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Basement control and transfer tectonics in the Recôncavo–Tucano–Jatobá rift, Northeast Brazil

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Abstract

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The Recôncavo–Tucano–Jatobá rift consists of a series of asymmetric grabens which are separated by basement highs and transfer faults. Opening of the rift took place in a NW direction oblique to the N–S rift trend. Well defined transfer faults parallel the opening direction. They were responsible both for offsetting en-echelon depocenters in the Tucano and Recôncavo basins and for switching of the asymmetry of half-grabens across the Vaza-Barris fault zone. The transfer faults show characteristic features such as change of movement sense along strike and with time, and "cactus-shaped" fault structures as well as flower structures in cross section.

The sigmoidal plan-form of the rift is probably due to faulting following pre-existing weaknesses through a complex mosaic of basement blocks. Basement anisotropy is thought to have controlled the asymmetry of the half-grabens and the localisation of the Vaza-Barris transfer.

A 2° anticlockwise rigid rotation of the East Brazilian Microplate relative to the São Francisco Craton around a pole located near the eastern termination of the Jatobá Graben describes the calculated 20% extension in the South Tucano and Recôncavo grabens, the oblique northwestward opening, and the eastward shallowing of the Jatobá Graben.

Gravity modelling suggests important crustal thinning, locally up to 45%, below the rift. Mantle upwarping is localized near the faulted margin of the rift. With localized thinning in a 100 km wide basin during a 20 Ma rifting event, lateral, as well as vertical heat conduction would be important and may account for the absence of a post-rift thermal subsidence phase.

Introduction

The Recôncavo–Tucano–Jatobá Cretaceous rift system is located in northeast Brazil (Fig. 1). It is an aborted intra-continental rift, filled with non-marine sediments, that opened in Late Jurassic to Early Cretaceous times during South Atlantic rifting. Oil exploration has been intensive since the first discoveries in the early 1940's. Over 1000 exploration wells have been drilled, which have resulted in proven recoverable reserves of 250 million m^3 of oil. Seismic reflection data are limited to the Recôncavo and South Tucano basins where known hydrocarbon reserves are concentrated (Fig. 1). In the rest of the Tucano and Jatobá basins only gravity, magnetics and seismic refraction data and information from 15 stratigraphic test wells are available.

Ghignone and Andrade (1970) reviewed the structural evolution of the Recôncavo Basin and

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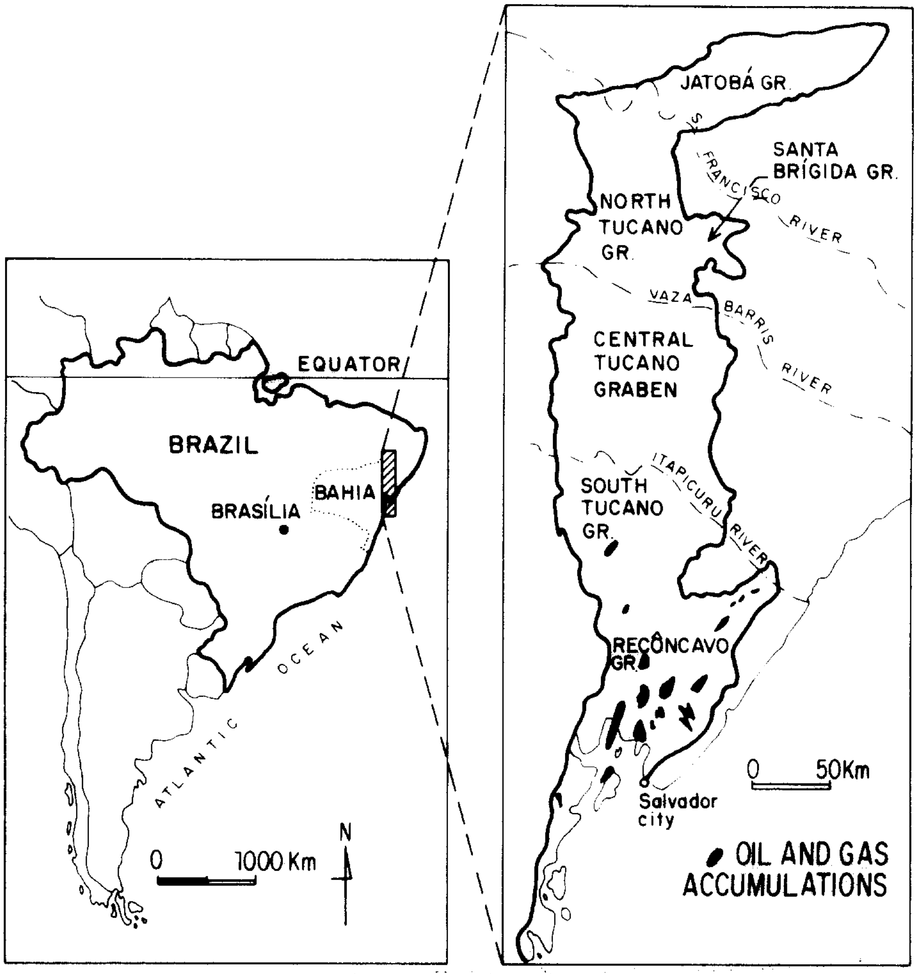


Fig. 1. Location map of the Recôncavo–Tucano–Jatobá rift system with major hydrocarbon occurrences shown.

concluded that this part of the rift was subjected to two discrete extensional faulting phases: the first, Berriasian phase, during the deposition of the Candeias Formation and a second, post-Barremian phase, after the deposition of the São Sebastião Formation. Subsequently, structural models have become more elaborate and diverse (Netto 1978; Ghignone, 1979; Cohen, 1985; Ussami et al., 1986). However, all models are based on individual basins within the rift system, or have focussed on particular aspects of tectonic evolution, with limited access to data. This paper presents a tectonic model for the evolution of the whole rift system, using all the published and PETROBRÁS proprietary data. The model presented here is integrated with surrounding basement structure, which is believed to have played a decisive role in the basin's architecture.

Rift stratigraphy

There are localized outcrops of thin continental Carboniferous and Permian sediments on the rift margins and in the Santa Brígida Graben (Fig. 1). Further study is required to explain their occurrence. Pre-rift Upper Jurassic to Lower Cretaceous continental red beds (Brotas Group, Itaparica Formation and Tauá Member of the Candeias Formation) reach a thickness of 1.5 km in the southern Recôncavo Graben and thin progressively north to the Jatobá Graben. The original extent of the pre-rift sedimentation was much larger than the present-day rift area as these sediments are found in the Gabon and Cabinda basins of Africa (Netto and Oliveira, 1985). No evidence of syn-depositional faulting has been observed in these sediments.

The rift phase was implanted during the Valanginian when faulting occurred along the eastern margin of the Recôncavo and Tucano grabens, and great thicknesses of fanglomerates were deposited (Salvador Formation). A deep lake developed and shales of the Gomo and Maracangalha units (main hydrocarbon source rocks) were deposited along with occasional turbidite influxes and sandstone fan incursions (Netto and Oliveira, 1985). In the Hauterivian, the subsidence rate declined and sediments filled the lake with prograding delta fans (Ilhas Formation). The rift phase terminated with fluvial deposits of the Marfim and São Sebastião formations. During the Aptian an unconformable post-rift phase of fluvial conglomerates (Marizal Formation) developed, and no further sedimentation is recorded after this. In the North and Central Tucano and Jatobá grabens, sandstones are much more frequent than in the Recôncavo Graben, indicating the sense in which the rift was filled. Correlations are not always easily made, but the general stratigraphic framework holds for all the rift system. A schematic stratigraphic column is presented in Fig. 2 (Netto and Oliveira, 1985).

Rift architecture

The rift system consists of a series of four asymmetric grabens: (1) Recôncavo, (2) South and Central Tucano, (3) North Tucano and (4) Jatobá (Fig. 3).

Recôncavo Graben

The South Tucano graben is separated from the Recôncavo graben by the basement Aporá High (Fig. 4), which continues south as the Boa União and Dom João Highs, where the basement is within 1 km of the surface. These highs also divide the Recôncavo into eastern and western sub-basins (Fig. 3). The western sub-basin is structured with a NW-dipping extensional fault system (Fig. 8). The fault planes dip around 60° and have planar domino style profiles to the depth of seismic resolution (crystalline basement). There is no obvious roll-over or differential rotation of bedding between fault blocks. The eastern sub-basin also has a SE-dipping basin floor but with SE-dipping

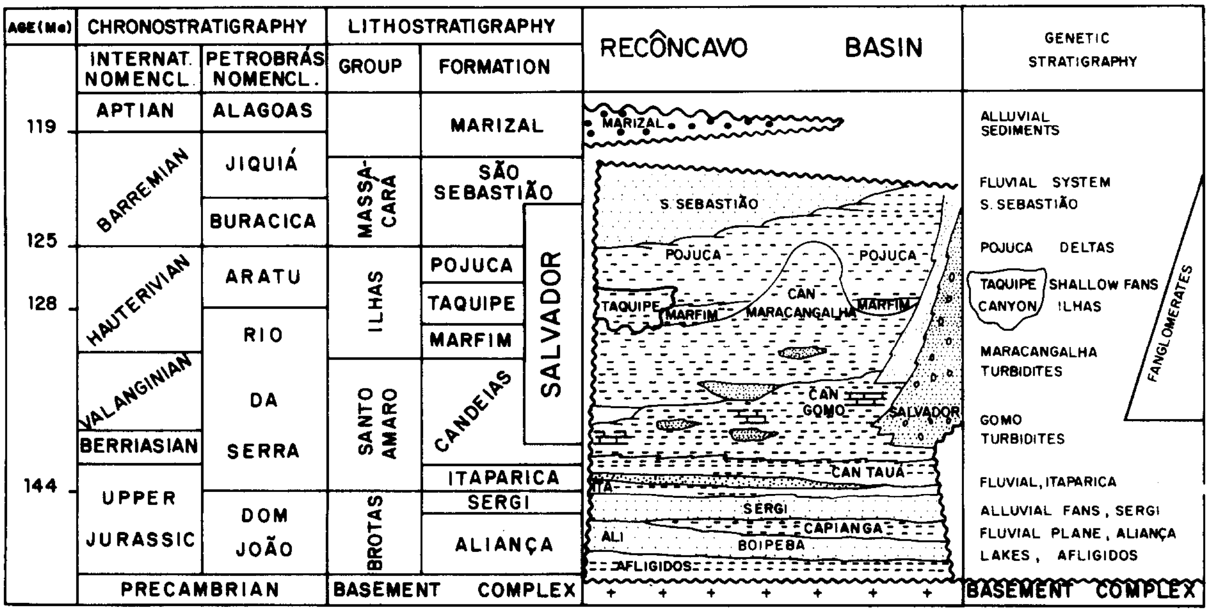


Fig. 2. Stratigraphy of the Recôncavo Graben (modified from Netto and Oliveira, 1985). The correlation between the international nomenclature and PETROBRÁS nomenclature is approximate.

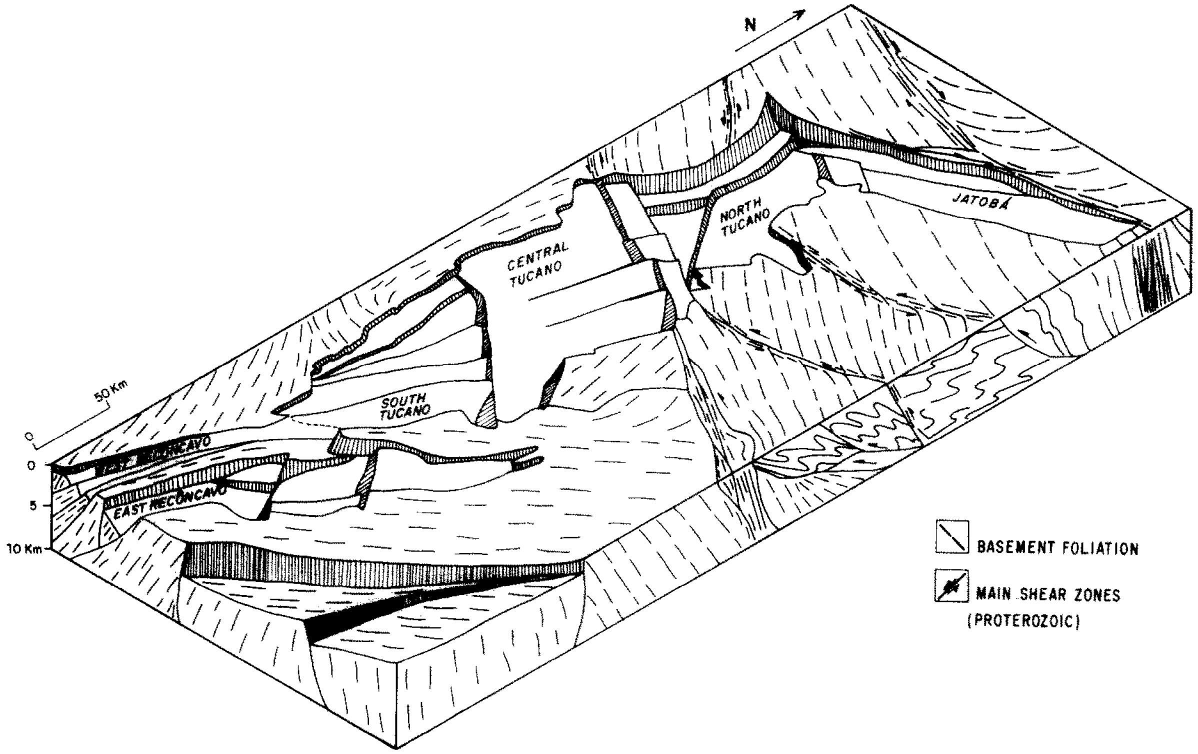


Fig. 3. Isometric diagram of rift architecture and basement structure.

extensional faults (Fig. 5). Close to the southeastern margin of this sub-basin, NW-dipping normal faults produced the asymmetric depocenters of Camaçari, Miranga and Quiambina (Fig. 4). The maximum frequency of fault directions throughout the Recôncavo is N30° E. This fault set is the main extensional system with large stratigraphic growth components of the Candeias and Salvador formations identified across the faults (Fig. 5).

Transfer faults in the east Recôncavo Graben

The other less dominant fault set trends N30° W (Fig. 4). All three faults (Mata-Catu, Itanagra–Araçás and Palmeiras) show characteristics of strike-slip faults (Christie-Blick and Biddle, 1985; Harding, 1985). They are interpreted as transfer faults (Gibbs, 1984). The first two faults separate the eastern Recôncavo Graben into three distinct compartments, each one with an individual tectonic history.

The Mata-Catu transfer fault (M-CT) terminates to both the northwest and the southeast against N30° E trending normal faults, the throw of which changes drastically across the M-CT. At the northwest end, the boundary fault of the Dom João–Boa União High shows a much larger throw northeast of its mutual intersection with the M-CT than to the southwest. This movement occurred principally during deposition of the São Sebastião Formation, producing the Alagoinhas depocenter (Figs. 4 and 6). Such a throw change across the M-CT affecting the São Sebastião Formation indicates transfer of a dextral strike-slip component along the M-CT during deposition.

At the southeastern end of the M-CT, the structural arrangement is different. Southwest of the M-CT, the Salvador Fault lies farther northwest than it does northeast of the transfer (Fig. 4). This indicates a sinistral strike-slip motion along M-CT in this region.

This illustrates an important feature of transfer faults, in which the movement sense changes from

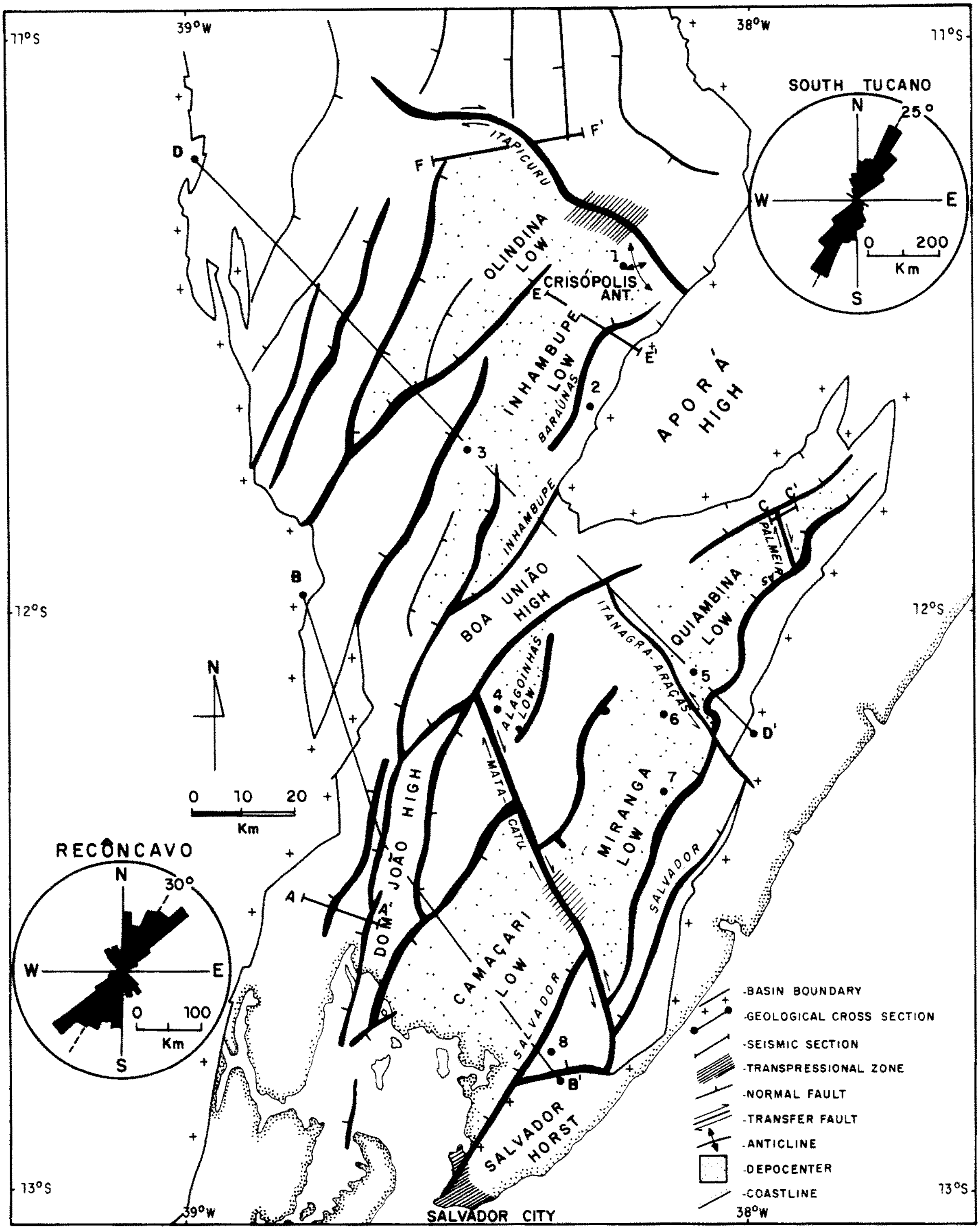


Fig. 4. Structural map of the Recôncavo and South Tucano grabens (PETROBRÁS/DEXBA, 1985). Rose diagrams show the cumulative length of faults in 5° intervals that cross-cut the basement and the pre-rift sedimentary sequence, defined from seismic reflection data. Numbers refer to wells in Fig. 6.

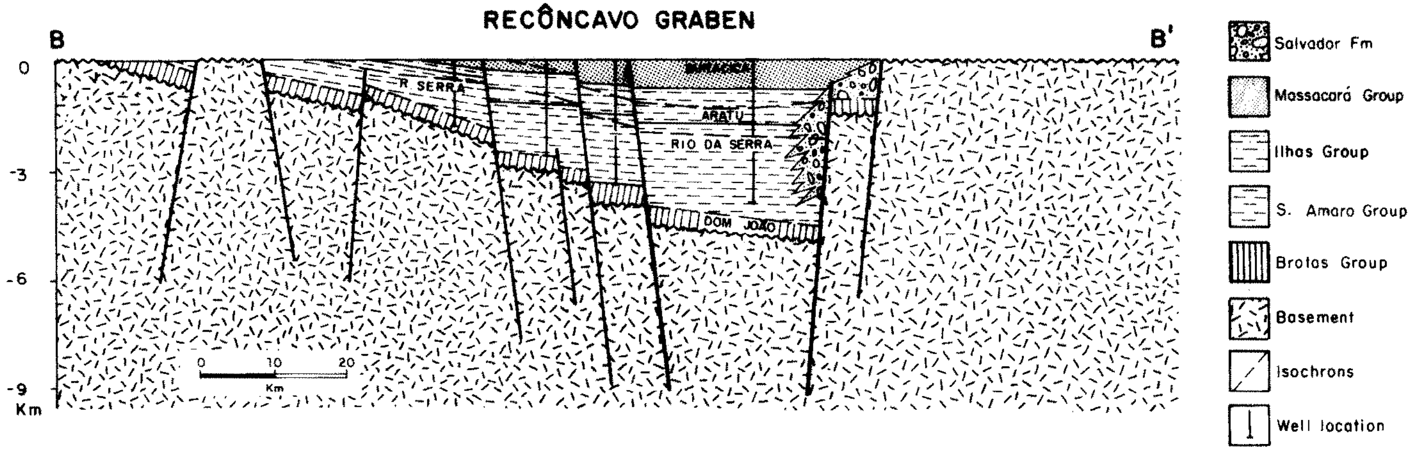


Fig. 5. Schematic geological section across the Camaçari depocenter of the Recôncavo Graben. Location in Fig. 4.

dextral (in the northwest) to sinistral (in the southeast) along strike. The Movement sense may also change through time along the same segment of the fault, but this will be harder to recognize.

In the central region of the M-CT, a zone of transpression was identified in seismic sections. Thrust repetition has been identified in wells, and surface folding mapped in the São Sebastião Formation. This is compatible with dextral strike-slip with transpression at a restraining bend (Fig. 4). The Camaçari and Miranga depocenter axes are each marked by a line of shale diapirs which show a dextral offset of approximately 15 km. This is an original depocenter offset because analyses of seismic profiles suggest a difference in extension of only about 3–5 km; a differential extension greater than 15 km would be required to produce the 15 km offset of depocenters because there is no offset of the northwest basin margin across the M-CT. This illustrates another characteristic of transfer faults, that they commonly accommodate original offsets in developing depocenters where upper crustal extension is at a maximum.

The Itanagra–Araçás Fault shows a sinistral offset of the southeast border fault of 3 km, but no offset is shown against the northwest termination at the Boa União High. The overall movement sense is difficult to determine. The shales of the Candeias Formation form diapirs in the Miranga depocenter but not in the Quiambina depocenter, on the other side of the transfer.

The Palmeiras Fault is a minor feature but shows characteristics interpreted as indicating strike-slip motion in seismic profiles (Fig. 9).

South and Central Tucano grabens

The South and Central Tucano grabens are separated by the Itapicuru transfer fault but their tectonic styles are similar (Fig. 3). The basin floor dips consistently to the southeast with depocenters situated along the eastern border of the rift (Figs.

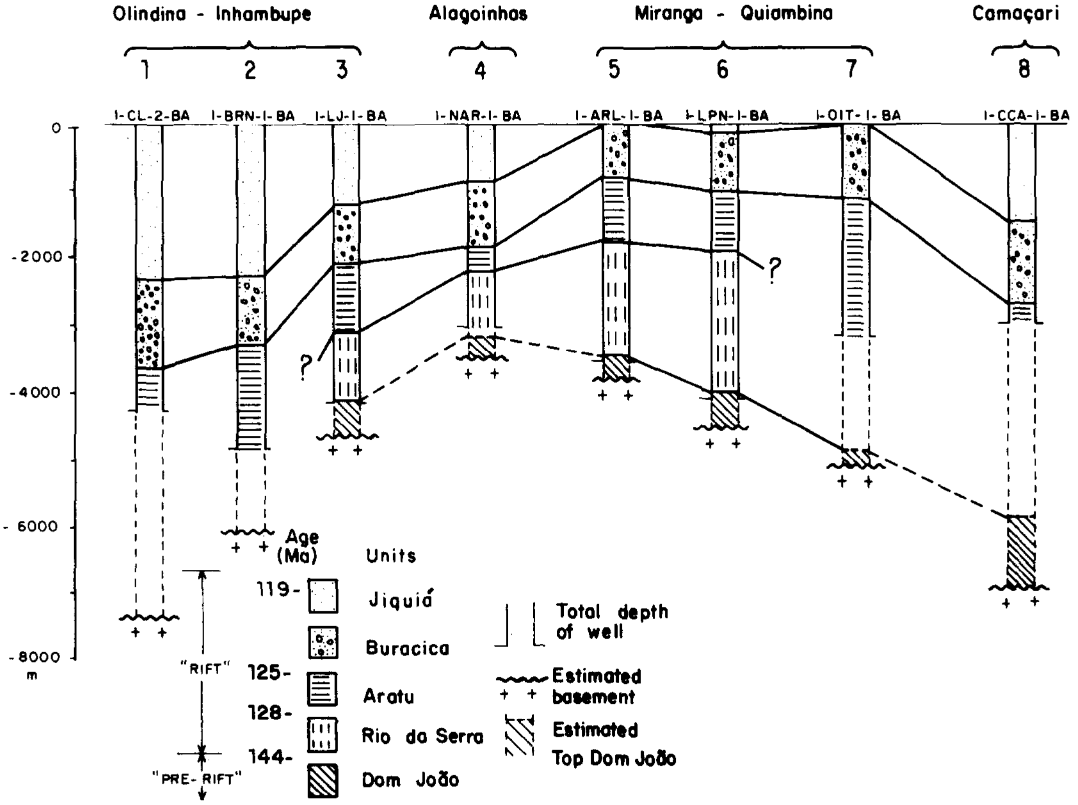


Fig. 6. Stratigraphy in the main depocenters of the South Tucano and Recôncavo grabens. The location of wells is shown in Fig. 4.

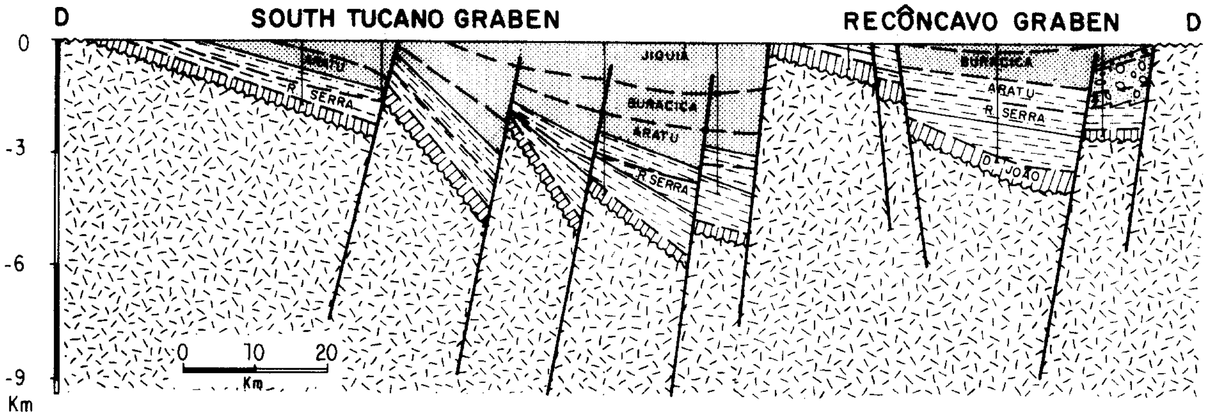


Fig. 7. Schematic geological section across the South Tucano and Recôncavo grabens. Legend: see Fig. 5. Location in Fig. 4.

4 and 7). The main extensional fault system trends N25° E, dipping to the northwest (Fig. 4). Reflection profiles in the South Tucano Graben indicate a planar domino-style faulting, with no differential block rotation identified. The throw of the main southeast boundary fault zone (Inhambupe Fault, Fig. 4) of the South Tucano Graben increases northwards to Crisópolis where up to 8 km of sediments are seen on seismic profiles, and almost 5 km of conglomerates were encountered without penetrating the fan base (Fig. 10) in PETROBRÁS well 1-BRN-1-BA (Fig. 6). The opposite western border of the basin shows down-flexing with very little faulting (Fig. 7).

The Itapicuru transfer fault

The Itapicuru transfer fault exhibits flower structures and transpressional folding (Fig. 4) and a special type of structure for which we propose the new name "cactus structure", for obvious reasons (Fig. 11). Cactus structures differ from flowers in that the upper part of the branching faults are listric; unlike flowers, whose branching faults are generally convex with shallower angles near the surface. We interpret the cactus branches as normal listric faults, which have been cut by, or merge with, the transfer fault, whereas flower "petals" are generally oblique-slip with minor reverse or normal components. The lower cactus branches should have shallower dips than the upper branches if a common detachment is shared by the listric faults. A full cactus structure will be formed only when opposing dips of normal faults occur on either side of the transfer fault, half-cactus structures are probably more common (Fig. 12).

North of the Itapicuru Fault, the depocenter has been mapped using gravity (see below), refraction data, and surface geology and lies along the eastern border of the rift (Fig. 13). The structure at depth is poorly constrained as most of the basin is covered by post-rift Marizal Formation and reflection data are not available.

North Tucano Graben

The North Tucano Graben is separated from the Central Tucano by an important NW–SE trending structure known as the Vaza-Barris Arch (Fig. 13). To this date, no seismic reflection data have been shot across this arch, but semi-detailed gravimetric data are available, and wells and surface geological mapping define it as a structural arch with shallow basement. Despite the NW–SE trend of the arch, there are very few faults which are mapped over it with this trend. Almost all the surface faults trend approximately N30° E and are normal faults with down-dip slickensides.

Surface geological mapping and gravimetric data indicate that the asymmetry of the rift flips across the Vaza-Barris Arch, with the basin depocenter on the east side of the Central Tucano Graben switching to the west side of the rift in the North Tucano Graben. Surface mapping of the

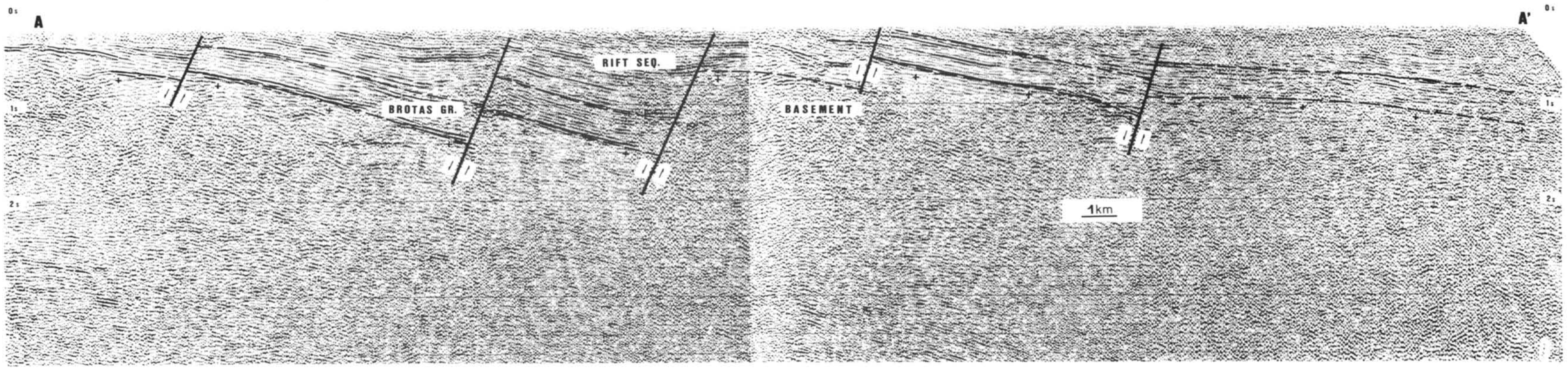


Fig. 8. Interpreted seismic section showing the structural pattern of the Palmeiras fault zone. PETROBRAS line 26-RL-730. Location in Fig. 4.

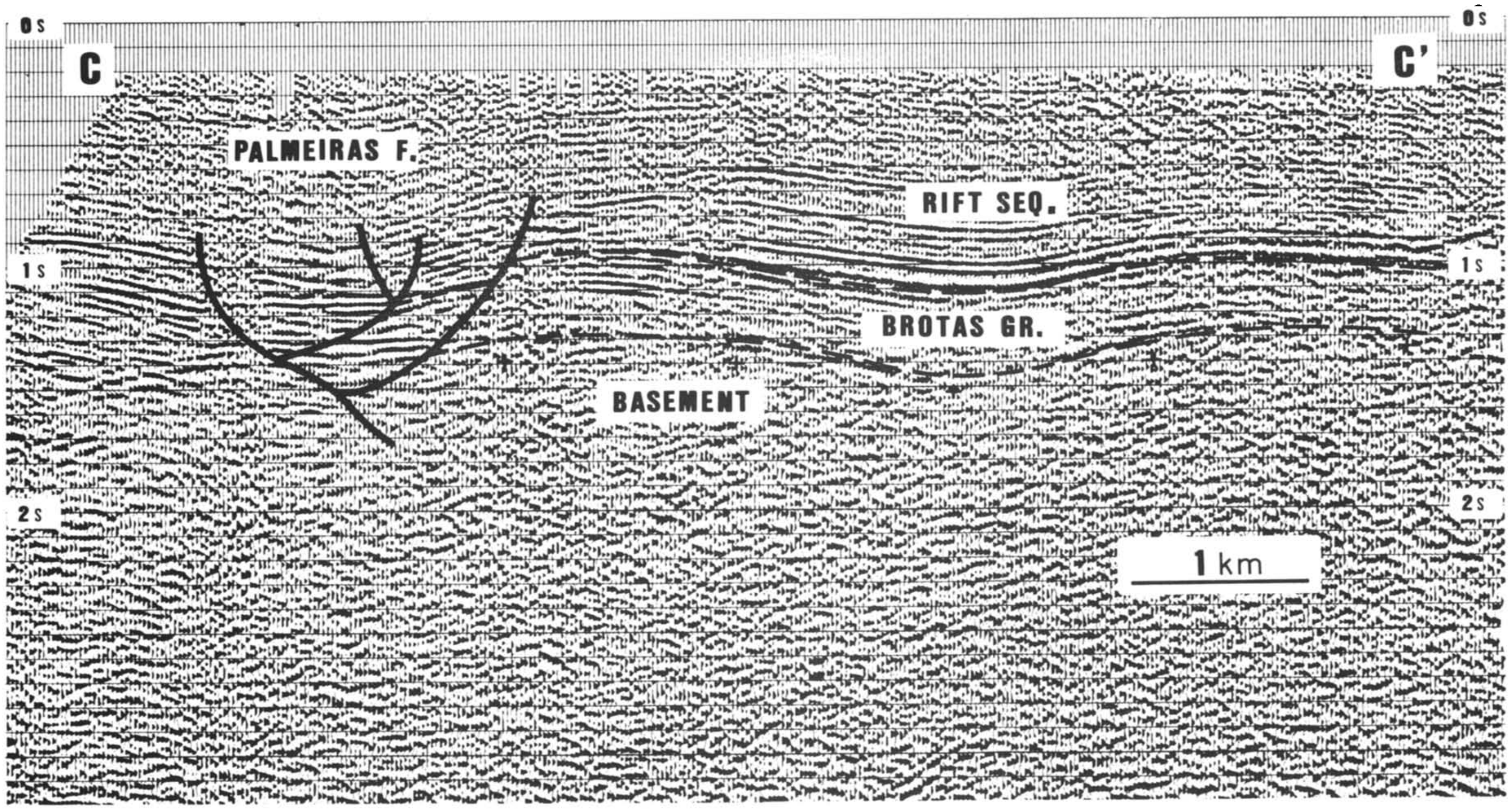


Fig. 9. Interpreted seismic section across the western Recôncavo Graben. PETROBRÁS line 26-RL-784. Location in Fig. 4.

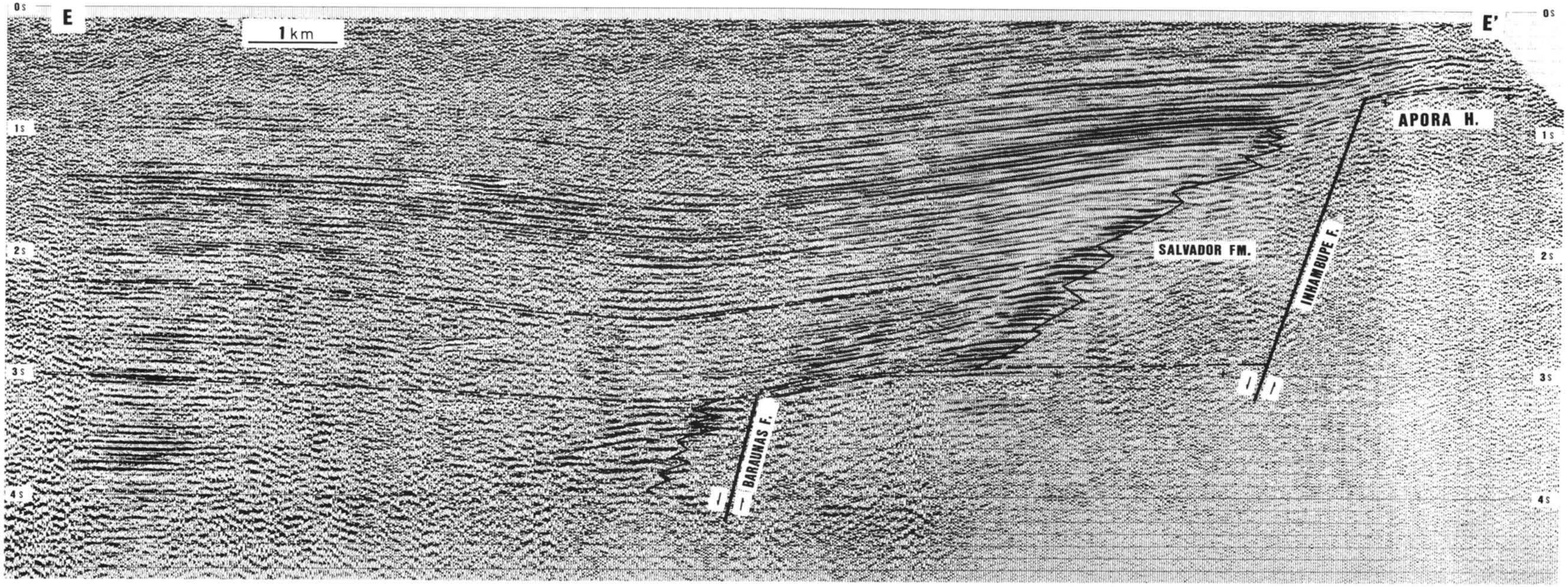


Fig. 10. Interpreted seismic section showing the conglomerate fan that borders the steep dipping Inhambupe Fault. PETROBRÁS line 26-RL-1079. Location in Fig. 4.

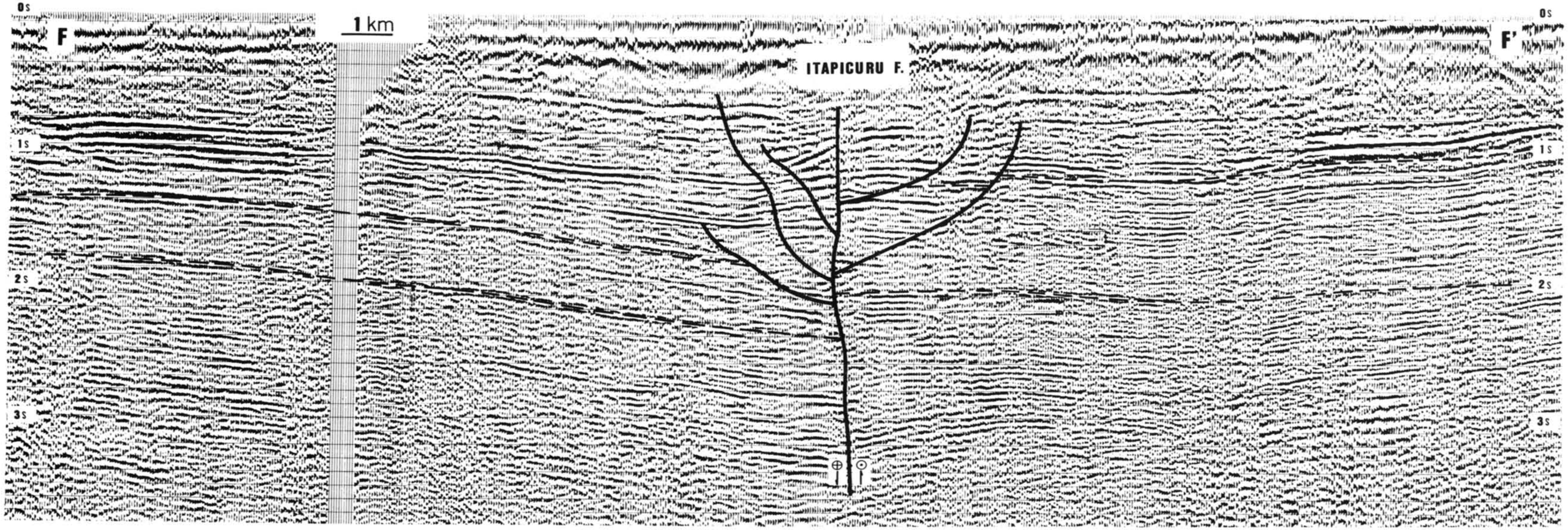


Fig. 11. Interpreted seismic section of the Itapicuru cactus structure. PETROBRÁS line 35-RL-54. Location in Fig. 4.

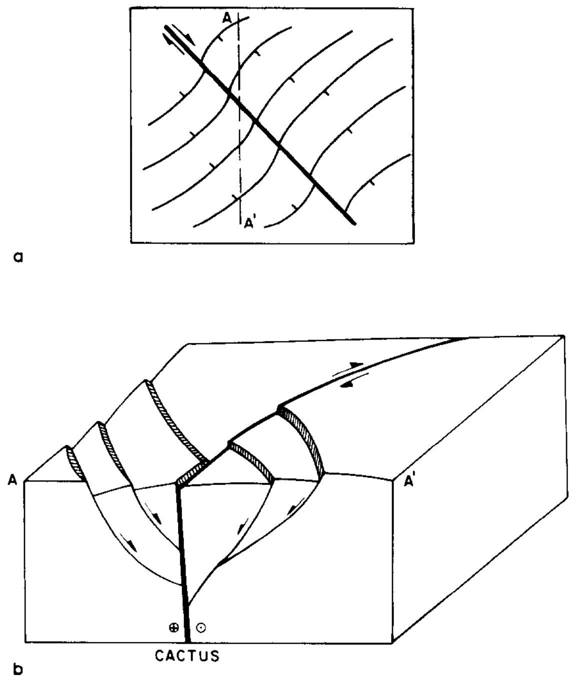


Fig. 12. Schematic map (a) and block diagram (b) of a cactus structure.

stratigraphic dips also shows this switch. Although there is no evidence of a simple fault structure trending NW–SE along the arch, we interpret the Vaza-Barris Arch as a transfer zone, similar to the accommodation zone defined by Bosworth (1985). Seismic refraction data from the North Tucano Graben indicate a more complex fold and fault geometry than in the other sub-basins of the rift (Fig. 13). Fold axes are variable and three fault sets are prominent: N15 ° E, N85 ° E and N25 ° W.

The N85 ° E fault set probably reflects controlling basement anisotropy. The variable fold axes indicate a complex compressional phase oblique to the margins. The northern border of the North Tucano Graben is bounded by the major N80 ° E Ibimirim Fault (Fig. 13), which has a large downthrow to the south; fanglomerates were deposited along it. Gravimetric data also indicate a large depocenter along this border.

Jatobá Graben

The Jatobá Graben is separated from the North Tucano by the São Francisco Arch which is defined by refraction data. The E–W trend of the basin is controlled by the Ibimirim Fault (Fig. 13), with the depocenter close to it. The depocenter shallows to the northeast where its northern border fault deflects 20 ° and merges with a major basement shear zone (Fig. 3). The southern and eastern borders of the Jatobá Graben are defined by gentle flexure without major normal faulting.

Gravity data

The most distinctive features of the Bouguer anomaly map are the strong negative anomalies which run along the central part of the rift and the strong gradients along the major boundary faults (Fig. 14). The switch of the rift asymmetry across the Vaza-Barris Arch is very clearly defined.

Using estimated densities of 2450 kg/m^3 for basin sediments, 2580 kg/m^3 for Palaeozoic sediments in the Jatobá Basin, 2620 kg/m^3 for conglomerates of Salvador Formation, 2850 kg/m^3 for the crystalline basement and 3300 kg/m^3 for the mantle, closely constrained models of the upper crustal structure have been constructed (Fig. 15). The modelling method used a computer program derived from Talwani et al. (1959) technique which calculates the vertical and horizontal gravity components produced by 2-D polygonal models. Starting from a simplified 2-D geological model based on reflection and refraction seismic data and surface geological mapping, the program computes a synthetic gravity profile which is compared with the real profile. The model was adjusted iteratively, within the confines of the existing data, until the closest fit was obtained. The basin structure is well defined in profiles *A*, *B*, *C*, and *D* and therefore the main variable in the models is the positioning of the Moho. Four models with calculated best fit and real gravity profiles are shown in Fig. 15. Profile *AA′* (Fig. 15a) shows the Jatobá Graben with a section perpendicular to the main gravity anomaly trend. The strong asymmetry of the basin with a northern dip of the basement is the main feature of this model. Profile *BB′* (Fig. 15b) exhibits a similar asymmetry across the Central Tucano Graben. This NW–SE profile traverses the Sítio do Quinto depocenter (Fig. 13), which is the deepest part of the whole rift system.

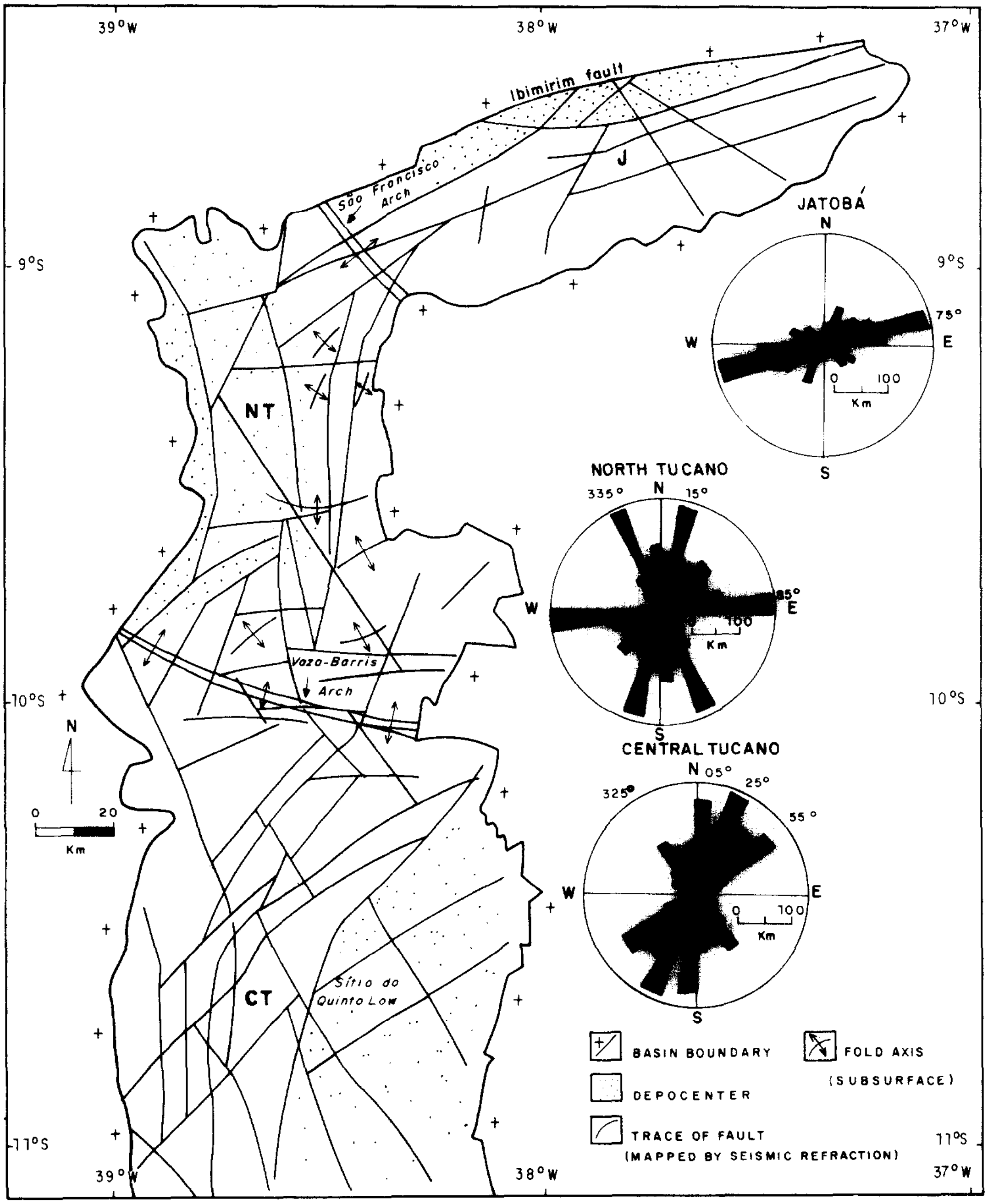


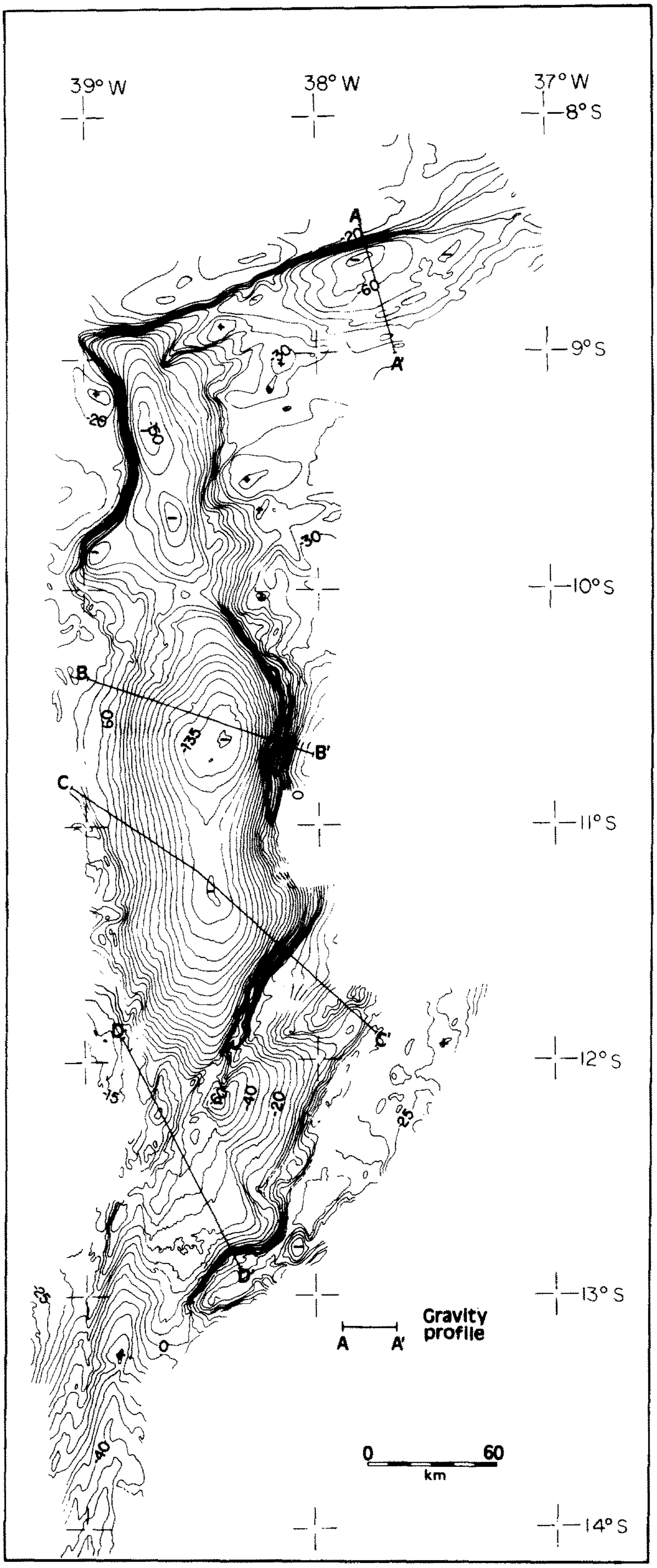
Fig. 13. Structural map of the Central and North Tucano and Jatobá grabens. Rose diagrams show the cumulative length of faults at the basement level in 5° intervals, defined from seismic refraction data (modified from Correia, 1965a, b).

The 150 mGal negative anomaly suggests the basement is deeper than 12 km in this area.

Profile *CC′* (Fig. 15c) shows a NW–SE section across South Tucano Graben, and profile *DD′* (Fig. 15d) lies across the Camaçari depocenter of the Recôncavo Graben.

The striking common feature of the four profiles is the offset of the largest negative anomaly

Fig. 14. Bouguer anomaly map of the Recôncavo–Tucano–Jatobá rift system (PETROBRÁS/RPBA, 1970).


39° W
38° W
37° W
8° S
9° S
10° S
11° S
12° S
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A
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D'
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Gravity profile
A A'
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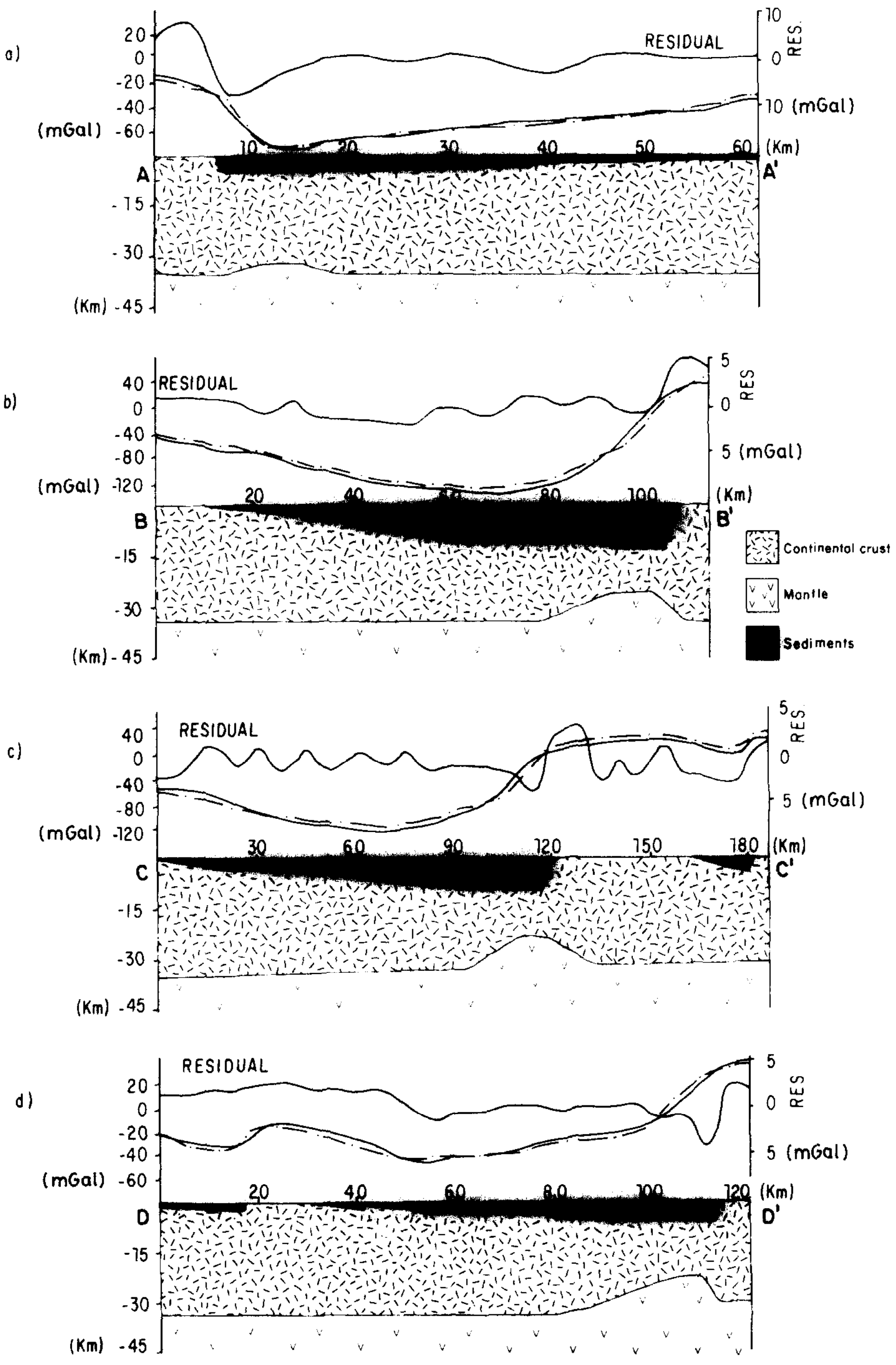

Fig. 15. Two-dimensional gravimetric models across the rift, with comparison of the calculated Bouguer gravity profile with the observed profile. A corresponding geological crustal section is shown below each gravity profile. Residual curves show the position of major border faults. Location of profiles is shown in Fig. 14.

a. Profile *AA'*, Jatobá Graben. b. Profile *BB'*, Central Tucano Graben. c. Profile *CC'*, South Tucano and Recôncavo grabens. d. Profile *DD'*, Recôncavo Graben.

Solid lines are observed gravity profiles and dot-dashed lines are calculated profiles derived from the geological models (modified from Milani, 1985, 1987).

from the deepest part of the sedimentary basin. Residual curves show the real position of major border faults that control the position of depocenters. There is also a consistent difference between the plateau anomalies on the opposing rift shoulders. These features require mantle relief similar to that shown in Fig. 15. The four profiles presented show that the calculated anomalies produced by the elevated Moho (crustal thinning) coincide with the area of deepest subsidence in the basin. This suggests that the isostatic compensation of the graben was a response to local mantle uplift.

Ussami et al. (1986) proposed an easterly-dipping crustal detachment fault beneath the Central Tucano. They used a simplified Bouguer anomaly map, which does not show positive anomalies flanking the basin, and suggested that the absence of flanking anomalies implies that there was no important crustal thinning below the rift. However, our more detailed Bouguer anomaly map shows positive flanking anomalies up to 50 mGal, which implies that crustal thinning along the northern and eastern margin of the rift was important. An easterly dipping detachment fault would be in direct conflict with the asymmetry of the Central Tucano Graben, where the major normal fault controlling basin asymmetry dips to the west.

Crustal stretching

Crustal profiles for the South Tucano and Recôncavo grabens, similar to those shown in Fig. 15, permitted construction of a simplified depth contour map of the Moho, which indicates localised thinning anomalies next to the Salvador and Inhambupe faults (Fig. 16).

Balancing of crustal cross sections perpendicular to the crustal thinning contours and the principal normal fault trend (i.e. parallel to the principal extension direction) should provide a rough quantitative estimate of the average crustal extension below the rift (Gibbs, 1983). Using the area balance principle on two sections *CC′* and *EE′*, which traverse the South Tucano and Recôncavo grabens in a NW–SE direction, and assuming that the original crustal thickness is equal to the present-day crustal thickness on the rift shoulders, the average crustal extension was estimated at 20% (Fig. 17). Locally, the extension reaches 45% below the eastern margin of the rift.

With the Moho anomalies similar to the ones modelled along profile *CC′*, one would expect significant lateral, as well as vertical conduction of heat into the rift margins during the rifting event. Although dating is not very accurate the ostracod biostratigraphy suggests that rifting occurred over a period of 20 Ma (Fig. 2). With such prolonged rifting, and a crustal thinning profile such as that shown in profile *CC′* (Fig. 17), it can be shown that the heat anomaly created during rifting would be dissipated during the rifting event itself, so that no post-rift thermal subsidence would be expected (Cochran, 1983). Post-rift sediments are absent indeed. Ussami et al. (1986) suggested that the absence of post-rift thermal subsidence in the Central Tucano Graben is another indication of a discrepant zone (Wernicke, 1985) and that rifting was affected by downslope sliding on a low-angle easterly-dipping detachment which links with the basal detachment surface below the Atlantic Ocean Basin.

Opening direction

It was demonstrated that the principal extensional faults strike N30°E throughout the Recôncavo, South and Central Tucano grabens and that the gravity data indicate that the depocenters within these grabens also have an approximate N30°E alignment. However, the general trend of the rift is N–S, suggesting that oblique rifting occurred. Withjack and Jamison (1986) showed experimentally that extensional faults do not always develop perpendicular to the extension but may vary up to 20° from this direction during oblique rifting. Thus, the major normal fault trend may be slightly oblique to the opening direction in the rift system.

The important N30°–40°W transfer faults have steeply dipping to vertical profiles and show both extensional and compressional structures along their strike suggesting they lie close to the opening direction. One can therefore conclude that the rift opening direction probably lies be-

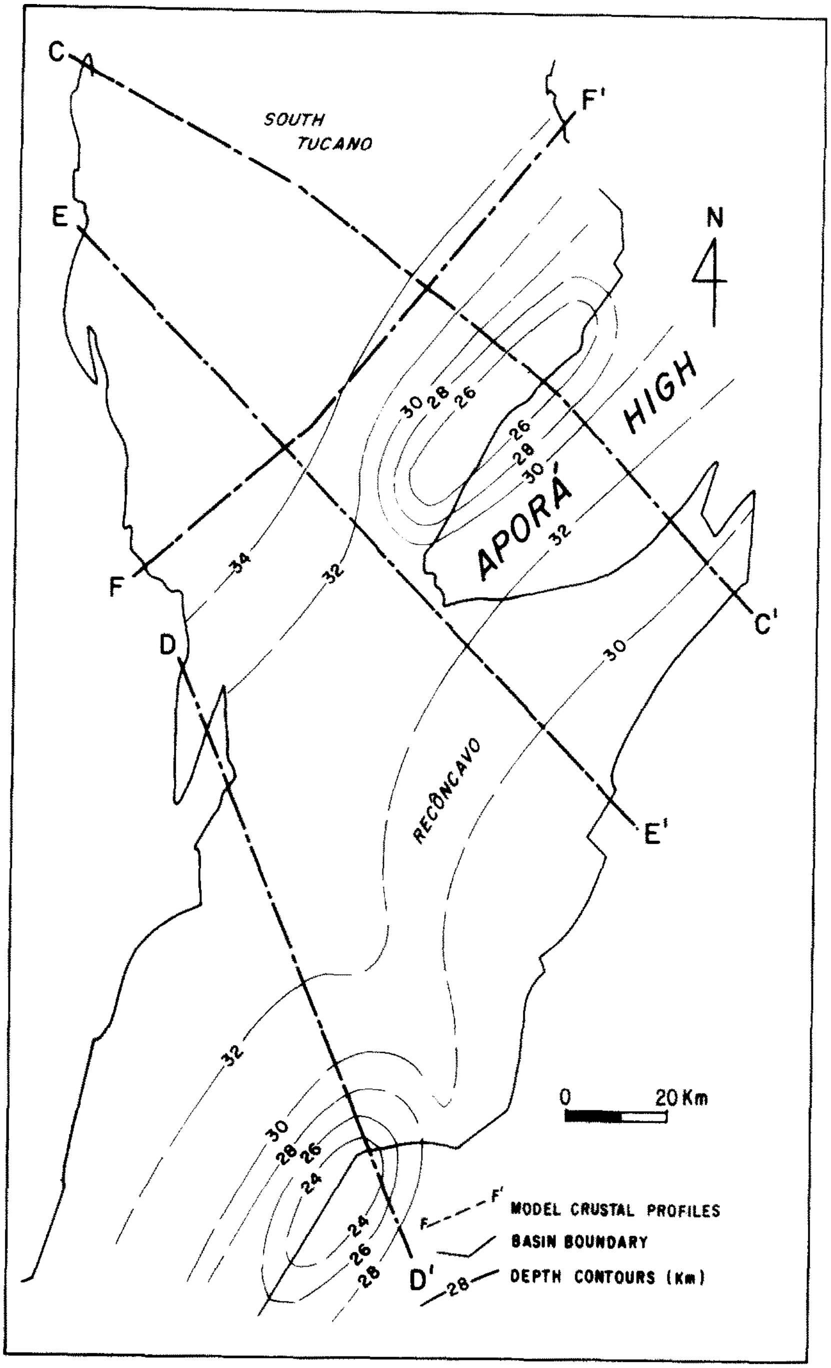

Fig. 16. Contour map of the modelled depth to the Moho below the Recôncavo and South Tucano grabens using four model crustal profiles (from Milani, 1987).

tween N30°–40°W. This interpretation differs from Cohen (1985) who suggests that the opening of the Recôncavo Graben was oriented E–W. Cohen based his conclusion on the orientation of faults mapped at the surface in the Recôncavo Graben and concluded that the N30°E faults were strike-slip faults with large normal components of throw. However, we fail to see how the NE-trending transcurrent shear zone, proposed by Cohen (1985), explains major NE-trending extensional normal faults which were active during sedimentation. Cohen also suggests that the

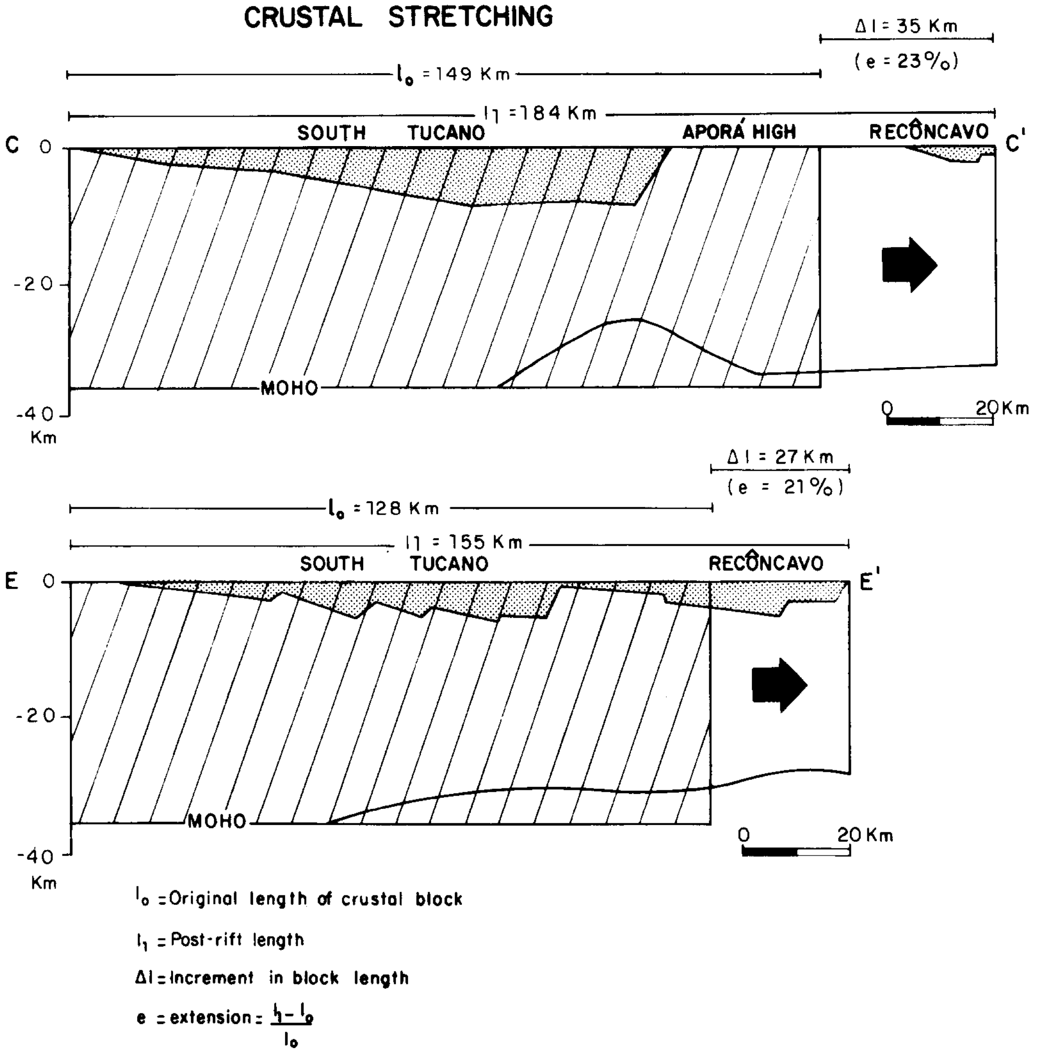

Fig. 17. Area balancing of two crustal sections, *CC′* and *EE′* (location on Fig. 16). The dotted area indicates the sedimentary basin fill and the diagonal lined area represents the original area of crust which was extended. Balancing assumed that the crust had an initial thickness equal to that on the undeformed rift shoulders (from Milani, 1987).

sigmoidal shape of the rift system indicates a northeast sinistral shear zone, but if the sigmoidal shape of the rift were to be explained as a mega tension gash, this would require a west-northwest sinistral or north-northeast dextral shear zone (Ramsay, 1980). The Recôncavo and Jatobá grabens should also be younger than the Tucano Graben, but this is not the case. An interpretation of the sigmoidal rift shape is presented in the following section.

Basement control

The rift cuts a complex path through the mosaic of basement blocks which played a decisive control in the rift geometry. Data of penetrative schistosities, shear zones and brittle faults within the basement have been collected from existing geological maps and field work to evaluate their control on basin opening (Figs. 3 and 18).

The eastern margin of the Recôncavo Graben is bordered by Early Proterozoic granulite gneisses with a general foliation strike of N30°E and steep NW dip of the gneissic banding. The Aporá High is composed of Early Proterozoic amphibolite gneisses which are transected by N30°E, 80°–90°NW oriented shears up to 1 km wide. The western border of the Recôncavo Graben is composed of granulite gneisses, but with a N30°W

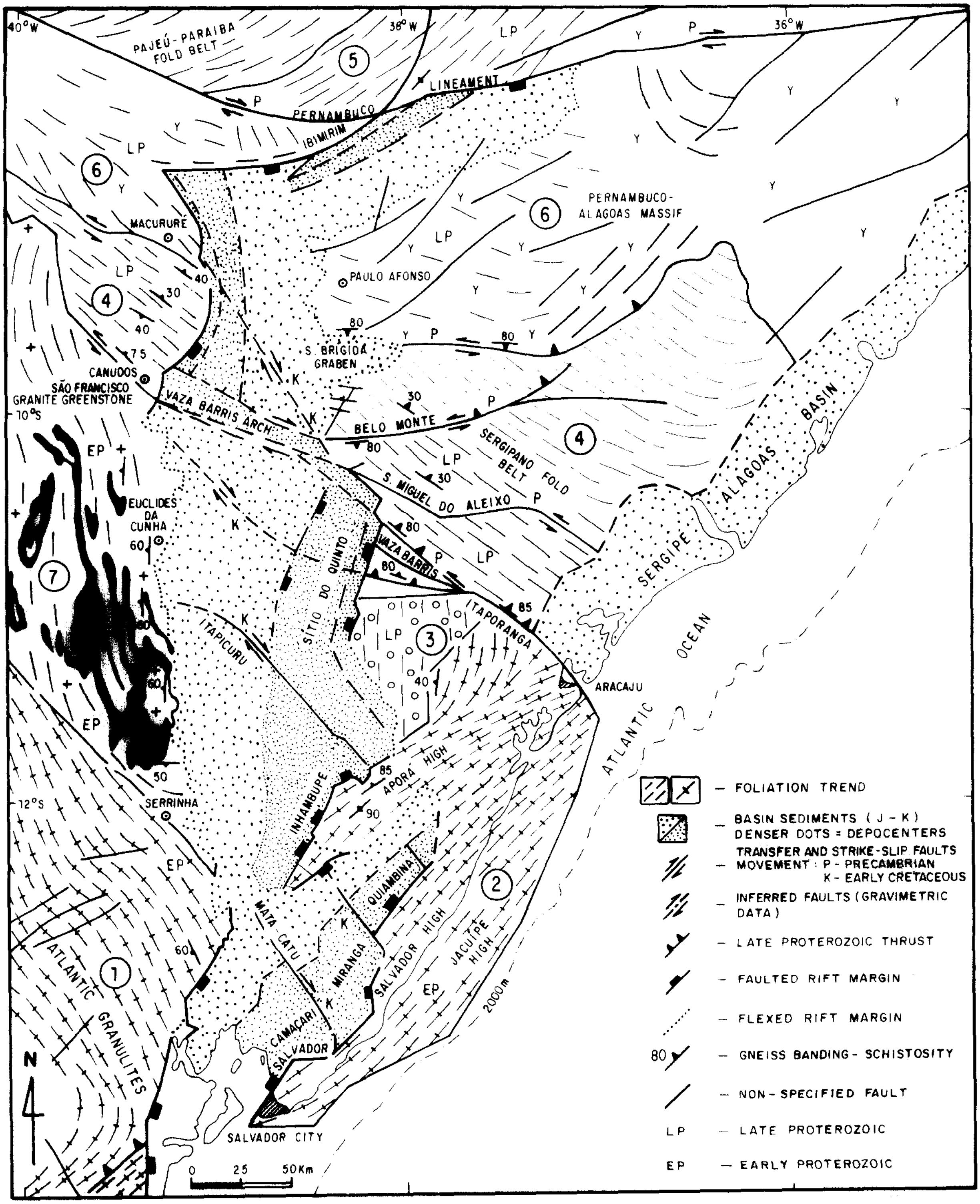

Fig. 18. Structural map of the basement surrounding the rift (modified from Brasil/DNPM, 1981, and field work by authors). *1* and *2*—Lower Proterozoic granulites–Atlantic Belt; 3—Upper Proterozoic sediments; *4* and *5*—Late Proterozoic fold belts; *6*—Reworked (Late Proterozoic) gneisses and granites; *7*—Lower Proterozoic granite–greenstone terrain; black areas correspond to the Rio Itapicuru Greenstone Belt.

foliation trend, dipping 70°–80°SW (Fig. 18). Farther north, between the towns of Serrinha and Euclides da Cunha, Lower Proterozoic granite–greenstone terranes strike N–S with a 60°W dip. Along the eastern border of the South and Central Tucano Graben the basement is covered by a veneer of flat-lying Upper Proterozoic sediments which may reach up to 2 km thick south of the Itaporanga Fault. The underlying crystalline basement may also be an Lower Proterozoic granite–greenstone terrane with a similar N–S orientation. The Itaporanga, São Miguel do Aleixo and Belo Monte faults are all interpreted as sinistral transcurrent shear zones formed before and during the Brazilian (Late Proterozoic) orogeny which produced the Sergipano Fold Belt (field work by authors). All these faults are steeply N-dipping or vertical, and converge towards the Vaza-Barris Arch. They are probably deep-reaching crustal scale faults which separate stratigraphic terranes. The São Miguel do Aleixo Fault can be traced across the Tucano Basin and emerges near Canudos town (Fig. 18). The Itaporanga Fault may control the orientation of a transverse residual gravity anomaly which is interpreted as a strike-slip fault. The southeast continuation of the Itaporanga Fault is also responsible for the southwest termination of the Sergipe–Alagoas Basin (Fig. 18).

The Sergipano Fold Belt consists of steep NNE-dipping folds south of the São Miguel do Aleixo Fault, and moderately NNE-dipping folds north of this fault. The Pernambuco-Alagoas Massif is dissected by a series of NE–SW trending shear zones and faults. The Ibimirim Fault parallels one such shear zone, but the most important shear zone is the Pernambuco Lineament which is the longest in Northeast Brazil. Drag structures and observation of stretching lineations indicate a transcurrent dextral shear movement of many kilometres, but towards its eastern end steep reverse faulting occurs. The age of the ductile transcurrent movement is thought to be Late Proterozoic, but the age of the localized brittle reverse faulting is probably Mesozoic, the same as the rifting episode.

From the above disposition of basement planar weaknesses, it is clear that some of these have been faithfully followed by the rift faults but other rifts cross-cut all visible basement structures. The rift system is an excellent example of nature's way of finding the easiest path through the labyrinth of a complex basement structure. The faults which developed parallel to pre-existing basement weaknesses (schistosity, lithological contacts and major shears) are shown in Fig. 19. The sigmoidal shape of the rift shows a convincing fit to the surrounding basement trends (Fig. 18). The asymmetry of the rift is also thought to be due to basement anisotropy. The eastern depocenters in the Recôncavo, South and Central Tucano are caused by westerly dipping master faults parallel to the shear zones, gneissic banding and lithological con-

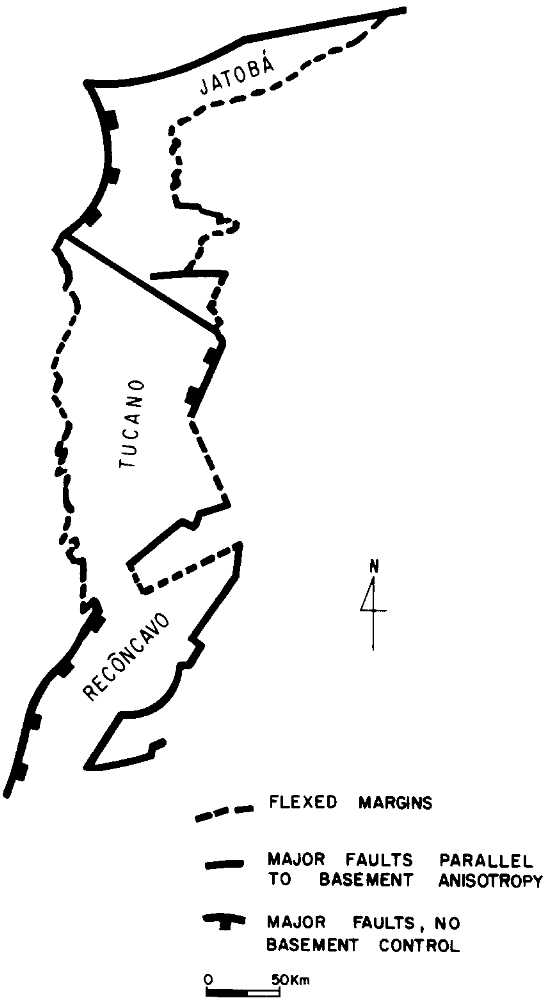

Fig. 19. Map of the rift system showing major faults that developed sub-parallel to schistosity, gneissosity, shear zones and faults within the basement.

tacts in the adjacent border of the rift, whereas the unfaulted western rift margin exhibits a basement orientation unfavourable for reactivation. The N–S orientation of the North Tucano Graben is not readily explained in terms of basement weakness as the rift cuts through regardless of the NW–SE oriented basement. However, the choice of the Vaza-Barris as the transfer zone to accommodate the switch of basin asymmetry between the North and Central Tucano grabens was controlled by the basement faults of São Miguel do Aleixo and Itaporanga. The abrupt northern termination of

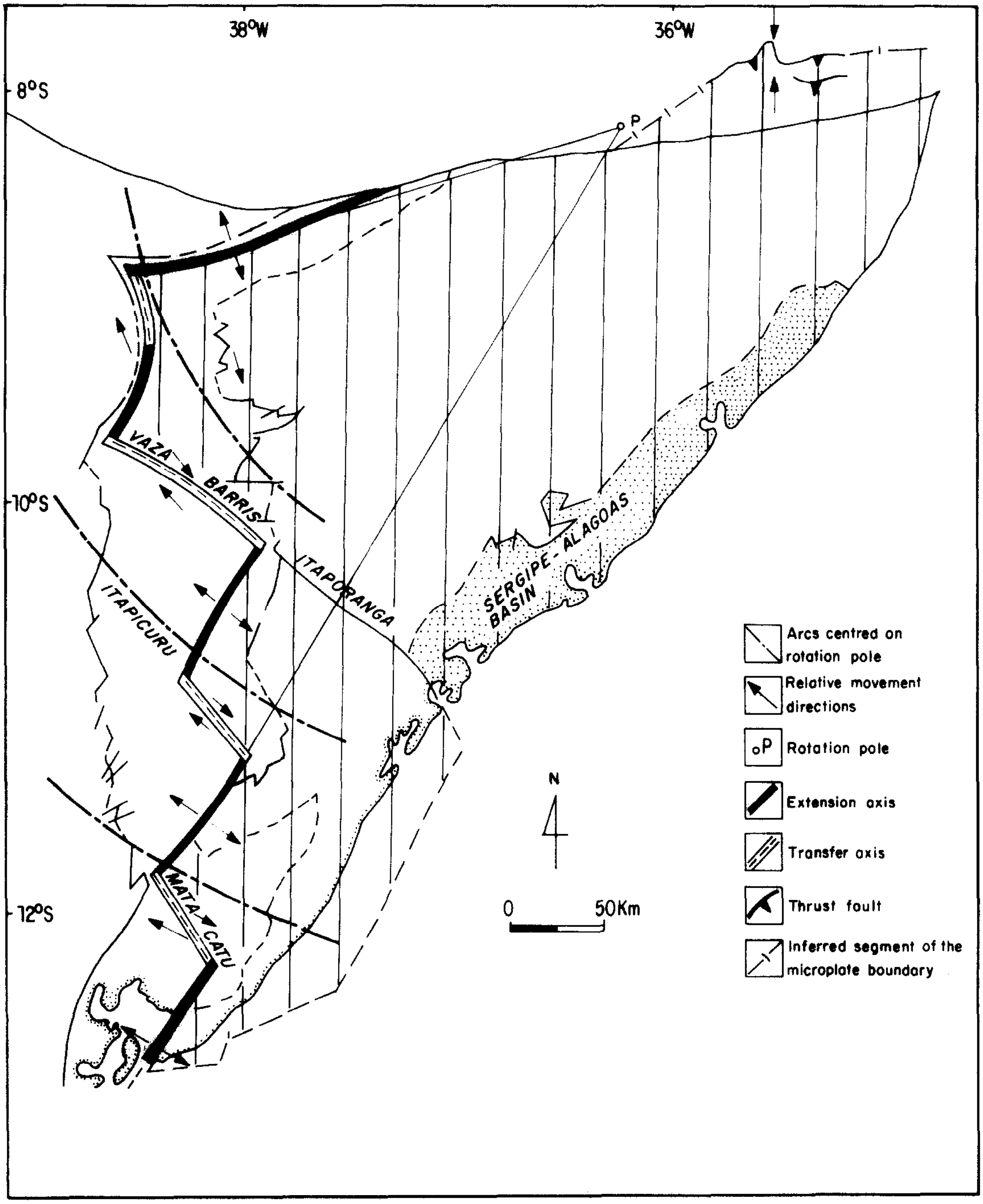

Fig. 20. The East Brazilian microplate (hatched area) with rotation pole marked (from Milani, 1987).

the rift system against the Pernambuco Lineament is clearly basement controlled. Ussami et al. (1986) suggested that an easterly-dipping low-angle detachment may have been activated along the basal thrust plane of the Sergipano Fold Belt. However, a postulated N–S trending low-angle basal thrust bears little relation to the known geology of this fold belt (Figs. 3 and 18). All presently outcropping major thrusts and strike-slip faults dip steeply NE–NNE. One can easily conclude that no clear evidence exists to support low angle crustal detachment below the Tucano Graben.

East Brazilian microplate

Szatmari et al (1985) suggested that a triangular-shaped crustal plate limited to the north by the Pernambuco Lineament, to the west by the opening axis of the Recôncavo–Tucano rift system, and to the southeast by the Atlantic Ocean, existed during the Early Cretaceous (Fig. 20). They explained rift opening by horizontal body rotation of a rigid plate. This is rather a simplistic model as internal deformation of the plate also probably occurred, but it is difficult to separate intraplate Precambrian deformation from Early Cretaceous deformation. Nevertheless, the model fits closely to the observed rift geometry. Iterative positioning of the rotation pole describing the plate rotation gave a best fit position of 8°11′S and 36°04′W (Fig. 20). The approximate 20% extension of the Recôncavo and South Tucano grabens (measured from section balancing) requires a 2° anticlockwise rotation of the rigid plate. A rigid rotation around the pole implies that basin extension should gradually decrease northwards along the rift system and reach a minimum in the North Tucano where NW–NNW strike-slip movement should have occurred without extension. Observed extension in the North Tucano Graben is larger than that predicted by the rotation model and internal deformation of the microplate is required to accomodate this extension. Although strike-slip deformation was probably important in the North Tucano, and caused widespread folding (Fig. 13), the basin also underwent important extension with large negative gravity anomalies indicating approximately 5 km of subsidence.

The progressive eastward narrowing of the Jatobá Basin is adequately explained by the rotation model. Further implication of the model are that the Vaza-Barris and the Itapicuru transfers are dextral transpressional, and the Mata-Catu transfer is dextral transtensional (Fig. 20). Existing seismic evidence does not contradict these movements.

To compensate for the rift extension, compression should occur east of the rotation pole, and this may explain the reverse fault movements seen at the eastern end of the Pernambuco Lineament (Fig. 20). The amount of shortening at the eastern end of the lineament should be approximately 6 km, considering a 2° rigid rotation. Unfortunately, correlations are not possible across the lineament to permit an independent estimation of shortening.

Discussion of transfer faults

Strike-slip faults that trend obliquely to the main rift axis and can be shown to be active during rifting have been described by several authors (Bally, 1981; Gibbs, 1984; Bosworth, 1985; Lister et al., 1986), although they have mostly been shown on theoretical diagrams. The transfer faults within the Recôncavo–Tucano rift are particularly clear natural examples. Their role in the rift tectonics described here has several special characteristics and produces some unusual structures which deserve further mention. They can be summarized as follows:

(1) They usually terminate against oblique normal faults, which may, or may not, exhibit a horizontal offset across the transfer (Fig. 21a).

(2) They can terminate at, or continue across, basin margins (Fig. 21a).

(3) There will generally be a change of throw, and perhaps dip, of the oblique normal faults at either side of their intersection with the transfer (Fig. 21b).

(4) The movement sense may change along strike of the same transfer, and they may show a null point (N) where there is no displacement (e.g. Mata-Catu transfer, Fig. 21c).

(5) The movement sense may change through time along the same fault segment.

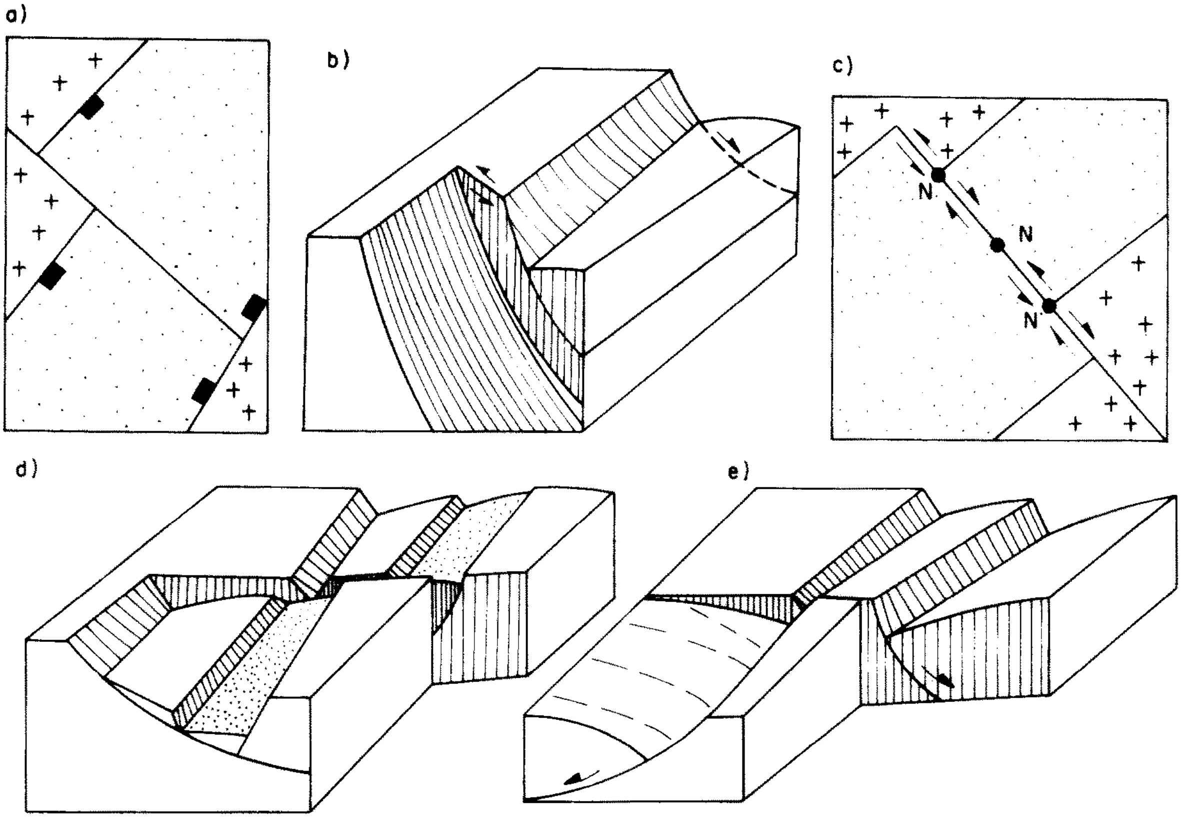

Fig. 21. Characteristic structures and effects of transfer faults. a. Termination of transfer fault at highly oblique normal faults; map view. b. Change of throw and dip of normal faults either side of a transfer. c. Movement sense changes along strike of the same transfer; map view. d. Offset of depocenters by transfer which are parallel to the rift opening. e. Flip of depocenter across a transfer.

(6) The age of fault movement usually varies along strike. The whole fault will very rarely, if ever, be active at the same time.

(7) They can accommodate initial offsets in the axes of maximum extension and subsidence, thus parallel transfer faults may show opposite apparent offsets (e.g. Mata-Catu and Itanagra–Araçás). If faults with opposite apparent offsets are vertical they should be sub-parallel to the rift opening direction (Fig. 21d).

(8) Basin asymmetry can change across the fault (e.g. the Vaza-Barris transfer, Fig. 21e).

(9) Oblique normal faults near a transfer cannot be used in the same manner as normal faults in classic wrench tectonics to determine strike-slip sense. Maximum stress should be vertical in transfer zones, unlike wrench faults where it is sub-horizontal.

(10) They usually show rapid changes of throw along strike.

(11) They exhibit characteristics of strike-slip faults in seismic sections (Harding, 1985).

(12) If the section is favourably oriented, oblique to the transfer, a cactus structure may be observed (e.g. Itapicuru transfer, Fig. 11).

Conclusions

The Recôncavo–Tucano–Jatobá rift is an aborted intra-continental rift which opened during the Early Cretaceous South Atlantic rifting. The Recôncavo–Tucano segment is believed to have opened obliquely to the overall N–S trend in a N30°–40°W direction, about a rotation pole situated at 8°11′S and 36°04′ W. The opening direction is roughly constrained by N30°W transfer faults. Calculation using area balance of approximately 20% extension in the South Tucano and Recôncavo grabens suggests that a 2° anticlockwise rotation of the East Brazilian Microplate took place relative to the São Francisco Craton. The Jatobá Graben is interpreted as having opened in a N–S direction.

Well-defined transfer faults were important in accommodating oblique opening. These faults show sudden changes of throw along strike, changes of movement sense along strike, offsetting of depocenters, and cactus and flower structures on seismic sections. "Cactus" is a new proposed term for a structure observed in oblique section cutting through opposing listric fans separated by a transfer fault.

Basin architecture is strongly controlled by a complex mosaic of basement blocks, and is a particularly good example of nature's way of finding the fracturing path of least resistance through the basement labyrinth. Basin asymmetry is strongly correlated with basement weakness. Depocenters are located close to the eastern margin of the Recôncavo, South and Central Tucano grabens, and are produced by N30°E steep NW-dipping normal faults developing parallel to basement shears and lithological contacts. The slightly flexured western margin has basement weaknesses which are unfavourably oriented for reactivation as down-to-the-basin normal faults. The flip of the depocenter to the western margin in the North Tucano Graben occurs across the Vaza-Barris Arch, which is a complex transfer zone controlled by Precambrian strike-slip faults separating stratigraphic terranes in the Sergipano Fold Belt. The E–W trend of the Jatobá Graben is controlled by the Pernambuco Lineament and subsidiary shear zone. Hence, the sigmoidal shape of the rift is believed to be controlled by basement anisotropies.

Positive Bouguer anomalies (up to +50 mGal) flank the eastern side of the Tucano and Recôncavo grabens, but are not found on the western margin. The anomaly produced by the basin fill does not coincide with the maximum depocenter in the basin defined by seismic methods. These two important features of the gravity field strongly suggest that crustal thinning occurred below the rift. The calculated crustal profiles in the Tucano and Recôncavo Grabens show localized thinning up to 45% near to the eastern basin margin, and this geometry implies that a large amount of lateral heat conduction probably occurred during the 20 Ma rifting period. This would cool the crust as it extended and may explain why no post-rift thermal subsidence phase exists.

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References

Bally, A.W., 1981. Atlantic type margins. In: A.W. Bally and A.B. Watts (Editors), Geology of Passive Continental Margins. Am. Assoc. Pet. Geol. Course Note Ser., 19: 1–47.

Bosworth, W., 1985. Geometry of propagating rifts. Nature, 316: 625–627.

Brasil/DNPM, 1981. Mapa geológico do Brasil e da área oceânica adjacente, incluindo depósitos minerais (Scale of 1 : 2,500,000). Departamento Nacional de Produçaõ Mineral, Brasília.

Christie-Blick, N. and Biddle, K.T., 1985. Deformation and basin formation along strike-slip faults. In: K.T. Biddle and N. Christie-Blick (Editors), Strike-Slip Deformation, Basin Formation and Sedimentation. Soc. Econ. Paleontol. Mineral., Spec. Publ., 37: 1–34.

Cochran, J.R., 1983. Effects of finite rifting times on the development of sedimentary basins. Earth Planet. Sci. Lett., 66: 289–302.

Cohen, C., 1985. Role of fault rejuvenation in hydrocarbon accumulation and structural evolution of Recôncavo Basin, Northeast Brazil. Am. Assoc. Pet. Geol. Bull., 64: 65–76.

Correia, E.G., 1965a. Contribuição da refração sísmica no delineamento do arcabouço estrutural da Bacia de Jatobá. PETROBRÁS/RPBA, Salvador, internal rep.

Correia, E.G., 1965b. Esqueleto tectônico da Bacia do Tucano Norte, segundo os dados da refração sísmica. PETROBRÁS/RPBA, Salvador, internal rep.

Ghignone, J.I., 1979. Geologia dos sedimentos fanerozóicos do Estado da Bahia. In: H.A.V. Inda (Editor), Geologia e Recursos Minerais do Estado da Bahia. Secretariat of Mines and Energy Basic Papers, 2: 24–117.

Ghignone, J.I. and Andrade, G., 1970. General geology and major oil fields of Recôncavo Basin, Brazil. In: M.T. Halbouty (Editor), Geology of Giant Petroleum Fields. Am. Assoc. Pet. Geol., 14: 337–358.

Gibbs, A.D., 1983. Balanced cross-section construction from seismic sections in areas of extensional tectonics. J. Struct. Geol. 5: 152–160.

Gibbs, A.D., 1984. Structural evolution of extensional basin margins. J. Geol. Soc. London, 141: 609–620.

Harding, T.P., 1985. Seismic characteristics and identification of negative flower structures, positive flower structures and positive structural inversion. Am. Assoc. Pet. Geol. Bull., 69: 582–600.

Lister, G.S., Etheridge, M.A. and Symonds, P.A., 1986. Detachment faulting and the evolution of passive continental margins. Geology, 14: 246–250.

Milani, E.J., 1985. Tectônica cisalhante na evolução do rift do Recôncavo–Tucano–Jatobá. Rev. Bras. Geociênc., 15: 287–292.

Milani, E.J., 1987. Aspectos da evolução tectônica das bacias do Recôncavo e Tucano Sul, Bahia, Brasil. PETROBRÁS Ciência-Técnica-Petróleo Ser., Rio de Janeiro, 18, 61 pp.

Netto, A.S.T., 1978. A implantação da fase rift na Bacia do Recôncavo. Congr. Bras. Geol. 30th, Recife, pp. 506–517.

Netto, A.S.T. and Oliveira, J.J., 1985. O preenchimento do rift-valley na Bacia do Recôncavo. Rev. Bras. Geociênc., 15: 97–102.

PETROBRÁS/RPBA, 1970. Mapa Bouguer das bacias do Recôncavo-Tucano-Jatobá (Scale of 1:250,000). Internal rep.

PETROBRÁS/DEXBA, 1985. Arcabouço estrutural das bacias do Recôncavo e Tucano Sul (Scale of 1:250,000). Internal rep.

Ramsay, J.I., 1980. Shear zone geometry: a review. J. Struct. Geol. 2: 83–99.

Szatmari, P., Milani, E.J., Lana, M.C., Conceição, J.C.J. and Lobo, A.P., 1985. How South Atlantic rifting affects Brazilian oil reserves distribution. Oil Gas J., 83: 107–113.

Talwani, M., Worzel, J.L. and Landisman, M., 1959. Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. J. Geophys. Res., 64: 49–59.

Ussami, N., Karner, G.D. and Bott, M.H.P., 1986. Crustal detachment during South Atlantic rifting and formation of Tucano–Gabon basin system. Nature, 322: 629–632.

Wernicke, B., 1985. Uniform sense normal simple shear of the continental lithosphere. Can. J. Earth Sci., 22: 108–125.

Withjack, M.O. and Jamison, J.R., 1986. Deformation produced by oblique rifting. Tectonophysics, 126: 99–124.