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Stratigraphic record of translation down ramps in a passive-margin salt detachment

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Abstract

Ramp syncline basins filled with synkinematic sediments record the incremental translation history and translation rates of strata transported over basement ramps. On passive margins, movement of strata over a stratabound salt detachment is stratigraphically recorded as an isopach thick on the seaward side of a monoclinal ramp. This growth syncline gradually moves seaward down and then off the monocline, as if on a conveyor belt. This shift creates accommodation space for a new isopach thick to form just landward of the older one. Repetition of this cycle creates a shingled series of isopach thicks within the ramp syncline basin. Kinematic forward models and restored cross sections from the Kwanza Basin, Angola, show that the stratigraphic pattern of ramp syncline basins is most influenced by three factors. (1) The relative rates of translation and aggradation control the curvature of the axial trace of the growth synclines. (2) Bathymetric scarps above basement ramps can create spectacular seaward-dipping onlap surfaces >30 km long downdip; adjoining ramps generate stacked, interfering onlap surfaces. (3) Salt diapirs or anticlines are commonly shortened at the top of the ramp, especially where this coincides with the base of the continental slope. Diapir shortening provides a buffer to absorb sliding from its landward side and impede sliding on its seaward side. This buffering can have a major control on the entire gravity-spreading system containing the diapirs.

Keywords: Angola; Gravity spreading; Kinematics; Modeling; Translation; Salt tectonics; Salt diapir; Stratigraphy; Restoration

1. Introduction

Linked structural systems driven by gravity are common on divergent continental margins, where evaporites (generalized here as 'salt') or overpressured shales provide a décollement. Analyses of such systems tend to focus on either the landward extensional domain or the basinward contractional domain. These two regions contain the margin's most spectacular structures and typically provide the firmest quantitative estimates of translation magnitude. By contrast, the intervening translational domain, which links the extensional and contractional domains, is much less studied. This domain is usually regarded as difficult to extract movement estimates from because of the paucity of fault cutoffs. A prevailing view is that the translational domain is structurally simple and acts as a kind of connecting rod that merely links updip extension to downdip shortening. Because the translational domain can harbor major deepwater oilfields (e.g. Girassol, Mars, Thunderhorse), there are strong economic incentives to understand its kinematic role.

We demonstrate how, under certain conditions, the translational domain can provide clear, accurate stratigraphic estimates of the amount of translation and the kinematic history. Such movement estimates can be more robust than those from updip extensional domains or those from downdip contractional domains because of imaging problems of complex fault arrays or the difficulty of separating salt-related deformation from extension or contraction (Hossack, 1995).

How can the translational domain record the amount of transport? As the detached cover moves seaward under gravity, as if on a conveyor belt, accommodation space for a growth syncline is created where the cover rides down a gentle monoclinal ramp in the detachment. This growth syncline is referred to as a ramp syncline basin.

The methodology for interpreting sliding history from synkinematic sedimentary wedges is rooted in studies of

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hanging walls of normal faults. Hamblin (1965) recognized that monoclinal rollover folds ('reverse drag', as he called it) result from hanging wall strain imposed by slip over concave-upward listric faults. More complex normal fault trajectories have an upper ramp separated from a lower ramp by a flat. Over such faults, a rollover anticline–syncline pair forms in the hanging wall of prekinematic strata (Gibbs, 1984). Crans et al. (1980) computed the shape of synkinematic sedimentary wedges in hanging walls as a function of variable rates of extension and aggradation. Later, physical modeling (e.g. McClay, 1990, 1995; McClay and Scott, 1991) showed that rollover anticlines formed in the hanging wall above each concave up fault segment and a hanging wall syncline formed above a convex-up segment. Away from the footwall, each synkinematic wedge pinched out against the top of the prekinematic interval. Towards the footwall, each wedge ended abruptly against the master normal fault.

These model-derived concepts have also been applied to ramp syncline basins in natural ramp-flat-ramp extensional systems. Onshore exposures of rift basins allow ramp syncline basins to be stratigraphically and sedimentologically analyzed. Oligocene extensional systems in the Matelles Basin (Benedicto et al., 1999) and Alès Basin (Sanchis and Séranne, 2000) in the Gulf of Lion (southern France) are instructive. In both basins, only the lower part of the ramp syncline basin is preserved. Upwards through the succession, synkinematic growth synclines and associated facies shift systematically towards the footwall, where the synclines truncate the uplifted and eroded deeper rollover anticline defined by the prerift interval. Here, as in the Devonian of western Norway (Osmundsen et al., 2000), stacked channel units define the trace of the rollover anticline. Other extensional ramp syncline basins have been reported from the Jeanne d'Arc (Tankard et al., 1989) and Carnarvon Basins (Driscoll and Karner, 1998).

Our paper focuses on the sedimentary record of cover translating across monoclinal ramps in thin autochthonous salt on a passive margin. Well-imaged on seismic profiles and present after time-to-depth conversion, these ramps are defined by local seaward steepening of the base salt horizon by a few degrees over a lateral distance of several kilometers. We speculate that the ramps result from the cumulative throw of down-to-the-basin faults below seismic resolution and rooted in the crust. For the purpose of kinematic restorations, ramps are assumed to be fixed in geometry, space, and time and to predate the onset of sliding. Later, we address the difficulty of determining the timing of ramp formation in our study area.

The present paper builds on previous observations—referred to above—that ramp syncline basins shift towards the footwall upwards in a succession. However, the setting of the present paper differs radically from the experimental and natural examples just described in several ways. (1) Our study area is in a deep-water, thin-skinned setting on a divergent continental margin rather than a fluvial setting in a synrift basin. (2) The detachment is a stratabound thin salt layer rather than a normal fault crosscutting stratigraphy or basement. (3) The amount of lateral sliding is greater than in the natural examples. (4) The ramp syncline basin is separated from the main extensional zone by a considerable distance updip, whereas in all the other examples, the master fault interferes structurally with the ramp syncline basin. (5) Regional onlap surfaces, which are shown below to be vital for estimating translation, are preserved throughout the ramp syncline basin instead of just locally near the master fault. (6) The entire translational system received synkinematic sediment and is preserved rather than having sedimentation restricted to the hanging wall (as in models) or having much of the system destroyed by erosion (as in natural examples). (7) The presence of salt diapirs and salt-cored anticlines complicate the geometry and kinematics of ramp syncline basins.

The importance of a salt-detachment ramp in recording the lateral movement of cover on passive margins was first recognized by Spencer et al. (1998), Peel et al. (1998) and Marton et al. (1998) in the Kwanza Basin, Angola. Using detailed restorations, they demonstrated the existence of ramp syncline basins. The geometry of the synclinal fill was inferred to depend on the relative rates of aggradation and translation. Restorations were shown in their poster and oral presentations but were never published until a restoration was included in a global review by Rowan et al. (2004). To estimate translation, the papers assumed that ramps remained fixed over time. Translation distances over the ramp in similar lines were estimated at 20 (Amoco team) and 24 km (BHP-BEG team). Peel et al. (1998) inferred a consistent amount of movement downslope in several lines. The inferred consistency and magnitude of movement are supported by our work in the Kwanza Basin. We expand these concepts in three major ways to examine the stratal patterns associated with (1) bathymetric scarps and the generation of regional onlap surfaces, (2) double ramps, and (3) salt diapirs and salt-detached anticlines. All these interactions have major stratigraphic effects and complicate the geometry and kinematics considerably. Accordingly, a precise nomenclature is necessary (Fig. 1). Building on a preliminary analysis (Jackson et al., 2001), we discuss the interpretation of stratigraphy in ramp syncline basins in two parts. First, simplified kinematic forward models of increasing complexity illustrate how sediment geometries in a ramp syncline basin are formed. Second, seismic examples and three new restorations from the Kwanza Basin demonstrate further complexities in the natural world.

2. Forward kinematic models

Area-balanced, forward models were constructed using GeoSec 2D. The models contain a constant-thickness, prekinematic interval gradually fed seawards above the detachment. The detachment contains one or two gentle

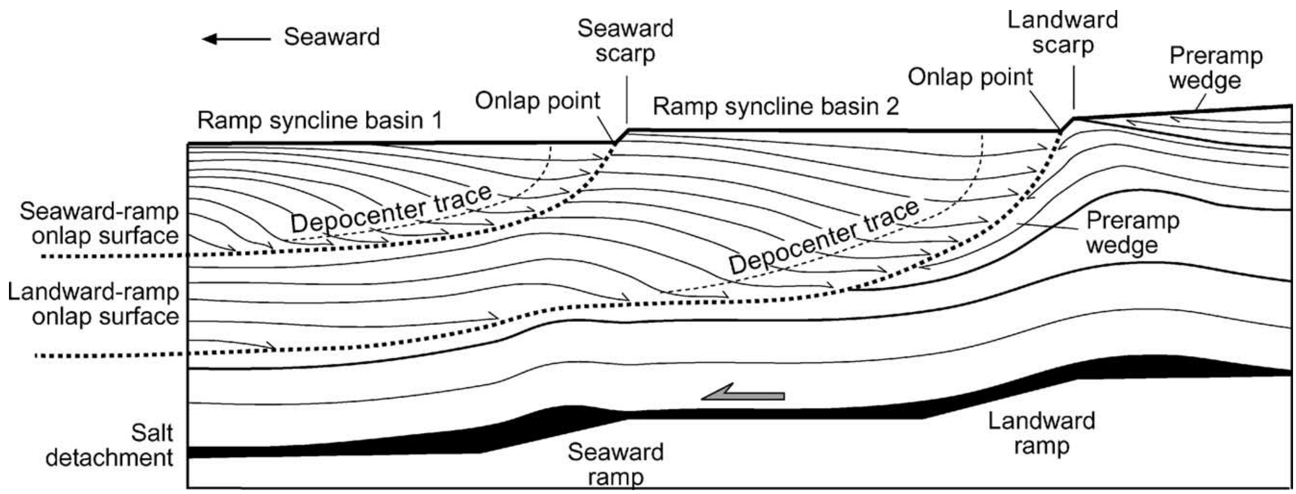


Fig. 1. Schematic cross section showing the nomenclature of ramps, scarps, onlap points, onlap surfaces, depocenter traces, ramp syncline basins, and preramp wedges.

monoclinal ramps. The ramps and subsalt regions are fixed in time and space, as was assumed for the Kwanza translation estimates previously cited. Thus, all translation estimates are with respect to the subsalt basement. The same patterns in the models could be produced by altering the reference frame so that the cover did not move laterally, but the basement ramp moved landward. At each increment of movement, synkinematic sediments infilled the ramp syncline basin. Although all five models are simplistic, they illustrate the most important stratigraphic hallmarks of translation, which are recognizable in more-complex natural examples described in a later section.

2.1. Single ramp

Model 1 illustrates the effects of a single detachment ramp lacking an overlying bathymetric scarp (Fig. 2). Aggradation is fast enough to continually bury the monoclinally draping older synkinematic layers. A gentle growth syncline—the ramp syncline basin—forms in the sag seaward of the ramp crest. As older depocenters move seawards, younger depocenters fill in their place. Continued translation produces a shingled stack of landward-dipping isopach thicks. Each thick is laterally bounded by a pair of growth axial surfaces. The lateral distance between (1) the top of the ramp and (2) the intersection of a horizon with the landward axial surface records the amount of translation since that horizon was deposited. The translation distance decreases upward as the horizons become younger. This model applies to most of the history in the particular section restored by Spencer et al. (1998) and Peel et al. (1998). Peel et al. (1998) recognized that the balance between aggradation and translation controlled stratal patterns. Fig. 2 illustrates how a low ratio of aggradation rate ($\dot{A}$) to translation rate ($\dot{T}$) produces gently dipping axial surfaces. Conversely, a high $\dot{A}/\dot{T}$ ratio produces steeper axial surfaces. This interplay is also a feature of models of normal fault hanging walls (Crans et al., 1980; McClay, 1990, 1995; McClay and Scott, 1991).

Model 2 illustrates the effects of a single ramp overlain by a bathymetric scarp (Fig. 3). A scarp is typically formed by a combination of (1) an abrupt bend at the top of the underlying detachment ramp, (2) a low $\dot{A}/\dot{T}$ ratio, or (3) bathymetric relief over a salt diapir at the ramp crest. Each stratum in the ramp syncline basin originally onlaps the scarp. Each onlap point then moves seaward, and the stratum tilts landward over time. The scarp thus seeds a prominent onlap surface that climbs landward from the oldest onlap point to the youngest onlap point at the present-day scarp. The lateral distance between (1) the top of the ramp and (2) the onlap point of a particular horizon records the translation distance since that horizon was deposited. This geometry more precisely records lateral movement than that in Model 1 because the onlap surface is much better defined than the axial trace of a gentle syncline. However, as will be evident from the restorations of natural sections, two uncertainties reduce the accuracy of translation estimates, even from onlap surfaces. First, the ramp may be so gentle that its top is diffuse. Second, the bathymetric scarp may not directly overlie the top of the ramp; typically, the scarp is displaced seaward of the ramp by the outward bulge of anticlines or diapirs perched above the ramp.

Fig. 4 shows a seismic example of the sedimentary pattern resulting from a single detachment ramp and scarp. The scarp results from a combination of monoclinal draping above the ramp and lateral squeezing and uplift of a salt-cored structure. Seaward of the scarp, the ramp syncline basin comprises reflectors that typically dip and expand landward. They terminate landward against the onlap surface that rises to the

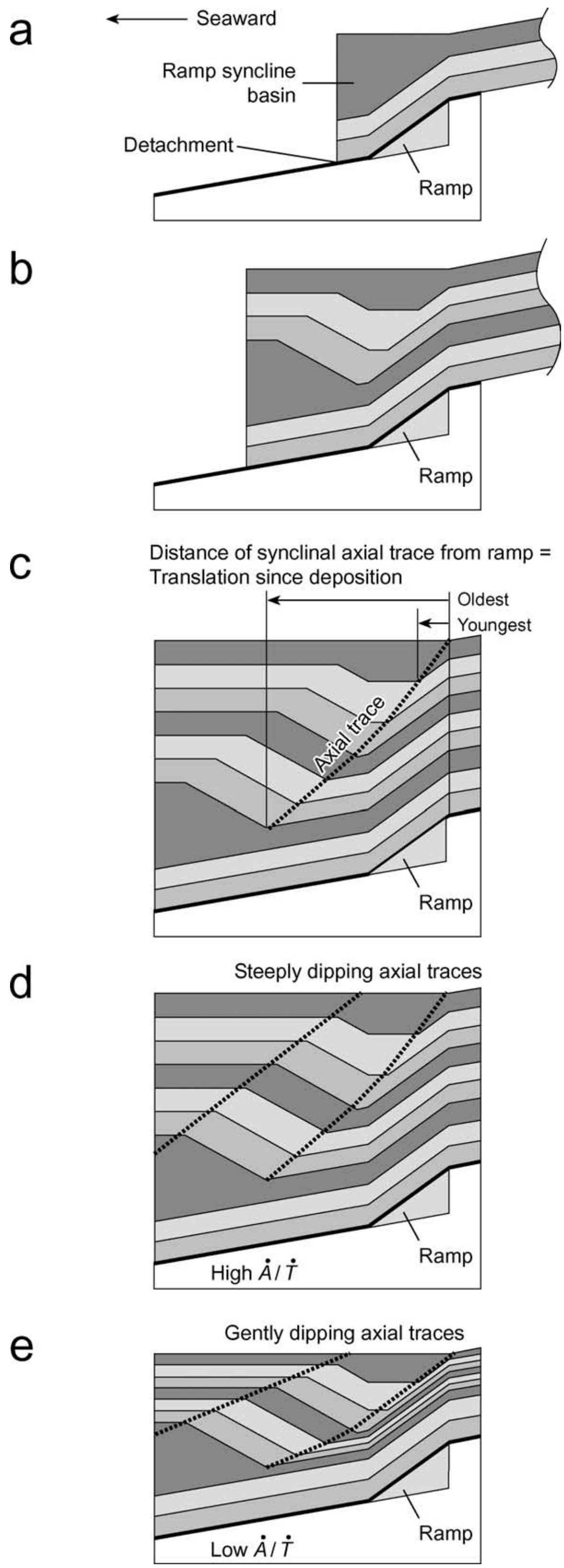


Fig. 2. Kinematic forward model showing the stratigraphic effects of a single ramp during overburden translation where the ramp does not generate a bathymetric scarp. (a)–(c) Evolution: translation can be estimated from the lateral separation of the synclinal axial trace and the top of the ramp. (d)–(e) Comparison of the effects of different ratios of aggradation rate ($\dot{A}$) versus translation rate ($\dot{T}$); where the ratio is high, fold axial surfaces dip more steeply.

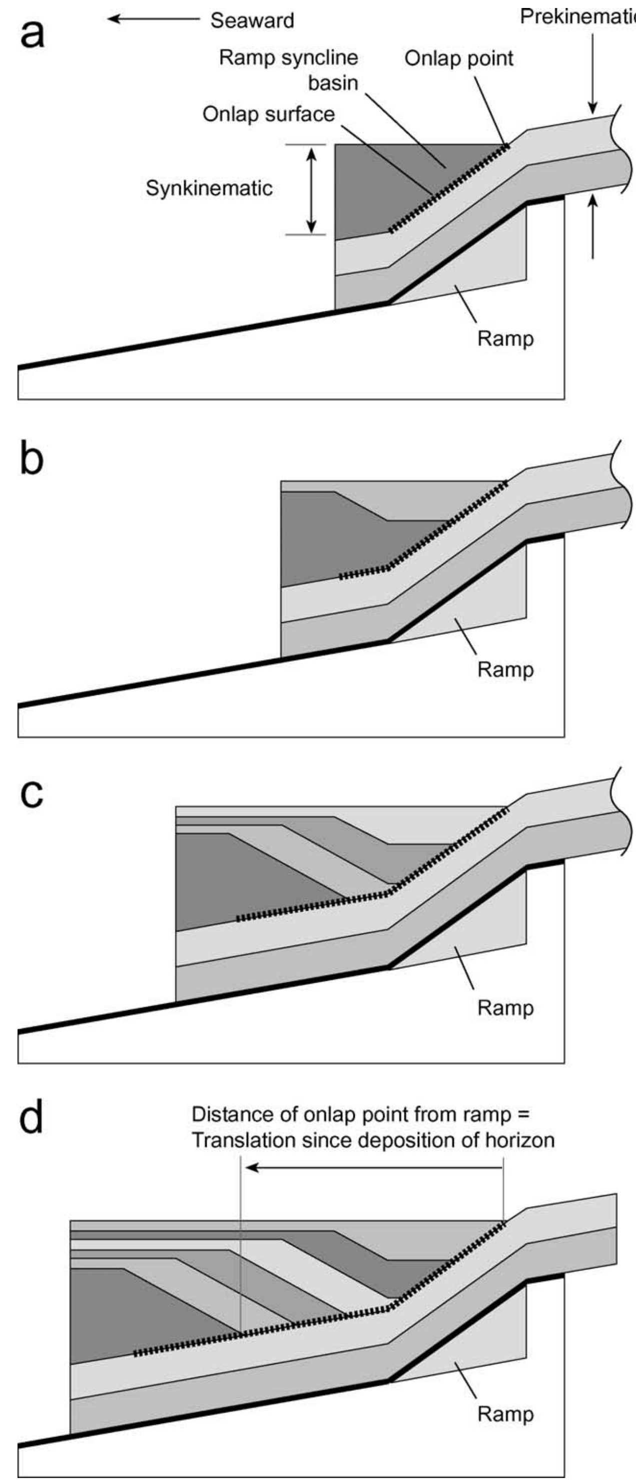


Fig. 3. Kinematic forward model showing the stratigraphic effects of a single ramp during overburden translation where the ramp generates an overlying bathymetric scarp. Translation can be estimated from the lateral separation of an onlap point and the top of the ramp.

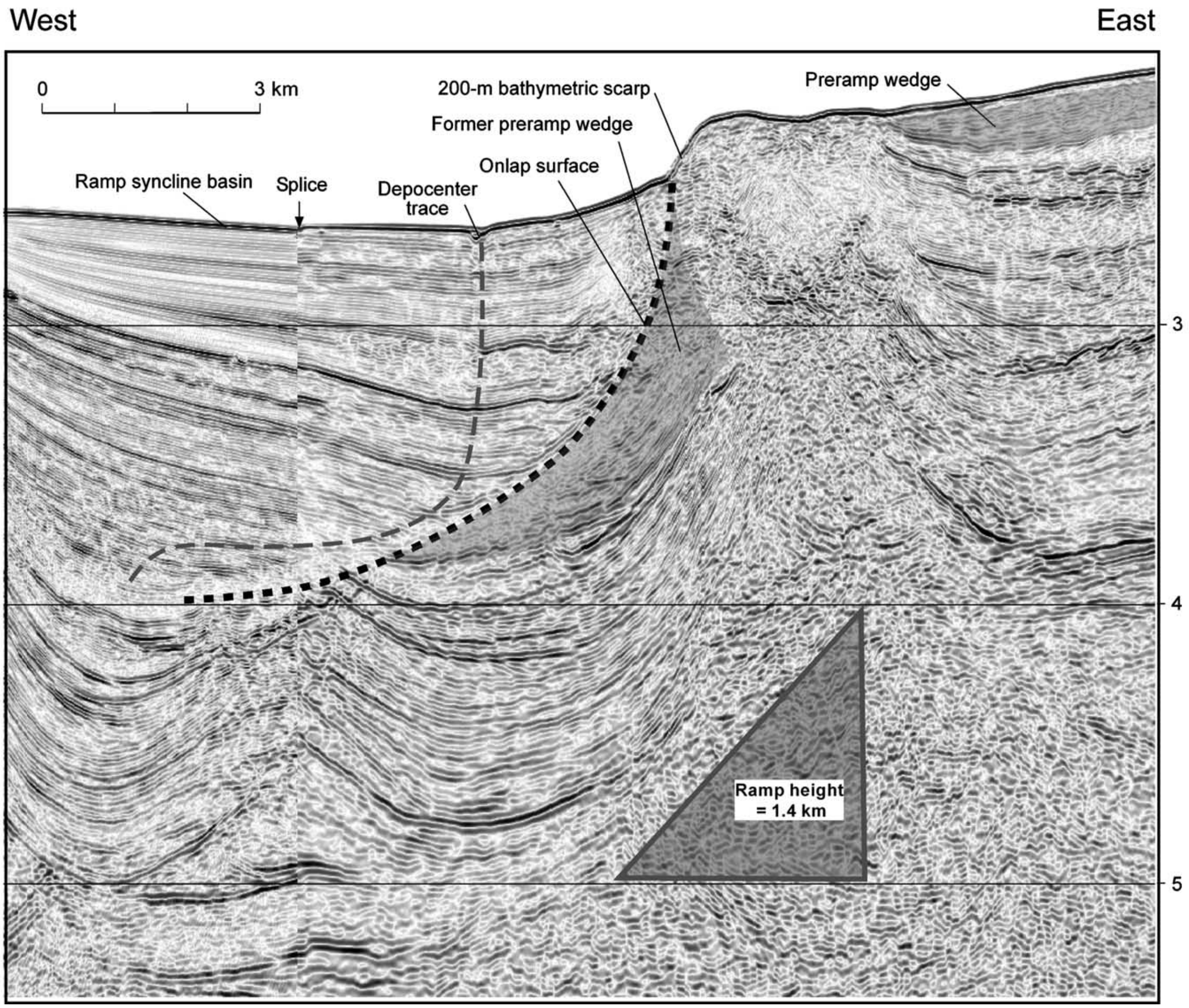


Fig. 4. Seismic profile of a single ramp, showing bathymetric scarp, preramp wedge, and ramp syncline basin. Line of section is shown in Fig. 10. Seismic data courtesy of WesternGeco.

present-day scarp. The lower part of the onlap surface dips gently seaward, indicating a low $\dot{A}/\dot{T}$ ratio. Conversely, the upper part of the onlap surface dips steeply seaward, indicating a high $\dot{A}/\dot{T}$ ratio.

Landward of the scarp is the preramp wedge. By thinning and truncation, this interval pinches out seaward against the bathymetric bulge above the ramp crest. Like the rest of the cover, the preramp wedge moves seaward as if on a conveyor belt. Fig. 5 shows present-day seismic images arranged like snapshots in a kinematic sequence. First, the seaward rim of the preramp wedge is erosionally truncated on approaching the top of the scarp, possibly as a result of flexural loading to seaward. Then, the wedge is draped over the ramp and further truncated. Finally, this truncation surface capping the wedge is completely buried by an onlapping ramp syncline basin.

2.2. Two ramps with scarps

Model 3 illustrates how sliding across two detachment ramps overlain by scarps creates two onlap surfaces (Fig. 6). Sedimentation against the landward scarp creates the landward-ramp onlap surface, whereas sedimentation against the seaward scarp creates the seaward-ramp onlap surface. As in Model 2, the lateral distance between the top of a ramp and the onlap point of a horizon records the lateral movement since that horizon was deposited. In Model 3, however, the two stacked onlap surfaces also provide a cross check: each onlap surface and its correlative ramp should record the same translation distance for the same stratigraphic horizon. Moreover, two onlap surfaces provide a powerful tool for horizon correlation because time-equivalent onlap points are separated by a lateral distance equal to

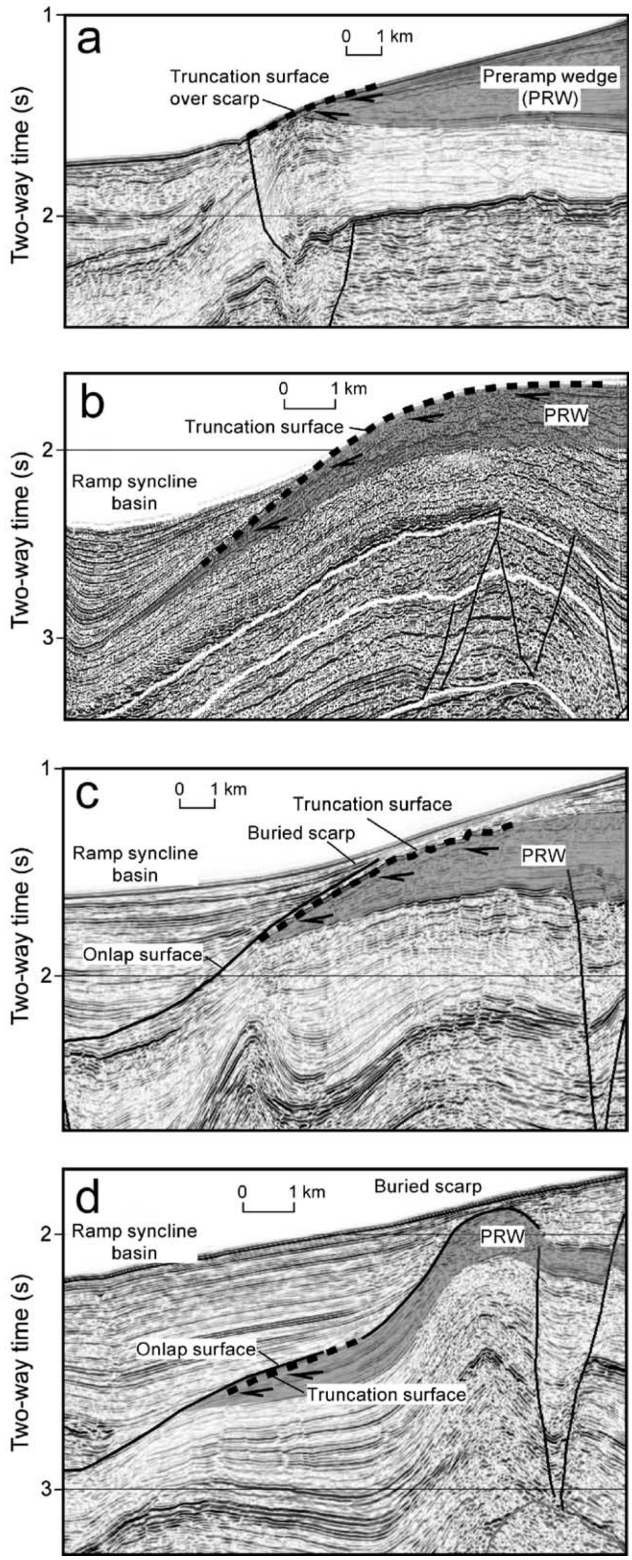


Fig. 5. (a)–(d) Seismic profiles across the Atlantic Hinge Zone, showing movement, truncation, and draping of preramp wedges above detachment ramps. The present-day images are arranged in a kinematic sequence to illustrate these processes. Onlap ((a), (b)) ends when the scarp becomes buried ((c), (d)). Lines of section are shown in Fig. 10. Because these examples are from different fault strands, their spatial arrangement does not match their inferred evolutionary stage. Seismic data courtesy of WesternGeco.

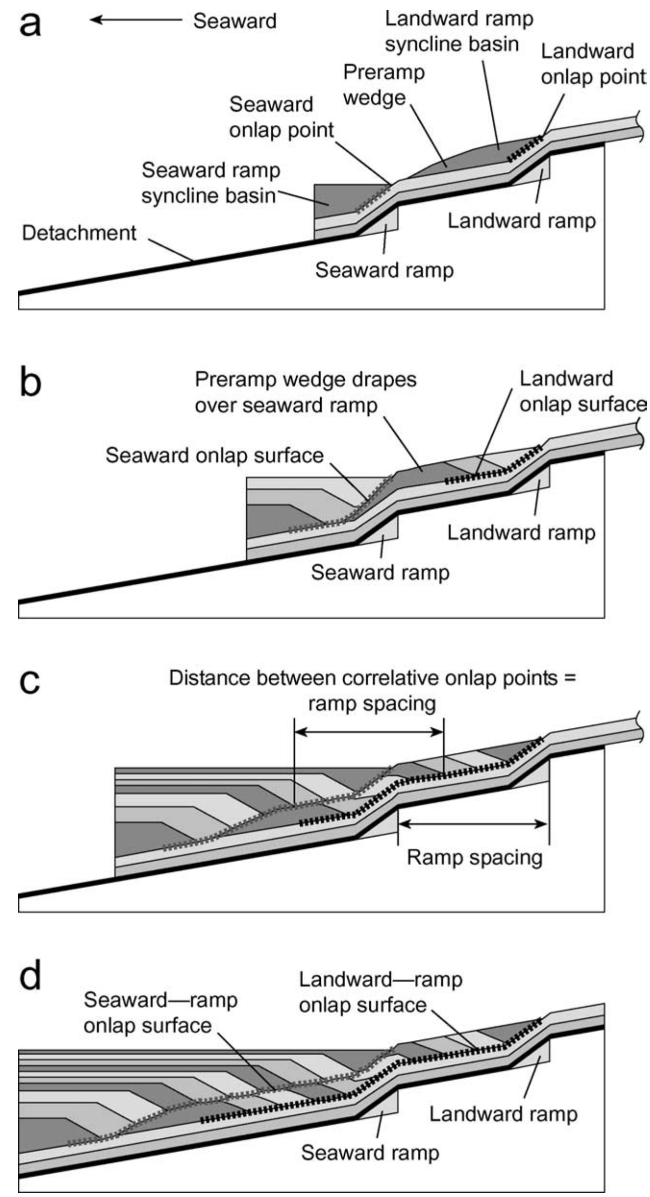


Fig. 6. Kinematic forward model showing the stratigraphic effects of two ramps with overlying scarps. During overburden translation, the scarps above each ramp each generate an onlap surface. The distance between correlative onlap points equals the ramp spacing. Translation can be estimated from the lateral separation of an onlap point and the top of the ramp that seeded the onlap surface.

the ramp spacing. In this model, the onlap surfaces merge seaward, but they may not merge wherever salt flow complicates the kinematics.

2.3. Single ramp with scarp and diapir

Diapirs can markedly affect the tectonostratigraphy because many diapirs begin to shorten laterally once they arrive at the ramp crest (Figs. 7 and 8). Diapirs arrive here after moving seawards with their encasing sediments as part of the gravitationally driven, thin-skinned linked system. Diapir shortening is directly observable on seismic lines

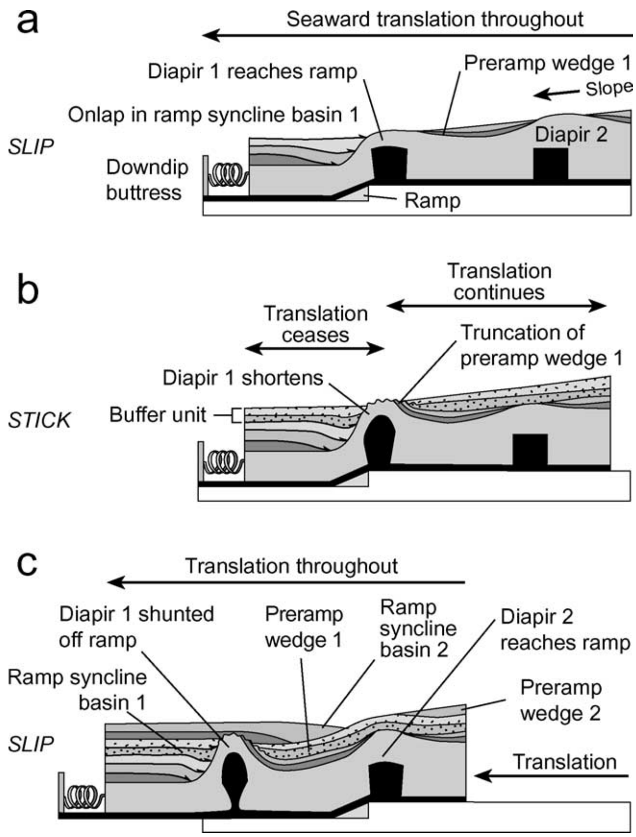


Fig. 7. Schematic cross sections showing evolution of the stick-slip cycle of translation of diapirs (black) moving seawards down a ramp.

(see later restorations and Section 4.3). Three factors favor diapiric shortening near the ramp. The first is toe-of-slope position. In many natural examples, the ramps are located at the foot of the continental slope. Thus, the diapir is ideally placed to be laterally compressed by the downslope shear-stress component of gravity. This shear stress would tend to drive the diapir off the ramp, except for the resistance created by the two types of buttress. One buttress type is seaward thickening of overburden into the ramp syncline basin. The other is the presence of flat-lying strata that continue >100 km farther seaward. The mass and flexural strength of both types of buttress resist translation and enhance diapir compression. This resistance is schematically represented by a spring in Fig. 7, although more complex mechanical models are appropriate.

A laterally shortening diapir can buffer translation. The diapir absorbs sliding on its landward side and prevents or reduces sliding on its seaward side. Once the diapir is squeezed shut and cannot shorten further, sediments flanking the diapir once again move in tandem. We refer to this as a 'shunt mechanism' by analogy to railroad wagons (analogous to rigid slabs of overburden) separated by buffers (analogous to soft intervening diapirs). When the lead wagon in a train of shunted wagons reaches an impediment, the intervening buffers compress and momentarily absorb the movement of the train. After the buffers are fully compressed (analogous to a fully closed diapir), the lead wagon once again starts moving with the rest of the shunted train.

The shunt mechanism is stratigraphically recorded. As the diapir approaches the ramp crest, an onlap surface forms in the ramp syncline basin on its seaward flank. While the diapir absorbs sliding from updip, sediments in the ramp syncline basin aggrade without the onlap or rotation characteristic of translation. Once the diapir is squeezed shut and shunted down the ramp, onlap recommences in the new ramp syncline basin that forms on the diapirs landward flank. The interruption in movement causes the onlap surface to jump to a higher stratigraphic level as it crosses the diapir in a landward direction. The stratigraphic interval that accumulated while the diapir was shortening as a buffer is called the buffer unit. The period represented by deposition of the buffer unit (the buffer stage) equals the duration that the diapir was absorbing movement. The buffer unit, which is recognizable by lacking an onlap surface, separates upper and lower intervals in which the onlap surface is present.

The diapir absorbs translation by expelling salt upward. If the diapir crest is exposed, salt from the passive diapir dissolves at the sea floor. If buried, the roof of the active diapir is pushed upward. Diapir rise can lead to uplift and erosional truncation of sediments on the landward flank of the diapir. This effect enhances the taper of the preramp wedge (Fig. 7).

2.4. Two ramps with scarps and diapir

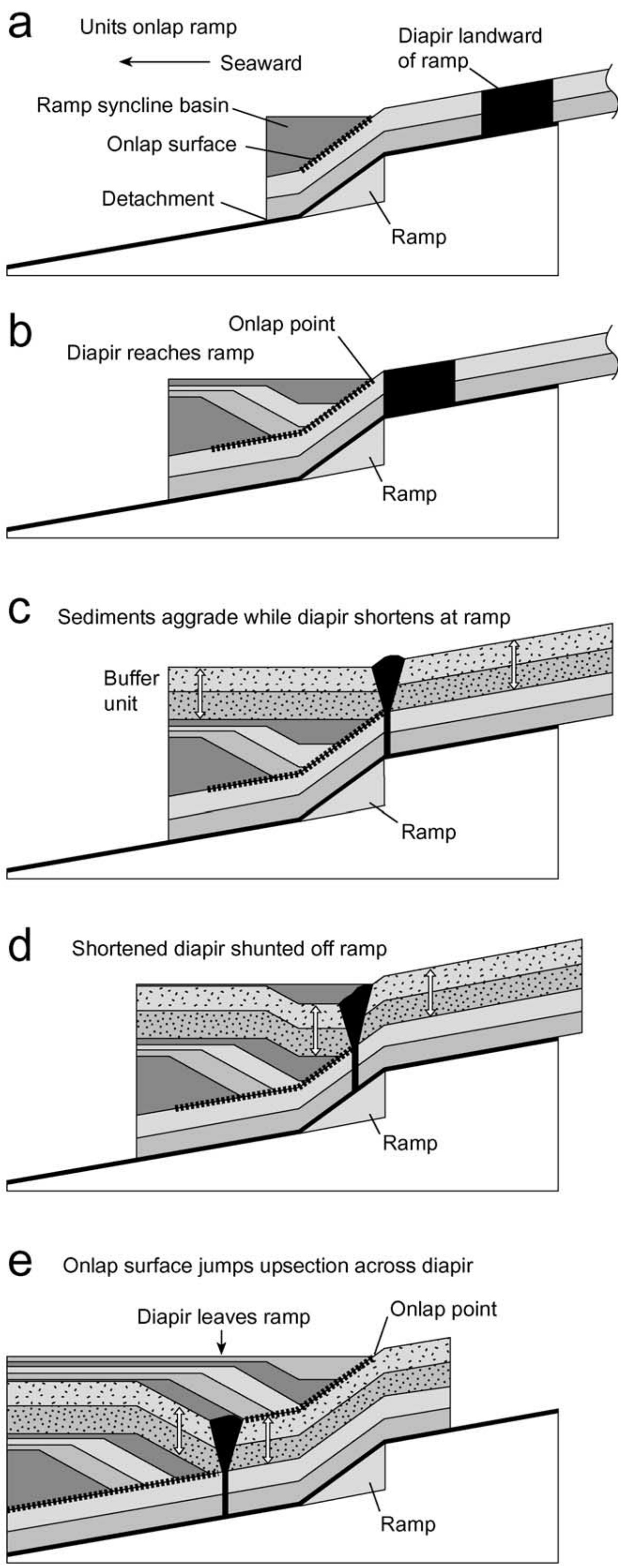
In its complexity, Model 5 (Fig. 9) synthesizes all the previous kinematic models. Sliding across the ramps creates two onlap surfaces. The structurally lower one climbs to the landward scarp, whereas the higher one climbs to the seaward scarp. The diapir causes a stratigraphic jump (across the buffer unit) in both onlap surfaces, which becomes abruptly younger crossing the diapir landward. The younger onlap surface has not completed its landward jump across the diapir because the diapir is still perched at the ramp crest. The younger buffer unit is still accumulating.

3. Structural restorations

3.1. Regional setting

Here we apply principles gained from inspection of seismic profiles and forward modeling to restore three seismic sections from the deep-water Kwanza Basin, Angola (Fig. 10). As well as illustrating the model-derived principles, these restorations reveal complexities absent in the simplistic forward models.

On the Angolan passive margin, sediments were transported seaward across the detachment ramps. Each ramp is a gentle monoclinal seaward bend in the base of salt,



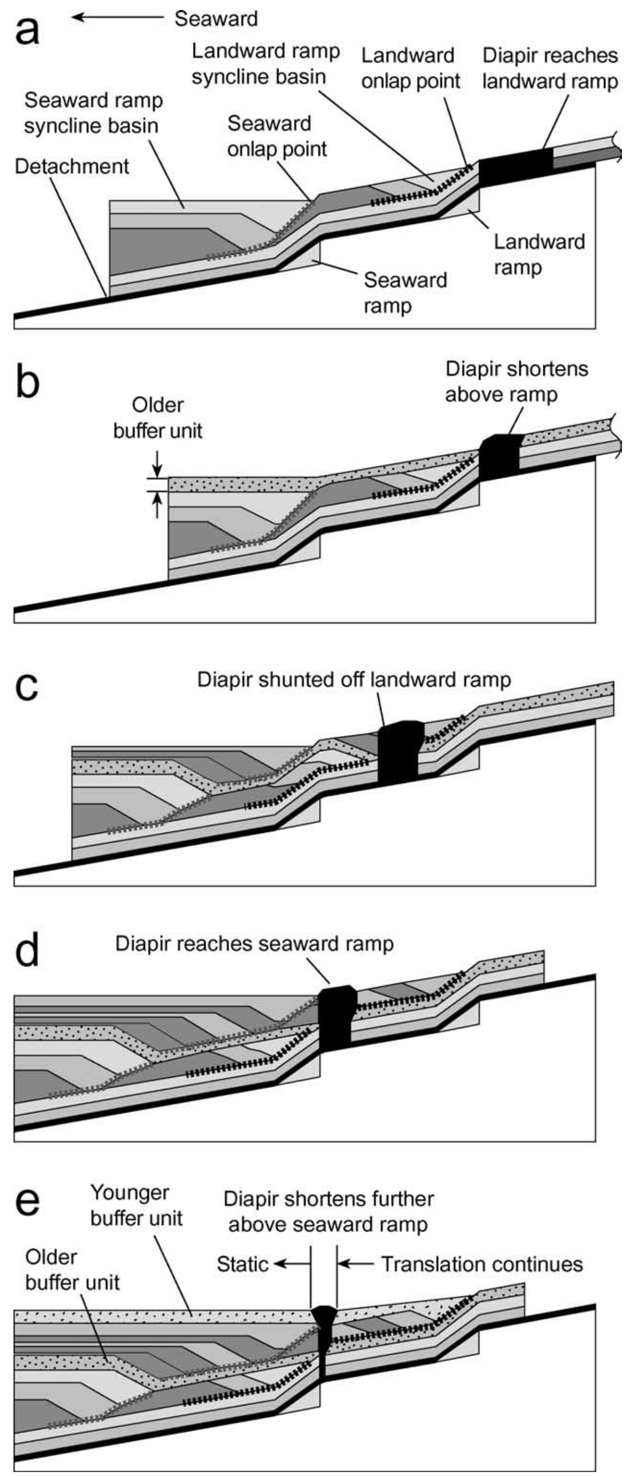


Fig. 9. Kinematic forward model showing the stratigraphic effects of two ramps having overlying scarps and a diapir during overburden sliding. This model combines the complex effects of a salt diapir (Fig. 8), which causes a stratigraphic jump of the onlap surface across the buffer unit, and two ramps, which create a stacked pair of onlap surfaces (Fig. 6).

Fig. 8. Kinematic forward model showing the stratigraphic effects of a single ramp with an overlying scarp and salt diapir. During overburden translation, the diapir reaches the ramp crest and laterally shortens, thereby absorbing movement from updip. This absorption temporarily impedes translation downdip of the diapir. The onlap surface in the ramp basin thus ceases to form while the buffer unit accumulates. Once the diapir is shunted down the ramp, the renewed translation is recorded by a new onlap surface above the buffer unit. The onlap surface thus jumps up-section across an aggradational buffer unit in a landward direction. Translation can be estimated from the lateral separation of an onlap point and the top of the ramp.

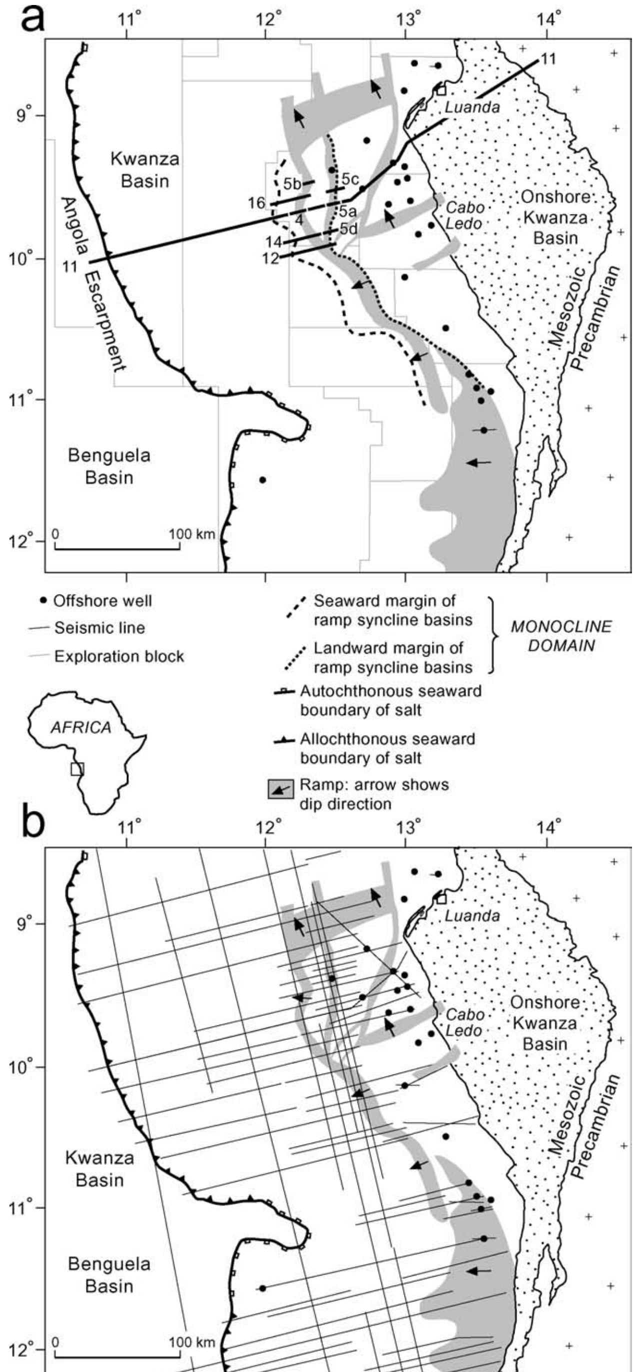


Fig. 10. Location maps of the Kwanza and Benguela basins, showing relevant tectonic elements, offshore well database, and exploration block boundaries. Figure numbers label section lines in (a). Tectonic elements were interpreted from the grid of 2D seismic lines shown in (b). Inset shows location of the map area with respect to Africa.

presumably formed by the cumulative throw of many small subsalt faults. Some of the ramps in the Kwanza Basin of Angola are underlain by concordant sag-stage strata overlying rift-stage half grabens. The ramps are collectively known as the Atlantic Hinge Zone (variously also termed a belt or flexure; Brink, 1974; Peel et al., 1998; Cramez and Jackson, 2000; Tari et al., 2003; Hudec and Jackson, 2004; Rowan et al., 2004). In the center of the Kwanza Basin, the hinge zone comprises two or three ramps (Fig. 10). These ramps merge southward into a continuous ramp about 20 km wide downdip. The relief of the Atlantic Hinge Zone increases southward from 1–2 km in the central Kwanza Basin to 3–4 km in the southern Kwanza Basin and northern Benguela Basin. Fig. 11 shows the setting of the Atlantic Hinge Zone in a vertically exaggerated, 320-km-long profile crossing the entire Kwanza Basin (Hudec and Jackson, 2002a,b, 2004). As for most of the northern Kwanza Basin (Fig. 10), the main (westernmost here) ramp lies at the base of the continental slope. This position promotes shortening of any diapirs or salt anticlines.

In the absence of high-resolution well data, Tertiary horizons were correlated in two ways. Younger horizons were directly tied from minibasin to minibasin using strike lines or were correlated by a distinctive seismic character, if present. Older Tertiary horizons could not usually be directly tied; instead they were correlated mostly by age relationships predicted by the forward kinematic models. Thus, the seismic interpretations and the structural restorations do not verify the kinematic models. Instead, the restorations are internally validated illustrations of how the complex effects recognized in the forward models could interact. Our models, interpretations and restorations make specific predictions on age relationships, some of which are nonintuitive. These predictions can only be verified by drilling and accurate biostratigraphic dating.

Using the methodology in Appendix A, we restored three seismic profiles: Lines 1, 2 and 3. These lines were selected for maximum seismic clarity and structural interest. As with previous interpretations of the Kwanza Basin and our kinematic models, we assume that cover translated seawards over a static ramp; the ramps did not move laterally throughout the restored history. An alternative assumption that the ramps moved landward while the cover remained static is negated by the presence of updip extension zones and downdip shortening zones in the cover (Marton et al., 2000; Hudec and Jackson, 2004; Rowan et al., 2004).

3.2. Restoration of Line 1

Fig. 12 is a seismic example of two stacked onlap surfaces produced by cover moving across two adjoining detachment ramps, each overlain by bathymetric scarps. The restoration (Fig. 13) depicts a translation stage followed by a buffer stage during which a diapir shortened at the top of the ramp. The restoration reveals the following new insights beyond the forward models.

The shape of the wedges in the ramp syncline basin reveals qualitative differences in the relative rates of aggradation and translation. A high $\dot{A}/\dot{T}$ ratio produces steeply tapering wedges in the ramp syncline basin (e.g.

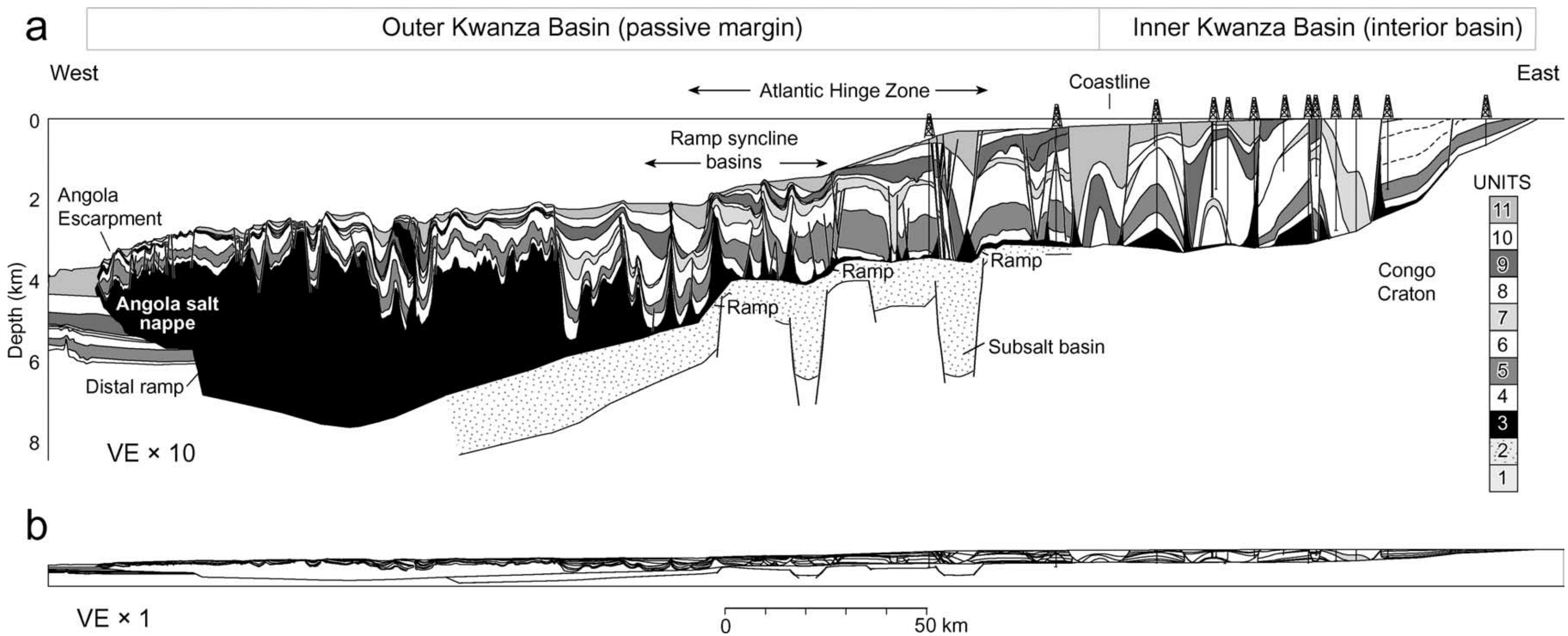


Fig. 11. Regional cross section across the Kwanza Basin, showing the location of the Atlantic Hinge Zone and the translation-related onlap surfaces. Cross sections are shown with 5x and 1x vertical exaggeration. Salt is colored black in (a) and white in (b) to contrast with the black overburden horizons. Line of section shown in Fig. 10. Stratigraphic/structural units: 1, prerift basement; 2, subsalt sediments (Cuvo Group, shown where observed on seismic); 3, Aptian salt; 4, lower Albian; 5, upper Albian; 6, Cenomanian–Eocene (Iabe Group); 7, Oligocene; 8, lower-middle Miocene (to 11.7 Ma); 9, upper Miocene (11.7–8.3 Ma); 10, uppermost Miocene (8.3–5.3 Ma); 11, Pliocene–Recent. Simplified from Hudec and Jackson (2004).

stages C–E). Conversely, a low $\dot{A}/\dot{T}$ ratio produces gently tapering wedges (e.g. stages I–O).

Not all ramp syncline basins are continually dominated by translation; some are periodically dominated by salt expulsion. For example, at stage J, the salt cushion that previously insulated the indentation of the small seaward ramp was expelled. After salt expulsion lowered the overburden closer to the seaward ramp, the ramp impinged for the first time. The resulting bending of the overburden created a short-lived scarp and onlap point above the small ramp, which only lasted during stage J. The subsequent buffer unit separates both onlap surfaces.

The position of the onlap point can shift with respect to the underlying ramp. Onlap points in all of the restorations shift because of two processes. The first is variations in $\dot{A}/\dot{T}$ ratio; decline of this ratio shifts onlap points seaward. The second is the presence of salt-cored bathymetric highs; a large bulge can shift the onlap point even halfway down the ramp.

Draping or sagging of the ramp syncline basin as it moved down the detachment ramp produced local extension. This extension results from outer-arc stretching during monoclinal draping. Extension is rare in other seismic lines, probably because of the dominance of lateral shortening here at the foot of the continental slope.

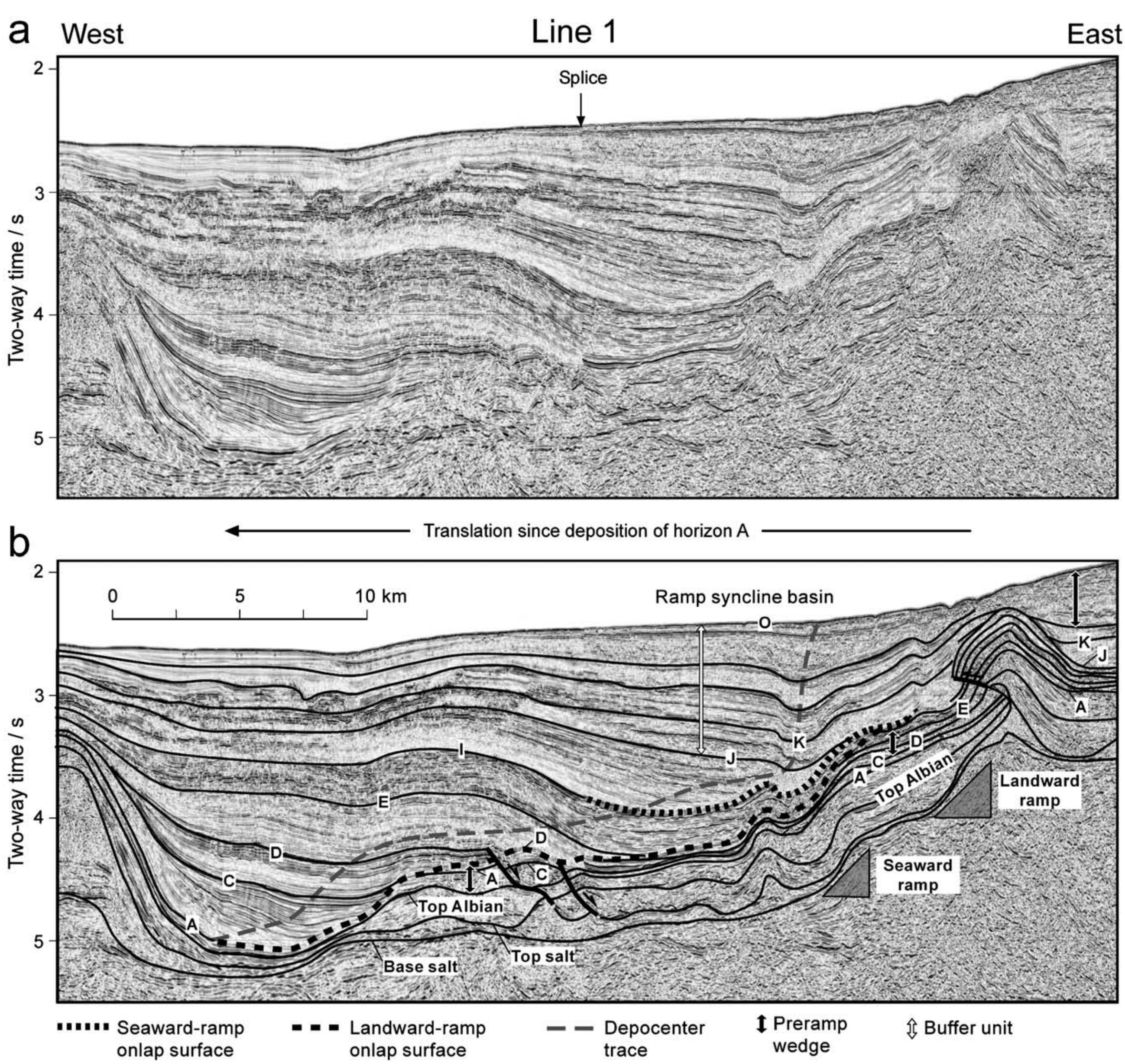


Fig. 12. Seismic line 1 shows two stacked onlap surfaces originating above two ramps. (a) Uninterpreted profile, (b) interpreted profile. Line of section shown in Fig. 10. See Fig. 13 for restoration and age of horizons. Seismic data courtesy of WesternGeco.

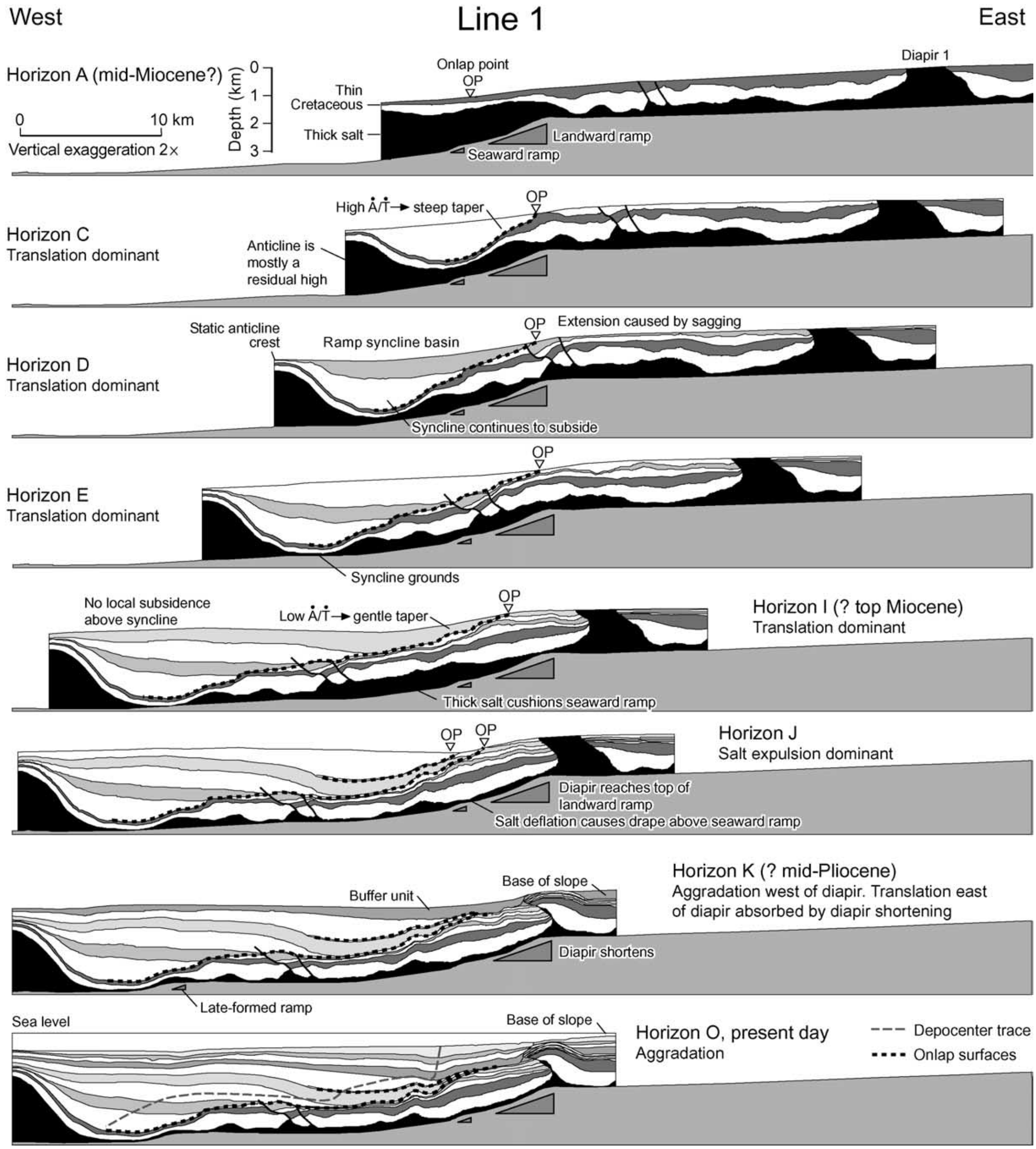


Fig. 13. Restoration of line 1, showing two stacked onlap surfaces originating above two ramps. The 'late-formed ramp' (Horizon K section) is suggested by a slight kink in the overburden, too subtle to be visible in Fig. 12. Fig. 10 shows location of line of section.

3.3. Restoration of Line 2

Fig. 14 shows two stacked onlap surfaces and two squeezed diapirs, one of which was shunted down the ramp. The restoration (Fig. 15) shows two stages of translation alternating with two buffer stages—one for each diapir. This restoration provides further insights over and above those in the forward models and in Line 1.

The ramp acted like a fold-generating conveyor belt. A train of three salt anticlines formed diachronously. The oldest anticline is the most distal, and the youngest anticline is the most proximal. Each anticline evolved as follows: (1) a seaward-facing monocline formed above the ramp crest; (2) the monocline moved down the ramp, tilted seaward, and tightened to form an anticline; (3) the anticline was further tightened seaward of the ramp; (4) adjoining synclines grounded by salt welding, and the anticline ceased to tighten or amplify.

Once each anticline grounded after salt expulsion from the flanking synclines, the fold geometry of the oldest layer (labeled A1–A3) changed little, even as younger anticlines formed just landward. Presumably, the three- to four-fold

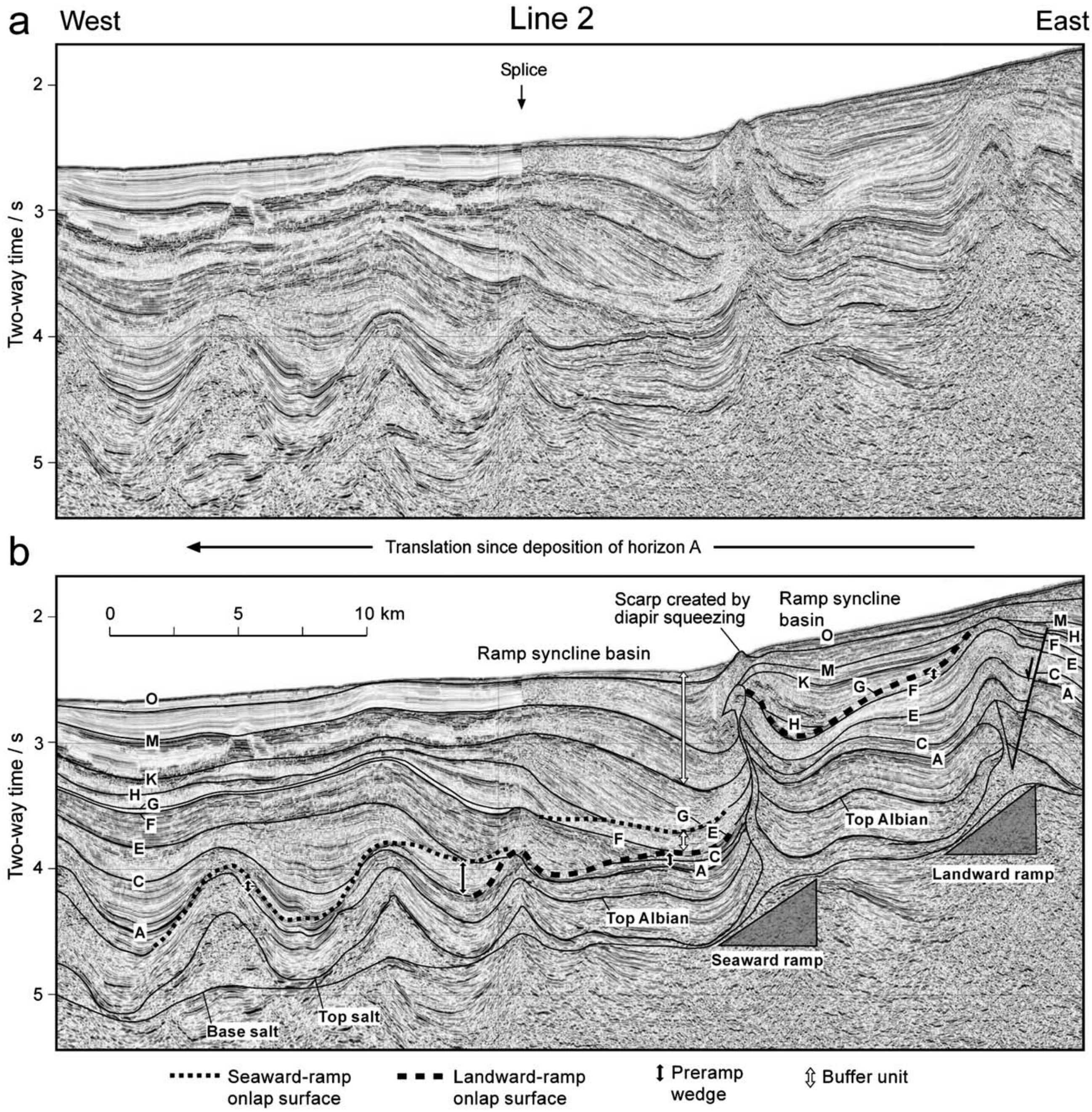


Fig. 14. Seismic line 2 shows two stacked onlap surfaces originating above two ramps and two stratigraphic jumps of the onlap surface: the older one is a jump in the seaward-ramp onlap surface; the younger one is a jump in the landward-ramp onlap surface across the diapir. (a) Uninterpreted profile, (b) interpreted profile. Fig. 10 shows line of section; Fig. 15 shows restoration and age of horizons. Seismic data courtesy of WesternGeco.

thickening of younger synkinematic strata resisted further shortening.

The onlap surfaces complexly interacted. Both the landward and seaward scarps generated onlap surfaces from the start (stage A); then only the seaward-ramp onlap surface was generated (stage E), while the landward area remained high and sediment starved; then only the landward ramp was onlapped (stage F) while the seaward scarp was swamped by aggradation. Stage G represents a buffer stage. After that, Diapir 1 resumed sliding, and both scarps renewed forming their onlap surfaces (stage H).

3.4. Restoration of Line 3

Fig. 16 shows four laterally squeezed diapirs separating four ramp syncline basins. Each basin is bounded on its landward side by a landward-climbing onlap surface. Despite the complexities imposed by four diapirs, the

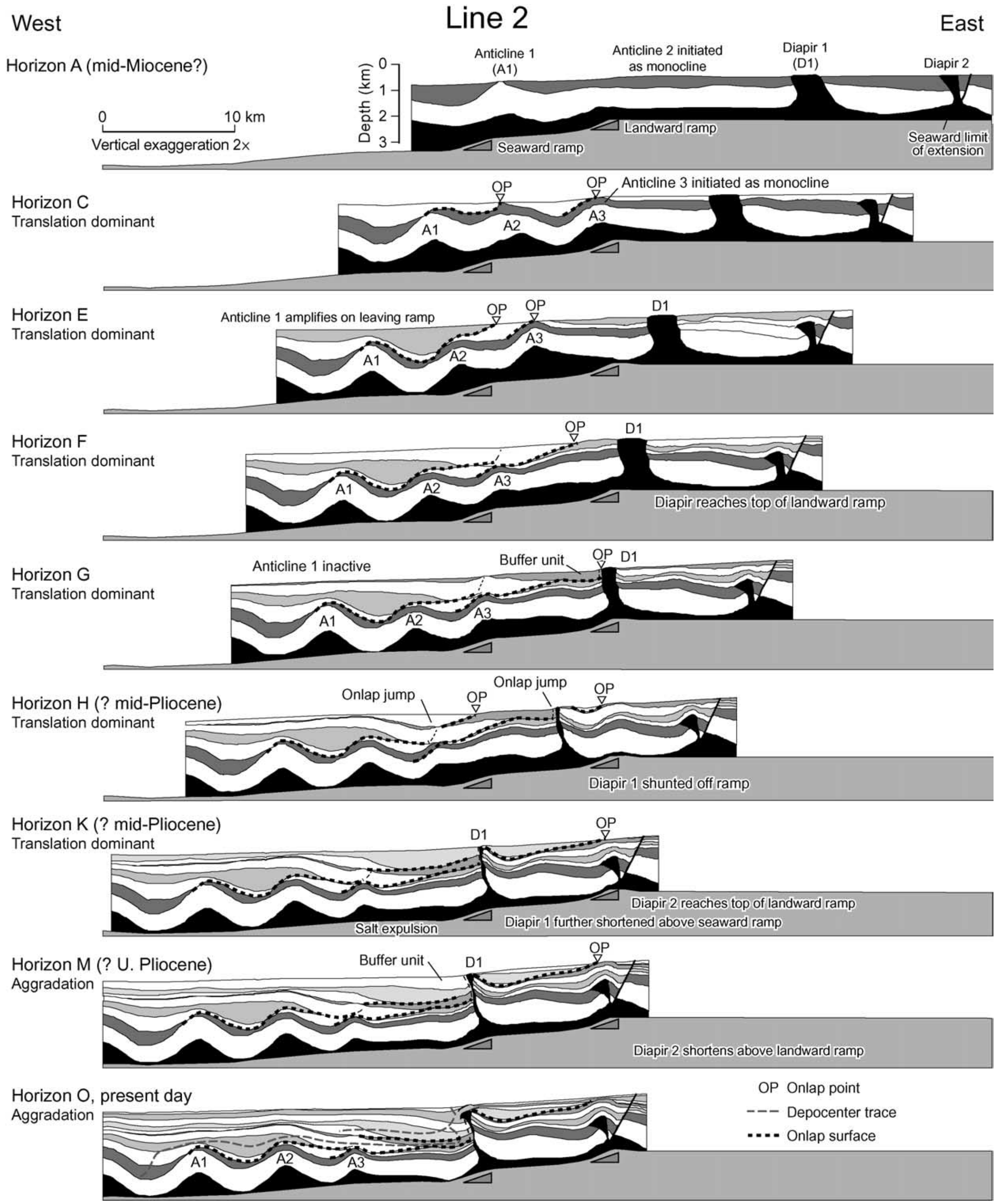


Fig. 15. Restoration of line 2, showing an anticline train generated above a landward ramp during translation. Two stacked onlap surfaces originated above two ramps. Two stratigraphic jumps in the onlap surface formed during periods of aggradation (buffer interval). Fig. 10 shows line of section; Fig. 14 shows seismic image in time.

system evolved remarkably uniformly. As shown by the restoration (Fig. 17), the system resembled a conveyor belt that transported and filled basins as they passed down the ramp. Each ramp syncline basin contains fill that is younger in a landward direction. Each basin sequentially generated an onlap surface as it moved seaward across the large detachment ramp. The curvature of the depocenter trace in each basin records the changing $\dot{A}/\dot{T}$ ratio: an early stage of fast sliding down the ramp is recorded by a gentle dip of the depocenter trace. Conversely in each basin, a late stage of slow sliding followed by buffering is marked by steepening of the depocenter trace; this steepening coincides with

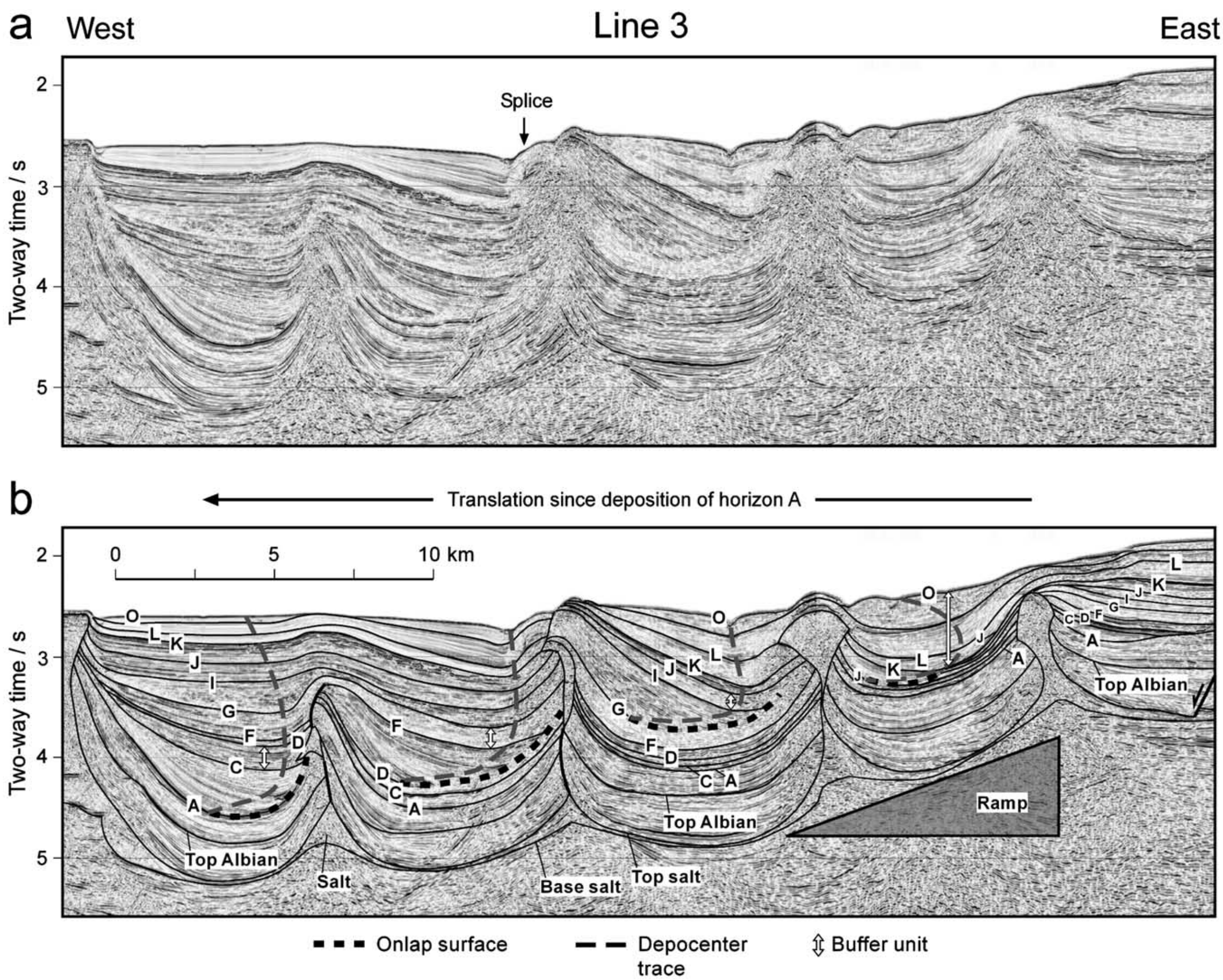


Fig. 16. Seismic line 3 shows cyclic growth of four ramp syncline basins during translation. Successive basins become younger landward and are separated by laterally shortened salt diapirs. (A) Uninterpreted profile, (B) interpreted profile. Fig. 10 shows line of section; Fig. 17 shows restoration and age of horizons. Seismic data courtesy of WesternGeco.

shortening of the diapir, which absorbed translation fed from updip. Diapirs continued to shorten even after being shunted down and off the ramp. Continued shortening was facilitated by the thinness of strata roofing the diapirs. This continued shortening contrasts with the 'fossilizing' of the anticline train in Line 2, whose further amplification was first retarded then prevented by the accumulation of much thicker overburden.

4. Discussion

4.1. Improving seismic interpretation and analysis

The techniques presented here could greatly improve seismic interpretation and analysis of synkinematic strata that have slid seaward down a ramp in a salt detachment. On the one hand, if detailed age control provided by wells is absent, then translational onlap surfaces can elucidate seismic interpretation in two ways. First, the relative position of onlap points and detachment ramps measures cumulative movement. Second, the relative positions establish age correlations between pairs of adjacent ramps and across diapirs.

On the other hand, if detailed age control is available, still more can be elucidated. First, the incremental translation history can be inferred and compared with changes in the petroleum system. For example, if hydrocarbons are generated in subsalt source rocks and the reservoirs are in the postsalt overburden, then the translation history can track the seaward-shifting positions of suprasalt reservoirs compared with the static subsalt source rocks. Second, translation rates can be calculated. Third, it is possible to estimate the duration of the buffer stage during which the kinematic system partly stalled while a diapir was laterally shortened above a ramp.

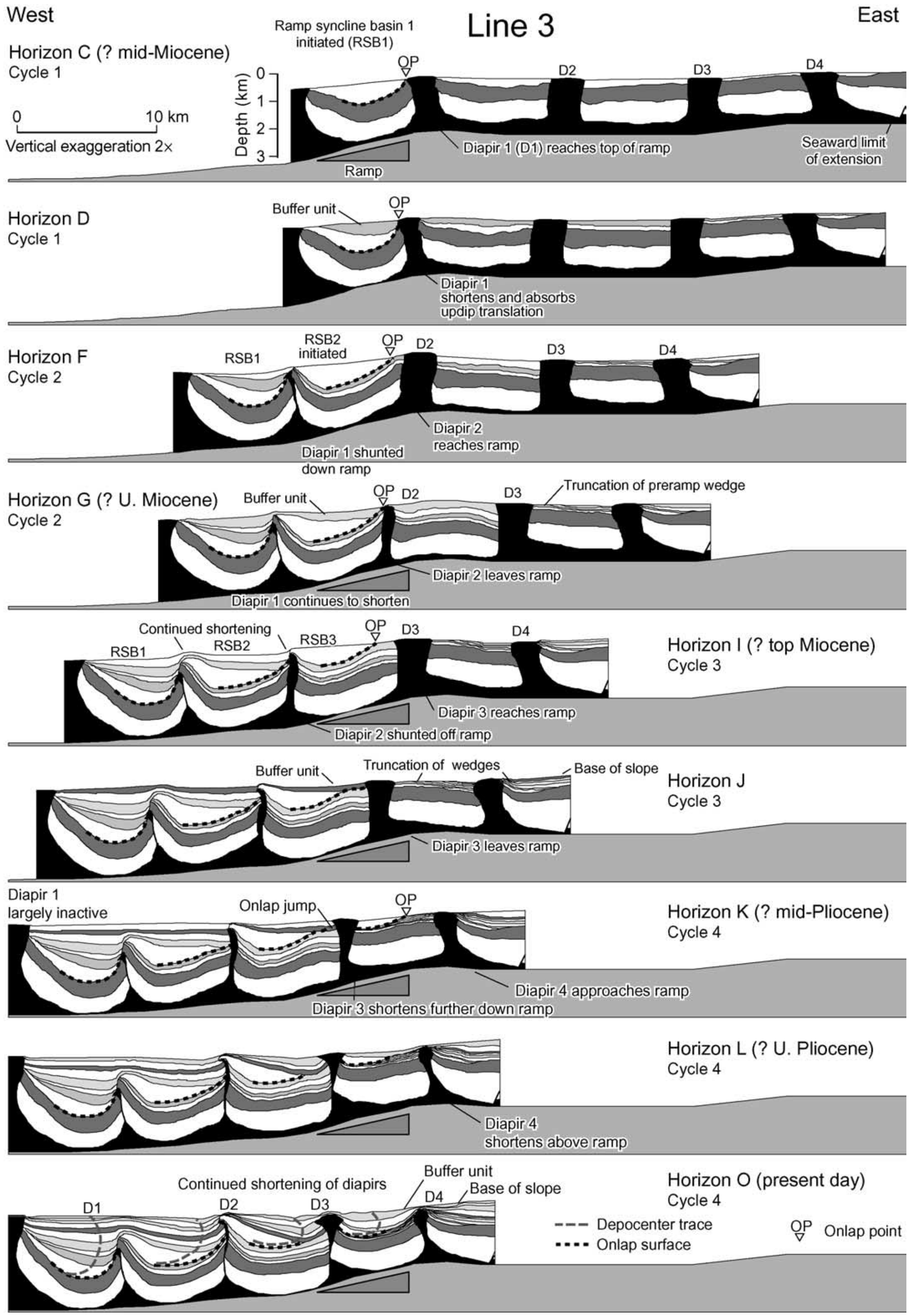


Fig. 17. Restoration of line 3, showing the cyclic formation of four ramp syncline basins. Each basin was filled in turn by onlapping strata during major translation and by uplapping strata during aggradation with only minor translation. Sequential filling of these basins illustrates the cycle of slip-stick schematically shown in Fig. 7. Line of section shown in Fig. 10. See Fig. 16 for seismic image in time.

4.2. Translation versus salt expulsion: interpretation alternatives

A common difficulty in interpreting salt tectonics is to distinguish between the effects of lateral salt expulsion (or salt deflation) and the effects of extension (Hossack, 1995). This difficulty also applies to the recognition of salt expulsion in ramp syncline basins. Both salt expulsion and the sliding of cover down a ramp create accommodation space for sediments and lower strata below their regional datum. It could therefore be argued on principle that some of the ramp syncline basins received extra-thick sediments because the underlying salt was expelled.

Certainly, expulsion has short-lived or second-order effects on these basins, as is most clearly illustrated in Line 1 (Fig. 13). At stage J, a salt cushion several hundred meters thick was expelled. The overburden sagged, which allowed the ramp to impinge for the first time. The resulting bending of the overburden created a short-lived scarp and onlap point above the small ramp, which only lasted during stage J.

The same line also shows evidence for larger amounts of salt expulsion. Between stages A and C, 1200 m of sediment accumulated in the ramp syncline basin. The restoration depicts this accommodation space created by a combination of translation and salt expulsion. The two processes work in tandem: creation of the ramp syncline basin by translation creates the space for the thickened sediments. They in turn apply the differential load that expels underlying salt and creates more space. Stage A could also have been restored with the cover several kilometers farther landward. This option was discarded in order to keep the amount of translation roughly equal to the other three restored lines (two in this paper and one in Hudec and Jackson, 2004).

Could the basins associated with ramps be formed entirely or largely by salt expulsion rather than translation? Several features make this implausible.

First, the onlap surface is discordant. This surface separates the underlying preramp wedge from the overlying ramp syncline basin. The transition is extremely abrupt and well defined. Such an abrupt transition is uncharacteristic of salt expulsion, where salt is gradually expelled over time by a gradually thickening load.

Second, onlap surfaces and ramp syncline basins jump upward and landward across the buffer interval of diapirs. This jump would require 100% of the salt expulsion to occur on the seaward side of a diapir, followed by 100% expulsion on the landward side. It is common for salt expulsion to vary on opposite sides of a diapir, but we are not aware of any example where the difference is so extreme.

Third, two onlap surfaces are stacked. The salt-expulsion scenario requires a stop–start history of salt expulsion in which stability is followed by expulsion then stability then expulsion. For a process driven by the mass of the overburden, which gradually increases, this seems implausible.

Fourth, the ramp syncline basins become younger to landward. Conversely, the best-known examples of salt expulsion typically have a depocenter that migrates seaward because the process is driven by progradation (Ge et al., 1997).

All these distinctive features are difficult to explain by salt-expulsion. At the same time, all these features are inherent in stratigraphy generated by seaward movement down a ramp in the salt detachment. Accordingly, we interpret the stratigraphy as translational ramp syncline basins (some having second-order salt expulsion effects)—as have previous authors in the Kwanza Basin (Spencer et al., 1998; Peel et al., 1998; Marton et al., 1998).

4.3. Onset of translation

Our three restorations all depict the onset of translation-related onlap at horizon A. What age is this? Based on regional correlations with other published cross sections by Marton et al. (2000) and with proprietary horizon picks, the stratigraphic age of horizon A is likely to be early Oligocene to mid-Miocene. Our best estimate is that movement began in the mid-Miocene. This estimate is based on the 330-km regional restoration by Hudec and Jackson (2004), in which Tertiary biostratigraphic data from the extensional domain were integrated with generation of translation-related onlap surfaces farther downdip. This integration suggests that in the three restorations described here, onlap surfaces began to form at about 12–13 Ma.

How does this onset of onlap relate to formation of underlying detachment ramps? The most straightforward answer is that timing of ramp growth is unclear. Several lines of evidence indicate that ramps may not have formed until the Oligo-Miocene. (1) Despite the fact that seaward transport on the continental margin began in the Albian, sediments did not start thickening seaward of the ramp until the abrupt initiation of ramp syncline basins in the mid-Tertiary (Figs. 4, 12, 14, and 16). If the ramps existed before the mid-Tertiary, any early transport would have to have been cushioned by thicker salt seaward of the ramp. (2) In the neighboring Benguela Basin (Fig. 10), the proximal salt is thin or absent, and the structure is simpler. There are no ambiguous complications caused by salt expulsion, so timing of the Atlantic Hinge Zone is clearer. In the Benguela Basin, the onlap surface associated with this ramp is mid-late Tertiary in age (roughly the base Pliocene). (3) The Oligocene to Recent has witnessed major uplift of the African continent (e.g. Bond, 1978; Partridge and Maud, 1987; Sahagian, 1988; Nyblade and Robinson, 1994; Burke, 1996; Gurnis et al., 2000). Formation of a seaward-dipping ramp at this time would therefore be consistent with regional geodynamics.

On the other hand, there are also indications that the ramps are related to older crustal structures. In most areas the ramps overlie half-graben-bounding faults downthrown seaward (Figs. 11, 12, and 14), suggesting that the structures were active during early Cretaceous rifting. Furthermore, regional reconstructions (Hudec and Jackson, 2004) suggest that a major salt basin 3–4 km deep lay immediately outboard of the ramp, indicating that structural relief must have existed here during salt deposition.

Both sets of arguments seem convincing. We therefore suggest that the ramps in the Atlantic Hinge Zone had complex histories that included multiple stages of reactivation. Evidence for multiple phases of basement activity is abundant elsewhere in the Kwanza Basin (Hudec and Jackson, 2002c).

Our restored cross sections begin after the Atlantic Hinge Zone formed. Although its time of formation has little bearing on the validity of the translation model, any reactivation of ramps that caused major change in its geometry would add uncertainty to the movement estimates.

4.4. Translation over time

In the central Kwanza Basin, translation has mostly ceased west of the detachment ramps but still continues east of the ramps. Fig. 18 shows the variation in cumulative movement since each horizon was deposited. The oldest horizon A records the start of translation-related onlap. Since then, the absolute translation of the western end of each of the restored lines 1, 2 and 3 is 26.3, 23.3 and 24.7 km, respectively. These uniform values are compatible with previous estimates of 20–24 km by the Amoco and BHP-BEG teams referred to earlier, which used similar methods and assumptions. Unsurprisingly, our inferred magnitudes of sliding are also compatible with estimates of updip extension and downdip overthrusting by the Angola salt nappe (Hudec and Jackson, 2004). The translation of the eastern end of the restored sections is greater than the western end by several kilometers because the additional translation was absorbed by diapir shortening. However, these eastern estimates are not especially meaningful because they depend largely on estimates of the paleo-widths of passive diapirs; such estimates are notoriously uncertain. The curves in Fig. 18 do not portray translation rates because the *x*-axis is not time. However, the curves do record the fact that movement in the study area largely ended at horizon K, estimated to be of mid-Pliocene age. This was also a time when sedimentation rates increased in the abyssal plain (Bolli et al., 1978; Marton et al., 2000; Fort et al., 2004). Buttress thickening would have impeded the advance of the Angola Salt Nappe, the principal agent of shortening in this part of the Kwanza Basin (Hudec and Jackson, 2002a,b, 2004). At the same time, translation continued east of the Atlantic Hinge Zone in this part of the Kwanza Basin and farther north, as evidenced by extension continuing to the present day (Anderson et al., 2000; Valle et al., 2001). This Plio-Pleistocene extension was absorbed by squeezing of salt structures east of the Atlantic Hinge Zone.

4.5. Spatial distribution of salt diapirs and detachment ramps

Diapirs presently overlie detachment ramps on many of the 17 seismic lines crossing the Atlantic Hinge Zone (Fig. 10b). Spatial correlations between diapirs and ramps define two domains. A northern domain (crossed by 10 seismic lines) extends from Luanda southward to a boundary at the approximate latitude of 9°55′S, just south of Cabo Ledo. A

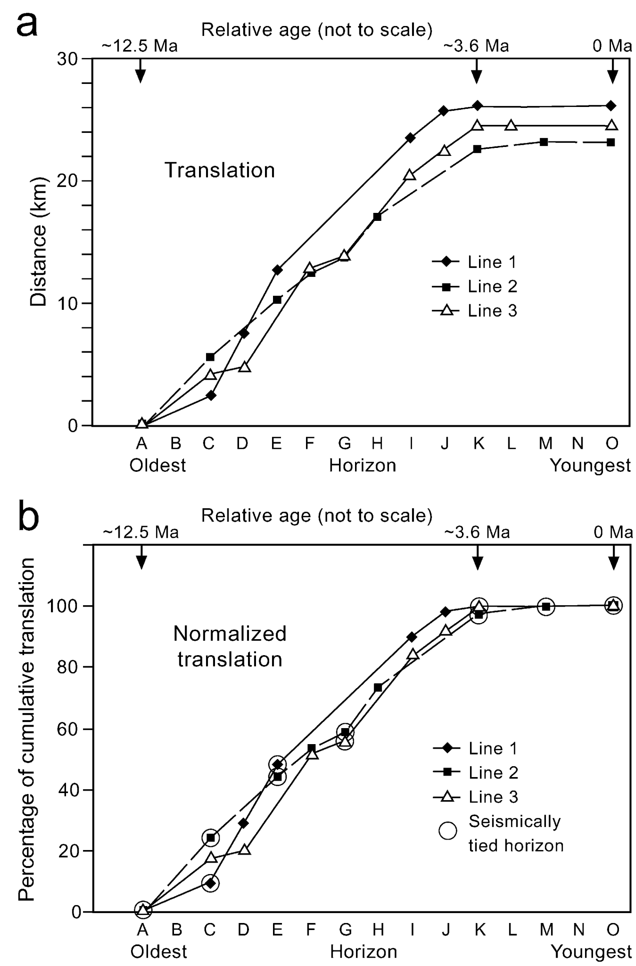


Fig. 18. Graphs showing cumulative translation in each of the three restored cross sections, as recorded by stratigraphic horizons since their time of deposition (Figs. 13, 15, and 17). Horizontal scale is seismostratigraphic and shows only relative age; absolute ages shown are approximate. (a) Absolute translation, (b) translation normalized as a percentage to compare the timing of movement. Some horizons (circled) are seismically tied; these provide interpolation benchmarks for relative age correlations between the three lines.

southern domain (crossed by 7 seismic lines) extends southward from this latitude to the southern boundary of the Kwanza Basin.

In the northern domain, 80% of the seismic lines show a diapir at the ramp crest; this pairing occurs in all three of our restored lines. Restorations (Figs. 13, 15, and 17) and upward steepening of the depocenter traces suggest that seaward movement west of the ramps has now markedly slowed or stopped in all three examples. Conversely, in the southern domain, only 14% of the seismic lines show a diapir at the ramp crest. What causes the difference in the two areas? Several reasons can be explored.

First, it could be merely a coincidence that a string of diapirs is now parked along the ramp crest in the northern area and not in the southern area. The possibility of coincidence cannot be eliminated, but it is statistically unlikely that 80% of the northern diapirs would be crossing the ramp at the same time. To appreciate this anomaly, recall that the average spacing of diapirs in the translation direction is 8 or 9 km. Why are these wide intervening nondiapiric segments only represented in 20% of the northern seismic lines?

Second, it could be argued that diapirs currently parked along the ramp crest are all connected along strike, forming one or two long walls of salt. We consider that long salt walls are unlikely: partly because none of the diapirs seaward of the ramp are aligned, as would be expected if these were merely adjoining sections through a strike-parallel salt wall; and partly because 3D seismic volumes in this area show no salt walls of the required length and continuity (Frank Peel, pers. comm., 2002).

Third, salt stocks could have arrived at the ramp crest at different times and places but became stuck there, failing to advance down the ramp even after being pinched off. Any such mechanism would have to answer three questions: (a) what causes a diapir to stick at the top of a ramp; (b) why was this mechanism not operative in the past, when diapirs were routinely shunted down ramps as soon as they finished shortening (e.g. Figs. 16 and 17); and (c) why did diapirs only stick in the north? We propose that such a mechanism does exist and that its operation in the Kwanza Basin illustrates several key features in the geodynamics of this passive margin.

Our hypothesis rests on the truism that basement-detached extension at the updip end of a passive margin produces seaward translation connected to a zone of downdip shortening. A less common corollary is that if the downdip area is too strong to be deformed then seaward translation is prevented. Patterns of extension and translation on a passive margin thus depend on the geometry and distribution of deformable lithologies in deep water.

Most of the downdip shortening in the Kwanza Basin was accommodated in two places: at the toe of the advancing Angola Salt Nappe and within diapirs shortening above ramps in the basal detachment (Hudec and Jackson, 2004). When both places could shorten, shortening was concentrated at the diapir above the ramp while the distant, downdip part of the system became inactive (Fig. 19a and b). Once the diapir finished shortening, advance of the Angola Salt Nappe resumed, and the diapir was shunted down the ramp.

However, a major event occurred in the Pliocene when the toe of the Angola Salt Nappe began to be buried (Hudec and Jackson, 2004). Eventually, this roof grew thicker and stronger and blocked nappe advance. In this scenario, a diapir arrived at the ramp crest when the nappe toe was only shallowly buried, and the nappe was still active. After gradually shortening over the next several million years, the diapir pinched off (Fig. 19c). However, diapiric shunting off the ramp was prevented because the nappe toe had become buried and could no longer advance. With shortening no longer possible in either previous place, diapirs landward of the ramp began to shorten as compressive stresses were imposed on other zones of weakness. The contractional toe of the system migrated updip of the ramp (Fig. 11), and the diapir is now stuck at the ramp crest.

Strain partitioning in nature is more complex than in our idealized model. For instance, diapirs at the crests of ramps continue to shorten while diapirs are being shortened farther updip. Also, a minor amount of shortening downdip of the ramps indicates that at least some down-ramp transport still occurs. However, several lines of evidence support that essence of the hypothesis. First, onlaps onto the toe of the Angola Salt Nappe indicate that the structure is currently pinned (Hudec and Jackson, 2004). Second, steepening of depocenter traces in ramp syncline basins indicates that negligible translation is occurring farther seaward (Figs. 4, 12, and 16). Finally, onlap patterns above diapirs updip of the ramp indicate that shortening there began very recently; that is, the zones of active shortening are now shifting updip.

Given this hypothesis, how can we explain the prevalence of parked diapirs at the top of ramps in the northern part of the study area, but their relative absence in the south? We argue that in the north gravitational forces driving seaward translation were insufficient to move diapirs down the ramps after the toe of the Angola Salt Nappe was buried, but that the fundamentally different configuration in the south permits translation to continue. Everywhere in the north, the base of the continental slope overlies part of the ramp. Bathymetric seaward dip changes from 2° on the slope to roughly 0° west of the ramp. Moreover, the structural relief of the Atlantic Hinge Zone is modest, ranging from 1 to 2 km. These observations contrast with the southern area, where the base of the continental slope overlies the ramp on only 60% of the lines; in the other 40%, the base of the continental slope lies seaward of the ramp. In addition, the structural relief of the Atlantic Hinge Zone increases to nearly 4 km in the south. These observations suggest that diapirs accumulated at the ramp crest in the north because (1) the lower relief of the Atlantic Hinge Zone is insufficient to destabilize the overlying sediments and (2) subhorizontal strata seaward of the ramp lack a bathymetric slope to drive translation and thus act as a buttress inhibiting sliding. In the southern domain, by contrast, the combination of large relief of the detachment ramp and a location within the continental slope rather than at its foot suggests that the top of the long, steep ramp is too unstable to allow diapirs to be parked there.

If this idea is correct, the Kwanza Basin shows how a translation system shifts from primary to secondary and even tertiary locations of shortening as preferred locations become unavailable. What will happen after the current generation of shortening diapirs is completely pinched off above ramps? In the absence of any other zones of weakness on the margin, the entire kinematically linked system could shut down until enough gravitational potential can be built up to overcome the strength and mass of the various buttresses downdip. This would be consistent with our conclusions from regional restoration (Hudec and Jackson,

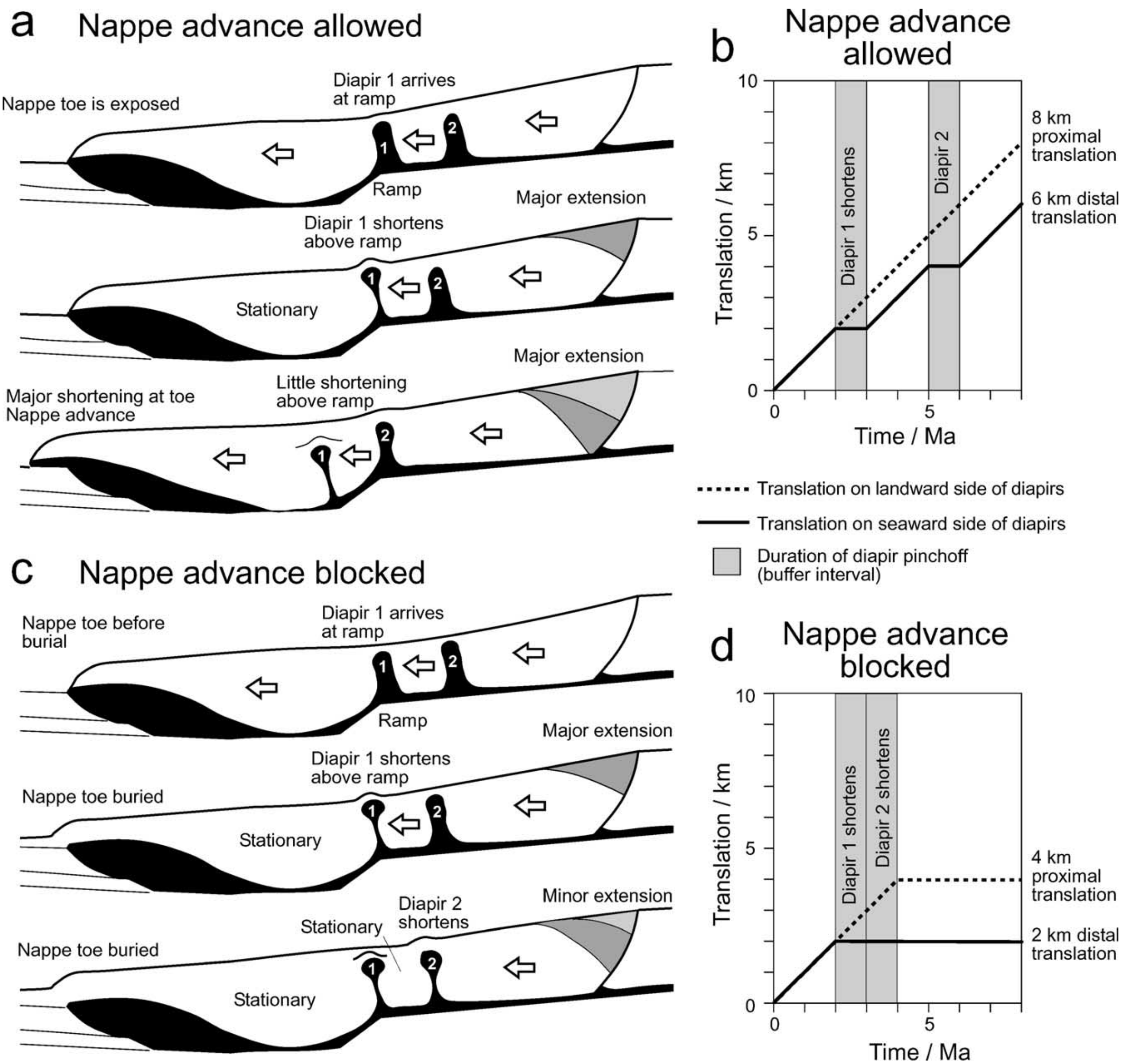


Fig. 19. Schematic relationships inferred between proximal and distal translation, extension, shortening, and the arrival and pinch-off of diapirs above a ramp in the translation domain. (a) Sections showing a diapir being shunted down a ramp, with salt depicted in black. The diapir can be shunted because shortening is accommodated by advance of a salt nappe at the seaward end of the system. (b) Graph showing translation history in (a), assuming an arbitrary translation rate of 1 km/Ma and a convenient (but unnaturally small) diapir width of 1 km. Units located landward of the ramp move steadily downdip from the extensional zone, as depicted by the dashed line on the graph. In contrast, because diapirs absorb shortening at the ramp crest, units seaward of the ramp are stationary until a diapir is shunted off the ramp crest, as shown by horizontal steps in the solid line on the graph. (c) Sections showing a diapir sticking at the top of a ramp because the salt nappe at the seaward end of the system can no longer accommodate shortening. (d) Graph showing translation history in (c), assuming the same translation rate and diapir widths as in (b). Units located seaward of the ramp become stationary after Diapir 1 reaches the ramp crest, as shown by the solid curve. Conversely, units landward of Diapir 2 continue to move until Diapir 2 is completely pinched off, as depicted by the sloping dashed line. Thereafter, if no other structures in the system can shorten, the kinematically linked system shuts down, and all seaward translation stops; the dashed line becomes horizontal.

2004) that the continental margin here was metastable because of a delicate balance between forces driving and resisting gravity spreading. In addition to changes in the basin geometry and sedimentation patterns, the present paper highlights the role of diapirs and detachment shape in affecting the rates and timing of updip extension and downdip contraction.

5. Conclusions

1. Ramp syncline basins form on passive margins by translation above gentle, seaward-inclined ramps in a stratabound salt detachment. Sedimentation during translation creates a shingled stack of isopach thicks in the ramp syncline basin. By assuming or deducing

that the underlying basement ramp is fixed in space, the geometry of ramp syncline basins can record the timing and magnitude of translation.

2. Regional onlap surfaces >30 km long downdip are seeded at bathymetric scarps above basement ramps. Onlap surfaces extend seaward and downward until dying out at a horizon marking the start of movement over the ramp. These surfaces can yield estimates of translation that are much more accurate than those based on the axial trace of a growth syncline. Accuracy is compromised by the fact that restorations suggest that the onlap point can shift slightly with respect to its underlying ramp.
3. Adjoining ramps create stacked onlap surfaces. Each onlap surface and its correlative ramp record the same translation distance for the same stratigraphic horizon. Two onlap surfaces aid horizon correlation because time-equivalent onlap points are separated by a lateral distance equal to the ramp spacing.
4. An origin by salt expulsion for the ramp syncline basins can be eliminated because the onlap surface is discordant, because the onlap surfaces and ramp syncline basins jump upward and landward across buffering diapirs, because two onlap surfaces are stacked, and because the ramp syncline basins become younger to landward.
5. Diapirs are commonly shortened at the top of the ramp, especially where the ramp coincides with the base of the continental slope. Downslope shear stress tends to drive the diapir down the ramp, but this stress is resisted by two types of buttress. One buttress is the seaward thickening of overburden into the ramp syncline basin. The other is the presence of flat-lying strata that continue much farther seaward. The mass and strength of both types of buttress resist movement and enhance diapir shortening.
6. Lateral shortening of diapirs and salt anticlines absorbs sliding from landward and impedes sliding farther seaward. This absorption is recorded by a buffer unit, which lacks an onlap surface and separates upper and lower intervals in which the onlap surface is present. Diapir shortening is recorded by a jump of the onlap surface across the buffer unit to a higher stratigraphic level across the diapir in a landward direction.
7. Salt anticlines continue to shorten laterally even after they are shunted down and off the ramp if the accumulating overburden remains thin; if this thickens three-fold, then the anticlines are not further deformed.
8. Where a train of diapirs moves sequentially down a ramp, the spaces between the diapirs are filled by diachronous ramp syncline basins. Each basin records an early stage of fast movement down the ramp followed by slow movement then buffering of translation as the landward-bounding diapir begins to shorten.
9. Ramp syncline basins in the Kwanza Basin record a remarkably consistent range (23–26 km) of translation. This confirms previous estimates of the sliding magnitude. However, our estimated translation rates are much higher because we infer that ramp syncline basins only began to form in the mid-Tertiary, rather than in the Albian (Spencer et al., 1998). The series of ramps constituting the Atlantic Hinge Zone appear to overlie rift-age (Lower Cretaceous) half grabens, but the ramps began to create a translational stratigraphic imprint only in the Oligocene to Pliocene.
10. Diapirs tend to accumulate at the ramp crest where the basement ramp has low relief or where buttressing sediments seaward of the ramp are subhorizontal. This is typical of the Kwanza Basin north of Cabo Ledo. Conversely, a combination of high-relief ramp and location within the continental slope rather than at its foot creates a long, steep ramp, which is too unstable to allow diapirs to be temporarily parked there. This situation applies to the southern Kwanza Basin.
11. Diapirs embedded in translational domains can influence how and when gravity spreading occurs on a passive margin. On a passive margin where advance of a salt nappe permits distal shortening, translation occurs over a wide area but is modulated above a ramp by the arrival of a diapir that shortens, pinches off, and is shunted off the ramp and replaced by its proximal neighbor. Conversely, on a passive margin where distal shortening is blocked by abyssal sedimentation, diapirs that would formerly have been able to move seaward down the ramp become temporarily arrested rather than shunted down the ramp; any translation fed in from landward is absorbed by squeezing of the next landward diapir.

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Appendix A

A.1. Forward-modeling methodology

The area-balanced ross-sections were modeled using GeoSec-2D. The illustrations show only a few key stages from each model. The cross sections are not to scale and are vertically exaggerated to enhance stratigraphic thicknesses. All deformation was by vertical shear. The salt detachment is thin in order to highlight the effects of translation and nullify the effects of salt mass transfer.

A.2. Restoration methodology

Seismic profiles in time were depth converted using LithoTect, based on time–depth data supplied by oil companies, modified according to newer exploration wells. Depth sections were then exported to GeoSec for restoration. Stratigraphic units were decompacted using lithology estimates derived from wells and seismic facies. Folds in extensional and halokinetic structures were restored using vertical simple shear. Contractional structures were restored using flexural slip. Salt cross sectional area was constrained by a salt budget that maintained area when all salt structures were buried, and which lost area forward in time whenever salt structures emerged at the surface and began to dissolve.

The paleogeometry of the sea floor was constrained by (1) the aforementioned salt budget, (2) the assumption of a rigid basement throughout the Neogene, except for a small, local adjustment of subsalt strata possibly present in Line 1 during the late Pliocene, (3) bathymetric scarps inferred during times of onlap generation, (4) the maintenance of either continual rise or fall of salt structures wherever they were consistently overlain by local thins or thicks (e.g. anticlines were assumed not to alternate times of rising and sagging). The restorations are independent of water depths.

After each diapir was moved to the top of the ramp, it began to be laterally squeezed, which continued as it was shunted down and off the ramp. Evidence of shortening is provided by the narrowness of the welded diapirs and their overthrust flanks. The diapirs emerged at the surface for most of their history, so no roof strata are preserved to record the paleowidths of the diapirs until late in their history. Thus the total shortening is mostly an educated guess. We estimated that the original widths of the diapirs were unlikely to be less than 2 km wide, which is roughly the lower size limit of unsqueezed salt diapirs around the world.

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