ELSEVIER

Marine and Petroleum Geology 17 (2000) 1095–1109

Marine and Petroleum Geology

www.elsevier.com/locate/marpetgeo

Superposed deformation straddling the continental-oceanic transition in deep-water Angola

C. Cramez[a], M.P.A. Jackson[b,*]

[a]TotalFina Elf Exploration and Production, 2 Place de la Coupole, 92078 Paris La Defense Cedex, France
[b]Bureau of Economic Geology, The University of Texas at Austin, Austin, TX 78713-8924, USA

Received 14 December 1999; received in revised form 7 August 2000; accepted 8 August 2000

Abstract

The Angolan margin is the type area for raft tectonics. New seismic data reveal the contractional buffer for this thin-skinned extension. A 200-km-long composite section from the Lower Congo Basin and Kwanza Basin illustrates a complex history of superposed deformation caused by: (1) progradation of the margin; and (2) episodic Tertiary epeirogenic uplift. Late Cretaceous tectonics was driven by a gentle slope created by thermal subsidence; extensional rafting took place updip, contractional thrusting and buckling downdip; some distal folds were possibly unroofed to form massive salt walls. Oligocene deformation was triggered by gentle kinking of the Atlantic Hinge Zone as the shelf and coastal plain rose by 2 or 3 km; relative uplift stripped Paleogene cover off the shelf, provided space for Miocene progradation, and steepened the continental slope, triggering more extension and buckling. In the Neogene, a subsalt half graben was inverted or reactivated, creating keystone faults that may have controlled the Congo Canyon; a thrust duplex of seaward-displaced salt jacked up the former abyssal plain, creating a plateau of salt 3–4 km thick on the present lower slope. The Angola Escarpment may be the toe of the Angola thrust nappe, in which a largely Cretaceous roof of gently buckled strata, was transported seawards above the thickened salt by up to ~20 km. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Angola; Basin evolution; Congo Canyon; Fold-and-thrust belt; Gravity tectonics; Kwanza Basin; Lower Congo Basin; Raft tectonics; Salt tectonics

1. Introduction

The West African margin in the South Atlantic Ocean has long been successfully explored for hydrocarbons. This is especially true for the area around Cabinda, which includes the continental margins of northern Angola, Congo, and Democratic Republic of Congo. This region forms part of the Lower Congo Basin, which mostly overlies rifted crust originally contiguous with that below the Campos Basin of Brazil before separation in the Early Cretaceous. The area includes the large, active Congo Fan, which is the greatest postsalt depocenter along the West African margin south of the Niger Delta. The current exploration boom along the Angolan margin focuses on the deep-water and ultradeep-water regions. The geology there is revealed by new seismic data showing salt provinces that comprise a spectacular mixture of fold belts and allochthonous salt canopies, recently reviewed by Marton, Tari, and Lehmann (2000). The contractional salt tectonics along the outboard of this divergent margin is one of the best examples in the world. The extensional inboard regions of this margin are the type area for raft tectonics (Duval, Cramez, & Jackson, 1992; Lundin, 1992; Spathopoulos, 1996).

This paper, which builds on previous abstracts (Jackson, Cramez, & Mohriak, 1998, Jackson, Fonck, & Cramez, 1999), is a reconnaissance survey of some of the most interesting features of salt tectonics straddling the continental-oceanic transition from the outer shelf to the base of the slope. The Aptian salt obscures this transition, so its precise position is unknown. We speculate on the causes and timing of salt tectonics and propose a history of superposed deformation that is more varied and complex than previously thought. We focus on an area near the Congo Canyon, the submarine extension of the Congo estuary separating the DRC from Angola (Fig. 1). Despite an overburden thickness of up to 6 km, the new seismic data reveal deep salt structures in remarkable detail.

2. Schematic regional section

The regional seismic profile in Fig. 2A splices four time-migrated seismic lines. Fig. 2B shows our interpretation of the composite section. Vertical exaggeration is about 7×

* Corresponding author. Tel.: +1-512-471-1534; fax: +1-512-471-0140.

PII: S0264-8172(00)00053-2

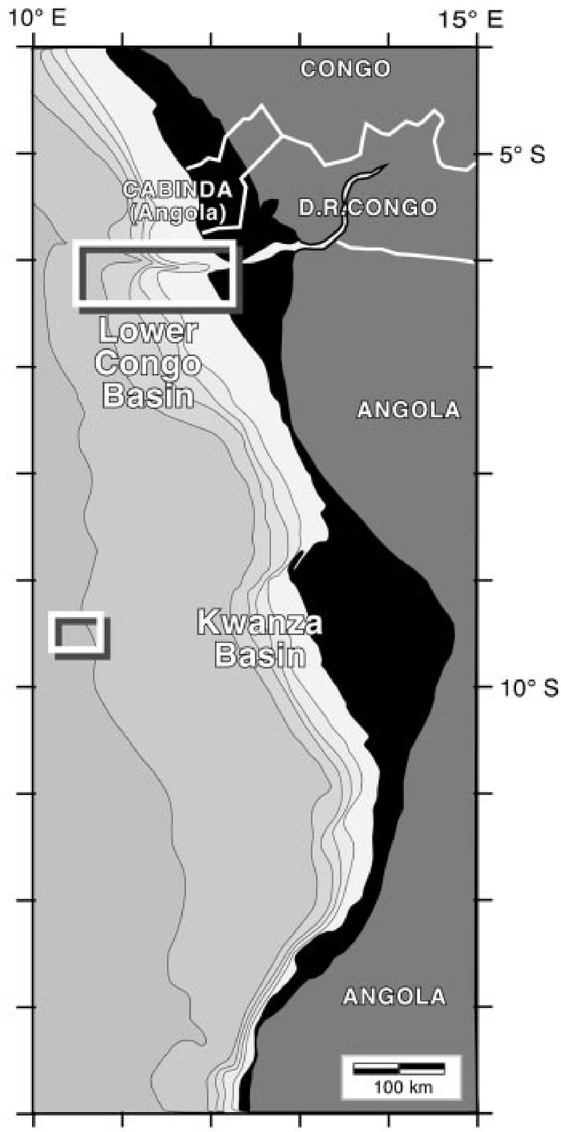

Fig. 1. Map showing locations (rectangles) of study areas in the Lower Congo Basin and Kwanza Basin along the Angolan continental margin. Onshore Cretaceous–Cenozoic basins shown in black.

(assuming average overburden sonic velocities of 2200 m/s). The westernmost segment of the composite line is from an area about 300 km south in the Kwanza Basin. These two regions roughly correspond with the areas shown as Transects A and B of Marton et al. (2000). The structures in the composite line depict our seismic interpretation, but their juxtaposition is schematic because the locations are composite. The role of this composite schematic line is not to document the geology of a particular area. Instead, the line is a vehicle for displaying and discussing concepts.

The three main bathymetric features are as follows. A truncated shelf was uplifted in the mid-Tertiary and even more recently. A uniformly dipping slope is interrupted by the 800-m-deep Congo Canyon. An elevated, flat-topped salt plateau represents a toe-thrust complex on this divergent margin.

Middle to upper Aptian evaporites are shown in black. Progressing seawards, the main salt-tectonic features are as follows. Thin salt and extensional rafts and turtles characterize the Shelf, Monocline, and Upper Slope Provinces. Thin salt and contractional structures underlie the Middle-Slope Province. Originally thick salt deformed into rejuvenated salt walls and a toe-thrust complex cored by tectonically thickened salt define the Lower Slope Province. The names of provinces are proposed here merely as a framework for this paper, not as a general model for the Lower Congo and Kwanza Basins.

The nature of the underlying crust is speculative. Continental crust, variably thinned and enclosing rift basins of half-graben geometry, underlies the shelf and upper slope. Continental crust and cover are gently kinked in the Monocline Province. This flexure, the Atlantic Hinge Zone, was originally called the "Atlantic hinge line" in Gabon by Brink (1974). The most seaward salt adjoins oceanic crust, recognizable because of the basement's hummocky top and incoherent reflectors and overlying flat sediments of the Angolan abyssal plain. The continental-oceanic crustal boundary is probably a broad transitional zone, possibly associated with subaerial flood basalts forming seaward-dipping reflectors. Any evidence for these reflectors is masked by the overlying salt-related structures (Jackson et al., 1998, Jackson, Fonck, & Cramez, 2000).

A seaward traverse along the composite section (Fig. 2B) focuses on geometric relationships that elucidate the causes and timing of deformation. We then synthesize an interpretation of the deformation history.

3. Shelf Province

The shelf is underlain by extensional rafts and turtle structures typical of the Angolan and Brazilian margins (Fig. 3). Small salt rollers and low, reactive diapiric walls are separated by primary salt welds. These salt bodies are overlain by Albian wedges that diverge and dip mostly landwards. These wedges record Albian subsidence of the seaward flanks of salt structures. We attribute this subsidence to extreme extension and seaward expulsion of salt.

Gentle folds overlie the rafted interval. Some of these folds are typical of extensionally driven subsidence; for example, rollover folds associated with listric faults. Other folds suggest subtle contraction in the Tertiary: parallel reflectors of Paleogene strata are gently folded between 1 and 2 s TWT. No faults are visible at this stratigraphic level. So this subtle folding is probably not caused by extension. Drape compaction seems implausible because these folds are absent over similar extensional structures elsewhere in the section. Moreover, some of the folded intervals are isopachous. Significantly, this evidence for subtle contraction is present in shallow strata on the shelf. Thus, contraction is not confined to either great water depths or great burial depths, as is commonly assumed. These buckle

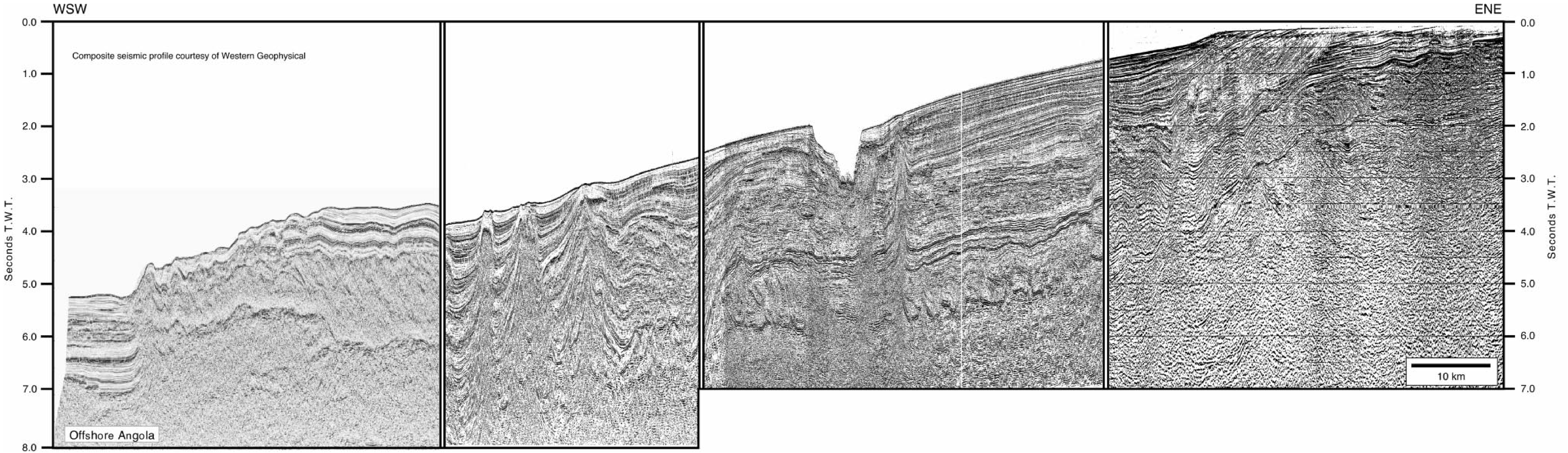

Fig. 2. (A) Seismic examples in following figures were all extracted from this uninterpreted composite seismic profile (foldout). The locations of the component segments are shown in Fig. 1. The westernmost segment is from the Kwanza Basin. The remaining segments are from the Lower Congo Basin about 300 km to the north. Seismic data courtesy of Western Geophysical. (B) Composite regional profile schematically showing the main features interpreted from four seismic profiles. K, Cretaceous; T, Cenozoic. Aptian salt is black in all illustrated cross sections.

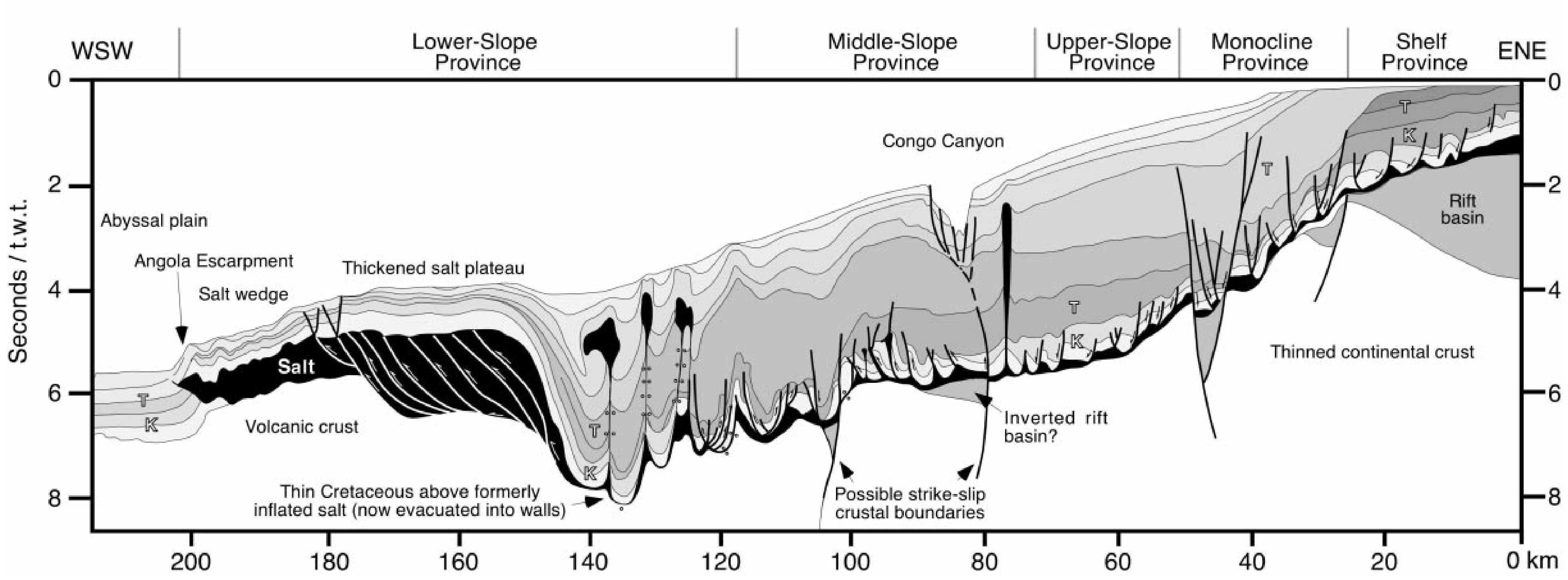

Fig. 2. (*continued*).

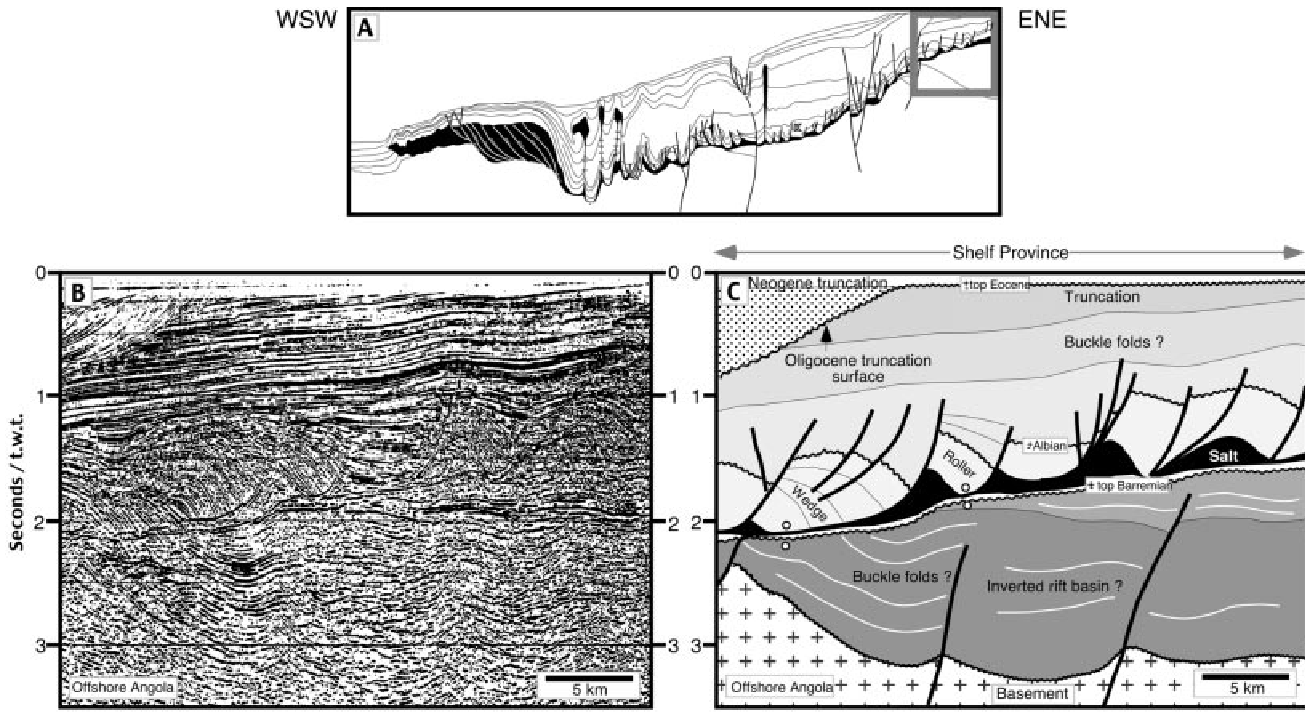

Fig. 3. Typical salt-tectonic structures in the Shelf Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

folds may be related to the same tectonic event that caused the Neogene truncation at the overlying sea floor (Fig. 4). Similar gentle, rounded folds are also present below the salt (Figs. 3 and 4). A large thickness of isopachous strata is folded in the rift basin. This style suggests buckling because there is no visible relationship to rift faults or to velocity effects. Folding may predate the salt, but this is uncertain. In a later section, we discuss possible effects of Tertiary inversion or reactivation below the salt underneath the Congo Canyon.

4. Monocline Province

The Monocline Province is defined by a gentle kink caused by steepening of the base of salt. This kink is

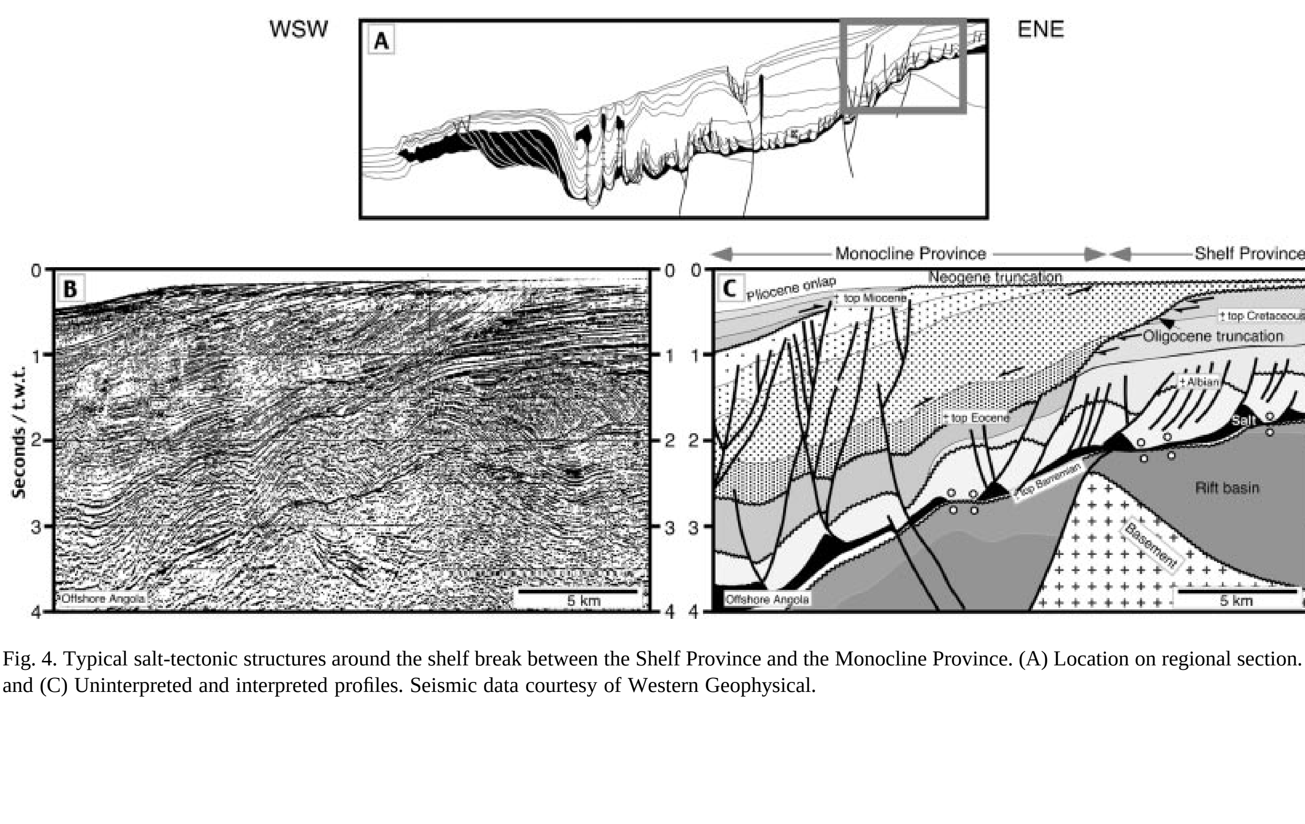

Fig. 4. Typical salt-tectonic structures around the shelf break between the Shelf Province and the Monocline Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

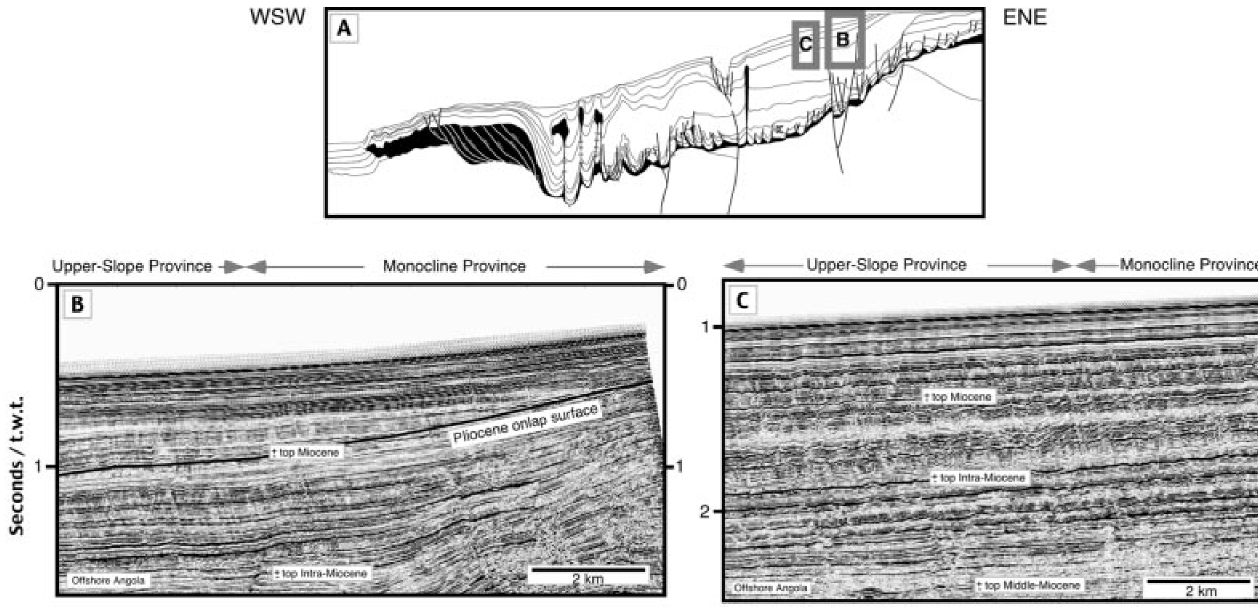

Fig. 5. Shallow structures in the Monocline Province and Upper-Slope Province. (A) Locations on regional section. (B) Pliocene onlap surface. (C) Compaction faults inferred to be polygonal in map view. Seismic data courtesy of Western Geophysical.

generally known as the Atlantic Hinge Zone, but we use "Monocline Province" as a broader term to include subsidiary hinge zones. The base of salt steepens from ~3° dip in the Shelf Province, to ~10° in the monocline, to ~6° in the Upper Slope Province. Farther seawards still, the base of salt is poorly imaged, so its dip is uncertain. But seawards of the overall Lower Congo depocenter, the dip is likely to reverse and slope landwards. Across the Monocline Province, the base of salt (and base of Tertiary) has a cumulative vertical offset of about 3 s TWT, equivalent to up to 3 km of structural relief.

4.1. Oligocene truncation and uplift

Two major truncations cut the outer shelf above the Monocline Province (Figs. 3 and 4). The deeper truncation is assigned to the middle-to-late Oligocene erosional hiatus and is onlapped by Miocene strata. This hiatus is well known along the West African margin. It was cut by 10–30 km landward erosion and 500 to 2000 m of vertical truncation of the Upper Cretaceous and Paleogene carbonate platform (Lavier, Steckler, & Brigaud, 2000; Steckler, Lavier, & Bigaud, 1997, in Congo Basin; Karner, Driscoll, McGinnis, Brumbaugh, & Cameron, 1997, in Gabon Basin). The truncation coincides with a eustatic fall in relative sea level at about 30 Ma of >300 m. But that eustatic fall is much less than the estimated depth of truncation so cannot be more than a minor contributor to the erosion. The same applies to the thermal subsidence following continental breakup in the Neocomian, which would have been largely complete by the Oligocene. Thus, we deduce that the Monocline Province was formed mostly by epeirogenic uplift of the shelf, as was proposed for the Kwanza Basin by Lunde, Aubert, Lauritzen and Lorange (1991). The cause of uplift is beyond the scope of our paper but a contributory factor could have been the thermal bulge above the initial Cameroon hotspot, which subsequently emplaced the Cameroon Volcanic Line in the Miocene (Meyers, Rosendahl, Groschel-Becker, Austin, & Rona, 1996). Fluid-inclusion temperatures in offshore Angola indicate a thermal pulse in the Miocene that raised temperatures by 30–40°C and the geotherm to 50–60°C/km (Walgenwitz, Pagel, Meyer, Maluski, & Monie, 1990). Temperatures increased northwards towards the Cameroon hotspot.

A period of tectonic stability was bracketed by the major truncations. This quiet period was dominated by overall progradation as relative sea level rose to present-day levels.

4.2. Neogene truncation and uplift

The shallow truncation bevels the youngest strata on the outer shelf. Across a width of at least 15 km on the shelf, Upper Cretaceous and Paleogene isopachous strata have been truncated at the sea floor (Fig. 3). Farther west at the present shelf break, a zone at least 8 km wide contains Neogene foresets that end abruptly at the sea floor (Fig. 4); their geometry suggests truncation rather than toplap. This truncation appears to be related to uplift and erosion of the entire Congo coastal plain, which created outcrop belts of successively older, truncated stratigraphic units in a landward direction.

The timing of the young coastal uplift is elucidated by the Neogene onlap surface at the upper left of Fig. 4 and shown in detail in Fig. 5A. This prominent onlap surface has been estimated as Pliocene (Uenzelmann-Neben, Spiess, & Bleil, 1997), indicating that this final stage of epeirogenic uplift of

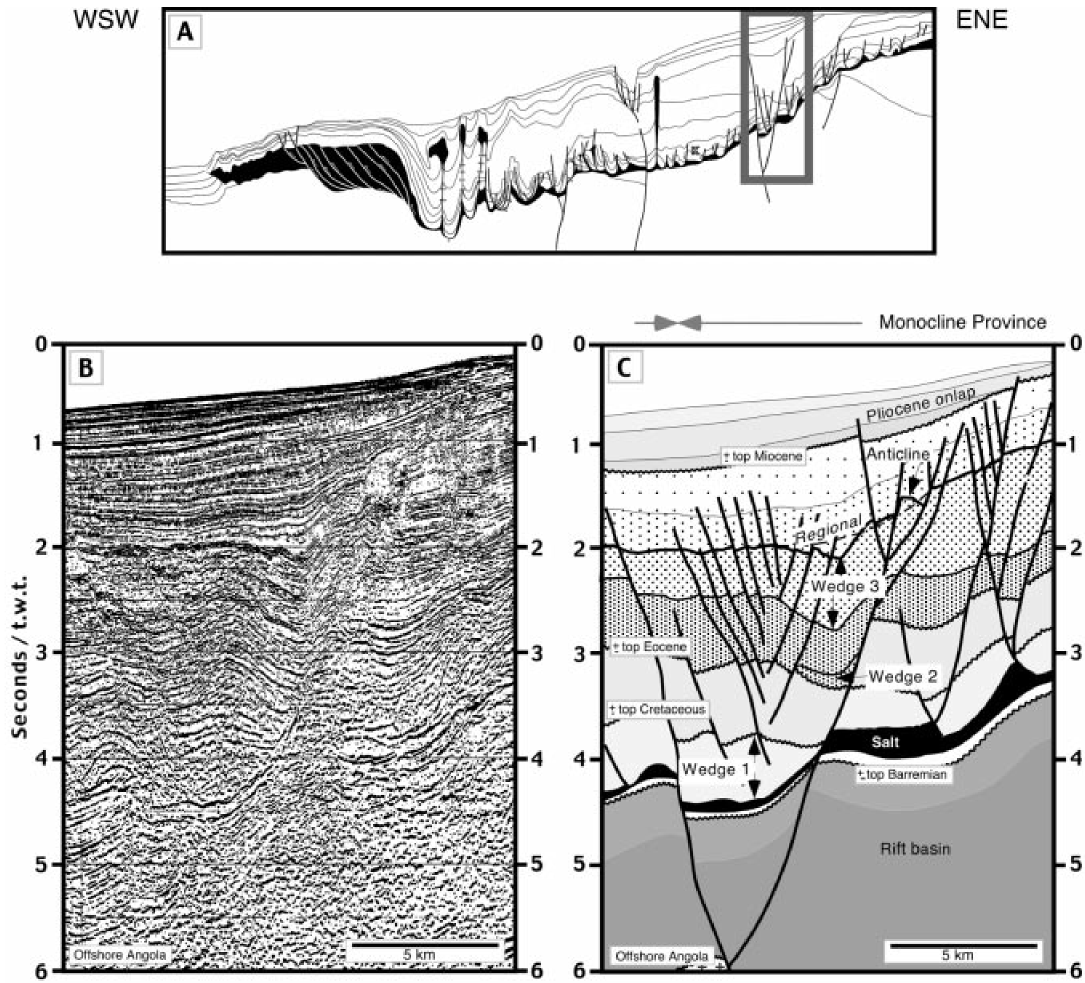

Fig. 6. Salt-tectonic structures in the graben at the foot of the Monocline Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

the shelf-break area occurred in the Pliocene. This relative uplift was at least 150 m but was minor compared with the Oligocene structural uplift. Since the Pliocene, the sedimentary record indicates that the upper slope was not uplifted. However, the shelf landwards of the Monocline Province could still be rising and being truncated even in the Holocene because this is an erosional process that destroys the sedimentary record.

4.3. Polygonal compactional faults

Only one kind of deformation is seismically visible in the Neogene interval of the upper slope seawards of the Pliocene onlap. Fig. 5C shows countless small faults having mostly extensional slip. The faults have small apparent throws (10s of m) and close spacing (~200 m). They are stacked in several tiers in which faulted intervals are bounded above and below by undeformed rock. Proprietary time slices through similar structures in the Lower Congo and Gabon Basins indicate that such faults are linked into polygonal networks. Closely similar polygonal networks of faults in the North Sea have been attributed by Cartwright and coworkers (Lonergan, Cartwright, Laver, & Staffurth, 1998) to compaction of low-permeability facies that contracted radially, like desiccation cracks in mud, as pore fluids were expelled.

4.4. Inverted breakaway zone

Near the foot of the Monocline Province, an extensional structure is present in many seismic lines as a large graben or half graben (Fig. 6). The Cretaceous intervals thin landwards in the base of the graben (Wedge 1), suggesting the former existence of a salt diapir or pillow there. Accommodation space in the graben could have been created by extension and seaward expulsion of salt. However, there is no sedimentary record of the latter process in the form of rolling folds and other migrating structures.

Two important events are recorded in the Cenozoic intervals (Fig. 6). First, two pulses of extension created two growth wedges. (1) A minor graben sag formed Wedge 2 in the early to middle Tertiary; this extension correlates

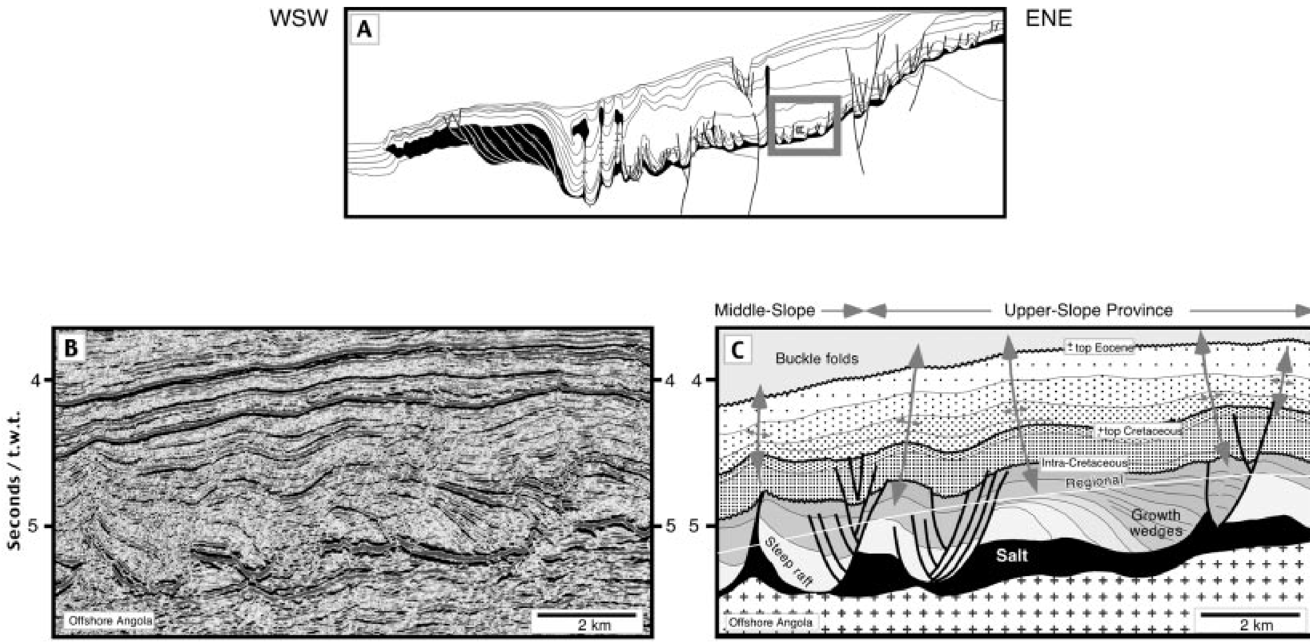

Fig. 7. Extensional rafts and superposed buckling at the boundary of the Upper-Slope Province and Middle-Slope Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

seismically with the Oligocene uplift and truncation. (2) A major phase of extension in the Miocene formed a very thick Wedge 3. Because the basal reflectors onlap a single surface, extension and related deepening began rapidly. The top of Wedge 3, in the upper Miocene or lower Pliocene, is a minor onlap surface caused by subtle uplift to landwards; that occurred before the slightly larger uplift recorded by the shallow onlap surface previously described (Fig. 4). The important episode of early Neogene extension recorded by the thick Wedge 3 coincided with renewed contraction farther down the slope, as shown later.

Second, after the early Neogene extension ended, the growth wedges buckled under compression to form the peculiar paired anticline and syncline in the hangingwall of the main fault (Fig. 6). The anticline could not have been caused by the curved step in the underlying listric fault because the crest of the anticline is at — rather than below — regional datum (labeled in Fig. 6C). The inferred buckling can be correlated with either or both of the Pliocene onlap surfaces. At this time, the landward half of the graben block, including the hanging-wall anticline, rose above regional datum along with the truncated modern shelf. During this uplift, the youngest Pliocene onlap surface formed. Coevally, the seaward half of the graben block sank below regional because of continued Quaternary extension in the graben, whose zone of maximum subsidence migrated about 6 km seawards (Fig. 6).

5. Upper-Slope Province

The Upper-Slope Province is seawards of the Monocline Province. It comprises mostly extensional salt tectonics above a gently dipping base of salt (Fig. 7). Upper Albian growth wedges thicken landwards and trail behind small tilted rafts of lower Albian carbonates above small salt rollers. This geometry indicates extreme extension soon after salt deposition, a style of raft tectonics common on the Angolan margin.

However, the significance of this example is the clear evidence for later shortening, more prominent than on the shelf (Fig. 3). The extensional rafts in Fig. 7 are overlain by smoothly undulating folds having a wavelength of 2–3 km. Lower folded strata are growth folds showing thickening in the synclines, whereas upper folded strata are isopachous. Anticlinal thinning indicates that folding occurred in the Eocene. How did these folds form? Once again, we rule out an extensional mechanism because there are no related normal faults at the stratigraphic level of the folds. Drape compaction is also implausible: folding is absent over other rafted structures in this line, and some folded units are isopachous. Moreover, some of the anticlines overlie expanded zones of younger strata. That geometry is incompatible with drape compaction: younger strata should have compacted more than older strata, which would create drape synclines rather than the observed anticlines. We thus conclude that the folds formed by buckling. This shortening correlates seismically with the major Oligocene truncation, which we attributed to epeirogenic uplift of the shelf.

An earlier episode of contraction could also have affected the Albian rafts. On the extreme left of Fig. 7, a raft is steeply tilted landwards. Its crest is above regional datum (labeled) and it adjoins an extremely narrow diapir that appears to have been pinched. Apart from the raft's

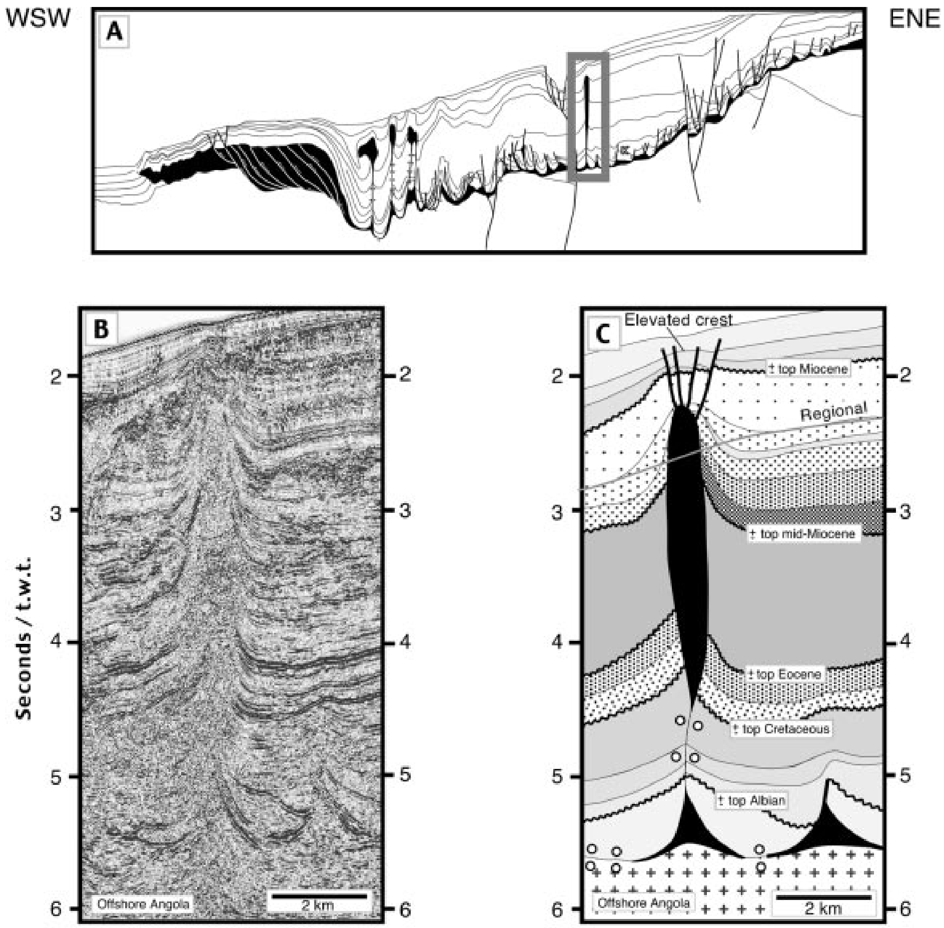

Fig. 8. Passive salt diapir rejuvenated by contraction in the Middle-Slope Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

steepness and height, it resembles the other rafts. So we infer that this is an originally extensional raft that was later steepened and lifted by lateral compression. Thinning and onlap onto its crest record the time of shortening as after the extension shown on the right but before the main contraction that formed the broad-wavelength buckles described in the previous paragraph. We conclude that this steepened raft marks the landward edge of the main contractional zone that absorbed some of the extensional rafting nearer land. This point marks the landward edge of the next structural province.

6. Middle-Slope Province

This province contains the zone of Late Cretaceous contraction over thin to moderately thick salt. The clearest images of this shortening are farther seawards and are illustrated in a later section. First, we discuss other features of this province.

6.1. Diapiric rejuvenation

The Middle-Slope Province also records later contraction. Immediately seawards of the region shown in Fig. 7, is the most-landward large diapir (Fig. 8), which almost reaches the surface. The diapir is narrow, about 5 km high and only 1 km wide at its widest point. Deep reflectors sweep closely together in the lower half of the diapir. This geometry and the narrowness of the diapir, suggest that its lower stem has pinched off to form a vertical secondary salt weld. Moreover, the roof of the diapir is elevated ~0.4 s TWT above regional datum and has stretched to form a crestal graben that offsets the sea floor. These data suggest that the lower part of the diapir was pinched by lateral contraction, which displaced the squeezed salt upwards, where it arched the diapir's roof.

Intervals thin fairly uniformly towards the diapir. It appears to have risen passively by overall downbuilding; this process consisted of repeated cycles of alternating burial and active diapiric rise back to the surface. The active rise may have been augmented by episodic contraction. Perhaps this is a salt wall that provided a laterally collapsing cushion to absorb some of the extension farther landwards. Tectonic buffering would continue until the side contacts of the diapir had been pressed together and no more salt could be expelled upwards.

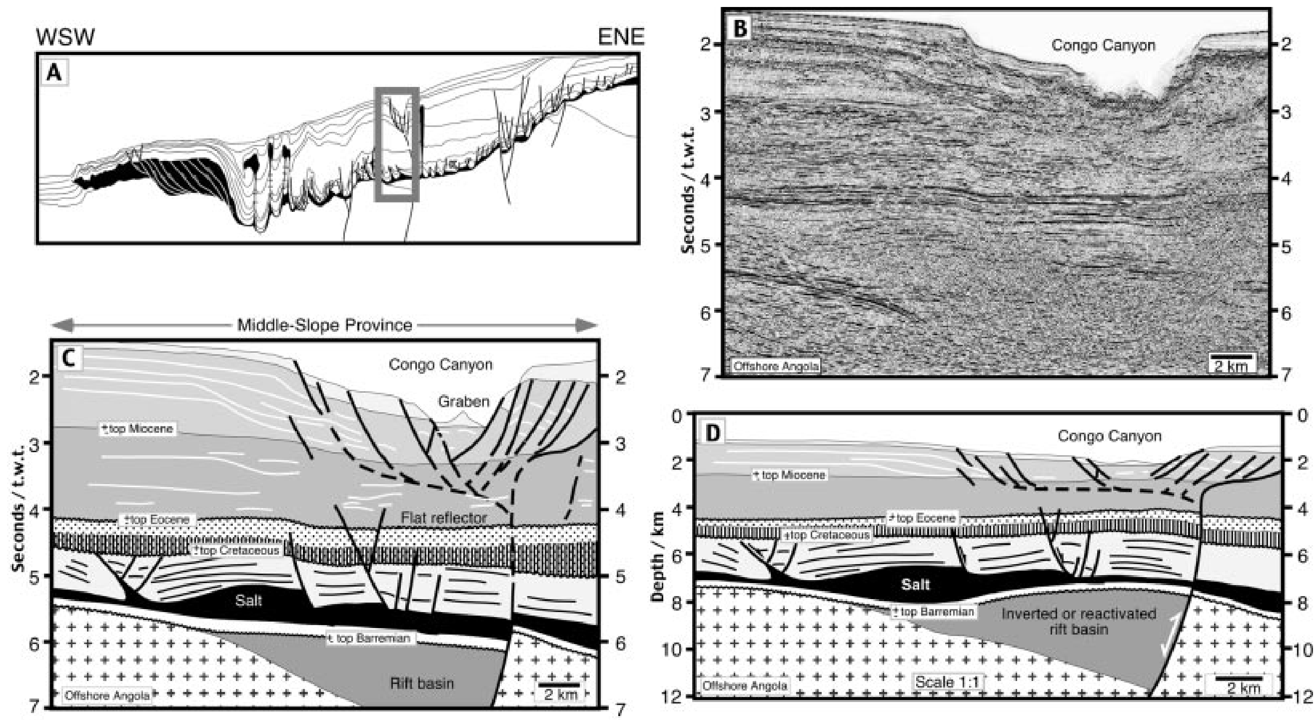

Fig. 9. Structures associated with the Congo Canyon in the Middle-Slope Province. (A) Location on regional section. (B) Uninterpreted profile. (C) Interpreted profile in time. (D) Interpreted profile in depth without vertical exaggeration. Seismic data courtesy of Western Geophysical.

6.2. Congo Canyon and inverted rift basin

Immediately seawards of the diapir shown in Fig. 8 is the Congo Canyon (Fig. 9). The huge Congo fan projects 900 km out across the ocean floor. For such a large fan, it has an unusually active turbidite system: Holocene turbidites have accumulated on axial levees at rates of about 60 cm/ka (Droz, Rigaut, Cochonat, & Tofani, 1996).

The Congo Canyon also has some intriguing relations to salt tectonics. We speculate that the course of the canyon is tectonically controlled. By analogy, certain submarine canyons (e.g. Keathley Canyon) in the Gulf of Mexico follow collisional sutures in the salt canopy. The Congo Canyon walls are stairstep normal faults (Fig 9B and C). Erosion, rather than deposition dominates this part of the canyon. Significantly, the lower Tertiary reflectors are more or less flat under the canyon. Yet the canyon is filled with more than 1 km of low-velocity water, which must create a large velocity pushdown on a seismic profile. Indeed, after this profile is depth converted and displayed without vertical exaggeration (Fig. 9D), the reflectors are gently bowed up below the canyon, rather than being flat. Two equally speculative hypotheses for the origin of the graben in the canyon both involve renewed basement tectonics in Tertiary time. (The large kink of the Monocline Province also involves the basement, which was differentially lifted in the Tertiary by up to 3 km in this profile.)

A first possibility is that the subsalt half graben below the Congo Canyon was inverted by contraction or transpression during the Tertiary. Arching of the cover above the inverted rift would stretch the outer arc of the arch, especially at the sea floor. Stretching would form a keystone graben, such as the observed extension centered on the canyon. Alternatively, the subsalt half graben below the Congo Canyon may have been reactivated extensionally or transtensionally in the Tertiary to create the graben within the canyon.

We speculate that a subsalt crustal lineament may have localized the original half graben during rifting. Cenozoic crustal inversion or reactivation of the hypothetical basement lineament created an overlying graben that, in turn, guided the modern Congo Canyon. Whatever the origin of the graben centered on the Congo Canyon, the modern canyon would be preferentially channeled down the graben trough. Canyon erosion would be aided and guided by plucking out fault blocks. This speculation is supported by the canyon's pattern on free-air gravity maps. The 200-km-long canyon trends in a straight line oblique to the shoreline, before curving southwards in its distal reaches. This straight trend parallels that of the major Conrad seamount chain off the Kwanza Basin at 11°S, which may not be purely coincidental.

6.3. Mid-Cretaceous thrust belt

Farther seawards, small mid-Cretaceous thrust structures all appear to verge seawards (Fig. 10). Some may be laterally squeezed diapirs (extreme left). The thrust slices are well imaged, considering their depth, but we cannot determine whether they are thrust imbricates overlain by an erosion surface or a duplex overlain by a roof thrust. Growth

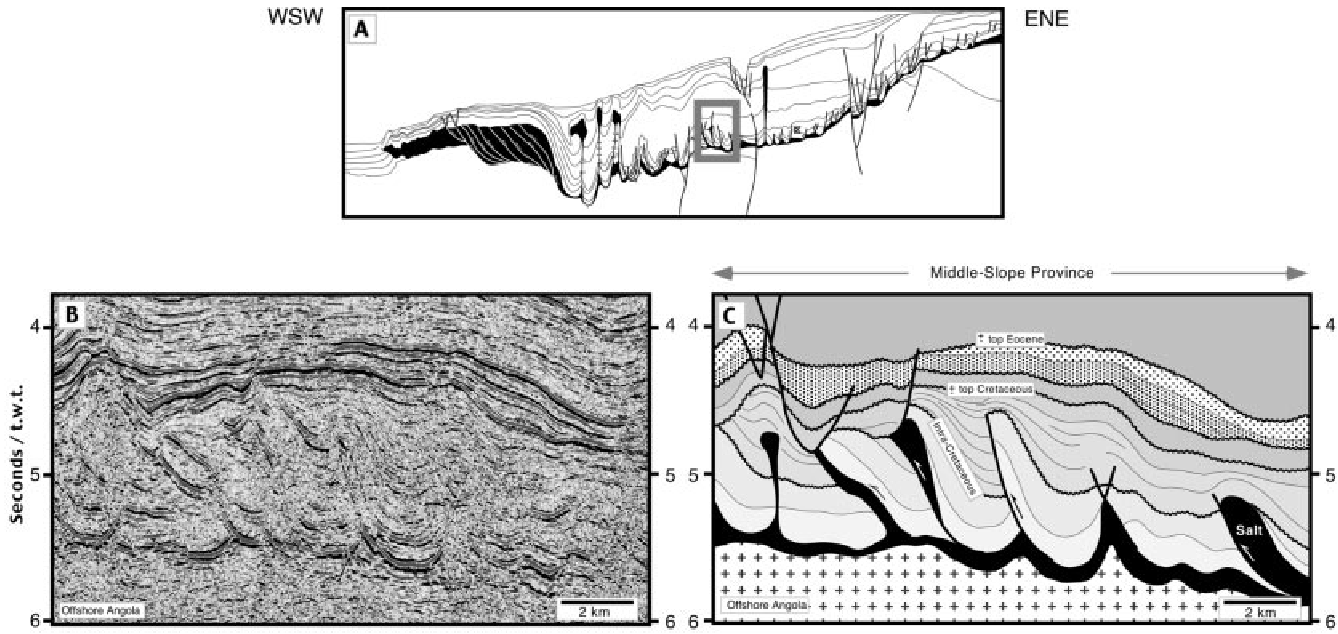

Fig. 10. Seaward-verging, Cretaceous thrust belt in the Middle-Slope Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

wedges between the thrusts record shortening as mostly Albian or Cenomanian. This is coeval with the main extension farther landwards, so this thrust belt must have absorbed much of the extension. Onlaps in the uppermost Cretaceous interval (Fig. 10) show that minor shortening continued after the Cenomanian.

Immediately seawards are two paired structural zones (Fig. 11). On the right (landwards) is a zone of large extension or salt expulsion. This subsidence took place in the Paleogene but mostly in the Neogene (when the main graben of the Monocline Province was most active). Extension would require the hangingwall to slip upslope,

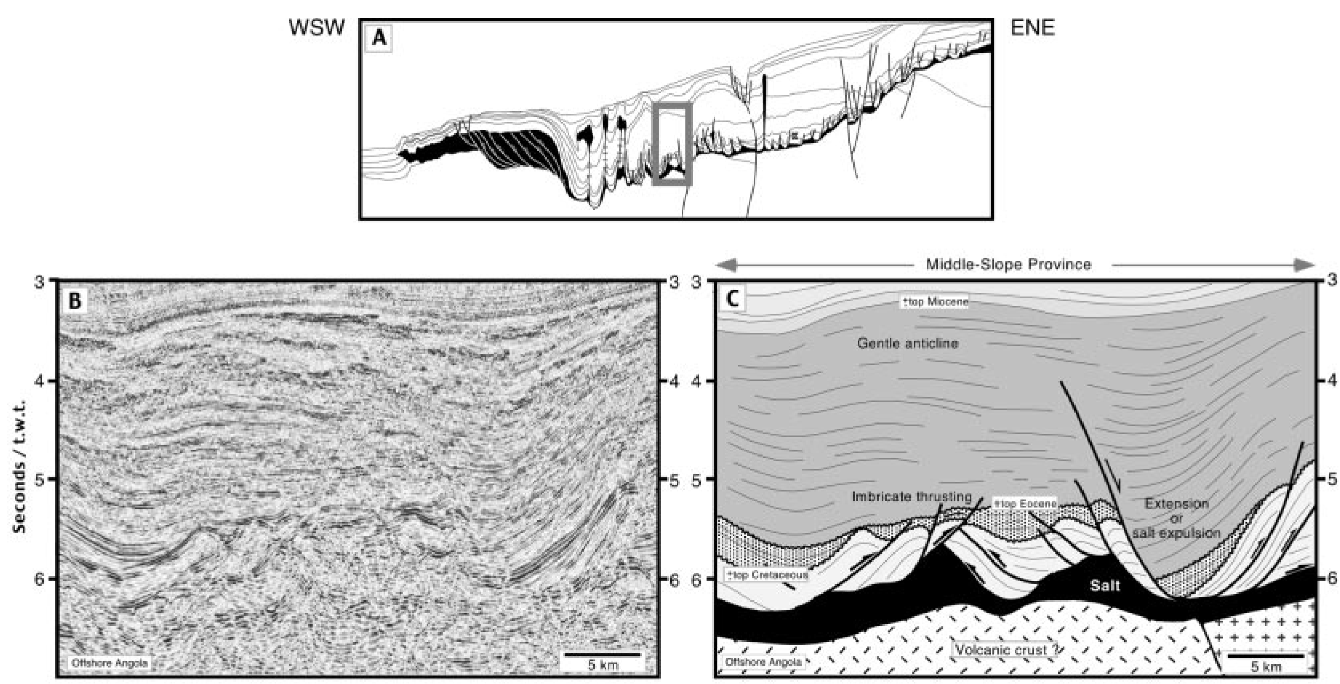

Fig. 11. Contrasting structural styles in the Middle-Slope Province. The abrupt lateral change each side of the large half graben hints at a component of transcurrent slip, possibly involving an underlying crustal boundary. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

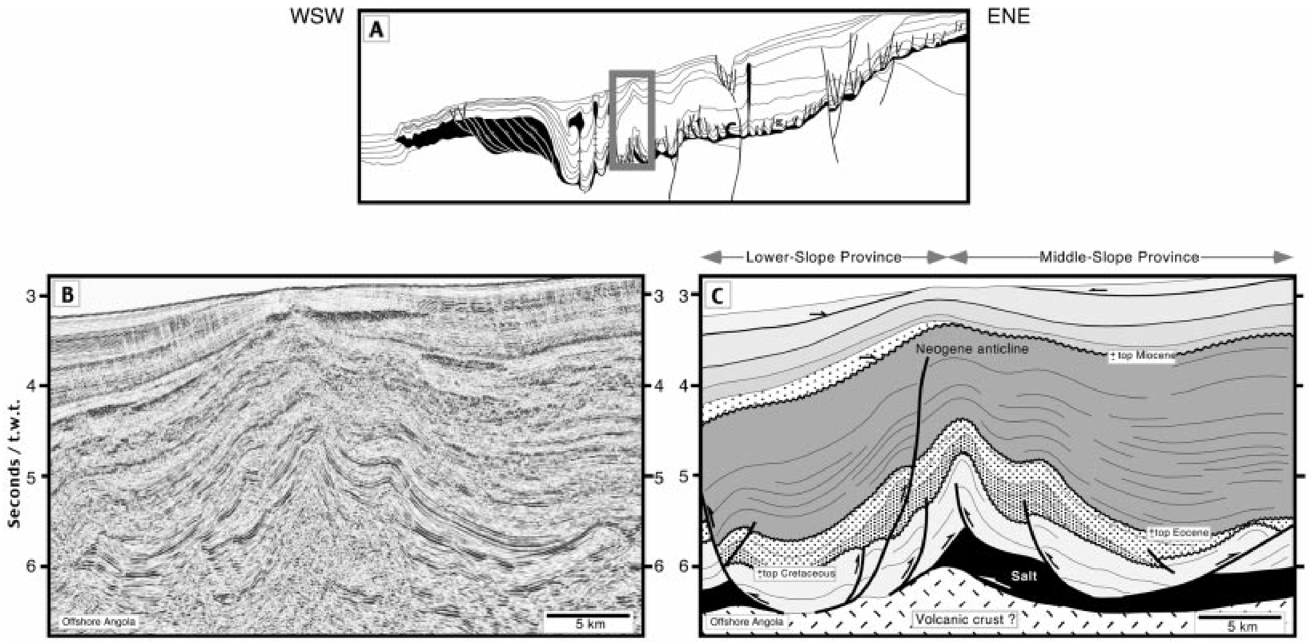

Fig. 12. Doubly vergent Cretaceous thrust belt in the core of a broad Neogene anticline. We infer that expulsion of thicker salt caused downward flexure of the seaward fold limb. The anticline may mark where the salt formerly thickened to seawards. Accordingly, the axial trace of this Neogene anticline defines the boundary between the Middle-Slope Province and the Lower-Slope Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

which seems implausible. Instead, the subsidence may have been caused by seaward expulsion of a salt mound that subsequently flowed out of the plane.

On the left (seawards) is another complex of mid-Cretaceous thrust slivers. However, these verge both landwards and seawards. A lack of preferred vergence is typical of contraction over moderately thick salt because of reduced drag along the detachment (Davis & Engelder, 1985). So it may be significant that the salt in Fig. 11 is thicker (~300 ms TWT) than that in Fig. 10 (~150 ms). The thrust complex forms the deep core of a broad gentle, young fold, which has subtle bulges in the sea floor.

The structural styles of these two adjoining zones (one strongly extensional and the other strongly contractional) in the mid-Cretaceous are so dissimilar that perhaps this could be a zone of Neogene strike slip, possibly involving the basement. This region corresponds to a steep increase in Bouguer gravity seawards, so it could overlie a major crustal feature.

7. Lower-Slope Province

Adjoining the gentle late-formed anticline in Fig. 11 is a more prominent anticline (Fig. 12). This, too, is of Neogene age and overlies a stack of doubly vergent mid-Cretaceous thrusts. However, the prominent anticline rose mostly in the Plio–Pleistocene, as evidenced by two onlap surfaces and anticlinal thinning at shallow levels. The anticline bulges the sea floor so is neotectonic.

This Neogene anticline appears to be a significant salt-tectonic boundary between the Middle-Slope and Lower Slope Provinces. The anticline forms a major downward flexure to seawards. We infer that this downward flexure was accommodated by expulsion of extra-thick Aptian salt, for reasons discussed in the next paragraphs. If so, this large Neogene anticline records a marked increase in former salt thickness, so that the Lower Slope Province could correspond with the Aptian salt depocenter.

7.1. Contractional rejuvenation of salt walls

The salt tectonics style changes radically across the Neogene anticline into a train of major, regularly spaced, salt walls (Fig. 13). Their large size, allochthonous offshoots, and possible canopies all suggest that the walls grew from thick salt. This thickness could be primary or increased by lateral creep of salt. The downward flexure in Fig. 12 is associated with major Neogene thickening accommodated either by deepening of the basin floor or by expulsion of salt into the salt walls. The basin floor is too indistinct to elucidate these possibilities, but some salt had to have been expelled into the growing salt walls.

The crests of both salt walls elevate the sea floor and are onlapped by Pleistocene strata in the adjoining withdrawal basins. These diapirs are clearly active today. Their tectonic position in the ultradeep water of the lower slope is likely to result in deviatoric compression imposed gravitationally from the upper slope. We cannot eliminate the possibility of autonomous growth by active diapirism, driven purely by

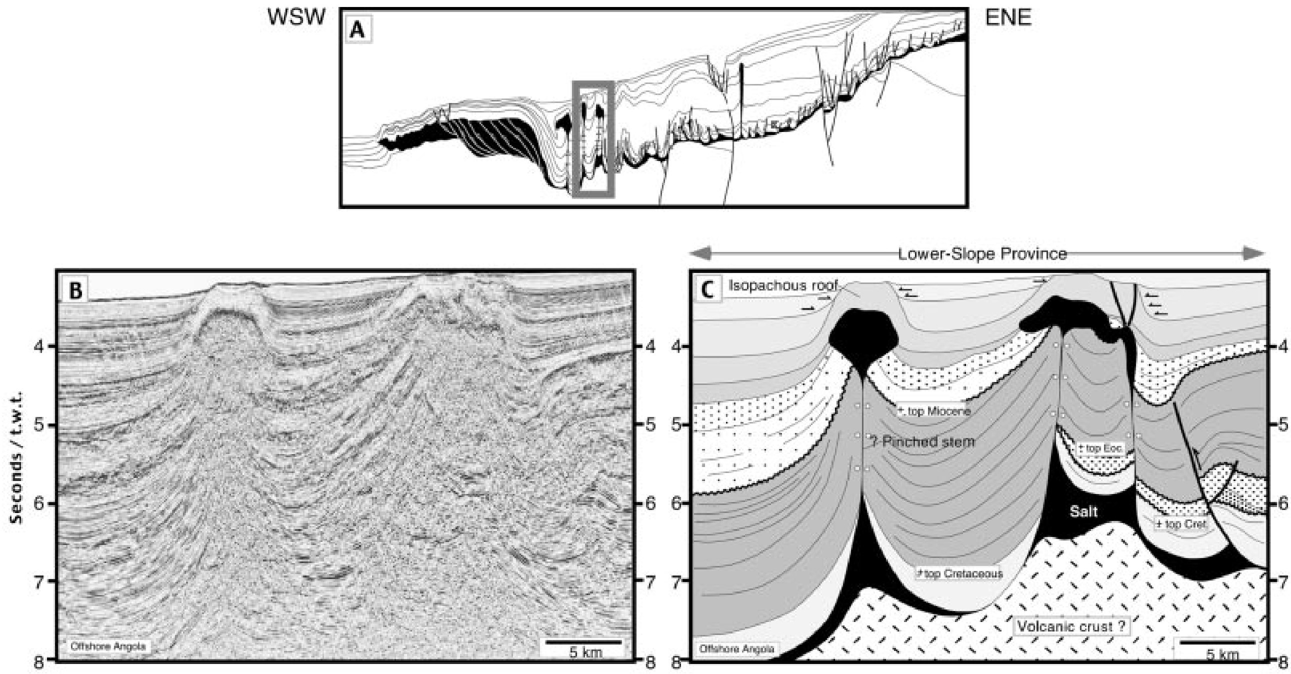

Fig. 13. Passive salt diapirs, some coalesced into a small canopy, rejuvenated by Neogene contraction in the Lower-Slope Province. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. Seismic data courtesy of Western Geophysical.

the weight of the surrounding overburden on the source layer. However, active diapirism of this type is continually driven by gravity, so it is unlikely to have stopped in the Pliocene long enough for isopachous roofs to form, which are now bulging the sea floor. On the other hand, contraction is typically spasmodic: stable periods when stresses accumulate updip alternate with contractional pulses that rejuvenate the salt walls by squeezing their contents upwards. This, we conclude that the active growth of these diapirs is induced by lateral squeezing.

7.2. Thickened salt plateau

A major feature in the Kwanza Basin is a plateau of Aptian salt, 3–4 km thick, which was termed the "massive salt domain" by Marton et al. (2000) (Fig. 14). Overlying isopachous Albian reflectors rise smoothly by 0.5–1.0 s TWT onto the rear of this salt plateau. This time shift is partly due to basinward salt withdrawal adjoining the plateau. However, the internal structure of the salt plateau suggests that it has been tectonically thickened. How? A natural assumption is that a salt plateau inflates purely by seaward inflow of salt expelled from the adjoining source layer by the prograding overburden. However, this salt plateau contains many oblique reflectors, whose regular spacing and landward dip resemble a thrust duplex or imbricate stack of thrust sheets. The oblique internal reflectors could result from interleaved anhydrite, carbonate, or siliciclastic beds or basalt flows imbricated together with salt. If the salt were internally imbricated, its bumpy upper surface would have to be a passive roof thrust separating the mildly buckled roof from a more shortened thrust duplex within the thickened salt plateau.

Significantly, the roof strata above the thickened salt remained undeformed until late in their history. The Cretaceous interval of the roof appears to be mostly prekinematic because it is isopachous and has parallel internal reflectors except for local structures. Thus, we infer that before salt tectonics began, roof strata above the thickened salt originally formed a fairly flat-lying, stable sequence in the abyssal plain. In the Neogene, salt flow and internal imbrication tectonically jacked up a formerly flatter abyssal plain to increase the lower slope.

The stratigraphy of similar roof strata is known farther south in the Benguela basin. DSDP hole 364 ended in Lower Albian strata, just above Aptian salt. In this well, the Albian and Iabe-equivalent (Cenomanian to Eocene) intervals are each about 400 m thick. The overlying Cenozoic interval is condensed into only 250 m thickness. The salt plateau is thus overlain by a mostly continuous, but variably condensed overburden. Accordingly, the salt plateau is stratigraphically autochthonous, though highly deformed within. The roof of the inflated salt plateau is seismically fairly uniform to the north of DSDP 364. We thus infer that the salt plateau shown in Fig. 14 is also overlain by a variably condensed but otherwise normal overburden of Albian to Holocene age.

7.3. Angola Escarpment salt wedge

The leading edge of the salt plateau is a seaward-tapering wedge of thinner salt about 20 km wide (Fig. 14). This wedge pinches out below the prominent Angola

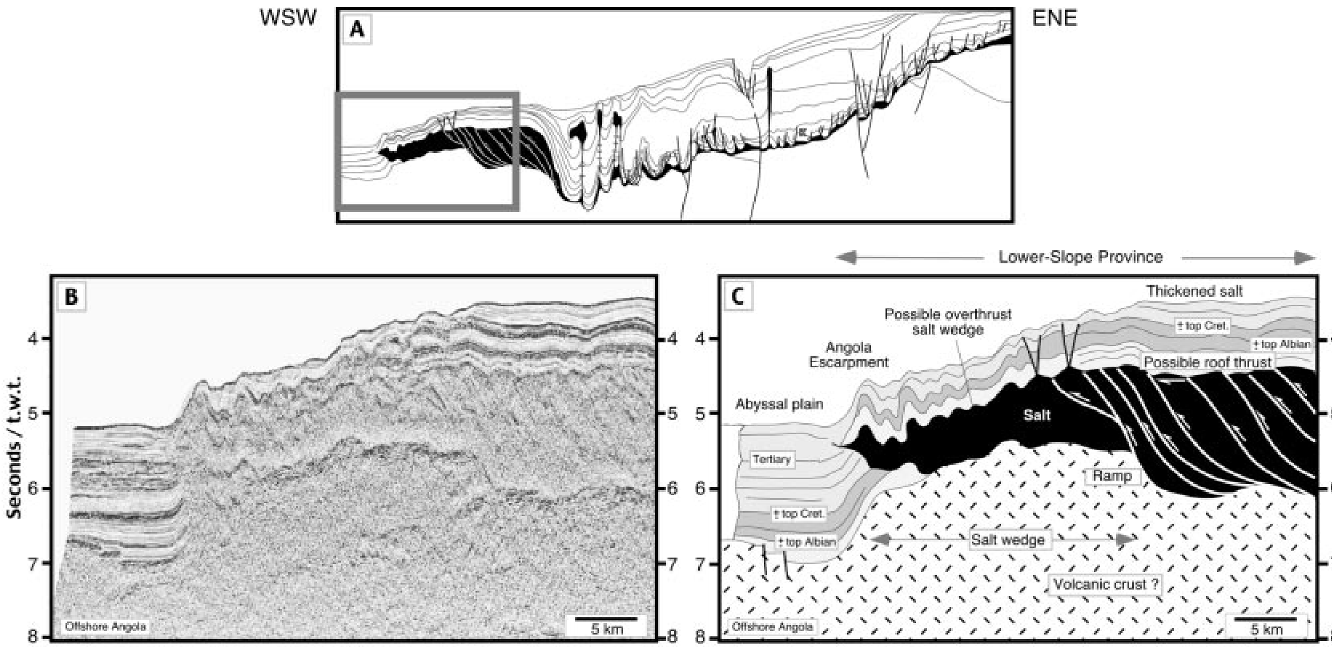

Fig. 14. Thickened salt plateau and salt wedge in the Lower-Slope Province, whose seaward limit is the Angola Escarpment. (A) Location on regional section. (B) and (C) Uninterpreted and interpreted profiles. The conservative tectonic interpretation is shown. Seismic data courtesy of Western Geophysical.

Escarpment, which seismically resembles the Sigsbee Escarpment in the Gulf of Mexico. The Angola Escarpment marks the seaward limit of salt tectonics and can be traced from the Benguela Basin northwards to the Douala Basin.

A major ramp in the base of the salt thins it from ~3500 m in the plateau to ~1750 m in the salt wedge. The salt wedge contains oblique internal reflectors suggestive of internal thrusting, but these are less common than in the thicker salt plateau. The leading tip of the salt wedge climbs smaller salt ramps towards the sea floor.

In the abyssal plain, the seismic record is clear because salt is absent. The acoustic basement resembles typical oceanic crust (mounded, hummocky basement surface overlying chaotic reflectors), including the flank of a possible volcano on the extreme left of Fig. 14. Acoustic basement rises gradually westwards towards the mid-Atlantic ridge. Deep strata in the abyssal plain seismically resemble the deep roof strata above the inflated salt. This similarity is to be expected because we infer that both strata once formed part of the same abyssal plain. Prekinematic roof strata should merge seawards into prekinematic strata of the same thickness and character in the present abyssal plain. Cretaceous strata in the abyssal plain are thus inferred to comprise ~400 m of Pinda equivalent (Albian) and ~400 m of Iabe equivalent (Cenomanian to Eocene). The overlying strata are inferred to be the remaining Cenozoic interval, 3–4 times as thick as the condensed roof of the tectonically elevated salt plateau.

7.4. Angola thrust nappe

This salt wedge fringing the salt province has ambiguous but potentially important implications. These hinge on the nature of the subsalt rocks, which coincide with a prominent and consistent high Bouguer residual anomaly (Jackson et al., 2000). The underlying crust is likely to be dense — possibly comprising a basement uplift or perhaps mafic igneous rocks.

Above this dense crust, layered rocks at least partly underlie the salt wedge and continue horizontally over the abyssal plain towards the mid-Atlantic ridge. Most reflectors below the salt wedge are poorly imaged (Fig. 14). But on some nearby lines, subsalt reflectors are clear and continuous; they appear to be flat-lying in true depth, as in large areas of the Gulf of Mexico (Diegel, Karlo, Schuster, Shoup, & Tauvers 1995; Peel, Travis, & Hossack, 1995). These reflectors are severely distorted by three velocity effects. Strata below the abyssal plain are depressed in time relative to the base of the slope because of: (1) greater depth of sea water; (2) thicker Tertiary interval; and (3) absence of salt. About 800 ms of pullup below the Angola Escarpment (Fig. 14) was calculated simplistically but empirically from data on nearby lines where the subsalt reflectors are clear and laterally continuous.

Even minor shifts in the estimated velocity pullup have huge tectonic implications. A large velocity pullup supports a conservative tectonic hypothesis, whereas a slightly smaller pullup supports a much more radical tectonic hypothesis. First, we examine the tectonically conservative implications of our estimate of ~800 ms pullup. This geometry indicates that the subsalt reflectors (Top Albian and Base Oligocene) are cut off by the salt wedge below the escarpment at points roughly 2 and 1 km, respectively, landwards of the salt pinchout (Fig. 14). Thus, Cretaceous strata

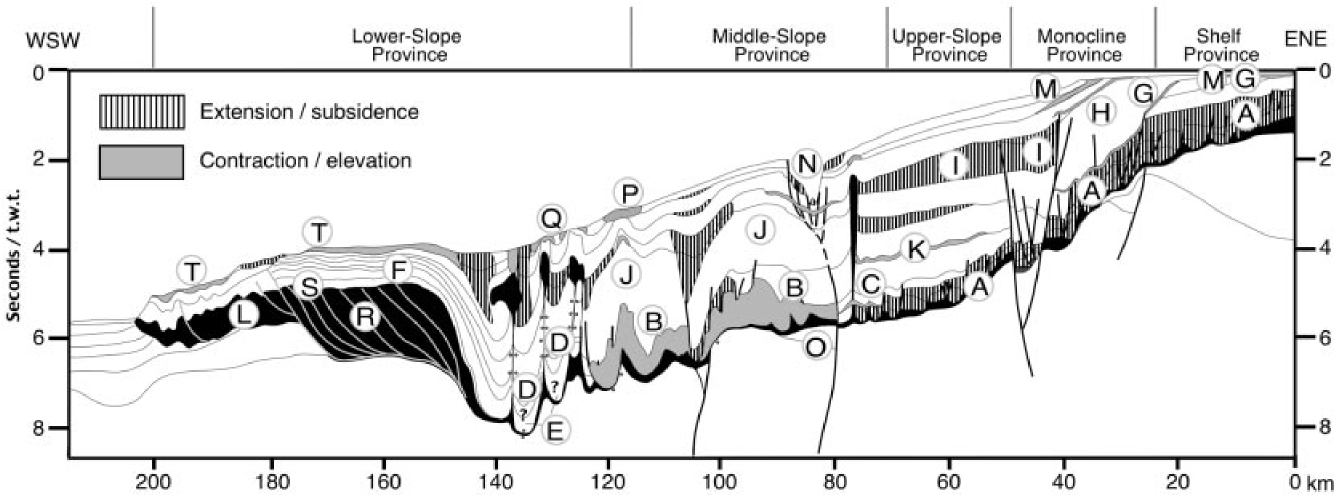

Fig. 15. Schematic regional section (simplified from Fig. 2) showing contrasting zones of: (1) extension or subsidence below regional datum; and (2) contraction or elevation above regional datum. Regional datums are omitted for clarity at this scale. Circled capital letters locate features referred to in the text.

might overlap above and below the tip of the salt wedge. Stratigraphic repetition is uncertain because in this line: (1) cutoffs of strata against the base of the salt have been estimated, not observed; and (2) the suprasalt structure is poorly imaged above the tip of the salt wedge. Any repeated section would indicate Tertiary overthrusting of a thrust nappe comprising the gently buckled roof riding on the thickened salt and its fringing wedge. The roof nappe would be displaced a few kilometers seawards. If this scenario is correct, rocks below the salt wedge must either be uplifted pre-salt (pre-Aptian) terrane or some kind of syn-salt volcanic pile; both are compatible with the observed gravity high. The subsalt lithology is unknown but could include subaerial flood basalts (Jackson et al., 2000). Against this topographic high, the Aptian salt could have ponded as it accumulated. The overlying salt wedge could result from either evaporative expansion of the original salt basin over time or an allochthonous glacial extrusion seawards from the original basin margin.

That is one hypothesis. But if our estimate of velocity pullup is slightly too high and the actual pullup is, say, only ~700 ms or less, the tectonic transport could be much more than a few kilometers. With a smaller velocity effect, pulled-up reflectors would pass landwards beneath the salt wedge, perhaps as far as 20 km where they would be cut off against the main salt ramp. That would have major implications. The main salt ramp would mark the original edge of the autochthonous salt basin. The allochthonous salt fringe would have been emplaced seawards as a glacial extrusion that overrode successively younger post-Aptian strata. Until structural restoration techniques are applied to this section, it is not possible to determine whether the overlying roof strata accumulated before, during, or after the allochthonous salt advanced seawards. If the roof strata accumulated before the salt advanced, then the roof constitutes a ~20-km-overthrusted nappe lubricated by underlying allochthonous salt. The Angola Escarpment would be the steep toe of this feature we call the Angola thrust nappe. Gentle buckling of the roof of the thrust nappe would have added a trivial extra shortening. Moreover, 20 km is a minimum estimate of cumulative shortening of post-salt strata because more Tertiary contractional structures are inferred farther landwards. These comprise mostly buckle folds and pinched diapers, whose closure could account for much more shortening than in the gentle buckle folds above the allochthonous wedge. If correct, this hypothesis indicates a major shortening along the seaward fringe of the Kwanza salt province. These speculations on the amount of shortening refer only to post-salt strata. If imbricated, the interior of the salt plateau must be much more shortened than its roof. In thrust terminology, this would be a passive roof duplex in which a little-deformed, but far-traveled roof is underlain by a roof thrust having bottom-to-seaward relative slip. The roof thrust overlies an intensely deformed thrust duplex within the inflated salt; the intrasalt geometry would be much more complex than a conventional thrust duplex, so the duplex analogy should not be overstretched.

In this hypothesis, two major episodes of thrusting should be conceptually separated. (1) Underthrusting of strata interbedded in salt thickened the salt plateau but caused little strain of the elevated roof. (2) Overthrusting of roof strata over the thickened salt also caused little strain of the roof here but transported it ~20 km basinwards as a thrust nappe.

8. Synthesis of superposed deformation events

To synthesize our conclusions, we summarize the deformation in a time sequence rather than from place to place as for the seismic examples previously discussed. Fig. 15 shows the distribution of two types of deformation zones:

(1) zones indicating either extension or subsidence below regional; and (2) zones indicating either contraction or uplift above regional. These zones are shown in two-dimensional space, but their stratigraphic position also indicates when the deformation took place. The timing of deformation events becomes increasingly uncertain into deep water away from well ties. As many as eight deformation events can be inferred from this profile. However, these events are more manageable if grouped into three longer episodes: Late Cretaceous, Mid-Cenozoic, and Neogene.

8.1. Late Cretaceous deformation events

The backstepping carbonate wedge resting on salt originally dipped seawards at 1–3°. This gentle, regular slope was sufficient to drive the Late Cretaceous gravity spreading. This deformation later subsided because salt thinned locally the overburden thickened and strengthened, and thermal subsidence decayed and tilting declined.

Extension in the form of rafting took place from the shelf to the boundary of the Middle-Slope Province (A in Fig. 15). Farther downdip, strata contracted in a zone seawards, probably to the foot of the backstepping wedge (B). The contractional zone may have eventually propagated slightly updip, so that originally extensional diapirs and rafts were compressed in a narrow zone (C).

Farther down the present slope, several massive salt walls were triggered (D). These diapirs may have broken through erosionally unroofed anticlines formed by buckling. However, the seismic record is too obscure to indicate their origin. We also speculate that the Cretaceous interval could be thin here if it accumulated over an inflated salt plateau that later migrated seawards ahead of the prograding margin (E).

Beyond the salt walls, isopachous strata in the roof of the present salt plateau indicate accumulation in a flat or gently dipping abyssal plain away from any tectonic disturbance during the Cretaceous (F).

8.2. Mid-Cenozoic deformation events

The Monocline Province was created in the Late Oligocene as the shelf and coastal plain rose by 2 or 3 km. The resulting erosion stripped off Paleogene cover on the shelf and cut several kilometers into the underlying Cretaceous carbonate platform (G). That caused the shelf break to retreat landwards by as much as 30 km. Steepening along the monocline created major accommodation space for Miocene progradation, which was enhanced by a major eustatic fall of 0.3 km (H). Uplift also greatly increased the regional dip of the salt and its overburden, which triggered a major episode of renewed gravity spreading.

The major graben in the hinge zone widened and caused Miocene strata to rotate landwards towards the graben (I). Seawards of the present Congo Canyon, another large half graben deepened, probably by expulsion of underlying salt.

Farther seawards in the Middle-Slope Province, the entire thickness of the overburden on the slope began to buckle gently on a wavelength of 20–30 km (J). Buckling began in the Eocene (K). The originally thick salt was depleted by expulsion into downbuilding diapiric walls.

The roof of the present salt plateau remained undeformed and flat-lying or gently dipping in what was then an abyssal plain. However, the salt could have broken out and flowed glacially over the sea floor to create an allochthonous sheet above younger strata (L). Alternatively, this salt wedge could have previously accumulated autochthonously by seaward enlargement of the original salt basin in the Late Cretaceous.

8.3. Neogene deformational events

Minor upwarping of 10–100 s of meters took place at the present shelf break (M). That could have been followed by further uplift of the shelf and coast, but no sedimentary record exists to test this hypothesis.

The modern Congo Canyon may have been structurally channeled along a Tertiary graben (N). The graben seems to overlie an inverted or reactivated subsalt half-graben (O). We speculate that either (1) contractional or transpressional inversion arched the salt's overburden and created a keystone graben, or (2) the subsalt half graben was extensionally reactivated to stretch the post-salt overburden. Either way, the Tertiary graben could have localized the present Congo Canyon.

In the lower slope, major anticlinal flexures continued rising to the present day (P). Adjoining salt walls are also still rising, possibly because of lateral squeezing by the prograding wedge (Q). The original salt thick below these walls was displaced seawards to form the modern plateau of thickened salt. Salt inflation jacked up its formerly undeformed abyssal roof and built the present lower slope (R). The salt could have thickened by lateral inflow of salt. But instead, it seems to have thickened by duplex thrusting of interbedded and imbricated sediments or flood basalts. The tectonically thickened salt is probably separated from its clastic roof by the broad equivalent of a passive-roof thrust (S). The roof buckled gently (T) and appears to have been overthrust for an uncertain distance ranging from 1 km to more than 20 km.

8.4. Causes of superposition

A typical divergent continental margin is generally envisaged to contain three zones: landward extension, seaward contraction, and intervening translation. Progradation of this margin should systematically superpose extension on contraction as deformation zones shift seawards (e.g. McClay, Dooley, & Lewis, 1998).

In contrast, the structures in Fig. 15 illustrate superposed deformation that is far more complex than even a shifting three-fold zonation. Deformation events in the Angolan margin have been superposed in a way that cannot be explained simply by progradation. The delineation of structural zones depends on the subjective choice of regional datums, which is likely to vary slightly among interpreters. However, deformation evidently occurred in pulses in a wide variety of locations, times, and sequences. A nonsystematic sequence of deformation such as this led Raillard et al. (1996) to propose that deformation zones could shift intermittently landwards in response to eustatic relative rise of sea level. However, any landward shifts of depocenters caused by eustatic rise are dwarfed by tectonic events such as the two-to-three-km vertical offset at the Monocline Province. By allowing absolute and relative uplift of the shelf and coastal plain, this monocline seems to have initiated deformation that had a chain effect far down the slope. In summary, deformation zones in the composite section appear to have been influenced by: (1) progradation of the margin; and (2) epeirogenic rise of the shelf and coastal plain in the Oligocene and the Neogene.

Acknowledgements

We thank Ian Davison and David Roberts for their helpful comments. We are grateful to TotalFina Elf's management for supporting all aspects of this research. Western Geophysical kindly authorized publication of their seismic data. This study is released with the approval of TotalFina Elf's exploration partners in Angola. Jackson's research was supported by the Applied Geodynamics Laboratory consortium, comprising the following oil companies: Amerada Hess Corporation, Anadarko Petroleum Corporation, BHP Petroleum, BP Amoco Exploration, Chevron Petroleum Technology Company, Conoco Inc., Elf Aquitaine, ENI-Agip S.p.A., Exxon Production Research Company, Marathon Oil Company, Mobil Exploration and Producing Company, Norsk Hydro, PanCanadian Petroleum Ltd., Petroleo Brasileiro, S.A., Phillips Petroleum Company, Saga Petroleum ASA, Shell Oil Company, Texaco Inc., Statoil, TotalFina SA, Vastar Resources, and Spirit Energy-Unocal. Publication authorized by the Director, Bureau of Economic Geology.

References

Brink, A. H. (1974). Petroleum geology of Gabon Basin. *American Association Petroleum Geologists Bulletin*, *58*, 216.

Davis, D. M., & Engelder, T. (1985). The role of salt in fold-and-thrust belts. *Tectonophysics*, *119*, 67–88.

Diegel, F. A., Karlo, J. F., Schuster, D. C., Shoup, R. C., & Tauvers, P. R. (1995). Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin. *Salt tectonics: a global perspective*. M. P. A. Jackson, D. G. Roberts & S. Snelson. *American Association Petroleum Geologists Memoir*, *65*, 109–151.

Droz, L., Rigaut, F., Cochonat, P., & Tofani, R. (1996). Active turbiditic sedimentation during highstands of sea-level: the large mud-rich Zaire Turbidite System (south-eastern Atlantic Ocean) (abstract). *American Association Petroleum Geologists Annual Convention*, A39.

Duval, B., Cramez, C., & Jackson, M. P. A. (1992). Raft tectonics in the Kwanza Basin, Angola. *Marine & Petroleum Geology*, *9*, 389–404.

Jackson, M. P. A., Cramez, C., & Mohriak, W. U. (1998). Salt-tectonics provinces across the continental-oceanic boundary in the Lower Congo and Campos Basins on the South Atlantic margins (abstract). *American Association Petroleum Geologists International Conference Exhibition* (pp. 40–41).

Jackson, M. P. A., Fonck, J. -M., & Cramez, C. (1999). Salt-tectonics provinces and superposed deformation across the continental-oceanic boundary in offshore Angola (abstract). *Houston Geological Society Bulletin*, *42* (2), 16.

Jackson, M. P. A., Fonck, J. -M., & Cramez, C. (2000). Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks. *Marine & Petroleum Geology*, *17*, 477–498.

Karner, G. D., Driscoll, N. W., McGinnis, J. P., Brumbaugh, W. D., & Cameron, N. R. (1997). Tectonic significance of syn-rift sediment packages across the Gabon-Cabinda continental margin. *Marine & Petroleum Geology*, *14*, 973–1000.

Lavier, L. L., Steckler, M. S., & Brigaud, F. (2000). An improved method for reconstructing the stratigraphy and bathymetry of continental margins: Application to the Cenozoic tectonic and sedimentary history of the Congo margin. *American Association Petroleum Geologists Bulletin*, *84*, 923–939.

Lonergan, L., Cartwright, J., Laver, R., & Staffurth, J. (1998). Polygonal faulting in the Tertiary of the central North Sea: implications for reservoir geology. *Geological Society London Special Publication*, *127*, 191–207.

Lunde, G., Aubert, K., Lauritzen, O., & Lorange, E. (1991). Tertiary uplift of the Kwanza Basin in Angola. *Géologie Africaine, Colloquium Géologique Libreville, Recueil des Communications, 6–8 May 1991* (pp. 99–117).

Lundin, E. R. (1992). Thin-skinned extensional tectonics on a salt detachment, northern Kwanza Basin, Angola. *Marine & Petroleum Geology*, *9*, 405–411.

McClay, K. R., Dooley, T., & Lewis, G. (1998). Analog modeling of progradational delta systems. *Geology*, *26*, 771–774.

Marton, L. G., Tari, G. C., & Lehmann, C. T. (2000). Evolution of the Angolan passive margin, West Africa, with emphasis on post-salt structural styles. In: W. Mohriak & M. Talwani (Eds.), *Atlantic rifts and continental margins. American Geophysical Union, Geophysical Monograph Series*, Vol. 115 (pp. 129–149).

Meyers, J. B., Rosendahl, B. R., Groschel-Becker, H., Austin, J. A., & Rona, P. A. (1996). Deep penetrating MCS imaging of the rift-to-drift transition, offshore Douala and North Gabon basins, West Africa. *Marine & Petroleum Geology*, *13*, 791–835.

Peel, F. J., Travis, C. J., & Hossack, J. R. (1995). Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: a preliminary analysis. *Salt tectonics: a global perspective*. M. P. A. Jackson, D. G. Roberts & S. Snelson. *American Association Petroleum Geologists Memoir*, *65*, 153–175.

Raillard, S., Allix, P., Guerin, G., Mauduit, T., Lecanu, H., & Brun, J.P. (1996). Eustatic control of gravity tectonics: concept, mechanism and limits (abstract). *American Association Petroleum Geologists Annual Convention*, A117.

Spathopoulos, F. (1996). An insight on salt tectonics in the Angola Basin, South Atlantic. In: G. I. Alsop, D. J. Blundell, & I. Davison (Eds.), *Salt tectonics. Geological Society London Special Publication, Vol. 100* (pp. 153–174).

Steckler, M. S., Lavier, L. L., & Bigaud, F. (1997). Reconstruction of the Cenozoic tectonic and sedimentary history of the Congo-Angola margin (abstract). *American Geophysical Union Fall Meeting*, F658.

Uenzelmann-Neben, G., Spiess, V., & Bleil, U. (1997). A seismic reconnaissance survey of the northern Congo Fan. *Marine Geology*, *140*, 283–306.

Walgenwitz, F., Pagel, M., Meyer, A., Maluski, H., & Monie, P. (1990). Thermo-chronological approach to reservoir diagenesis in the offshore Angola Basin: a fluid inclusion, ^{40}Ar–^{39}Ar and K–Ar investigation. *American Association Petroleum Geologists Bulletin*, *74*, 547–563.