Pergamon

Journal of Structural Geology, Vol. 16, No. 5, pp. 647 to 661, 1994

0191-8141/94 $07.00+0.00

Faulting in the Early Cretaceous Rio do Peixe basin (NE Brazil) and its significance for the opening of the Atlantic

J. B. L. FRANÇOLIN and P. R. COBBOLD

Géosciences, Université de Rennes, 35042 RENNES Cedex, France

and

P. SZATMARI

PETROBRAS Research Centre (CENPES), Cidade Universitaria, 21910 Rio de Janeiro, Brazil

(*Received* 21 *September* 1992; *accepted in revised form* 29 *June* 1993)

Abstract—The intracratonic Rio do Peixe basin (NE Brazil) developed during the Early Cretaceous. Ductile shear zones in the Precambrian basement became reactivated as brittle master faults, bounding the Brejo das Freiras, Sousa and Pombal sub-basins. Sediments are well-dated as Berriasian to Barremian. Large growth folds are distributed en échelon along the master faults, which are dominantly strike-slip.

We have measured the attitudes of 300 minor faults and striations at 11 localities in basin sediments. For 160 faults, we found the sense of slip to be unequivocal. Most common are right-lateral strike-slip faults, striking NNE; then normal faults, striking ENE; then reverse faults, striking ESE; and finally, left-lateral strike-slip faults, striking ENE. We have used a kinematic contouring method to estimate regional strain and the method of Etchecopar to estimate stresses. At eight localities, the principal direction of compression is nearly horizontal and strikes ENE; at three localities it is nearly vertical. At eight localities, the principal direction of extension is nearly horizontal and strikes SSE; at three localities, it is nearly vertical. Thus the regional pattern is one of wrenching, with local deviations towards either transpression or transtension.

Stratigraphic constraints on the timing of fault motions are sparse. Master faults were active throughout the entire history of sedimentation. In the Pombal sub-basin, transtensional conditions prevailed. In the Brejo das Freiras sub-basin, transpression replaced transtension some time after the Berriasian.

From stress trajectories and other data, we infer that left-lateral wrenching along the E–W Patos shear zone dominated over right-lateral wrenching along smaller faults striking NE–SW. This is confirmed by palaeomagnetic results, indicating small block rotations about vertical axes, counterclockwise in the northwest and clockwise in the southeast.

Early Cretaceous wrenching along the reactivated Patos shear zone appears to correlate with that reported for the Benue trough in Africa. Intracontinental deformation was probably associated with a northward-propagating rift zone, prior to opening of the South Atlantic.

OPENING OF THE ATLANTIC

THE current rate of opening of the South Atlantic ocean is well constrained. Model NUVEL-1, a least-squares fit to worldwide data assuming rigid plates (De Mets *et al.* 1990), predicts a counterclockwise rotation of South America with respect to Africa, at an angular velocity of $0.32 \pm 0.01° \text{ Ma}^{-1}$, about a pole located near the southern tip of Greenland.

To constrain the history of opening, most models assume rigid plates (Bullard *et al.* 1965, Le Pichon & Hayes 1971, Rabinowicz & LaBrecque 1979, Pindell & Dewey 1982). During the Late Cretaceous and Tertiary, the South Atlantic seems to have opened rather steadily, velocities and rotation poles being similar to current ones (Cande *et al.* 1988, Shaw & Cande 1990).

In contrast, the very first stages of opening are not so clear, for three reasons. First, there is a lack of data off the coast of Brazil (Nürnberg & Müller 1991, Chang *et al.* 1992), where a wide magnetic quiet zone extends from the earliest Aptian (Chron M0, 118.7 Ma) to the earliest Campanian (Chron 34, 84 Ma). Second, it is difficult to identify truly oceanic crust. Third, Africa and South America were not rigid at that time (Burke & Dewey 1974, Pindell & Dewey 1982, Vink 1982, Matos 1992).

Jurassic and Cretaceous rifts are widespread across the Africa and South America (Fig. 1). In Africa, notable examples are the Benue Trough, Niger Rift and Central African rift system (Popoff *et al.* 1983, Fairhead 1988, Fairhead & Binks 1991, Guiraud & Maurin 1991). Along the Benue axis, rifting was associated with left-lateral wrenching during the Early Cretaceous (Guiraud & Maurin 1991). In Brazil, there are prominent inland rifts (Fig. 2), including the Recôncavo–Tucano–Jatobá rift, the Potiguar rift and the smaller basins of north-eastern Brazil (Szatmari *et al.* 1985, 1987, Milani 1985, Milani & Davison 1988, Sénant & Popoff 1989, 1991, Matos 1992). Cretaceous deformation has also been postulated to occur in the Ponte Grossa arch of southern Brazil (Conceição *et al.* 1988). In Argentina, Cretaceous rifting occurred in the Salado and Colorado basins (Urien & Zambrano 1973), as well as the Chaco-Paraná basin.

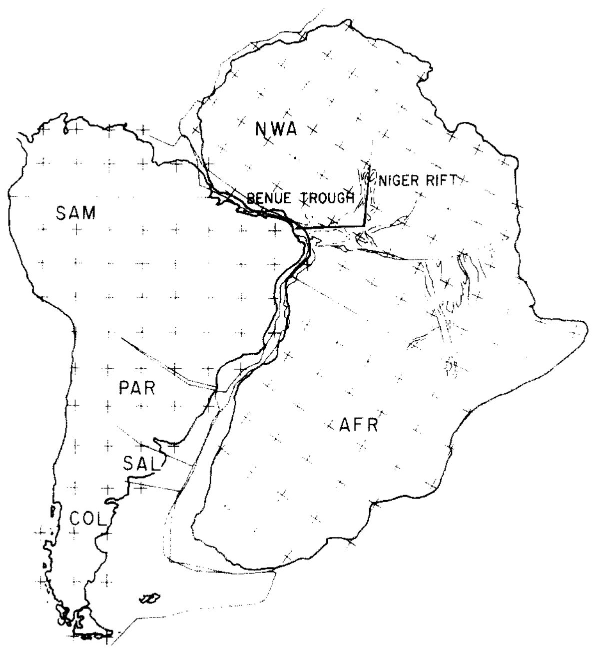

Fig. 1. Reconstruction of plates and sub-plates around the incipient Atlantic Ocean in the Hauterivian (Chron M4, 126.5 Ma), according to Nürnberg & Müller (1991, fig. 11). Africa consists of two sub-plates, North West Africa (NWA) and Southern Africa (AFR), separated by the Benue–Niger–Central African rift system. Stable South America (SAM) and the Paraná (PAR), Salado (SAL) and Colorado (COL) subplates are separated by right-lateral rifts. Oceanic crust has started to form near the southern tip of Africa.

The most recent models of Atlantic opening do consider deformable continents (Fairhead & Binks 1991, Nürnberg & Müller 1991). The models suggest that the South Atlantic Ocean formed as a northwards-propagating rift system (Fig. 1). Near the Walvis ridge, Chrons M0 to M4 are well developed and earliest sea-floor is thought to have formed near the Aptian–Albian boundary (113 Ma); whereas further south, sea-floor spreading started in the Hauterivian (Chron M4, 126.5 Ma). Rift propagation may have been responsible for intraplate deformation. In southern Brazil, the main period of crustal stretching (130–120 Ma, Chang *et al.* 1988, Conceição *et al.* 1988), was coeval with the peak of volcanic activity in the Paraná basin (125–135 Ma, Rocha Campos *et al.* 1988) and possibly also in the offshore Campos and Santos basins (Mizusaki *et al.* 1988). Rift sediments are unconformably overlain by an Aptian megasequence containing marine evaporites. Later extension within the basement has been recognized only in the Sergipe-Alagoas basin.

The rifting history of the Equatorial margin of Brazil (Fig. 2) appears to be rather different (Szatmari *et al.* 1987). Most of the tectonic activity and syntectonic sedimentary sequence is of mid-Cretaceous (Aptian) age. Pre-Aptian rifting is known only in the extreme east, in the Potiguar basin, and Aptian salt has been found only locally in the offshore Ceará basin. In Late Cretaceous times, right-lateral transcurrent deformation became dominant (Zalan *et al.* 1985, Matos 1992); but it is not clear if this was preceded by orthogonal rifting, due to clockwise rotation of South America relative to Africa (Françolin & Szatmari 1987, Zanotto & Szatmari 1987). The lack of pre-Albian sediments along its northeastern end suggests that the South Atlantic margin was still contiguous with Africa at the end of the Aptian (Szatmari *et al.* 1985).

According to the most recent models (e.g. Nürnberg & Müller 1991), based on non-rigid plates, opening propagated northwards, reaching the Benue trough and northeastern Brazil between Chron M4 (126.5 Ma) and Chron M0 (118.7 Ma). From then onwards, Africa and South America appear to have separated as rigid plates.

EARLY CRETACEOUS DEFORMATION IN NE BRAZIL

There is clearly a need for detailed and reliable tectonic studies in the northeastern tip of Brazil, where the South Atlantic and Equatorial margins intersect (Fig. 2). Here, basement rocks of the Borborema province (Almeida 1967, Almeida *et al.* 1981) have yielded radiometric ages (Brito Neves 1975) ranging from Early Proterozoic (2150 ± 200 Ma) to Cambro-Ordovician (500 ± 25 Ma). Ductile deformation and metamorphism of greenschist to amphibolite grade were widespread during the Brasiliano (Pan-African) tectonic cycle of Upper Proterozoic age (Almeida 1967, Brito Neves 1975). The basement and overlying basins, containing clastic sediments and carbonates, became reworked within a network of major ductile shear zones. Individual zones are up to several tens of km wide and several hundred km long. They have two main trends: E–W and NE–SW. In most zones, especially those trending E–W, the mylonitic foliation is steeply dipping and carries a gently plunging stretching lineation, associated with right-lateral shear indicators (Françolin & Szatmari 1987, Corsini *et al.* 1991). The Patos and Pernambuco shear zones are the longest and appear to accommodate most of the ductile deformation.

Many of these ductile shear zones show brittle reactivation that is difficult to date. Nevertheless, in the Patos shear zone, brittle shear indicators are left-lateral, so that there was a reversal in the sense of shear (Françolin & Szatmari 1987). The left-lateral shear is compatible with fault motions observed in Cretaceous sediments, suggesting that the brittle overprint is itself Cretaceous.

Cretaceous basins are well developed along both the South Atlantic and Equatorial margins of northeastern Brazil and they contain well-dated marine sediments (for reviews, see Chang *et al.* 1992, Matos 1992). There are also several small basins well inland (Fig. 2). The Rio do Peixe, Icó and Iguatu basins are located along the northern margin of the E–W-trending Patos shear zone, where it truncates other shear zones of the NE–SW family. The Rio do Peixe basin is the most easily accessible of the three. Although the relief is moderate (up to 600 m or so), the area is a semi-desert and exposures are good, especially on the edges of the basin. The sediments are now well-dated as Early Cretaceous (see below) and there are abundant minor structures, especially faults. Nevertheless, the area has received little attention from structural geologists.

From a preliminary study, Françolin & Szatmari (1987) concluded that wrenching was significant in the Rio de Peixe during the Early Cretaceous, with left-lateral reactivation of the Patos shear zone. More recently, Sénant & Popoff (1989, 1991) found that most faults in the Rio do Peixe basin were normal faults. They therefore concluded that the area underwent crustal thinning, with NW–SE stretching, during the Early Cretaceous. Similar conclusions were reached by Matos (1992), on the basis of regional data. Although our

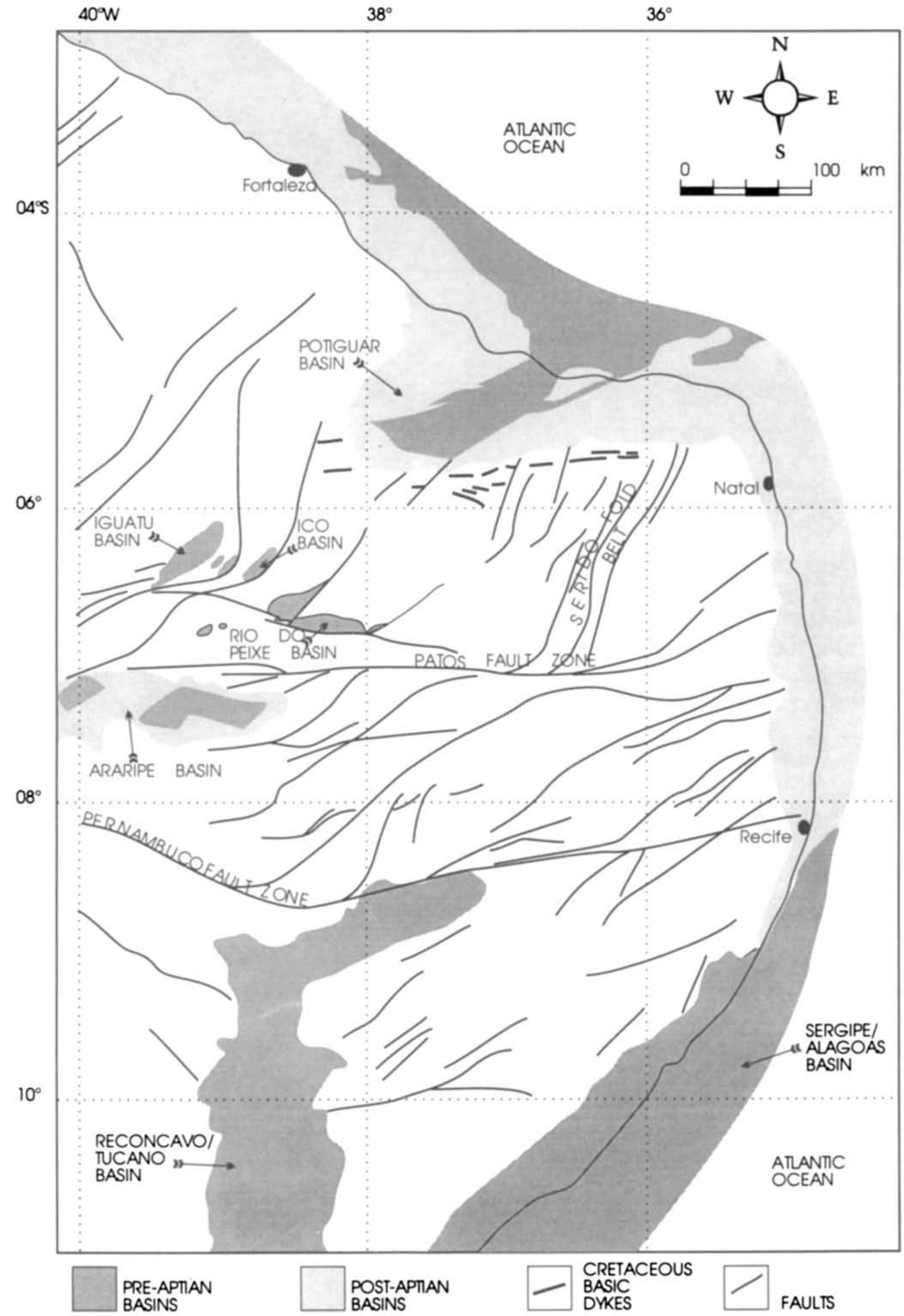

Fig. 2. Creteacous basins of NE Brazil. Marginal basins are Potiguar in the northeast and Sergipe-Alagoas in the southeast. Large inland basin is Recôncavo–Tucano–Jatobá. Smaller inland basins are Araripe, Iguatu, Icó and Rio do Peixe. Map distinguishes Pre-Aptian rift basins (dark grey) from Post-Aptian basins (light grey). Locations and shapes of basins are strongly controlled by basement faults (full lines), many of which are high-grade shear zones of Upper Proterozoic age, reactivated under brittle conditions in the Cretaceous. Prominent are the Patos and Pernambuco fault zones. Thick line segments at southern edge of Potiguar basin are Cretaceous basic dykes.

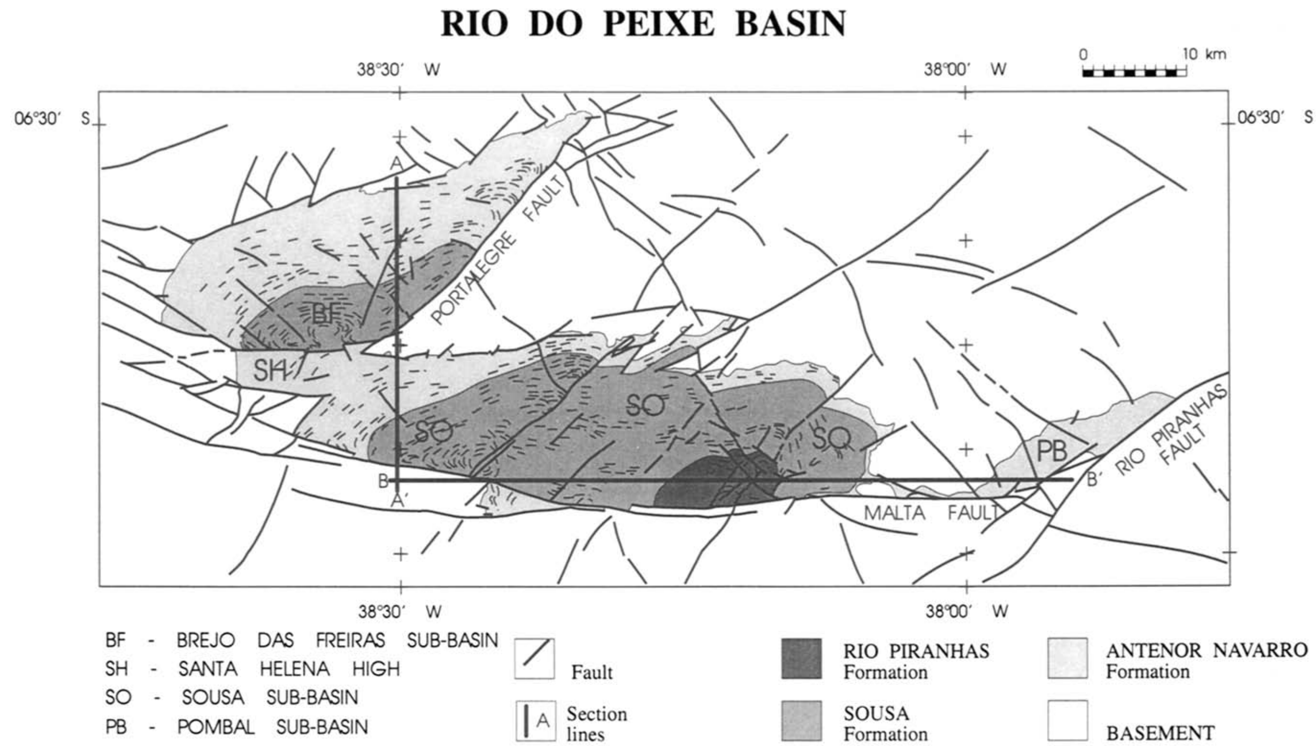

Fig. 3. Simplified structural map, Rio do Peixe basin (after Françolin 1992). Early Cretaceous sediments belong to three formations (key). Surrounding areas of basement contain mylonitic shear zones, reactivated as brittle faults. Sub-basins (Brejo das Freiras, Sousa and Pombal) are bounded on their southeastern sides by master faults (Portalegre, Malta and Rio Piranhas). Santa Helena High is at restraining intersection of Portalegre and Malta fault systems. Bedding (traces shown by short line segments) dips gently towards SE, except along master faults, where it dips steeply or forms en échelon folds. For sections A and B, see Fig. 4.

methods of analysis are similar to those of Sénant & Popoff, our data and our tectonic interpretation are significantly different. We describe strike-slip faults, reverse faults and folds and we conclude that wrenching, not crustal thinning, was the dominant mode of deformation during the Early Cretaceous.

RIO DO PEIXE BASIN

On a geological map, the Rio do Peixe basin appears as a composite structure (Fig. 3). Three sub-basins (from west to east, Brejo das Freiras, Sousa and Pombal), separated by basement highs, lie near the northern edge of the Patos shear zone. Major faults bound the sub-basins, especially on their southeastern sides. Most prominent are the steep Malta, Portalegre and Rio Piranhas faults, formed by reactivation of ductile shear zones in the basement. The basement protoliths are gneisses, migmatites, granites, pegmatites, metaconglomerates and schists.

Sediments

According to Braun (1969), the sediments of the Rio do Peixe Group were first described by Crandall in 1910 and Moraes in 1924. Braun defined three stratigraphic units, which Albuquerque (1970) named, from bottom to top, Antenor Navarro, Sousa and Rio Piranha formations (Fig. 3). The Antenor Navarro Formation consists of basal conglomerates and grits, passing upwards into sandstones and mudstones, all deposited in a fluviatile environment. In the Brejo das Freiras sub-basin, palaeocurrents are southerly or southeasterly, as are sediment dips (Alves 1990). The Sousa Formation consists mainly of mudstones, with rare sandstones and marls. It was deposited by meandering rivers on floodplains, or within shallow lakes. Mudcracks are common, suggesting frequent aerial exposure. The Rio Piranhas Formation consists of conglomerates and coarse sandstones, interspersed with sandy mudstones. It is restricted to the southeastern edge of the Sousa sub-basin and is the only formation with northerly palaeocurrents. Presumably it indicates a renewal of activity on the Malta fault.

Braun (1969) considered the sediments of the Rio do Peixe to be Early Cretaceous (Berriasian to Barremian), on the basis of dinosaur footprints and remains of freshwater crustacea found by himself and by Barbosa (1966). Mabesoone & Campanha (1974) found abundant non-marine ostracods and dated them as late Jurassic to Barremian. Lima & Coelho (1987) found fossil pollen in 26 core samples from a stratigraphic well and assigned them to the Hauterivian. More recently, Arai *et al.* (1989) studied 57 surface samples and nine core samples, concluding that the sediments are Berriasian to Barremian (between 144 and 124 Ma). This makes them coeval with: (1) the lowermost sediments in the Benue trough of Africa (Popoff *et al.* 1983, Guiraud & Maurin

1991); (2) volcanic activity in the Paraná Basin; and (3) the main period of crustal stretching on the South Atlantic margin of Brazil.

Structure of the basin

During two field seasons (1989–1991), we mapped the Rio do Peixe area structurally, measuring the attitudes of bedding and of minor and major structures. Françolin (1992) has compiled a geological map at 1:100,000, based on topographic maps at 1:100,000 (SUDENE 1982), geological maps at 1:2,500,000 (DNPM 1984), LANDSAT TM satellite images and radar images at 1:100,000 and aerial photographs at 1:70,000. In this paper, we present a simplified version of the map (Fig. 3).

The northern margins of the sub-basins are gentle flexures of the basement, sometimes with small faults. In contrast, the southern and southeastern margins are steep master faults. Hence the sub-basins appear to be half-rifts (Matos 1992). Indeed, from abundant striations on associated minor faults, the Malta, Portalegre and Rio Piranhas faults do have components of normal dip-slip. However, these are overshadowed by components of strike-slip, left-lateral for the Malta fault and right-lateral for the other two. At many localities, oblique striations pitch at 20° or less down the fault surfaces.

Over most of the area, beds dip at a few degrees towards the south or southeast; but near the master faults, bedding has been tilted into a steep or overturned attitude. Large open folds, readily visible on LANDSAT images, are distributed en échelon along master faults (Fig. 3). We infer that the folds resulted from strike-slip motions. From a study of bed thicknesses, the folds appear to be synsedimentary. We infer that master faults were active throughout the history of sedimentation. Immature conglomerates and tectonic breccias occur as footwall facies within all three geological formations.

Unfortunately, there is little information on the deep structure of the basin. No seismic surveys have been carried out so far. One stratigraphic well (LF-1-PB) was drilled in 1980 at Lagoa do Forno, near the depocentre of the Sousa sub-basin. There are also a regional gravity survey (Rand 1984) and a magnetic survey (Rand 1982). From these and by extrapolating surface data, we have drawn a tentative isopach map (Françolin 1992) and two schematic sections (Fig. 4). According to our interpretation, the westernmost (Brejo das Freiras) sub-basin is the deepest (about 2000 m) and the easternmost (Pombal) sub-basin is the shallowest (about 300 m). The lowermost Antenor Navarro Formation is about 1300 m thick in the Brejo das Freiras sub-basin, becoming much thinner (less than 500 m) in the other two sub-basins. In contrast, the Sousa Formation is thickest in the Sousa sub-basin and the Rio Piranhas Formation exists nowhere else. This suggests that tectonic activity started in the Brejo das Freiras sub-basin and migrated eastwards. However, the late stages in this process are obscure, because of possible uplift and erosion since the Cretaceous.

Minor structures

The commonest minor structures within the basin are faults (Figs. 5 and 6). Some faults appear to have formed as shear zones in unconsolidated sediments (Sénant & Popoff 1991), according to the criteria of Petit *et al.* (1983), Petit (1987) and Maltman (1988). The zones are

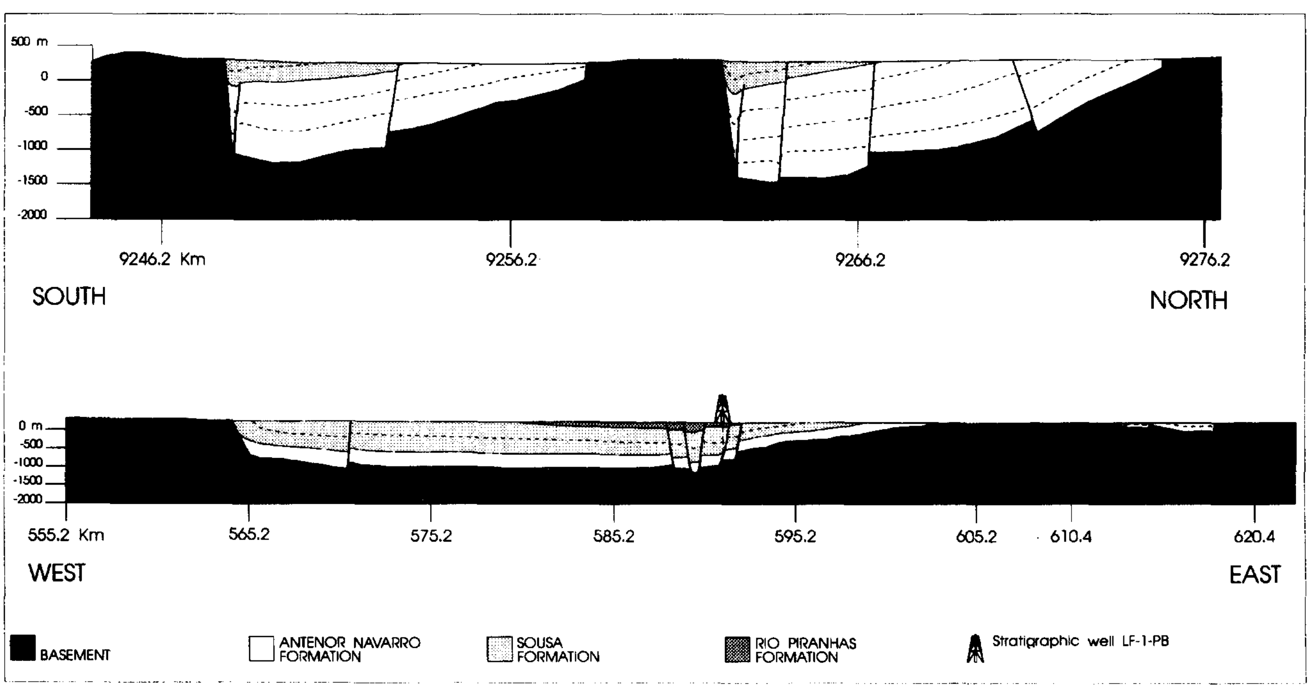

Fig. 4. Two schematic but representative cross-sections through the Rio do Peixe basin. Section B is constrained by a stratigraphic well. For section lines, see Fig. 3.

up to several metres wide and they contain anastomosing narrower zones, several cm or mm wide (Figs. 5c & d). Detrital grains are often preserved, but the matrix is deformed and shear bands are common. The bands commonly are striated, sometimes with mechanical grooves, sometimes with crystal fibres. Most of these faults can be diagnosed as synsedimentary, because they bound small grabens, where stratigraphic thicknesses are greater (Fig. 5b). Other faults however appear to have formed in lithified sediment. These are discrete planar surfaces which cut through original detrital grains. Adjacent beds tend to be of uniform thickness.

We tried to be extremely careful in evaluating the sense of slip from striations. In some instances, independent evidence was provided by vertical offset of bedding (Fig. 6b). Crystal fibres are the most reliable indicators of sense of slip (Fig. 6c), as they often are elsewhere (Petit 1987). Next most reliable are duplex structures (Fig. 5d), mechanical striations (asperity ploughing) and shear bands in clay seams.

Oblique-slip faults are ubiquitous in the Rio do Peixe basin (Fig. 6c). Dominantly dip-slip faults are almost as common as dominantly strike-slip faults. Reverse faults (Figs 6a & b) are almost as common as normal faults (Fig. 5b).

At outcrop scale, faults of various categories are commonly associated, forming flower structures that branch upwards (Fig. 5). By mapping these, we were able to check for consistency of slip criteria and bedding offsets.

Minor folds are relatively common in the Rio do Peixe basin, especially in the southern parts. Many of them are of chevron type, with constant bed thicknesses (Fig. 6d). We infer that they informed by post-depositional flexural-slip, in a sequence partly or completely lithified. In contrast, major folds are synsedimentary, on stratigraphic evidence.

DISCUSSION ON METHODS OF FAULT ANALYSIS

Many attempts have been made to interpret fault-slip data in terms of bulk stress, strain, or deformation, assuming these to be homogeneous at some scale. Most early attempts were in terms of stress, possibly because it is easier to imagine a homogeneous state of stress, than a homogeneous state of strain. Even so, a mechanical basis is required for interpreting fault slip. Usually, the striation is taken to be parallel to the maximum resolved shear stress on the fault surface (Bott 1959). If so, given a state of homogeneous stress and a population of pre-existing faults, it is possible to seek a best-fit stress tensor, by minimization of some simple function of the angular difference, α, between the striation and the maximum resolved shear stress. Many methods and computer programs are available for doing this (see Carey & Brunier 1974, Angelier 1979, 1984, Angelier & Mechler 1977, Etchécopar *et al.* 1981, Armijo *et al.* 1982, Etchécopar 1984, Lisle 1987, Reches 1987). Whether or not a real state of stress is determined depends on how valid are the assumptions, especially that of Bott (1959). Where faults record an accumulating finite deformation, with possible rigid block rotations, the calculated stress may not be truly representative of any of the real stress states acting at various times throughout the deformation history. Some check on this may be provided by measures of compatibility between the calculated stress and the data. Usually such information is given as a histogram of α values.

If Bott's stress hypothesis is not acceptable, it can perhaps be replaced by an incremental strain hypothesis. A striation is then assumed to coincide with the direction of maximum resolved incremental shear strain along the fault surface. This should be reasonable if bulk strain is small and homogeneous, implying small rotations and negligible interference between active faults of differing orientations. Most of the methods of stress analysis referred to previously then become methods of incremental strain analysis.

Another way of estimating a bulk infinitesimal strain ellipsoid is to sum tensors of incremental simple shear, one for each fault. This yields an asymmetric tensor, representing the bulk deformation. From the symmetric part of this tensor may be extracted the principal values and orientations of incremental strain (Allmendinger *et al.* 1989). The result depends on how representative is the sampling of faults of differing orientations. Alternatively, the contribution of each fault may be weighted by a factor proportional to the observed or estimated amount of slip (Marrett & Allmendinger 1990).

There are several simple graphical techniques for determining principal orientations, be they of stress or strain (Arthaud 1969, Aleksandrowski 1985). In the method of right dihedra, quadrants of compression and extension are first determined for each fault. Then the quadrants are superimposed and the frequency of superpositions contoured, to yield modal axes of bulk compression and extension (Pfiffner & Burckhardt 1987). We use a kinematic contouring method (Françolin 1992), based on principal directions of shortening and lengthening for each fault. These directions bisect the right dihedra. Strictly speaking, they are thus kinematic directions. The principal directions for all faults are then plotted on a single stereographic projection and the densities are contoured. The maxima are assumed to represent principal directions of strain, provided strain values are infinitesimal.

For the Rio do Peixe basin, we have used: (1) simple statistics of angular orientation; (2) our kinematic contouring method (Françolin 1992); and (3) the method of Etchécopar *et al.* (1981), for estimating a best-fit stress tensor.

SLIP DATA FOR MINOR FAULTS IN THE RIO DO PEIXE BASIN

We collected slip data for 300 striated fault surfaces at 11 localities in Early Cretaceous sediments. For each

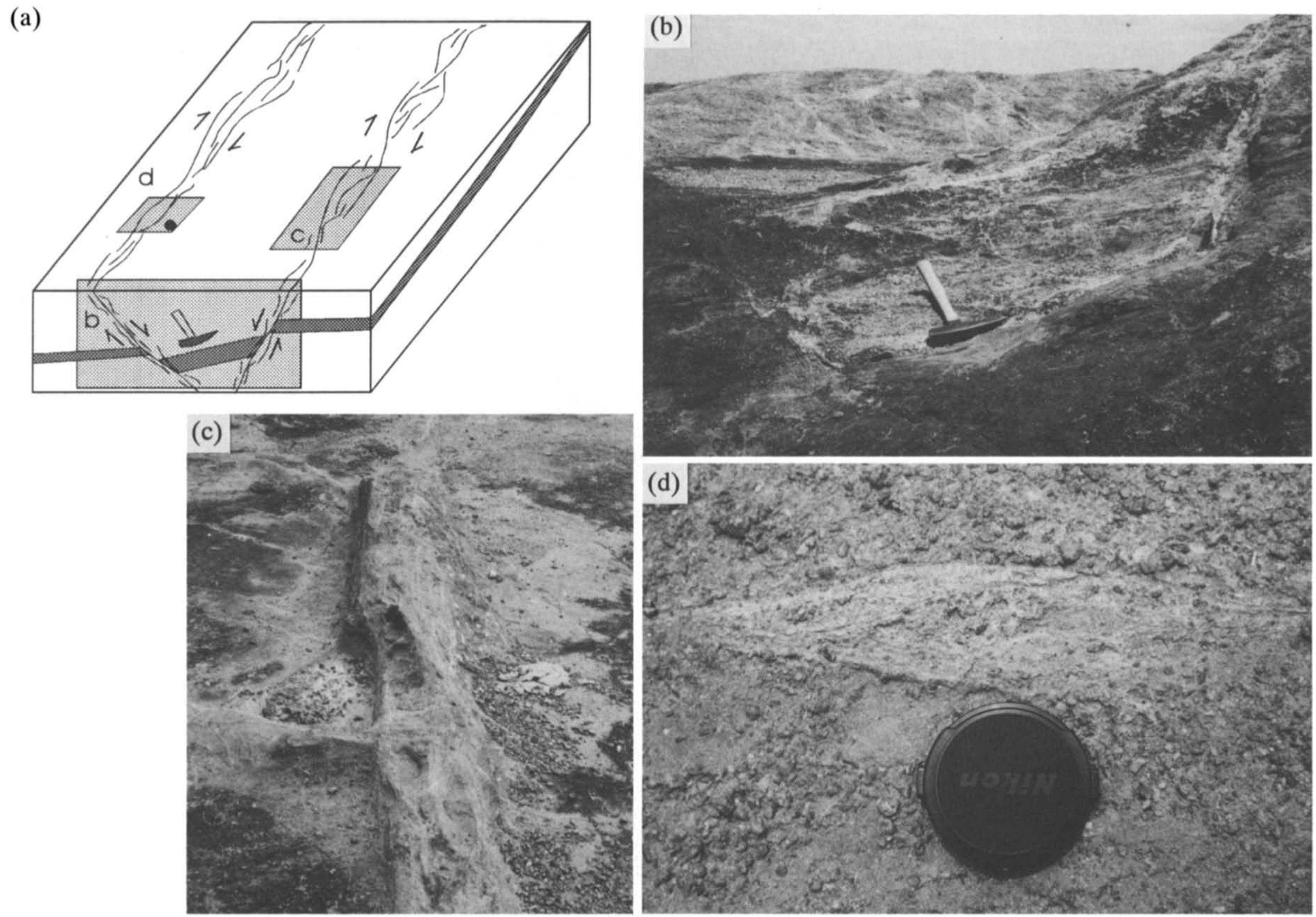

Fig. 5. Synsedimentary negative flower structure in sandstones, Santa Helena High (38°32.7′W, 06°42.5′S). Block diagram (a) shows bedding, offset across two fault zones. In section (b), faults are normal and enclose small rift basins. In plan (c & d), faults are right-lateral. Microscopic shear zones cut through sandstone matrix, but avoid coarse detrital grains (d), suggesting soft-sediment deformation. Individual fault surfaces carry oblique striations (quartz fibres). Fault zones strike NNE. Scale is given by hammer.

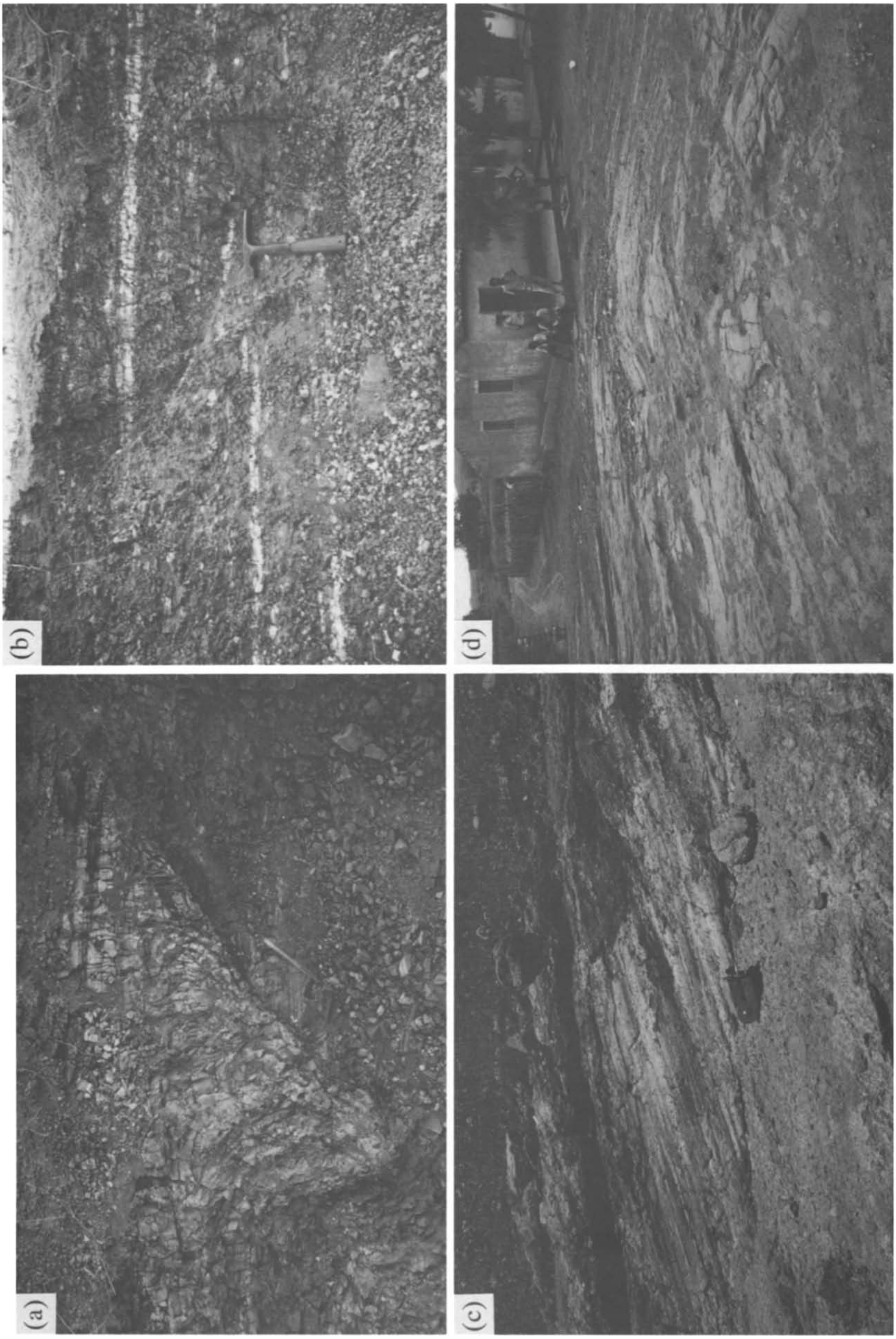

Fig. 6

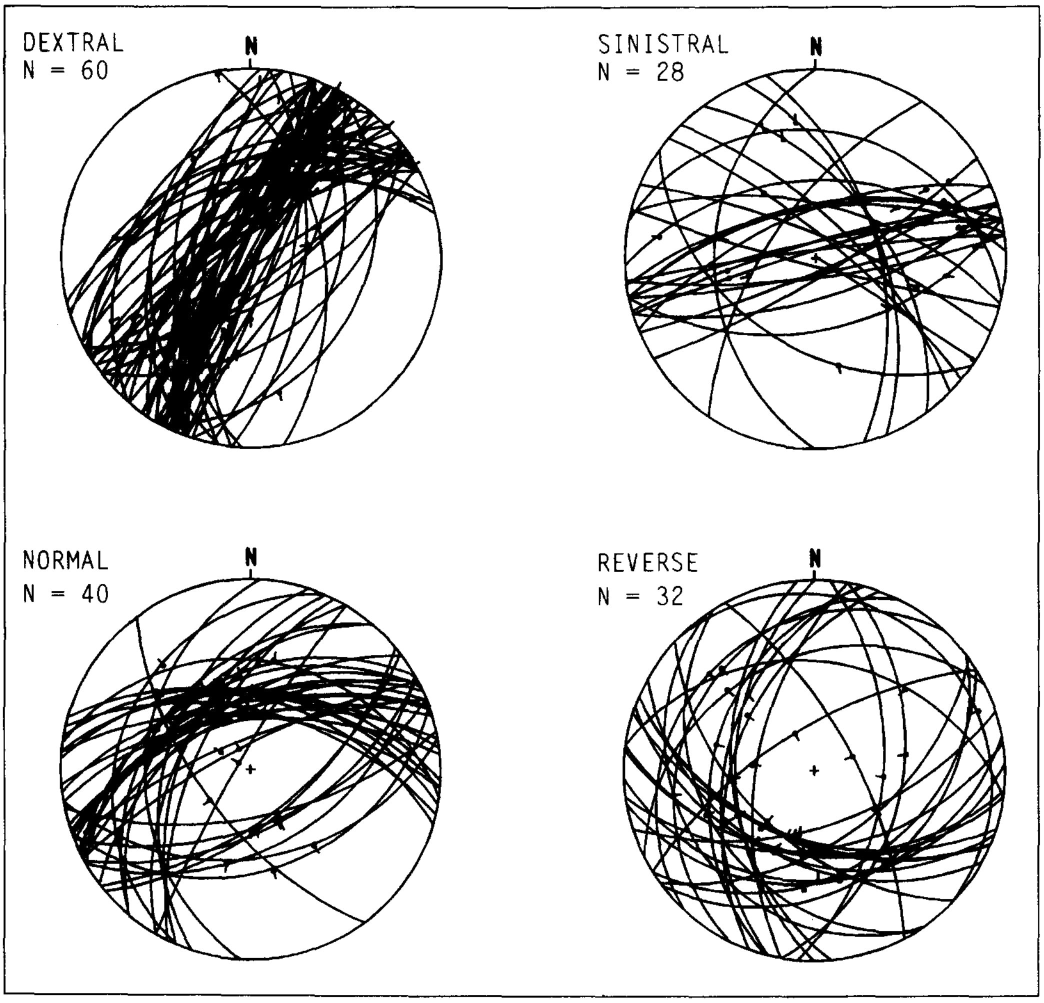

Fig. 7. Orientation of minor faults and striations, Rio do Peixe basin. Stereographic projections (lower hemisphere) show fault surfaces (great circles) and striations (small open circles, with tails pointing in slip direction of upper block). Faults are grouped into four families, according to pitch of striation and sense of slip: right-lateral or dextral (top left), left-lateral or sinistral (top right), normal (bottom left) and reverse (bottom right).

fault, even if curved, we took only one representative measurement of the dip and strike of the surface and of the plunge and strike of the striation. Of the 300 faults, only 160 had good striations, with clear evidence for the sense of slip, according to the criteria of Petit (1987). All other minor faults we have therefore ignored in the analyses that follow.

Generally speaking, the average spacing of minor faults was observed to be larger than the average fault length. We therefore assumed that bulk strains are small, even infinitesimal.

The 160 faults with acceptable data came from 11 localities in four subareas: three localities were from the Brejo das Freiras sub-basin; three from the Sousa sub-basin; two from the Pombal sub-basin; and three from the Santa Helena High. We will therefore consider the data at three different scales: (1) for the entire Rio do Peixe basin; (2) for the 11 individual localities; and (3) for the four subareas.

Strains for the entire basin

Figure 7 shows the measured fault-slip data in stereographic projection. To represent all 160 fault surfaces in one diagram is not practical, so we have separated them into two categories (dip-slip and strike-slip) and four classes (normal, reverse, right-lateral and left-lateral). The criterion for separating dip-slip and strike-slip faults is a 45° pitch of the striation in the fault surface.

Dominant are 60 right-lateral faults, mostly steep and striking about northeasterly. Next most common are 40 normal faults, mostly dipping moderately towards the

Fig. 6. Minor compressive structures, Rio do Peixe basin. (a) Right-lateral reverse fault with hangingwall anticline in siltstones, Brejo das Freiras sub-basin (38°34.5'W, 06°37'S, view towards the south). Fault surface dips 35° towards 110°. Striations pitch 60° northerly. Offset of bedding is about 50 cm. Scale is given by hammer. (b) Reverse fault in marls, Brejo das Freiras sub-basin (38°34.5'W, 06°37'S, view towards the south). Fault surface dips 43° towards 265°. Offset of two light-coloured beds (at top and bottom of hammer) is about 30 cm. (c) Left-lateral reverse fault within tectonic breccia, Pombal sub-basin (37°57.1'W, 06°49.2'S, view towards South). Grooved fault surface (scarp facing the observer) dips 80° towards 010°. Striations (quartz fibres) plunge 28° towards 095°. Scale is given by compass. (d) Anticlinal chevron fold in rhythmically bedded sandstones, Antenor Navarro formation, Varzea da Ema, southern edge of Sousa sub-basin (view towards the northwest). Fold axis plunges gently NW. Scale is given by houses.

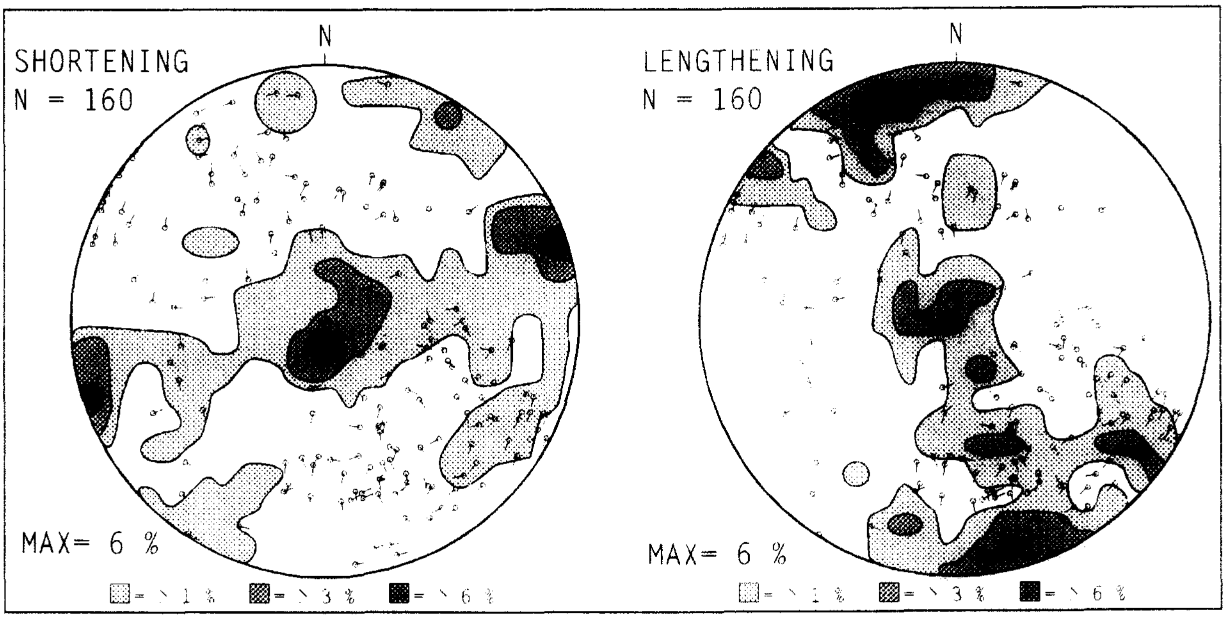

Fig. 8. Orientation of shortening and lengthening axes for 160 faults, Rio do Peixe basin. Equal-area stereographic projections (lower hemisphere) show principal directions of shortening (left) or lengthening (right), one for each fault. Contours are for point density of principal directions (key at bottom gives percentages). Circles with tails are slip linears (Aleksandrowski 1985).

NNW, with some conjugates dipping SSE. Of 32 reverse faults, most have moderate dips towards the W or SW. Finally, the 28 left-lateral faults have a range of dip values, but mostly strike ENE. For normal faults, the striation directions cluster around a NNW direction; for reverse faults, there is a wider scatter about an ESE direction. Thus the data seem to be indicating a fairly uniform bulk deformation, with a NNW lengthening direction and an ENE shortening direction.

To follow up these results, we have used our kinematic contouring method (Fig. 8). Shortening axes are concentrated in two girdles, the major one vertical and striking ENE, the minor one horizontal. Within these girdles are two main concentrations, one vertical, the other horizontal and ENE. Lengthening axes are similarly concentrated in two girdles, the major one vertical and striking NNW, the minor one horizontal. Within these girdles are two main concentrations, the major one horizontal and NNW, the minor one vertical. The bulk horizontal strains (ENE shortening and NNW lengthening) are regionally consistent. However, the vertical strains are not consistent: some indicate crustal thickening; others, thinning.

Palaeostresses for individual localities

We have used the method of Etchécopar *et al.* (1981) to calculate peleostress tensors for 11 localities in the Rio do Peixe basin (Fig. 9). A total of 138 faults have been used in the analyses (seven for locality A, 10 for B, 16 for C; 10 for D, 16 for E, 13 for F; five for G, 26 for H, seven for I; six for J and 22 for K). The calculated stresses must be considered as no better than estimates, because the average α values are rather large (23° for locality A, 25° for B, 30° for C; 31° for D, 61° for E, 12° for F; 20° for G, 19° for H, 10° for I; 34° for J, 13° for K). Further rejection of deviant faults results in smaller average α values, but the estimated stress tensors are little changed (for further details, see Françolin 1992). Given the small numbers of faults available, we do not feel that it is warranted to reject any more data.

The estimated paleostresses vary in a small but systematic way across the Rio do Peixe basin.

(1) At seven localities in the west of the basin (A, B, C, D, E, F, and I) and one locality in the far east (K), the maximum compressive stress (compression, for short) is nearly horizontal and bears E to NE, following the regional strain pattern previously discussed. At the remaining three localities (G, H, and J), in the central part of the basin, the maximum compression is nearly vertical.

(2) At eight localities (A, B, C, D, E, G, H and J), the minimum compression is nearly horizontal and bears N to NW; whereas it is nearly vertical at three localities, of which two (F and I) are in the southwestern part of the basin.

(3) If we look at nearly horizontal principal components, the E to NE compression is always stronger than N to NW compression.

Thus the estimated paleostresses are broadly compatible with the regional strain pattern; but they also show some systematic variations. In particular, stress states leading to crustal thickening are more prevalent in the southwestern part of the area, whereas those leading to crustal thinning are more prevalent in the central part.

Applied to the same 11 localities, our kinematic contouring method yields results almost identical to those obtained by the method of Etchécopar (Françolin 1992).

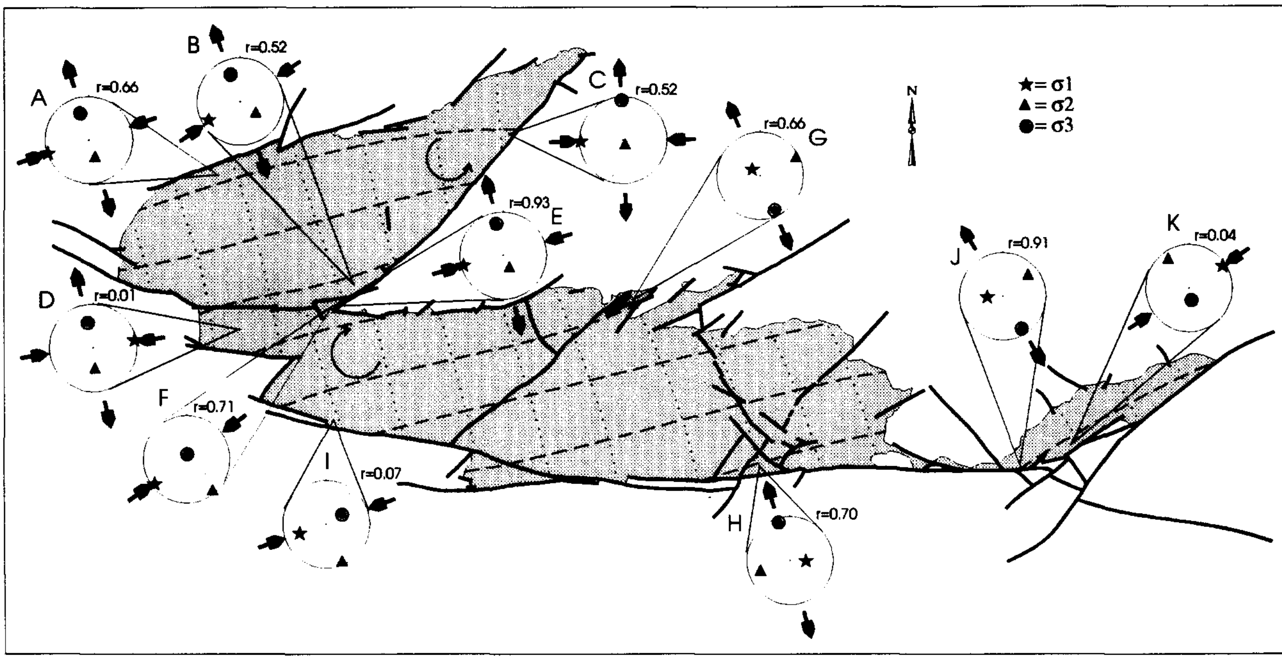

Fig. 9. Principal directions of compression, Rio do Peixe basin. For 11 localities (A–K), equal-area stereographic projections (lower hemisphere) show all three principal orientations of compressive stress (see key, top right), calculated by the method of Etchécopar *et al.* (1981). Black arrows indicate strikes of nearly horizontal principal stresses. A total of 138 faults were used in the analyses (seven for locality A, 10 for B, 16 for C; 10 for D, 16 for E, 13 for F; five for G, 26 for H, seven for I; six for J and 22 for K). Average α values are rather large (23° for locality A, 25° for B, 30° for C; 31° for D, 61° for E, 12° for F; 20° for G, 19° for H, 10° for I; 34° for J, 13° for K). Within the basin (stippled), trajectories of horizontal compressive stress (dashed for maximum, dotted for minimum) have been drawn manually. They appear to bisect acute angles between master faults (solid lines).

Timing of faulting

Stratigraphic control on the timing of fault motions in the Rio do Peixe basin is rather sparse.

Judging from associated growth folds, the master faults (Malta, Portalegre, Rio Piranhas and others) were active throughout most, if not all, of the history of sedimentation (Berriasian to Barremian).

Minor faults within specific formations appear to have been active for shorter periods.

(1) For the Antenor Navarro Formation (probably Berriasian), Sénant & Popoff (1991) recorded normal synsedimentary faults within the Sousa sub-basin. We recorded both normal and strike-slip synsedimentary faults at locality E in the Santa Helena High (Fig. 5). In contrast, throughout the Santa Helena High, reverse faults appear to post-date lithification and are not associated with variations in stratigraphic thickness.

(2) For the Sousa Formation (probably Valanginian), we recorded both strike-slip and reverse faults at locality B in the Brejo das Freiras sub-basin.

(3) For the Rio Piranhas Formation (probably Barremian), we recorded both normal and strike-slip faults at locality H in the Sousa sub-basin (see also Sénant & Popoff 1991).

Thus transtension (normal and strike-slip faulting) appears to have been dominant throughout the entire history of sedimentation in the Sousa sub-basin; whereas, further west, there seems to have been a change, from transtension to transpression, sometime after the end of the Berriasian.

TECTONIC INTERPRETATION FOR THE RIO DO PEIXE BASIN

Of the principal stress directions calculated for each locality by the method of Etchécopar *et al.* (1981), we have used those that are nearly horizontal to construct a trajectory map (Fig. 9). Our method of construction was purely manual.

Regionally, the trajectories form a regular, almost Cartesian, network, systematically oblique with respect to most major basin-bounding faults (such as the Malta and Portalegre faults). The ENE trajectories tend to bisect the acute angles between intersecting master faults. Thus the trajectories inferred from minor faults are compatible with the motions of master faults, which are dominantly strike-slip. Because the master faults have vertical offsets of up to several kilometres and horizontal offsets which are probably even greater, we believe our interpretation should hold at the scale of the upper crust.

Perturbations in the attitudes of trajectories occur in the Santa Helena High and Brejo das Freiras sub-basin. We interpret the Santa Helena High as an area of transpression and crustal thickening, at one of the restraining intersections of the Malta and Portalegre fault systems, where two basement triangles have converged (Fig. 9). At one of the releasing intersections is a normal fault, bounding the Brejo das Freiras sub-basin on its southeastern side.

At the scale of the Rio do Peixe basin, left-lateral wrenching seems to have dominated over right-lateral wrenching (Fig. 10). The Malta fault is much longer than the Portalegre fault, suggesting that the former is synthetic and the latter antithetic. The regional variation, between late thickening in the west and thinning in the east, we attribute to westwards attenuation of left-lateral wrench displacements that built up along the Malta fault system.

Although the total strains do not seem large, there is evidence for block rotations about vertical axes. Parallel to the Portalegre fault are several other major faults, fairly evenly spaced and presumably antithetic. These all appear to terminate against the Malta fault. Domino rotation of antithetic fault blocks appears to be responsible for some excess thickening or thinning at block corners. Françolin and Perroud (work in progress) have obtained palaeomagnetic evidence for block rotations in redbeds of the Antenor Navarro Formation (Françolin 1992). With respect to a Cretaceous (118 Ma) reference direction, measured rotations are about 10° counter-clockwise in the Brejo das Freiras sub-basin and 7° clockwise in the Sousa sub-basin (Fig. 10).

Our tectonic interpretation is similar to that of Françolin & Szatmari (1987). It is significantly different from that of Sénant & Popoff (1989, 1991), who nevertheless collected fault data from 17 localities in the Rio do Peixe basin and analyzed them with methods similar to ours. The problem appears to be, not with the methods, but with the data. Sénant & Popoff (1991) analysed 500 striated fault surfaces, but they published the original slip data for only four of their localities. Apparently, almost all of their 500 fault are normal faults, even at localities where we found strike-slip and reverse faults. From their data, they have calculated stress tensors with nearly vertical principal compression. Thus they have attributed faulting and basin formation to an episode of crustal thinning with NNW extension direction. We agree with the NNW extension direction, but we claim that wrenching was the main mechanism of deformation in the Rio do Peixe basin (Fig. 10).

IMPLICATIONS FOR OPENING OF THE ATLANTIC

Our tectonic interpretation of the Rio do Peixe may have important implications for constraining the early history of opening of the Atlantic. However, we believe that there are not enough data to warrant improving the models of opening. Instead, we will compare our results with those available for other areas in Brazil and Central Africa, briefly discussing the possible consequences.

In the large Potiguar basin of NE Brazil (Fig. 2), Pre-Aptian sediments are not exposed. From subsurface data, rifting started in the Early Cretaceous (Neocomian to early Barremian), the principal direction of extension being NW–SE in present geographical co-ordinates (Szatmari *et al.* 1985, Françolin & Szatmari 1987, Matos 1992). Because of occasional folds and flower structures, some Lower Cretaceous wrenching has also been inferred (Françolin & Szatmari 1987), but the subject is controversial. Upper Barremian sediments were deposited unconformably on the eroded rifts and show few associated faults.

A critical area further south, where Cretaceous sediments and faults are indeed exposed and subsurface data are abundant, is the Recôncavo–Tucano–Jatobá (RTJ) rift (Fig. 2). On stratigraphic and seismic evidence, this formed in two discrete phases, the main one Berriasian to Valanginian, a subsidiary one Barremian to Aptian (Milani & Davison 1988, Magnavita 1992). Crustal thinning was dominant, but transfer faults and wrench faults were also active. According to Milani & Davison (1988),

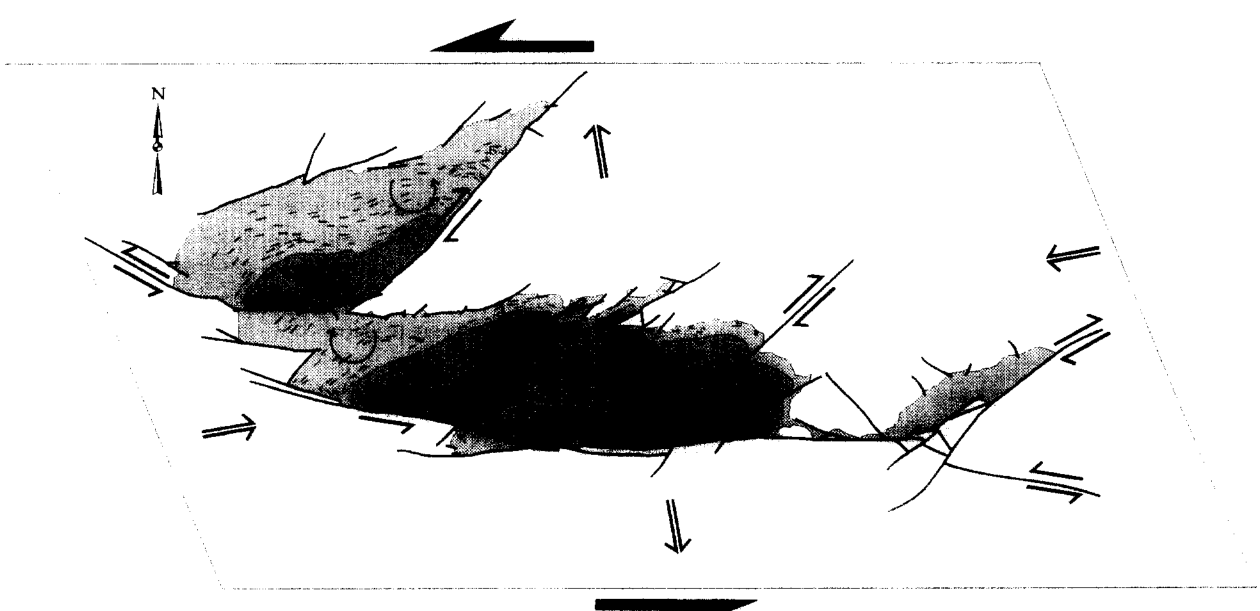

Fig. 10. Inferred Early Cretaceous tectonics, Rio do Peixe basin. Paired arrows indicate strike-slip senses on master faults. Hollow arrows indicate principal directions of bulk strain. Circular arrows show block rotations inferred from palaeomagnetic study. Large black arrows (top and bottom) indicate bulk left-lateral wrenching.

rifting was oblique and the extension direction is NW–SE (in present geographical co-ordinates). The structural data, including the triangular shape of the RTJ rift, fit the model of an East Brazilian microplate, that rotated about 2° counterclockwise relative to stable South America, about a pole at 8°11'S, 36°04'W in northeastern Brazil (Szatmari *et al.* 1985, Milani & Davison 1988). This implies a small component of left-lateral wrenching along the Pernambuco fault zone, at the northern termination of the rift (Magnavita 1992). Some fault-slip data are available for the RTJ rift (Magnavita 1992), but they are insufficient for interpretation in terms of stress or strain. Hence it is difficult to assess the relative proportions of crustal thinning and wrenching in the area.

For Africa, recent structural studies of the Benue trough (Guiraud & Maurin 1991) have demonstrated Early Cretaceous rifting and synsedimentary left-lateral wrenching (positive flower structures) in a NE–SW direction (present geographical co-ordinates). By fitting Africa and South America together (Fig. 1), it can readily be seen that the Benue trough and associated structures coincide both in position and in orientation with the strip between the Potiguar basin in the north and the Pernambuco shear zone in the south. The style of deformation (left-lateral wrenching) and the broad timing (Early Cretaceous) also coincide, although wrenching in the Benue trough may not have started before the Barremian. The simplest conclusion is that left-lateral wrenching in the Rio do Peixe basin can be correlated along the Patos fault zone into the Benue trough. Possibly the wrenching propagated eastwards.

We believe it is important to investigate the other Cretaceous basins of northeastern Brazil, with a view to collecting fault-slip data and constraining the kinematics, especially the extent and importance of wrenching. Meanwhile, a reasonable working hypothesis is that a northward-propagating South Atlantic rift system reached the RTJ area in the Valanginian and aborted. The main extension then transferred eastwards to the present Atlantic margin. Associated left-lateral wrenching occurred in northeastern Brazil and Central Africa until the Aptian–Albian (Chron M0, 118 Ma), after which the equatorial Atlantic began to open (Nürnberg & Müller 1991, Matos 1992).

CONCLUSIONS

(1) The Rio do Peixe basin formed during the Early Cretaceous (Berriasian to Barremian), by reactivation of Pan-African dextral ductile shear zones in the basement. These shear zones are of two families, longer ones trending E–W and shorter ones trending NE–SW.

(2) The Rio do Peixe basin is a composite structure, with three sub-basins, separated by basement highs. The sub-basins are asymmetric, with steep master faults on their southern and southeastern sides.

(3) Basin sediments are of continental origin, fluviatile or lacustrine. There are three easily differentiable stratigraphic units. Conglomerates are common in both the lowermost and uppermost stratigraphic units, indicating two erosional pulses.

(4) From stratigraphic thicknesses we infer that basin formation started in the west and migrated eastwards with time.

(5) Minor faults within the sediments are common. Some formed in unconsolidated sediment; others, in lithified sediment.

(6) Folds are less common. Large open folds are associated with major faults and are synsedimentary (growth folds). Other folds formed later.

(7) Of 160 minor faults with striations and unambiguous senses of slip, 60 are dominantly right-lateral, 40 are normal faults, 32 are reverse faults and 28 are left-lateral. From an analysis by the method of superimposed dihedra, the bulk principal direction of shortening is ENE–WSW; of extension, NNW–SSE. This indicates that wrenching was the main mechanism of deformation in the area.

(8) From an analysis of faults at 11 separate localities, we infer that paleostresses and strains vary regionally. There is a tendency towards transpression in the west and transtension in the centre.

(9) There is structural and palaeomagnetic evidence for small block rotations about vertical axes, counterclockwise in the west, clockwise in the centre. We therefore interpret the Rio do Peixe basin as a zone of left-lateral wrenching along the E–W Malta fault. Wrenching attenuates along the fault, producing crustal thickening in the west and thinning further east.

(10) Our tectonic interpretation is not easily accounted for by simple models of opening of the Atlantic between two rigid plates. Instead, it requires intracontinental deformation within northeastern South America. In the Early Cretaceous, left-lateral wrenching may have propagated northeastwards, from the Rio do Peixe, into the Benue trough of Africa. It may have occurred in front of a northward-propagating rift system, that led to progressive opening of the South Atlantic ocean, followed by the Equatorial Atlantic.

Acknowledgements—J. Françolin gratefully acknowledges a bursary from PETROBRAS, without which his Ph.D. studies at Rennes would not have been possible. PETROBRAS also loaned satellite imagery and air photographs and contributed towards field expenses for all three authors in the Rio do Peixe area. We thank G. Estrella (CENPES-PETROBRAS) for his advice and encouragement. Ian Davison and an anonymous reviewer provided constructive criticism.

REFERENCES

Albuquerque, J. P. T. 1970. Inventário hidrogeológico básico do Nordeste, Folha 15 Jaguaribe-SE. Superintendência de Desenvolvimento do Nordeste do Brasil (SUDENE), Divisão de Documentação, Serie Hidrogeológica, Recife **32**.

Aleksandrowski, P. 1985. Graphical determination of principal stress directions for slickenside lineation populations: an attempt to modify Arthaud's method. *J. Struct. Geol.* **7**, 73–82.

Allmendinger, R. W., Strecker, M., Eremchuk, J. E. & Francis, P. 1989. Neotectonic deformation of the southern Puna Plateau, northwestern Argentina. *J. S. Am. Earth Sci.* **8**, 111–130.

Almeida, F. F. M. 1967. Origem e evolução da plataforma brasileira. Ministério de Minas e Energia, Departamento Nacional de Produção Mineral (DNPM), Rio de Janeiro. *Bol. Div. Geol. Mineral.* **241**.

Almeida, F. F. M. de, Hasui, Y., Brito Neves, B. B. de & Fuck, R. A. 1981. Brazilian structural provinces: an introduction. *Earth Sci. Rev.* **17**, 1–29.

Alves, A. C. 1990. Nota preliminar sobre medidas de paleocorrentes efetuadas na Bacia do Rio do Peixe. Relatório Interno (unpublished internal report), PETROBRAS/Debar/Dinter/Selab, Natal.

Angelier, J. 1979. Determination of the mean principal directions of stresses for a given fault population. *Tectonophysics* **56**, 17–26.

Angelier, J. 1984. Tectonic analysis of fault slip data sets. *J. geophys. Res.* **89**, 5837–5848.

Angelier, J. & Mechler, P. 1977. Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et séismologie: la méthode des dièdres droits. *Bull. Soc. géol. Fr.* **19**, 1309–1318.

Arai, M., Hashimoto, A. T. & Uesugui, N. 1989. Significado cronoestratigráfico da asociação microflorística do cretáceo inferior do Brasil. *Bol. Geociên. Petrobrás* **3**, 87–103.

Armijo, R., Carey, E. & Cisternas, A. 1982. The inverse problem in microtectonics and the separation of tectonic phases. *Tectonophysics* **82**, 145–160.

Arthaud, F. 1969. Méthode de détermination graphique des directions de raccourcissement, d'allongement et intermédiaire d'une population de failles. *Bull. Soc. géol. Fr.* **11**, 729–737.

Barbosa, O. 1966. Inventário dos recursos minerais do Estado da Paraíba. Relatório Interno (Unpublished internal report), Ministério de Minas e Energia, Departamento Nacional de Producáo Mineral (DNPM), Rio de Janeiro.

Bott, M. H. P. 1959. The mechanics of oblique-slip faulting. *Geol. Mag.* **96**, 109–117.

Braun, O. P. G. 1969. Geologia da Bacia do Rio do Peixe, Nordeste do Brasil. Relatório de Prospeção, Ministério de Minas e Energia, Departamento Nacional de Produção Mineral (DNPM), 4° Distrito do Nordeste, Natal.

Brito Neves, B. B. 1975. Regionalização geotectônica do précambriano nordestino. Tese de Doutorado, Instituto de Geociências, Universidade de São Paulo.

Bullard, E. C., Everett, J. E. & Smith, A. G. 1985. The fit of the continents around the Atlantic. In: *A Symposium on Continental Drift* (edited by Blackett, P. M. S., Bullard, E. C. & Runcorn, S. K.). *Phil. Trans. R. Soc. Lond.* **A258**, 41–51.

Burke, K. C. & Dewey, J. F. 1974. Two plates in Africa during the Cretaceous? *Nature* **249**, 313–316.

Cande, S. C., LaBrecque, J. L. & Haxby, W. F. 1988. Plate kinematics of the South Atlantic: CHRON C34 to present. *J. geophys. Res.* **94**, 13,479–13,492.

Carey, E. & Brunier, B. 1974. Analyse théorique et numérique d'un modèle mécanique élémentaire appliqué à l'étude d'une population de failles. *C. r. Acad. Sci. Paris* **D279**, 891–894.

Chang, H. K., Kowsmann, R. O. & Figueiredo, A. M. F. 1988. New concepts on the development of East Brazilian marginal basins. *Episodes* **2**, 194–202.

Chang, H. K., Kowsmann, R. O., Figueiredo, A. M. F. & Bender, A. A. 1992. Tectonics and stratigraphy of the East Brazil rift system: an overview. In: *Geodynamics of Rifting. Volume II. Case History Studies on Rifts: North and South America and Africa* (edited by Ziegler, P. A.). *Tectonophysics* **213**, 97–138.

Conceição, J. C. J., Zalan, P. V. & Wolff, S. 1988. Mecanismo, evolução e cronologia do rift sul-atlântico. *Bol. Geociên. Petrobrás* **2**, 255–265.

Corsini, M., Vauchez, A., Arcanjo, C. & Sá, E. F. J. de. 1991. Strain transfer at continental scale from a transcurrent shear zone to a transpressional fold belt: The Patos–Serido system, northeastern Brazil. *Geology* **19**, 586–589.

De Mets, C., Gordon, R. G., Argus, D. F. & Stein, S. 1990. Current plate motions. *Geophys. J. Int.* **101**, 425–478.

DNPM. 1984. Mapa geológico do Brasil e da área oceanica adjacente incluindo depósitos minerais. Escala 1:2,500,000. Ministério de Minas e Energia, Departamento Nacional de Produção Mineral (DNPM), Brasília.

Etchécopar, A. 1984. Etude des états de contrainte en tectonique cassante et simulations de déformations plastiques. Unpublished thèse d'Etat, Université des Sciences et Techniques du Languedoc, Montpellier.

Etchécopar, A., Vasseur, G. & Daignières, M. 1981. An inverse problem in microtectonics for the determination of stress tensors from fault striation analysis. *J. Struct. Geol.* **3**, 51–65.

Fairhead, J. D. 1988. Mesozoic plate tectonic reconstuctions of the central South Atlantic Ocean: the role of the West and Central African rift system. *Tectonophysics* **155**, 181–191.

Fairhead, J. D. & Binks, R. M. 1991. Differential opening of the Central and South Atlantic Oceans and the opening of the West African rift system. *Tectonophysics* **187**, 191–203.

Françolin, J. B. L. 1992. Analyse structurale du bassin du Rio do Peixe (Brésil). *Mém. et Docum. Centre Armoricain d'Etude Struct. Socles, Rennes* **46**.

Françolin, J. B. L. & Szatmari, P. 1987. Mecanismo de rifteamento da porção oriental da margem norte brasileira. *Rev. Brasil. Paleont.* **17**, 196–207.

Guiraud, M. & Maurin, J. 1991. Le rifting en Afrique au Crétacé inférieur: synthèse structurale, mise en évidence de deux étapes dans la genèse des bassins, relations avec les ouvertures océaniques péri-africaines. *Bull. Soc. géol. Fr.* **162**, 811–823.

Le Pichon, X. & Hayes, D. E. 1971. Marginal offsets, fractures zones and early opening of the South Atlantic. *J. geophys. Res.* **26**, 6283–6293.

Lima, M. R. & Coelho, M. P. C. A. 1987. Estudo palinológico da sondagem estratigráfica de Lagoa do Forno, Bacia do Rio do Peixe, Cretáceo do nordeste do Brasil. *Bol. Inst. Geociên. Univ. São Paulo* **18**, 67–83.

Lisle, R. J. 1987. Principal stress orientations from faults: an additional constraint. *Annales Tectonicae* **1**, 155–158.

Mabesoone, J. M. & Campanha, V. A. 1974. Caracterização estratigráfica dos grupos Rio do Peixe e Iguatu. *Estud. Sediment. Natal* **3/4**, 21–41.

Magnavita, L. 1992. Geometry and kinematics of the Recôncavo–Tucano–Jatobá rift, northeastern Brazil. Unpublished Ph.D. thesis, University of Oxford.

Maltman, A. 1988. The importanceof shear zones in naturally deformed sediments. *Tectonophysics* **145**, 163–175.

Marrett, R. & Allmendinger, R. W. 1990. Kinematic analysis of fault-slip data. *J. Struct. Geol.* **12**, 973–986.

Matos, R. M., de. 1992. The northeast Brazilian rift system. *Tectonics* **11**, 766–791.

Milani, E. J. 1985. Tectônica cisalhante na evolução do Rift do Recôncavo–Tucano–Jatobá. *Rev. Brasil. Geociên.* **15**, 287–292.

Milani, E. J. & Davison, I. 1988. Basement control and transfer tectonics in the Recôncavo–Tucano–Jatobá Rift, Northeast Brazil. *Tectonophysics* **154**, 41–70.

Mizusaki, A. M. P., Thomaz Filho, A. & Valensa, J. 1988. Volcano-sedimentary sequence of Neocomian age in Campos basin (Brazil). *Rev. Brasil. Geociên.* **18**, 247–251.

Nürnberg, D. & Müller, R. D. 1991. The tectonic evolution of the South Atlantic from Late Jurassic to present. *Tectonophysics* **191**, 27–53.

Petit, J. P. 1987. Criteria for the sense of movement on fault surfaces in brittle rocks. *J. Struct. Geol.* **9**, 597–608.

Petit, J. P., Proust, F. & Tapponnier, P.M. 1983. Critères de sens de mouvement sur les mirroirs de failles en roches non calcaires. *Bull. Soc. géol. Fr.* 7 *Sér.* **19**, 541–551.

Pfiffner, O. A. & Burkhard, M. 1987. Determination of paleo-stress orientation from fault, twin and earthquake data. *Annales Tectonicae* **1**, 48–57.

Pindell, J. & Dewey, J. F. 1983. Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region. *Tectonics* **1**, 179–211.

Popoff, M., Benkhelil, J., Simon, B. & Motte, J. J. 1983. Approche géodynamique du fosse de la Bénoué (N.E. Nigéria) à partir des données de terrain et de télédétection. *Bull. Centres Rech. Expl. & Prod. Elf-Aquitaine* **7**, 323–337.

Rabinowicz, P. D. & LaBrecque, J. 1979. The Mesozoic South Atlantic and evolution of its continental margins. *J. geophys. Res.* **84**, 5973–6002.

Rand, H. M. 1982. Levantamento magnetométrico na Bacia do Rio do Peixe (PB). *Estud. Pesquisas Univ. Fed. Pernambuco* **B5**, 71–74.

Rand, H. M. 1984. Reconhecimento gravimétrico da Bacia do Rio do Peixe, Paraíba. Anais do XI Simpósio de Geologia do Nordeste (unpublished), Sociedade Brasileira de Geologia, Núcleo Nordeste, Natal, 42–47.

Reches, Z. 1987. Determination of the tectonic stress tensor from slip along faults that obey the Coulomb yield condition. *Tectonics* **6**, 849–861.

Rocha, Campos, A. C., Cordani, U. G., Kawashita, K., Sonohi, H. M. & Sonohi, I. K. 1988. Age of the Paraná flood volcanism. In: *The Mesozoic Flood Volcanism of the Paraná Basin: Petrogenetic and Geophysical Aspects.* Instituto Astronõmico e Geofísico da Universidade de São Paulo, São Paulo, 24–45.

Sénant, J. & Popoff, M. 1989. Les bassins du Rio do Peixe (NE Brésil): Extension intracontinentale crétacée et réactivation des grands cisaillements ductiles panafricains. *C. r. Acad. Sci. Paris, Sér.* 2, **308**, 1613–1619.

Sénant, J. & Popoff, M. 1991. Early Cretaceous extension in northeast Brazil related to the South Atlantic opening. *Tectonophysics* **198**, 35–46.

Shaw, P. R. & Cande, S. C. 1990. High-resolution inversion for South Atlantic plate kinematics using joint altimeter and magnetic anomaly data. *J. geophys. Res.* **95**, 2625–2644.

SUDENE 1982. Superintendência de Desenvolvimento do Nordeste do Brasil. Topographic maps of Brazil, Scale 1:100000.

Szatmari, P. Françolin, J. B. L., Zanotto, O. & Wolff, S. 1987. Evolução tectônica da margem equatorial brasileira. *Rev. Brasil. Geociên.* **17**, 180–188.

Szatmari, P., Milani, E. J., Conceição, J. C. J. & Lobo, A. P. 1985. How South Atlantic rifting affects Brazilian oil reserves distribution. *Oil & Gas J.* **14**, 107–144.

Urien, C. M. & Zambrano, J. J. 1973. The geology of the basins of the Argentine continental margin and Malvinas Plateau. In: *The Ocean Basins and Their Margins. Vol.* 1. *The South Atlantic* (edited by Nairn, A. E. M. & Stehli, F. G.). Plenum, New York, 135–169.

Vink, G. E. 1982. Continental rifting and the implications for plate tectonic reconstructions. *J. geophys. Res.* **87**, 10,677–10,688.

Zalan, P. V., Nelson, E. P., Warme, J. E. & Davis, T. L. 1985. The Piauí Basin: Rifting and wrenching in an Equatorial Atlantic transform basin. In: *Strike-slip Deformation Basin Formation and Sedimentation* (edited by Biddle, K. T. & Christie-Blick, N.). *Spec. Publ. Soc. econ. Paleont.* **37**, 177–192.

Zanotto, O. & Szatmari, P. 1987. Mecanismo de rifteamento da porção ocidental da margem Norte Brasileira, Bacia do Para-Maranhão. *Rev. Brasil. Geociên.* **17**, 189–195.