Structural Framework of Lower Cretaceous Half Grabens in the Presalt Section of the Southeastern Continental Margin of Brazil

Oscar López-Gamundi
C&C Energy, Carrera 4 72-35, Bogota, Columbia (e-mail: olopezgamundi@ccenergy.com.co)

Roberto Barragan
Hess Exploration Malaysia, 207 Jalan Tun Razak, 5400, Kuala Lumpur, Malaysia (e-mail: rbarragan@hess.com)

ABSTRACT
Recently acquired and processed prestack depth-migrated seismic data have helped to identify the key elements of the asymmetric Lower Cretaceous half grabens in the presalt, synrift-to-postrift transitional (sag) section of the Greater Campos Basin (Santos, Campos, and Espirito Santo basins), offshore Brazil. Evidence of such a structural configuration is provided by seismic reflection geometries, such as fanning (strongly divergent internal configuration) on fault borders, thinning (convergent internal configuration), and onlap onto flexural margins. Moreover, compaction synclines over basement footwall cutoff points have been identified. In poorly imaged areas, the termination of the divergent seismic configuration can be used to place the master fault of the half graben. Differential compaction at half-graben border fault margins caused by the contrasting nature of rift-fills and adjacent basement highs is postulated to have been a critical factor for the creation of counterregional dips necessary to form structural four-way closures at the sag level. Although the sag sequence extends beyond the underlying rift fill, commonly onlapping or draping over the basement, the key risk in these types of traps is the possibility that the overlying salt layer may rest directly on the basement. Fault-plane reflections indicate the predominance of planar fault-plane geometries. This is consistent with the absence of rollover anticlines or hanging-wall antiforms, which are a direct function of nonplanar listric faults. The final configuration of the traps may also be modified by important basin-scale factors (i.e., uplift resulting from magmatic underplating in the Santos Basin).

INTRODUCTION
Recent success in exploration efforts in the Cretaceous (Barremian to Aptian) presalt rift and sag sequences of offshore Brazil (Santos, Campos, and Espirito Santo basins, collectively known as Greater Campos; Figure 1) has revived interest in the difficulty in properly imaging a section characterized by asymmetric half grabens and
covered by a conspicuous salt layer of variable thickness. Although the sedimentary velocity variation is considered relatively smooth, depth migration is required for properly imaging the presalt section (Huang et al., 2009). Additional complicating factors are isolated igneous intrusions (dikes and sills) and seismically fast carbonates above and below the salt layer (Gerrard et al., 2009). The importance of having an adequate imaging of the presalt sequence is key to understanding not only the recent discoveries in this section, but also the probable extent of the prolific presalt source rocks that charged the pre- and postsalt reservoirs in Santos, Campos, and Espirito Santo basins (Mello et al., 2006). Newly acquired seismic reflection data, particularly data processed using prestack depth migration (PSDM), allow us to unveil some details of the structural framework of these individual half grabens that, in turn, may shed light on the basin-fill evolution of the synrift (half graben) and postrift (sag) stages in the offshore basins of Brazil. The tectonic setting of the rifting during the opening of the South Atlantic has been amply documented elsewhere (Rabinowitz and LaBrecque, 1979; Zanotto and Szatmari, 1987; Conceição et al., 1988; Szatmari, 2000; Rosendahl et al., 2005). This contribution deals with the influence that the tilt block nature of the presalt section had on (1) the sedimentary evolution of both the syn- and postrift presalt section and on (2) the associated trap geometries. Seismic examples provided in this contribution are from the Santos, Campos, and Espirito Santo basins (Figure 1). It is expected that the characteristics highlighted below, derived from selected dip lines with very good quality particularly for the presalt section, will help in areas with mild to poor imaging caused mainly by extreme

Figure 1. Offshore basins of central Brazil. Salt does not extend south into the Pelotas Basin. The presence of salt over the synrift and sag sections is widespread in the Santos, Campos, and Espirito Santo basins. 200 km (124 mi).
The initial structural style of the South Atlantic opening is dominated by rifting. A key element in this tectonic stage is the presence of asymmetric half grabens (Szatmari, 2000; Gibbs et al., 2003; Bueno, 2004; Dias, 2005). This seems to be the dominant individual geometry on both the South American and African margins. This rifting was diachronous, beginning in the south during the Jurassic and propagating northward to the equatorial segment during the Early Cretaceous (Conceição et al., 1988; Bueno, 2004) as the South American continent rotated clockwise relative to Africa about a pole located in northeast Brazil (Rabinowitz and LaBrecque, 1979; Szatmari et al., 1985). The initial phase of opening is characterized by intracontinental rifting associated with Late Jurassic–Early Cretaceous tholeiitic basalts (Cobbold et al., 2001; Meisling et al., 2001; Mohriak et al., 2002). In the central offshore of Brazil (Santos, Campos, and Espirito Santo basins; Figure 1) and its African counterpart (Kwanza and Lower Congo basins), this first stage of opening was followed by a period initially dominated by nonmarine (primarily lacustrine) facies during the Barremian that evolved to a shallow-water engulfment, culminating with evaporite sedimentation in the Aptian. It has been suggested that rifting in the Santos and Kwanza basins is strongly asymmetric with oblique extension (trans-tension), resulting in rhombochasmic subbasins and listric fault geometries (Lentini and Fraser, 2008; Wilson et al., 2008). The Campos and Lower Congo basins are characterized by orthogonal stretching and simple half-graben geometries with planar master faults (Lentini and Fraser, 2008). Dias (2005) identified an eastward displacement of the rift and the exposure of the proximal areas during the Early Aptian, with significant expansion of the size of individual half grabens basinward (eastward) followed by a sag phase characterized by thermal subsidence and predominantly marine sedimentation over the pre-Late Aptian times (Figure 2). Inboard, the initial fill phase in these asymmetric half grabens was dominated by alluvial fan deposition.

**Figure 2.** Schematic cross sections showing evolution of the offshore basins during the transition from the synrift stage to the sag stage. Note the increasing marine influence toward the top of the section and eastward in the synrift and postrift (sag) sections. The pre-Upper Aptian unconformity (pre-Alagoas unconformity) separates the synrift section dominated by tectonically driven subsidence and the overlying sag section characterized by regional thermal subsidence. The pre-Upper Aptian unconformity is equivalent to the base of sag marker as defined in this contribution. Marine sedimentation over the pre-Upper Aptian unconformity occurred under predominantly clastic-starved conditions toward the eastern part of the basins during the sag phase in the Late Aptian. Note the regional basinward thickening of the sag section caused by differential thermal subsidence (modified from Dias, 2005).
deposits associated with rift-generated local topography; locally, coquinas were deposited in rift shoulders isolated from high clastic sediment input (i.e., presalt coquinas in the Pampo and Badejo fields of Campos Basin; Bertani and Carozzi, 1985a,b; Horschutz and Scuta, 1992; Rangel and Carminatti, 2000). Outboard, the lower clastic sequences of Early Barremian tend to be made up of sandy to silty fine-grained lacustrine facies (Guardado et al., 1990), whereas the upper units (mid-to Late Barremian) consist of lacustrine carbonates and prolific organic-rich black shales (Dias et al., 1988; Rangel and Carminatti, 2000), which constitute the source rocks for all of the presalt, and most postsalt, hydrocarbon accumulations in offshore Brazil (Mello and Maxwell, 1990; Guardado et al., 2000). The synrift section exhibits increasing marine influence eastward and is separated by a regional unconformity (pre-Uppt Aptian unconformity, also known as the pre-Alagoas unconformity) from the overlying sag deposits (Figure 2). This unconformity was produced during a phase of uplift and regional truncation and has been considered to be responsible for the development of restricted environments conducive to the formation of evaporites (Chang et al., 1992; Azevedo, 2004; Mohriak et al., 2008).

The sag phase (transitional megasequence; Guardado et al., 1990) was dominated by carbonate sedimentation in shallow-water environments (Dias, 1998, 2005; Carvalho et al., 2000; Gibbs et al., 2003), which probably evolved from a brackish-to-saline lacustrine environment to a broad saline lake, possibly punctuated by marine incursions and dominated by microbial limestones (Dias, 1998, 2005; Wright and Racey, 2009).

ARCHITECTURE AND FILL EVOLUTION OF THE ASYMMETRIC HALF GRABENS: EVIDENCE FROM SEISMIC DATA

Time and depth reflection seismic data have been used in this contribution to analyze the presalt half grabens of the Greater Campos basins. Although time seismic provides a good imaging of the presalt section in some areas and can highlight the general structural and stratigraphic framework (Figure 3), recently acquired PSDM seismic has been preferentially used in this contribution to constrain the geometry and internal configuration of the half-grabens because of its exceptional quality. The seismic was shot with a basin strike-and-dip orientation using an airgun source, a streamer length of 8100 m (26,574 ft), and a record length of 12 s. The spacing ranges approximately between 8 and 20 km (~5–10 mi) for the strike lines and 3 and 4 km (~2–2.5 mi) for the dip lines.

The external configuration of the half grabens is evidenced by several characteristics present on the border fault margin, namely fault-plane reflections. Fault-plane reflections (Figure 3) indicate planar geometries for the master fault of the half grabens, particularly in the Campos and Espirito Santo basins. Most boundary faults of the half-grabens are clearly defined as single fault systems (sensu Rosendahl et al., 1986); in some cases, the displacement is partitioned in distributary border fault systems (Figures 4, 5), a feature also common in the East African rift basins (Rosendahl et al., 1986). This feature may indicate migration of the boundary fault that typically occurs late in the evolution of a half graben (Morley, 2002). This migration expands the basin on both the fault and flexural margins (late-stage half graben of Morley, 2002). At the fault margin, the basin expands until the boundary fault is reestablished and footwall uplift and erosion occur. On the flexural margin, basin expansion is achieved by progressive onlap (Figures 3, 6). Onlap is herein defined as the stratal termination against a reflection of greater dip (cf. Mitchum, 1977). Onlap surfaces are most easily recognizable in the highly convergent zone, toward the flexural or ramp margin of the tilt blocks. This progressive onlap has been labeled as flexural margin transgressions by Morley and Wescott (1999) in the half-grabens of the East African rifts system. It has been related to a displacement increase on the boundary fault system (flexural margin rollback; Morley and Wescott, 1999).

Two distinct seismic sequences can be discerned in the presalt section based on the nature of the bounding surfaces and their seismic internal configurations. The synrift seismic sequence is characterized by a concordant base and top, a gradual fanning of the horizons, strongly divergent internal configuration on the fault border, and thinning (convergent internal configuration) on the flexural (ramp) margin (Figures 3–6). A hanging-wall onlap of successive horizons (progressive onlap) is common on the flexural margin of the half grabens (Figures 3, 6). This divergent internal configuration of the half grabens has been interpreted as the product of differential subsidence caused by an early episode of block rotation (rift phase 1; Karner, 2000). Reflection terminations of diverging configuration define, in the absence of other criteria (fault-plane reflectors, compaction synclines; see discussion below), the approximate location of the planar master fault of the half graben (cf. Roberts and Yielding, 1991). Commonly, chaotic to hummocky seismic facies can be identified close to the footwall scarp in areas with good seismic resolution. The continuity and concordance of the synrift divergent stratal reflections suggest that sediment supply and fault-controlled subsidence were
closely matched for most of the period of the active development of the half graben (Cartwright, 1991).

Compaction synclines (Figures 6, 7) occur in the hanging wall over the basement footwall cutoff point close to the border fault margin (Figure 8). When compaction occurs in a thick sequence with high initial fluid content at the time of deposition on the hanging wall of a normal fault, the differential compaction against the more rigid footwall gives rise to a syncline (White et al., 1986; Gibson et al., 1989). This folding causes dip reversals in the hanging wall close to the master fault (Figure 8). Compaction synclines have been identified from seismic data in many half-graben settings like the Viking Graben (see Bradley et al., 1988; Frost, 1989; Roberts and Yielding, 1991) and the Central Graben in the Danish sector of the North Sea (Cartwright, 1991), the Sirte Basin in offshore Lybia (Skuce, 1996), and the Tertiary (Paleogene) rifts of Indonesia (Atkinson et al., 2006).

Because compaction synclines are subsurface deformation features, with compaction decreasing to zero toward the top of the sedimentary pile, they cannot influence the distribution of sediments on the sea floor and hence cannot generate stratal terminations (i.e., onlap) but differential thicknesses of individual beds (Butler et al., 1998). Seismic examples and results from forward modeling (Barr, 1991) show geometric similarities and confirmed two key features of compaction synclines: the steepness of the dips is greater on deeper horizons and the synclinal axial plane is approximately
vertical (Skuce, 1996). Significant sag in the Miocene post rift section above Paleogene syn rift depocenters has been identified in the rifts of Indonesia and related to differential compaction by Atkinson et al. (2006).

The top of the syn rift section is identified by a marker (base of sag; Figures 3, 6B, 7) that separates the areally confined syn rift seismic sequence from a more regionally extensive sag seismic sequence characterized by progressive onlapping on the basement. This sag fill takes the form of a more passive, parallel onlap-fill geometry (cf. Cartwright, 1991). The contact between the syn rift fill and the base of sag seismic sequence can be classified as a strong angular unconformity, a minor angular unconformity, or a disconformity (Figures 3, 5A, 9). These variations reflect different structural positions within the basin at the transition from the syn rift to the post rift (sag) stages (cf. Kyrkjebø et al., 2004). Strong angular unconformities are identified when the contact is located on the flexural margins of the half graben where onlap is the most common seismic configuration (Figures 3, 9). Similar angular relationships have been identified in the half grabens of the Central Sumatra Basin by Shaw et al. (1997). These authors noted that the angularity between the syn rift and overlying sag strata gradually decreases toward the hanging wall depocenters. Consequently, strata above (sag section) and below (syn rift section) the unconformities are concordant in the deeper parts of the half grabens.

Seismically, the base of the sag commonly shows a pronounced impedance contrast characterized by a clear and continuous reflection. However, it exhibits in places lateral changes in seismic character, bright on both flanks (shoulders and ramps of the underlying rifts) and dim toward the depocenters, probably reflecting the change in lithology from margins dominated by shallow-water conditions to deeper basin centers where similar lithologies are more likely to occur below and above the base of the sag, inducing a subdued impedance contrast instead. The upper sag is dominated by parallel, reflection-free internal seismic facies (Figures 3, 6, 7, 9). Wells that reached the presalt section in the basin show a range of facies associations ranging from clastic (alluvial-fluvial in the rift section) to calcareous (ramp margin of the rift and sag; Dias, 2005). The latter facies association is the key objective of the emerging presalt prospectivity in offshore Brazilian basins.

IMPLICATIONS FOR FACIES DEVELOPMENT

The structural asymmetry of half grabens exerts a fundamental control on sedimentary facies (Gibbs, 1984; Leeder and Gawthorpe, 1987; Schlische and Olsen, 1990; Lambiasse, 1990; Leeder, 1995; Morley and Wescott,
Figure 5. Examples of distributary border fault systems in the presalt section from the regional line in Figure 4. The sag section in panel A tends to drape over the rift shoulder whereas the sag section in panel B appears to pinch out on the flexural margin of the half graben. The prestack depth migration seismic is courtesy of TGS-NOPEC Geophysical Company.
Figure 6. Trap types in the synrift and postrift (sag) sections illustrated in a depth-converted, dip-oriented section from the northern Campos Basin. (A) Regional configuration of presalt high with opposing half grabens on both flanks. (B) Detail of regional line. Differential compaction on the flanks of large basement high created counterregional dip necessary to form structural (four-way) closures at the sag level (trap type A). Moreover, the smaller subsidiary A traps on the flanks of the large four-way closure are controlled by differential compaction evidenced by compaction synclines at the rift level and more tenuously expressed at the sag level. Updip onlap and three-way dips define combined structural-stratigraphic traps (trap type B). Examples of these geometries can be identified on preexisting half-graben shoulders (half-graben ramp margins; B2) and on the ramp flank of the half graben (B3). See text for discussion. The prestack depth migration seismic is courtesy of TGS-NOPEC Geophysical Company. (C) Linking mode with overlapping half grabens. Note the similarity between cross section A and the seismic section in panel B (based on Rosendahl et al., 1986).
Figure 7. Trap types in the synrift and postrift (sag) sections illustrated in the dip section of central Espirito Santo Basin. Hanging wall compaction syncline created counterregional dip necessary to form structural (four-way) closures at the sag level (trap type A). Combined traps (B trap family) are illustrated: trap type B2 defined by an updip pinchout component at the base of the sag or at any horizon within the sag interval in the case of trap type B1. Examples of these geometries are common inboard (B1) and also on preexisting half-graben ramp margins basinward (B2). A potential for onlap/pinchout traps is also present at the rift-fill level on the ramp flank of the half graben (trap type B3). See text for discussion. The prestack depth migration seismic is courtesy of The Geological Society (TGS). PSDM = prestack depth migration seismic.
The fault margin is characterized by a low potential for good-quality clastic reservoirs because of underfilled conditions and provenance (volcanic basement). The flexural margin of the half graben is a site of low subsidence, is likely to undergo little deposition, and can even be affected by uplift and subsequent erosion. This area is characterized by low accommodation space, suitable for the development of high-energy carbonates (oolitic calcarenites and/or coquinas).

The half grabens of the East African rift system provide excellent modern analogs for the depositional systems and facies distribution that could have been present in the presalt half-grabens of the Greater Campos area. The open waters of Lake Tanganyika are, in practical terms, fresh but are more saline than those of Lake Malawi and have an uncommonly high Mg:Ca ratio. Lake Tanganyika is characterized by the presence of several carbonate facies, all exhibiting high Mg:Ca ratios, composed of Chara beds in sheltered shallows, ooid shoals, stromatolites, shelly bioclastic debris sheets, and algal bioherms in the deeper waters (Cohen and Thouin, 1985; Casanova, 1986).

Although the regional thermal subsidence that characterizes the sag phase tends to finally drown and

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**Figure 8.** Evolution of sedimentary fill from initial synrift phase, characterized by asymmetric half-graben configuration, to postrift (sag) phase and development of hanging-wall compaction synclines (based on the forward modeling of North Sea examples by Barr, 1991). Basement is defined as any noncompactable or precompacted sedimentary, metamorphic, or igneous rocks such as the pre rift. Note that the steepness of the dips is greater on deeper horizons, the location of the synclinal fold axis immediately above the hanging-wall cutoff of the basement and approximately vertical to the synclinal axial plane. Moreover, note the increasing steepness through evolution from the initial stage (A) to the final stage (D). A stretching factor of $B = 1.5$ was used.
smooth the relief of the synrift stage, rift shoulders remained as important paleogeographic elements that influenced the distribution of depositional environments in the early phase of the sag. Differential compaction is evidenced by the presence of hanging-wall synclines (Figures 6B, 7, 8). There is abundant seismic evidence that the sag phase expanded beyond the limits of the half-grabens (Figures 3, 6). Facies distribution in the lower part of the sag section was still controlled by highs inherited from the underlying asymmetric half graben (rift shoulders and ramps). Moreover, at this stage, the rift shoulders could have acted as efficient bathymetric highs that define shallow high-energy areas prone to the deposition of coquinas and oolitic shoals. These rift shoulders still had a positive bathymetric expression during the late sag phase as a series of distal, intermittently exposed basement highs in the clastic-starved environments prone to the development of a broad carbonate platform in the Early Aptian.

A distinctive sag facies association formed on bathymetric highs developed on underlying rift shoulders. This association was deposited in subtidal to peritidal environments where microbially mediated precipitation of carbonates produced microbial limestones (cf. Pratt et al., 1992). Subtidal stromatolites composed of peloidal discontinuous lamination are inferred to have formed by the trapping and binding of loose carbonate sediments in microbial mats. These subtidal stromatolites produced by in-situ precipitation are considered part of a carbonate-to-evaporite transition (Pope et al., 2000). Microbiolites (stromatolites and microbial lamination) have been described in the sag sequence of the Campos Basin (Dias, 1998). Calcareous organic shales and marls deposited in broad saline lakes are also present in the sag section of the Santos and Campos basins (Gibbs et al., 2003). In some extreme cases, the rift shoulders may have persisted through time as highs exposed to nondeposition and/or erosion during the sag phase, eventually leading to bald highs where salt was deposited directly over the basement (Figure 3).

**IMPLICATIONS FOR TRAP GEOMETRIES**

The rift section in Santos, Campos, and Espirito Santo basins shows a clear asymmetric configuration with a flexural border or ramp generally in the east and a steep fault border commonly in the west. This structural asymmetry caused by differential, tectonically induced subsidence created optimal conditions for the development of lacustrine-to-brackish source rocks in the hanging-wall area of maximum accommodation space next to the fault-margin of the half grabens (Gawthorpe et al., 1994; Howell and Flint, 1996). Internally, the asymmetric half grabens are characterized seismically by fanning of the horizons (strongly divergent internal configuration) on the fault border and thinning (convergent internal configuration) and onlap on the flexural (ramp) margin. In contrast to this gradual thickening toward the bounding fault observed in the half grabens analyzed herein, when the extension in half grabens is accommodated by normal faults that commonly flatten with depth, a collapse of the hanging wall and a formation of inclined rollover panels occur (Hamblin, 1965). This geometry leads to rollover traps that are absent in the half grabens of offshore Brazil. Seismically, the curved rollover above a nonplanar listric normal fault is evidenced by an abrupt thickening of strata toward the fault above the rollover panels (Xiao and Suppe, 1995).
The nonplanar (flattening with depth) geometry of border faults and the consequent development of rollover structures are common in other rift settings (Nunns, 1991; Shaw et al., 1997) but are conspicuously absent in the half-grabens of offshore Brazil. The absence of rollover anticlines or hanging-wall antiforms suggests that the overall structure of the half grabens of Greater Campos is of tilted fault blocks bounded by planar faults in some form of a domino model, either of rigid dominoes (Barr, 1987; Jackson et al., 1988; Yielding, 1990) or soft dominoes (Gibson et al., 1989; Kuszmir and Egan, 1989). Geometries similar to those interpreted here as compaction synclines have been assigned to fault-bend folds by Neto Cavalcanti de Araújo et al. (2009). These authors relate these synclines in the presalt synrift section of the Campos and Santos basins to the half-graben development above a normal fault that flattens to horizontal through bends although acknowledge the function of differential compaction in the formation of such synclines as well.

The effects of the differential postrift subsidence (and thus the creation of accommodation space) have been modeled for asymmetric half grabens by Barr (1991). Configurations similar to compaction synclines resulted from forward modeling based on North Sea data (Barr, 1991) assuming a basement (prerift) domino-style fault block generated by rotated planar faults. The results show the development of hanging-wall compaction synclines with marked thickness variations and substantial compaction-induced dips into the basin center (Figure 8) after significant thermal subsidence. He further showed that hanging-wall compaction synclines affected the subsidence of overlying sag sediments. This was evidenced by marked thickness variations and substantial compaction-induced dips into the basin center. Consequently, the thickest section of synrift sediments is overlain by the thickest section of postrift deposits. This relationship is also present in the half grabens of offshore Brazil (Figures 6, 7). As warned by Barr (1991), compaction-induced differential subsidence would probably give rise to faulting within the sag fill (the drape-slip faulting of Bertram and Milton, 1989) or, in ductile regimes, simply to a compaction syncline. In either case, uncritical evaluation of isopach maps and footwall–hanging-wall sediment thickness ratios may erroneously lead to the inference of renewed rifting without taking into consideration the effects of differential compaction.

Internal seismic configurations within the half-graben fill can be used to infer the presalt architecture in poorly imaged areas and consequently help reconstruct the basin geometry and predict the location of possible traps. Where fault-plane reflections are poorly imaged, the structural interpretation of the master fault in the half-graben can be based mainly on identifying divergent stratigraphic terminations against the fault. The termination of the fanning seismic package indicates the approximate position of the fault plane (cf. Prosser, 1993; Figure 9). Compaction synclines can also be used to determine the footwall cutoff with the downward projection of their synclinal axes (cf. Prosser, 1993; Figure 9).

The overlying sag phase expands beyond the limits of the half grabens. The distribution of facies in the lower section is still controlled by highs inherited from the underlying asymmetric half graben (rift shoulders and ramps). Onlap-pinchoff traps at the sag level are also indirectly controlled by preexisting half-graben geometries and have a tendency to develop on the flexural margins or on the inboard shoulders (Figure 7). This type of stratigraphic onlap onto eroded basin margins is common on previous uplifted footwalls.

The influence of differential compaction in the creation of base-salt structural highs has been recently highlighted by López-Gamundi and Barragan (2008) for the Santos, Campos, and Espirito Santo basins and by Teasdale and Jensen (2008) for the Santos Basin. Differential compaction at the half-graben border fault margin is a key factor to create counterregional dip necessary to form structural (four-way) closures at the sag level (A trap type in Figure 7). Combined structural-stratigraphic traps are defined by an updip pinchout component at the base of the sag or at any horizon within the sag interval (Figures 6B, 7). Updip onlap and three-way dips define these combined traps (B trap type in Figure 7). Examples of these trap geometries at the sag level are common inboard (B1 type) as part of the regional updip onlap of the sag interval and also for intermediate levels within the sag section on preexisting half-graben shoulders (half-graben ramp margins) basinward (B2 type). A potential for onlap-pinchoff traps is also present at the rift-fill level on the ramp flank of the half graben (B3 type).

Differential compaction seems to act at different scales as exemplified by the presence of a large four-way closure (trap type A) with a thin sag section draping the high (Figure 6B) and additional smaller four-way closures on both flanks of the large structure. The polarity of the half grabens on both flanks suggests an opposite alternate cross section linked by an intervening accommodation zone (Figure 6C) in a similar pattern as the one described by Rosendahl et al. (1986) for the East African rifts. Rosendahl et al. (1986) describe three families of half-graben linking modes. Family 1 comprises overlapping opposing half grabens (Figure 6C) linked by an intervening accommodation zone. This architecture is also identified in offshore Brazil (Figures 4; 6A, B) and is characteristic of four-way
closures with optimal conditions of focusing for hydrocarbon charging.

CONCLUSIONS

- New two-dimensional PSDM seismic seems to be a viable tool to at least partially solve the problem of identifying the key elements of the basic motif of asymmetric half grabens: a border fault margin and a flexural or ramp margin. Evidence of this asymmetric half-graben nature is provided by seismic signatures like fanning (strongly divergent internal configuration) on fault borders, thinning (convergent internal configuration), and onlap on flexural margins. After block tilting ceased (synrift stage), the half grabens were onlapped (locally downlapped) by the postrift (sag) sequence, and this angular discordance provides a good criterion for locating on seismic data the base of the sag sequence.

- Compaction synclines over basement footwall cutoff points have been identified. Differential compaction at half-graben border fault margins caused by the contrasting nature of rift fills and adjacent basement highs is postulated to have been a critical factor for the creation of counterregional dips necessary to form structural four-way closures at the sag level, where most of the recent discoveries have been made. Consequently, the sag sediments expand over the shoulders of the fault margins and low-angle ramps of the flexural margins of the preexisting asymmetric rifts, creating potential for traps. Alternatively, the sag sequence, the key objective of the emerging pre-salt perspective, commonly extends beyond the underlying rift-fill draping over the basement. The key risk in this type of traps is the possibility that the overlying salt layer may rest directly on basement highs restricting the areal extent of the traps.

- Rift shoulders were topographic highs during the synrift stage and remained as lower relief, bathymetric highs during the sag phase. Hence, these were sites where shallow-water high-energy facies may have developed (Figure 11). Seismically, the base of the sag is concordant and exhibits lateral changes in its seismic character, bright on both flanks (shoulders and ramps of the underlying rifts) and dim toward the depocenters, probably reflecting the change in lithology from margins dominated by shallow-water conditions to deeper basin centers. The final configuration of the traps may also be modified by some important basin-scale factors such as uplift resulting from magmatic underplating like in the Santos Basin (Gomes et al., 2008).

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