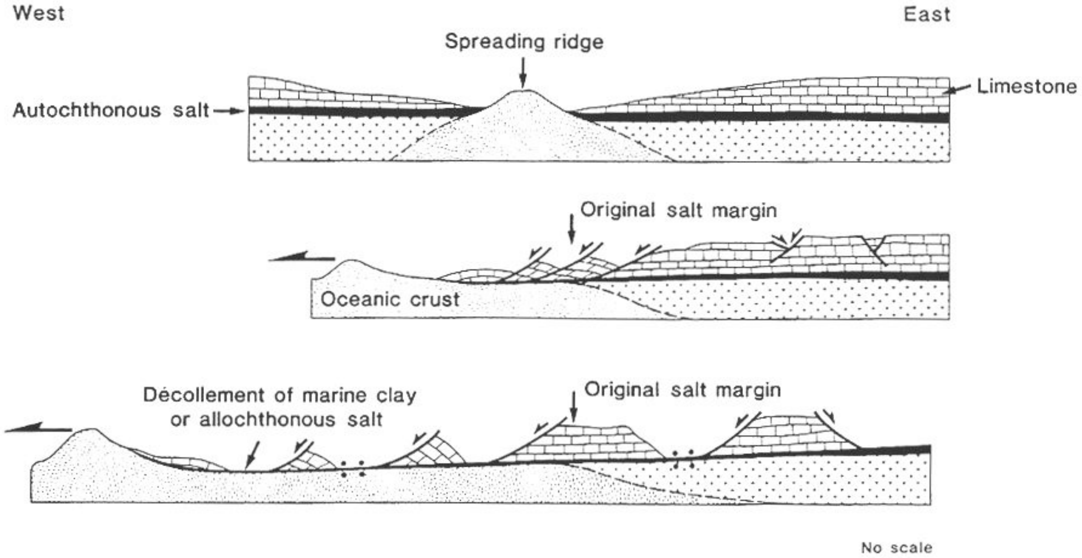

Figure 15 Creation of lateral space for raft tectonics by the generation of oceanic crust by a spreading ridge. The extended fault blocks slide over newly formed oceanic crust lubricated by an underlying décollement layer of allochthonous salt or marine clay

rate of at least 20 mm yr^{-1}. Apart from sea-floor spreading, subordinate space was also created locally by downdip fold and thrust belts and by transfer of salt to higher stratigraphic levels in the form of allochthonous sheets.

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References

Barron, E. J. and Harrison, C. G. A. (1980) An analysis of past plate motions: the South Atlantic and Indian Oceans. In: *Mechanisms of Continental Drift and Plate Tectonics* (Eds P. A. Davies and S. K. Runcorn), Academic Press, London, pp. 89–109

Baumgartner, T. R. and van Andel, T. H. (1971) Diapirs of the continental margin of Angola, Africa *Geol. Soc. Am. Bull.* **82**, 793–802

Brice, S. E., Cochran, M. D., Pardo, G. and Edwards, A. D. (1982) Tectonics and sedimentation of the South Atlantic rift sequence: Cabinda, Angola. In: *Studies in Continental Margin Geology* (Eds J. S. Watkins and C. L. Drake), *Am. Assoc. Petrol. Geol. Mem. No. 34*, pp. 5–18

Brink, A. H. (1974) Petroleum geology of Gabon Basin *Am. Assoc. Petrol. Geol. Bull.* **58**, 216–235

Brognon, G. P. and Verrier, G. R. (1966) Oil and geology in Cuanza basin of Angola *Am. Assoc. Petrol. Geol. Bull.* **50**, 108–158

Burollet, P. F. (1975) Tectonique en radeaux en Angola (Raft tectonics in Angola) *Bull. Soc. Géol. Fr.* **XVII**, 503–504

Diegel, F. A. and Cook, R. W. (1990) Palinspastic reconstruction of salt-withdrawal growth-fault system, northern Gulf of Mexico *Geol. Soc. Am. Abs. Prg.* **22**, A48

Dingle, R. V. (1982) Continental margin subsidence: a comparison between the east and west coasts of Africa. In: *Dynamics of Passive Margins* (Ed. R. A. Scrutton), *Am. Geophys. Union Geodyn. Ser. No. 6*, pp. 59–71

Emery, K. O. and Uchupi, E. (1984) *The Geology of the Atlantic Ocean* Springer Verlag, New York, 1050pp

Freeth, S. J. (1980) Can membrane tectonics be used to explain the break-up of plates. In: *Mechanisms of Continental Drift and Plate Tectonics* (Eds P. A. Davies and S. K. Runcorn), Academic Press, London, pp. 135–149

Gerrard, I. and Smith, G. C. (1982) Post-Paleozoic succession and structure of the southwestern African continental margin. In: *Studies in Continental Margin Geology* (Eds J. S. Watkins and C. L. Drake), *Am. Assoc. Petrol. Geol. Mem. No. 34*, pp. 49–74

Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G. and Walters, R. (1982) *A Geologic Time Scale* Cambridge University Press, Cambridge, 131 pp

Hossack, J. R. and McGuinness, D. B. (1990) Balanced sections and the development of fault and salt structures in the Gulf of Mexico (GOM) *Geol. Soc. Am. Abs. Prg.* **22**, A48

Jackson, M. P. A. and Cramez, C. (1989) Seismic recognition of salt welds in salt tectonics regimes. In: *Gulf Coast Section of the Society of Economic Palentologists and Mineralogists Tenth Annual Research Conference Program and Abstracts, Houston, TX, USA*, pp. 66–71

Jackson, M. P. A. and Talbot, C. J. (1991) A glossary of salt tectonics. In: *Geological Circular 91-4*, Bureau of Economic Geology, University of Texas at Austin, 44pp

Kooi, H. and Cloetingh, S. (1989) Intraplate stresses and the tectono-stratigraphic evolution of the central North Sea. In: *Extensional Tectonics and Stratigraphy of the North Atlantic Margins* (Eds A. J. Tankard and H. R. Balkwill), *Am. Assoc. Petrol. Geol. Mem. No.46*, pp. 541–558

Larson, R. L. and Ladd, J. W. (1973) Evidence from magnetic lineations for the opening of the South Atlantic in the Early Cretaceous *Nature* **246**, 209–212

Logar, J. F. *et al.* (1983) 1983 West Africa well evaluation conference, Part 1: Geology. In: *1983 West Africa Well Evaluation Conference* Schlumberger, Paris, pp. I-1–I-69

Martin, A. K., Hartnady, C. J. and Goodlad, S. W. (1981) A revised fit of South America and South Central Africa *Earth Planet. Sci. Lett.* **54**, 293–305

Masson, P. (1972) L'exploration du pétrole en Angola *Rev. Assoc. Franç. Tech. Pétrole* **212**, 21–34

Norton, I. O. and Sclater, J. G. (1979) A model for the evolution of the Indian Ocean and the breakup of Gondwanaland *J. Geophys. Res.* **84**, 6803–6830

Rabinowitz, P. D. (1982) Gravity measurements bordering passive continental margins. In: *Dynamics of Passive Margins* (Ed. R. A. Scrutton), *Am. Geophys. Union Geodyn. Ser. No. 6*, pp. 91–115

Rabinowitz, P. D. and LaBreque, J. (1979) The Mesozoic South Atlantic Ocean and evolution of its continental margins *J. Geophys. Res.* **84**, 5973–6002

Rona, P. A. (1982) Evaporites at passive margins. In: *Dynamics of Passive Margins* (Ed. R. A. Scrutton), *Am. Geophys. Union Geodyn. Ser. No. 6*, pp. 116–132

Schultz-Ela, D. D. and Duncan, K. D. (1991) *Restore Users Manual and Software*, The University of Texas at Austin, Bureau of Economic Geology, Austin, TX, 75pp

Sclater, J. G., Parsons, B. and Jaupart, C. (1981) Oceans and continents: similarities and differences in the mechanisms of heat loss *J. Geophys. Res.* **86**, 11535-11552

Scrutton, R. A. and Dingle, R. V. (1976) Observations on the processes of sedimentary basin formation at the margins of southern Africa *Tectonophysics* **36**, 143–156

Smith, A. G., Hurley, A. M. and Briden, J. C. (1981) *Phanerozoic Paleocontinental World Maps* Cambridge University Press, Cambridge, 102pp

Uliana, M. A., Biddle, K. T. and Cerdan, J. (1989) Mesozoic extension and the formation of Argentine sedimentary basins. In: *Extensional Tectonics and Stratigraphy of the North Atlantic Margins* (Eds A. J. Tankard and H. R. Balkwill), *Am. Assoc. Petrol. Geol. Mem. No. 46*, pp. 599–614

Veevers, J. J., Powell, C. M. and Johnson, B. D. (1980) Seafloor constraints on the reconstruction of Gondwanaland *Earth Planet. Sci. Lett.* **51**, 435–444

Vendeville, B. C. and Jackson, M. P. A. (1992) The fall of diapirs during thin-skinned extension *Mar. Petrol. Geol.* **9**, 354–371