Stress orientations in Brazilian sedimentary basins from breakout analysis: implications for force models in the South American plate

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SUMMARY
Regional patterns of crustal stresses in Brazil were studied with a detailed breakout analysis performed in 541 wells distributed throughout the country: 481 from basins along the continental margin, and 60 from intracratonic basins. A total of about 591 km of cumulative well length, digitally sampled at 0.15 m intervals, was analysed. Most intervals (80 per cent) are confined between −400 and −4000 m. Only wells that deviate less than 10° from the vertical were considered. For a given well (1) the mean orientation and the standard deviation of each interval with breakouts were calculated, (2) all intervals with mean breakout orientations less than 10° from the orientation of the hole deviation were discarded, (3) all intervals with standard deviations less than 12° were selected, (4) the selected breakouts were weighted by their interval length to calculate the mean orientation and standard deviation of the whole well, and (5) the final results were classified according to the World Stress Map criteria. Thus, 16 wells were classified as A (a total of 7.2 km of breakouts), 42 as B (7.1 km), 78 as C (7.4 km), 205 as D (3.3 km), 184 as E (0.7 km) and 16 were discarded.

In most basins, the breakout orientations from different wells were usually consistent for qualities A, B and C, allowing a good estimate of the regional maximum horizontal stress ($S_{\text{Hmax}}$); wells classified as quality D showed a large scatter. The regional $S_{\text{Hmax}}$ determined from breakouts is generally in good agreement with the available nearby focal mechanisms. The main trends of $S_{\text{Hmax}}$ are (1) NW–SE, parallel to the coast, along the equatorial marginal basins, (2) E–W in the Alagoas Basin, (3) NNE–SSW, parallel to the coast, in the Sergipe and Reconcavo basins, and (4) NW–SE in the Middle Amazon Basin.

In the equatorial and eastern continental margins, north of 15°S, breakouts and focal mechanism measurements indicate that the $S_{\text{Hmax}}$ orientation is remarkably parallel to the coastline, following a 90° bend of the coast in northeastern Brazil. Because the theoretically predicted intraplate stresses in northern Brazil trend about WNW to ENE (e.g. Meijer 1995; Coblentz & Richardson 1996), we interpret our observations as indicating that local sources of stress at the continental margins (e.g. flexural stresses and lateral density contrasts) dominate the plate-wide stresses and may have been underestimated in theoretical stress models of the South American plate.

The new stress data (136 A–C quality out of a population of 541 wells) cover a region of mid-plate South America where only 23 data points had been compiled previously in the World Stress Map database. The more detailed observed patterns of the intraplate stress field should be helpful in better constraining future models of the forces driving the South American plate.

Key words: borehole breakout, South America, stress distribution.
INTRODUCTION

Although the geometry of the South American plate is relatively simple, the main driving forces for its \( \approx 30 \text{ mm yr}^{-1} \) westward motion are not yet completely understood. Ridge push is known to be a major source of intraplate stresses and is one of the main parameters in theoretical models of the South American plate (Mendiguren & Richter 1978; Richardson et al. 1979; Stefanick & Jurdy 1992; Meijer 1995; Coblenz & Richardson 1992, 1996). Subduction of the Nazca and Antarctic plates marks the 6000 km long western boundary of the South American plate. The collisional forces between the Nazca and South American plates seem to be relatively simple, despite the variations of age and dip along the subduction zone, and probably depend only on the relative convergence direction, as evidenced by the fact that the observed regional maximum horizontal stresses in the western part of the plate seem to be oriented roughly E–W along the entire Andean region (Assumpção 1992); also, theoretical modelling by Meijer (1995) indicates that there is no evidence that the collisional forces have any significant dependence on the age or dip of the slab. The other external forces in the contact with the Caribbean and Scotia plates are relatively less important and seem to affect the stresses only near those plate boundaries (Stefanick & Jurdy 1992; Meijer 1995).

More important, however, in determining the mid-plate stresses are the forces related to large-scale lateral variations of topography and plate structure such as the Andean chain and the continent/ocean transition. Recent stress models that take into account the forces related to topography/density variations (Meijer 1995; Coblenz & Richardson 1996) roughly match the first-order pattern of the observed stress data, such as the direction of \( S_{\text{Hmax}} \) and the nature of the intraplate stress regimes.

The nature of the shear stresses at the lithosphere/asthenosphere boundary depend on the pattern of flow in the upper mantle, which is largely unknown. If the basal shear helps the westward plate motion then upper mantle flow could be the main driving mechanism for the South American plate; if the basal shear resists the plate motion, then the movement of the lithospheric plate is controlled by other forces and could be completely independent of any possible flow in the asthenosphere or lower mantle. The basal shear can only be determined by theoretical modelling of the resulting intraplate stresses, and is still not well constrained with the present data.

Recent work has suggested that the South American plate moves coherently with the upper mantle. Russo & Silver (1994) proposed that the forces causing the Andean deformation are related to deep upper mantle flow under the Nazca and South American plates with the subducting slab playing only a passive role. Seismic tomography of the upper mantle in SE Brazil (VanDecar, James & Assumpção 1995) showed a sharp low-velocity anomaly down to about 600 km depth that was interpreted as the remnant of the plume from which the Mesozoic continental flood basalts originated; this strongly suggested that the continental plate had moved coherently with the upper mantle since the breakup of Gondwanaland. Also, seismic anisotropy determined from SKS splitting in SE Brazil (James & Assumpção 1996) correlates well with the major Brasiliano tectonic features and is also consistent with the upper mantle being preserved under the lithosphere since at least the Early Palaeozoic.

Interestingly, the best stress models of Meijer (1995) and Coblenz & Richardson (1996) seem to favour a small driving basal shear, which would be consistent with coherent upper mantle flow driving the South American plate. However, as pointed out by Meijer (1995), the uncertainties in the various parameters of the force models still prevent a definite conclusion about the nature of the basal shear. Because both the absolute motion and the effects of ridge push are oriented in about the same E–W direction, the orientations of the modelled maximum horizontal stresses \( (S_{\text{Hmax}}) \) are roughly the same whatever the nature of the basal drag. To constrain the force models better, it is necessary to use information on the magnitude of the regional stresses, and not just \( S_{\text{Hmax}} \) orientation. Stress magnitudes can be estimated by analysing the effects of known local sources on the regional stress field (e.g. Assumpção & Araujo 1993; Richardson & Coblenz 1994; Zoback & Richardson 1996).

The observed intraplate stress field is a major constraint for force models. In the World Stress Map project, the regional intraplate stress field in South America was based mainly on focal mechanisms (43 per cent) and Quaternary fault-slip data (50 per cent) with most of the data in the Andean region (Assumpção 1992). Moreover, for mid-plate South America only 23 data points (mostly focal mechanisms) were available. In this paper we present new stress data from breakouts in most Brazilian sedimentary basins (136 points with A–C quality out of a population of 541 wells). Clearly, a better observational database for the mid-plate stresses and their relationship with local geological features will further constrain the force models and help clarify the nature of the plate driving forces.

ANALYSIS OF BREAKOUTS

Breakout analysis has been used extensively as a good technique to determine stress orientations. When a borehole is drilled, the far-field natural tectonic stress is perturbed around the hole. Borehole breakouts result from shear failure induced by stress concentrations in the direction of the minimum horizontal stress \( (S_{\text{Hmin}}) \) (Gough & Bell 1982; Zoback et al. 1985; Plumb & Hickman 1985; Bell & Babcock 1986; Dart & Zoback 1989; Zoback et al. 1989; Bell 1990; Evans & Brereton 1990; Gowd & Rao 1992; Muller et al. 1992; Zoback 1992).

A very important constraint on the use of breakouts to estimate the far-field stress orientation is the angular deviation \( (\phi) \) of a borehole from the vertical. From theoretical considerations, small values of \( \phi \) could easily induce breakouts that are not parallel to the regional orientation of \( S_{\text{Hmin}} \) if a well is drilled at a site subjected to a normal- or reverse-faulting stress regime or if the difference between the magnitudes of \( S_{\text{Hmax}} \) and \( S_{\text{Hmin}} \) is small. Under these conditions, breakouts are poor far-field stress indicators. In contrast, for a site in a strikeslip-faulting stress regime, breakouts are good far-field stress indicators for \( \phi \) up to 30° (Mastin 1988).

In this study a detailed breakout analysis was performed with a Schlumberger software package (BOL—breakout orientation log) followed by statistical treatment of the BOL results. The BOL processing uses data from four-arm calliper logs to measure long-axis orientations in caved boreholes (e.g. the High Resolution Dipmeter Tool, recording one sample per centimetre, and the Stratiigraphic High Resolution Dipmeter Tool, with four samples per centimetre; Schlumberger 1987).
In the BOL processing the measured diameter is compared with the nominal diameter of the borehole. If an abrupt enlargement above the nominal bit size (more than 10 per cent) is observed, its azimuth is calculated. This is repeated every 15.24 cm down the borehole. To eliminate enlargements close to directions of the borehole deviations, and to classify the data according to the quality ranking of the World Stress Map (WSM, Zoback 1992), the results from the BOL processing were then analysed statistically.

In the WSM project, breakout results are classified as follows (Zoback 1992). Quality A: more than 300 m of breakouts with standard deviations (std) ≤ 12°; quality B: more than 100 m of breakouts with std ≤ 20°; quality C: more than 30 m with std < 25°; quality D: less than 30 m with std ≥ 25°; quality E: breakouts with extreme scatter of orientations (std > 40°). We have used tougher criteria to define and rank our breakout intervals. First, to eliminate enlargements close to the direction of the borehole deviation from the vertical, the intervals with azimuths of enlargements less than 10° from the azimuth of the borehole inclination were discarded. Second, for every interval with an identified breakout the average and the standard deviation of the enlargement orientations were calculated (samples every 15.24 cm). Third, only breakout orientations with standard deviations ≤ 12° were retained. The vectorial average orientation and the standard deviation of all retained breakouts were then calculated. In the calculation of the average, the orientation of each breakout was weighted by its interval length.

The results were then classified according to the WSM rank system above. Sometimes breakout data can be classified following specific circumstances not adequately accounted for in the WSM general quality ranking. In our classification, we have been generally conservative, because we have downgraded the quality of a well if either the thickness or the standard deviation criterion was not fulfilled. In a few cases, however, we have upgraded the quality of a well, such as well I-RJS-138 (Campos basin, SE margin), which was classified as A despite having 296 m of breakouts: this was done because the combined breakout length was close to that required for an A-quality well (300 m) and its standard deviation (8.8°) was small compared to that of the ranking (12°).

It should be noted that a well can be given different qualities depending on the choice of the intervals to be investigated. For example, Weller (1993) analysed some wells in the Amazon basin with resulting $S_{\text{hmax}}$ oriented roughly NNE and classified as A quality (Zoback & Richardson 1996). Our analysis of three of those wells showed a greater depth range with identified breakouts (445 m, 500 m, 482 m, respectively) as compared to the depth range used by Weller (290 m, 260 m and 420 m). While our estimated $S_{\text{hmax}}$ orientations are also roughly NE–NNE, our wells were classified as D quality! Thus, we prefer to use the BOL results in our analysis, using the same criteria for identifying breakouts in all wells, even at the risk of downgrading some of the data, rather than studying individual wells with different (and sometimes subjective) criteria to identify the 'best' breakouts. This is not critical in the analysis of the regional stress field because consistency among wells in close geographical proximity is more important than individual well quality.

We have analysed 541 wells that have depths ranging from −62 to −5540 m. Most intervals (80 per cent) are confined to between −400 m and −4000 m. Among the studied wells, 136 were classified as A, B or C quality, with about 21 km of combined intervals of breakout, with every single breakout interval having a standard deviation less than 12° (Fig. 1). Mean $S_{\text{hmax}}$ directions for Brazilian basins were calculated using 528 wells (384.6 km of drilled rock; about 3.8 × 10^6 individual samples) (Table 1). The remaining 13 wells were geographically isolated and were not considered in the calculations of mean $S_{\text{hmax}}$ orientations. Amongst them, the only one that has been ranked as a reliable stress indicator (C quality; Central Brazil) will be discussed below. The results (well name, location, investigated depths, $S_{\text{hmax}}$ orientation, standard deviation and quality ranking) can be requested from the authors.

**REGIONAL PATTERNS OF STRESS ORIENTATION**

In Fig. 1 we present our breakout $S_{\text{hmax}}$ data, together with other stress indicators (mainly focal mechanisms) taken from the WSM project (Assumpção 1992; Assumpção & Araujo 1993). Breakout data tend to be clustered due to the distribution of the exploration wells in sedimentary basins; for this reason, for the sake of clarity only breakout data with qualities A–C are shown in Fig. 1. Additional focal mechanism data are also included for northeastern and southeastern Brazil (Ferreira et al. 1995; Assumpção 1994). It is clear that the new breakout data greatly improve the coverage of the middle part of the South American plate.

Any single stress data point, even those of high quality, may be affected by local stress concentrations not related to the crustal tectonic stresses in the plate. This is especially true for well data in sedimentary basins where the shallow depths (mostly less than 3 km in our case) make them more susceptible to local stress perturbations. To estimate the orientation of the maximum horizontal stress of tectonic origin we have taken averages of breakouts and focal mechanisms in all clusters with three or more points in a radius of 100–200 km, assuming that local perturbations of smaller wavelengths tend to cancel out. By doing this we are defining the 'tectonic' stress orientation as the mean orientation in areas about 2° to 4° in diameter. D-quality breakouts showed a larger scatter than qualities C or better, so in general we have only used breakouts with qualities A, B and C in determining average orientations.

The following statistical treatment was carried out with each clustered data set. Initially, the existence of a preferred orientation in the cluster was determined using the Rayleigh test for oriented data (Mardia 1972; Coblenz & Richardson 1995; Swan & Sandilands 1995). A 90 per cent confidence limit was used to select the clusters that showed a significant preferred orientation. This usually requires a standard deviation of the data of less than 15° for a set of three points, and less than 33° for a set of 10 points. Focal mechanisms with quality D were included in the averages so as to increase the coverage outside sedimentary basins. In calculating the average orientation, data ranked as A, B, C and D were weighted as 1.0, 0.70, 0.35 and 0.17, respectively. The mean $S_{\text{hmax}}$ values of the selected clusters of breakouts and focal mechanisms had their 95 per cent confidence limits determined (e.g. Swan & Sandilands 1995, chapter 5) and are shown in Table 2 and Fig. 2.

In the following sections we shall discuss the stress data in each basin, comparing the observations with two stress models...
Stress orientations in Brazilian sedimentary basins

Figure 1. Data for the maximum horizontal stress ($S_{\text{Hmax}}$) directions in eastern South America from breakouts (BO), focal mechanisms (FM), geological fault analysis (GF) and in situ measurements (IS). Symbol size indicates qualities from A to D (breakout data with quality D are not plotted). Closed and open symbols indicate reverse and normal faulting (or stress regime), respectively; half-closed symbols indicate strike-slip faulting. Solid lines in the continent denote the main Palaeozoic basins: Solimões or Upper Amazon (SOL), Mid-Amazon (MA), Parnaiba (PB), and Paraná (PR). Details of marginal and rift basins, such as the Tucano basin (TU), are shown in Figs 5–9. The shaded area is the Atlantic Ocean, with solid lines denoting the 200 and 2000 m bathymetry. The dashed line is the Brazilian political boundary.

for the South American plate: those of Meijer (1995) and Coblentz & Richardson (1996). They used finite-element techniques assuming a 100 km thick elastic plate subjected to various plate boundary forces, as follows: mainly ridge-push from the Mid-Atlantic Basin, collisional forces with the Nazca and Antarctic plates on the western boundary and the Caribbean plate to the north, and basal drag forces from the lithosphere/asthenosphere boundary. The stresses due to these main plate boundary forces tend to be compressive throughout the intraplate areas. However, the lateral density contrasts in the lithosphere at the continent/ocean transition cause extension in the continental crust and compression in the oceanic crust (e.g. Bott & Dean 1972; Turcotte & Schubert 1982; Stein et al. 1989). The internal stresses due to the continent/ocean transition are of the same order of magnitude, around 20 MPa, as the stresses caused by the plate boundary forces (Coblentz & Richardson 1992) and were also taken into account in the models of Meijer (1995; his Fig. 3.36) and Coblentz & Richardson (1996; model 3). Although the two models do not agree exactly due to different values of the force parameters, the main patterns are the same, as seen in Fig. 2: E–W compression in the oceanic lithosphere of about 20 MPa; generally strike-slip stress regimes in the eastern part of the continent, with $S_{\text{Hmax}}$ oriented roughly E–W in southern Brazil to WNW–ESE in northern Brazil; low stress magnitudes (less than about 10 MPa) in southern Brazil and high stresses (20 MPa or more) in northern Brazil. These two stress models will be called M95 and CR96 after Meijer (1995) and Coblentz & Richardson (1996), respectively.

**Intracratonic basins**

**Amazon Basin**

Fig. 1 shows the breakout data in the intracratonic Amazon Basin. In the Solimões (Upper Amazon) Basin no preferred orientation was found. Although the mean orientation of the data was NE, similar to the breakout interpretation of Weller (1993) used by Zoback & Richardson (1996), the statistics of the data imply a random orientation, i.e. no regional tectonic stress could be detected in the analysed wells west of 63°W (see Table 1).

In the Middle Amazon Basin, three wells (two B and one C quality) show a significant mean orientation (at the 90 per cent confidence level) about a NW–SE direction (azimuth of $144^\circ \pm 13^\circ$, see Tables 1 and 2). In the Amazon Mouth (Lower Amazon) Basin, four wells give a significant mean $S_{\text{Hmax}}$ at $082^\circ \pm 19^\circ$. While these orientations are roughly consistent with the E–W to SE–NW predictions of the M95 and CR96 stress models (Fig. 3), a clear stress rotation near the lower-crust mafic intrusion is observed. A chain of high Bouguer gravity anomalies, up to +90 mGal, roughly coincident with the axis of maximum sediment thickness of the Middle Amazon Basin, was interpreted by Nunn & Aires (1988) as being due...
Table 1. Summary of the breakout analysis performed in this study. In eight basins random $S_{\text{max}}$ orientations can be rejected with 90 or 95 per cent confidence, as indicated by the Rayleigh test in the last column. For those basins, A-, B- and C-quality wells were used to calculate the mean $S_{\text{max}}$ direction and its 95 per cent confidence limit. The Potiguar Basin is the only one for which D results were included in the calculation of regional mean $S_{\text{max}}$ directions since such results have passed the Rayleigh test (at the 95 per cent confidence limit). The statistical treatment employed is described in the text.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Total No. of wells</th>
<th>Total interval length (km)</th>
<th>Retained wells</th>
<th>Total interval length of retained wells (km)</th>
<th>Combined accum. breakouts (km)</th>
<th>Qual.</th>
<th>$S_{\text{max}}$ (azimuth from north)</th>
<th>Pass Rayleigh test at:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Amazon (Fig. 3)</td>
<td>3</td>
<td>2.9</td>
<td>3</td>
<td>2.9</td>
<td>0.51</td>
<td>BC</td>
<td>144±13 (*)</td>
<td>90%</td>
</tr>
<tr>
<td>Upper Amazon (Fig. 3)</td>
<td>35</td>
<td>18.4</td>
<td>30</td>
<td>15.9</td>
<td>1.15</td>
<td>BCD</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>Paraná (Fig. 4)</td>
<td>10</td>
<td>14.0</td>
<td>9</td>
<td>13.2</td>
<td>1.76</td>
<td>ABCD</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>Barreirinhas/Para/Maranhão (Fig. 5)</td>
<td>26</td>
<td>31.1</td>
<td>16</td>
<td>20.2</td>
<td>1.30</td>
<td>ABCD</td>
<td>120±13</td>
<td>95%</td>
</tr>
<tr>
<td>Amazon Mouth Onshore (Fig. 5)</td>
<td>5</td>
<td>14.4</td>
<td>5</td>
<td>8.4</td>
<td>1.17</td>
<td>ABC</td>
<td>121±15 (*)</td>
<td>95%</td>
</tr>
<tr>
<td>Amazon Mouth Offshore (Fig. 5)</td>
<td>7</td>
<td>13.7</td>
<td>5</td>
<td>8.4</td>
<td>1.17</td>
<td>ABCD</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Ceará (Fig. 6)</td>
<td>17</td>
<td>25.1</td>
<td>14</td>
<td>21.4</td>
<td>0.39</td>
<td>BCD</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>Potiguar (Fig. 6 and 7)</td>
<td>129</td>
<td>109.4</td>
<td>65</td>
<td>59.1</td>
<td>1.14</td>
<td>BCD</td>
<td>129±8 (*)</td>
<td>95%</td>
</tr>
<tr>
<td>Alagoas (Fig. 8)</td>
<td>40</td>
<td>68.6</td>
<td>30</td>
<td>52.9</td>
<td>3.69</td>
<td>ABCD</td>
<td>102±10</td>
<td>95%</td>
</tr>
<tr>
<td>Sergipe (Fig. 8)</td>
<td>32</td>
<td>20.0</td>
<td>17</td>
<td>12.6</td>
<td>0.88</td>
<td>BCD</td>
<td>41±19</td>
<td>95%</td>
</tr>
<tr>
<td>Recôncavo Offshore/Tucano (Fig. 8)</td>
<td>61</td>
<td>59.7</td>
<td>5</td>
<td>3.9</td>
<td>0.64</td>
<td>BC</td>
<td>42±17 (*)</td>
<td>95%</td>
</tr>
<tr>
<td>Recôncavo Offshore/Camamu/Almada (Fig. 8)</td>
<td>18</td>
<td>20.6</td>
<td>14</td>
<td>16.8</td>
<td>2.04</td>
<td>ABCD</td>
<td>02±12</td>
<td>95%</td>
</tr>
<tr>
<td>Espírito Santo (Fig. 9)</td>
<td>30</td>
<td>32.9</td>
<td>23</td>
<td>26.1</td>
<td>0.92</td>
<td>BCD</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>Campos (Fig. 9)</td>
<td>104</td>
<td>122.5</td>
<td>59</td>
<td>79.8</td>
<td>3.04</td>
<td>ABCD</td>
<td>–</td>
<td>No</td>
</tr>
<tr>
<td>Santos</td>
<td>11</td>
<td>23.8</td>
<td>6</td>
<td>18.0</td>
<td>0.59</td>
<td>ABD</td>
<td>–</td>
<td>No</td>
</tr>
</tbody>
</table>

(*) Adopted $S_{\text{max}}$ mean orientation for the basin, with 95 per cent confidence limits.
Table 2. Average $S_{\text{hmax}}$ orientations as used in Fig. 2. Significance is the probability that the data has a preferred orientation and is not randomly oriented, according to the Rayleigh test. Rmean is the mean vector length of the summed orientation vectors. BO and FM are the numbers of breakout and focal mechanism data, respectively, used in the average.

<table>
<thead>
<tr>
<th>Lat. (°)</th>
<th>Long. (°)</th>
<th>Azimuth (°)</th>
<th>Signif. (%)</th>
<th>No. BO</th>
<th>No. FM</th>
<th>Qualities</th>
<th>Rmean</th>
<th>Locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.00</td>
<td>-54.50</td>
<td>144±13</td>
<td>92</td>
<td>3</td>
<td>0</td>
<td>BC</td>
<td>0.92</td>
<td>Mid–Amazon</td>
</tr>
<tr>
<td>-1.55</td>
<td>-49.76</td>
<td>82±19</td>
<td>92</td>
<td>4</td>
<td>0</td>
<td>ABC</td>
<td>0.79</td>
<td>Marajó Island</td>
</tr>
<tr>
<td>-2.50</td>
<td>-43.12</td>
<td>128±9</td>
<td>98</td>
<td>4</td>
<td>0</td>
<td>ABC</td>
<td>0.95</td>
<td>Maranhão coast</td>
</tr>
<tr>
<td>-4.10</td>
<td>-40.18</td>
<td>103±17</td>
<td>90</td>
<td>0</td>
<td>4</td>
<td>C</td>
<td>0.86</td>
<td>West Ceará</td>
</tr>
<tr>
<td>-4.58</td>
<td>-38.21</td>
<td>117±10</td>
<td>98</td>
<td>0</td>
<td>13</td>
<td>BC</td>
<td>0.94</td>
<td>East Ceará</td>
</tr>
<tr>
<td>-4.93</td>
<td>-36.97</td>
<td>120±18</td>
<td>98</td>
<td>1</td>
<td>5</td>
<td>BCD</td>
<td>0.54</td>
<td>Potiguar coast</td>
</tr>
<tr>
<td>-5.68</td>
<td>-37.52</td>
<td>120±13</td>
<td>99</td>
<td>13</td>
<td>5</td>
<td>BCD</td>
<td>0.62</td>
<td>Potiguar onshore</td>
</tr>
<tr>
<td>-9.76</td>
<td>-35.90</td>
<td>102±12</td>
<td>99</td>
<td>20</td>
<td>0</td>
<td>ABC</td>
<td>0.64</td>
<td>Alagoas coast</td>
</tr>
<tr>
<td>-10.67</td>
<td>-37.12</td>
<td>39±15</td>
<td>98</td>
<td>5</td>
<td>0</td>
<td>BC</td>
<td>0.83</td>
<td>Sergipe coast</td>
</tr>
<tr>
<td>-12.33</td>
<td>-38.18</td>
<td>31±11</td>
<td>99</td>
<td>27</td>
<td>0</td>
<td>ABC</td>
<td>0.62</td>
<td>Recôncavo, BA</td>
</tr>
<tr>
<td>-14.24</td>
<td>-39.00</td>
<td>01±14</td>
<td>99</td>
<td>7</td>
<td>0</td>
<td>ABC</td>
<td>0.80</td>
<td>S. Bahia coast</td>
</tr>
<tr>
<td>-20.68</td>
<td>-45.16</td>
<td>84±20</td>
<td>90</td>
<td>0</td>
<td>4</td>
<td>CD</td>
<td>0.77</td>
<td>SE shield, MG</td>
</tr>
</tbody>
</table>

Figure 2. Comparison of observed average $S_{\text{hmax}}$ directions (thick bars) with theoretical results (thin lines) from two finite-element models of the South American plate: M95 (Meijer 1995) and CR96 (Coblentz & Richardson 1996). No magnitudes are implied for the observed data. The observed average orientations were obtained with clusters of three or more points within a radius of 100–200 km having a significant preferred mean orientation, as shown in Table 2. In southeastern Brazil, near 22°S, '∙' indicates areas with high concentrations of stress indicators (Fig. 1) but no significant mean orientation.

to mafic intrusions in the lower crust forming steep-sided bodies about 100–200 km wide and up to 30 km high. In Fig. 3, we show the location of the modelled mafic body in the lower crust. Zoback & Richardson (1996) used 2-D finite-element modelling to show that the load of such a heavy mafic intrusion can produce local compressive bending stresses up to about 70 MPa in the upper crust above the load axis. These local bending stresses can exceed the regional stresses caused by the plate-boundary forces. In this way, the observed SE–NW orientation above the mafic body could be the combined effect of an ESE–WNW regional stress superimposed on a local N–S flexural compression.

If we take the regional stresses from the M95 or CR96 models to be the far-field stresses, and use the observed $S_{\text{hmax}}$ orientation (144°) to be the resultant combination of the far-field stresses with a local flexural N–S compression, the magnitude of the local compression can be calculated using the rotation angle (e.g. Zoback & Richardson 1996). For both the M95 model ($S_{\text{hmax}}$ orientation 120°; $S_{\text{hmax}}$–$S_{\text{hmin}}$ = 24 MPa) and the CR96 model ($S_{\text{hmax}}$ orientation 105°; $S_{\text{hmax}}$–$S_{\text{hmin}}$ = 18 MPa) we obtain a value of 20 MPa for the local N–S compression. Although these calculations are based on very simple models of a 100 km thick elastic plate, they demonstrate that local flexural stresses can significantly change the resultant $S_{\text{hmax}}$ orientation (Zoback & Richardson 1996).

The two focal-mechanism P axes [also used by Zoback & Richardson (1996) as evidence for the observed stress rotation] are about 100–200 km off the axis of the main load, so they may not be affected by the maximum axial bending stresses. However, the earthquake occurrence could be facilitated by

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the peripheral flexural stresses, which can be as high as 10–20 MPa according to Zoback & Richardson's calculations. More detailed interpretation of the earthquake data will require stress calculations with 3-D models.

In the Lower Amazon Basin (near Marajo Island, Fig. 2) the mean observed $S_{\text{Hmax}}$ trends more E–W than any of the M95 or CR96 models. Contrary to in the Middle Amazon Basin, the observed rotation is anticlockwise. Local flexural stresses from the sediment load in the Amazon Fan may help to explain part of the observed rotation. Driscoll & Karner (1994) showed that flexural deformation due to the sediment load from the Miocene to the present (up to 5 km thickness north of the Marajo Island) causes an uplift in the peripheral bulge in the continent (up to 50 m elevation) consistent with topographic and drainage features. Although the peripheral uplift is small in Marajo Island (less than 10 m), N–S extensional flexural stresses are predicted by Driscoll & Karner's (1994) modelling. This N–S extension (i.e. local E–W compression) may well contribute to the anticlockwise rotation of the resulting $S_{\text{Hmax}}$ stress.

**Paraná Basin**

Six wells with qualities A to C were found in the Paraná basin, as shown in Figs 1 and 4, but no significant trend was found. Focal-mechanism $P$ axes of earthquakes in the basement both west and east of the Paraná Basin show a common ENE–WSW orientation (Fig. 1). The mean orientation of the breakout $S_{\text{Hmax}}$ in the basin sediments is about 057°, roughly consistent with the earthquake data, but the scatter in the breakouts is too large to make it a reliable estimate of the regional stress in the basin interior. Local effects near the wells are probably more important than the crustal tectonic stresses. This interpretation is consistent with the very low stress magnitudes, about 6 MPa, predicted by the models of both Meijer (1995) and Coblentz & Richardson (1996), as seen in Fig. 2.

**Central Brazil**

One C-quality breakout in central Brazil (about 14°S, Fig. 1) has an $S_{\text{Hmax}}$ orientation roughly intermediate between that of a hydrofracturing measurement to the west and a reverse-faulting mechanism to the east. The few data points in central Brazil are not enough to pass the Rayleigh test for the existence of a preferred orientation at a 90 per cent confidence limit. However, it is interesting that the observed data seem to show a clockwise rotation in the $S_{\text{Hmax}}$ orientation, from E–W to NW–SE, similar to the predicted stress pattern of Meijer (1995) shown in Fig. 2a.
Further south, east of the Paraná Basin at about 20°–22°S, a few earthquake focal mechanisms (Assumpção 1994; Blum 1993) show a significant ENE–WSW average orientation for $S_{\text{Hmax}}$ which is quite close to that predicted by both models M95 and CR96 (Fig. 2). Both theoretical models predict a strike-slip stress regime, which might help explain the varied faulting mechanisms seen in Fig. 1: reverse-, strike-slip- and normal-faulting earthquakes may depend on the orientations of local pre-existing faults.

Equatorial marginal basins

Fig. 5 shows the breakout data for the marginal basins from the Amazon Delta to the Barreirinhas Basin. The onshore data in both the Amazon Mouth (also shown in Fig. 3) and the Barreirinhas basins show a significant $S_{\text{Hmax}}$ trend about E–W to ESE–WNW. The offshore data, however, do not show any significant trend. A similar pattern occurs in the Ceará and Potiguar basins (Fig. 6), with the offshore data having a large scatter, and the onshore wells showing a more consistent $S_{\text{Hmax}}$ orientation roughly parallel to the coastline.

In the Potiguar Basin, mean $S_{\text{Hmax}}$ orientations from the breakouts were taken at regular points, averaging the data within a radius of about 40 km from each point (Fig. 7) and compared with the inferred $S_{\text{Hmax}}$ orientations from focal mechanisms of earthquakes in the basement around the basin (Ferreira et al. 1995). A clear pattern of coast-parallel $S_{\text{Hmax}}$ orientations is apparent in Fig. 7. It is interesting to observe that even the poor breakouts (quality D) show consistent orientations (Fig. 6). The earthquake data indicate that strike-slip faulting predominates in this area. According to Mastin (1988), in a strike-slip stress regime the breakouts depend more on the far-field tectonic stresses and are less affected by local perturbations near the wells. Thus, it is not too surprising that in the strike-slip environment of the onshore Potiguar Basin even the D-quality breakouts give a consistent regional picture for the $S_{\text{Hmax}}$ orientation.

The strike-slip stress regime in the onshore Potiguar Basin was interpreted by Assumpção (1992) as the superposition of a roughly E–W regional compression (due to plate-wide forces such as ridge push) and a local extension perpendicular to the coastline. This local extension would be due both to lateral crustal density variations in the continent/ocean transition and to peripheral flexural stresses caused by the sediment load in the continental margin (e.g. Stein et al. 1989). The stress models M95 and CR96, which take into account the forces due to the lateral density variation across the continental margin, both predict strike-slip stresses in continental NE Brazil in general agreement with the data, the M95 giving better orientations (Fig. 7). Meijer (1995) also showed that the forces related to the continental margin produce stresses that better explain the observed earthquake slip angles, compared to models without margin forces.

Eastern marginal basins

Fig. 8 shows the breakout results in the continental margins from 9° to 15°S.

Excluding the D-quality wells, which show a large scatter, the $S_{\text{Hmax}}$ trend is clearly parallel to the coast in the Recôncavo, Tucano, and Sergipe basins. In the Alagoas Basin a large scatter was found (standard deviation of 28°), but the large number of available wells (20 with A, B or C quality) allows the mean orientation (102°) to be statistically significant at the 99 per cent level (Table 2).

The $S_{\text{Hmax}}$ orientations in the continental margins from 10 to 15°S are almost perpendicular to the predicted stress directions of both the M95 and the CR96 models (Fig. 2). Two possible explanations are proposed:

**Figure 5.** Breakout data at the northern Brazilian coast.

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Figure 6. Breakout data at the northeastern Brazilian coast (Ceará and Potiguar basins).

Figure 7. Pattern of $S_{\text{max}}$ near the Potiguar Basin (PO). Average $S_{\text{max}}$ (thick bars) was obtained from breakout data within a radius of 0.4° around grid points. Different bar thicknesses indicate significance levels for the existence of a preferred orientation, according to the Rayleigh test. Short lines with a circle indicate $S_{\text{max}}$ from focal mechanisms shown by the beach balls (Ferreira et al. 1995). Mechanisms with grey shading are less well constrained. Thin lines M and CR are the theoretical $S_{\text{max}}$ orientations from the models of Meijer (1995) and Coblentz & Richardson (1996), respectively.
(1) The observed stresses in the sedimentary layers are decoupled from the tectonic stresses in the upper crust, so that the SHmax orientation in the models has little relation to the local stresses inside the basin; 
(2) Other forces not taken into account in the theoretical finite-element models should be included.

The regional consistency of the breakout data along a 500 km segment of the continental margin (where several A-quality wells were found), and the fact that in the Potiguar Basin the breakout data agrees with the focal mechanisms in the basement, argue against the decoupling hypothesis. We interpret the mismatch between observed and predicted SHmax orientations as being caused by the lack of an additional force in the M95 and CR96 models: flexural stresses from the sediment load on the continental shelf. In this part of the eastern continental margin, besides the load of the sediments on the continental shelf, the Tucano Basin is also expected to contribute significantly to the total stresses, as will be shown below.

Southeastern marginal basins

The breakout data in the Espirito Santo, Campos and Santos basins (Fig. 9, Table 2) are too scattered to define any significant mean orientation. In the Campos basin, 103 wells were analysed but no reliable regional SHmax orientation could be detected (Table 2). The best breakout results, found in wells drilled close to the shelf break, seem to show a trend of SHmax oriented roughly parallel to the local trends of the isobaths (Fig. 9a).

The observed scatter in the continental shelf of the Campos and Santos basins probably reflects local dynamics of the sedimentary layers. In those two basins extensive salt structures, found in two different bathymetric domains, have been active from the Albian to the present. Near the coast there is
an upper domain, 100–200 km wide, with a suite of extensional structures, and seawards of that there is a lower domain, 100–400 km wide, with contractual structures. From the balance between extension and contraction, thin-skinned salt tectonics has been considered to be gravitationally driven and independent of any basement tectonics (Demercian, Szatmari & Cobbold 1993). Since the breakout data in these basins come from depths above the salt layers, the observed scatter may result from complex local stress patterns due to salt tectonics, which may decouple the stresses in the upper part of the sediments from the more regional stresses in the basement.

DISCUSSION OF THE CONTINENT-OCEAN EFFECT

The new breakout data presented in this paper have shown a clear pattern of stresses in the Brazilian continental margins: coast-parallel $S_{\text{shmax}}$ was found in the onshore part of most marginal basins; in the offshore areas, near the continental shelf break, the breakout data is more scattered. While the data in the equatorial margins are roughly consistent with stress models that take into account the effects of lateral density contrasts across the continent/ocean transition, the data in the eastern margins clearly demand an additional local force not included in the models. We propose that flexural stresses caused by the sediment load on the continental shelf can produce the observed coast-parallel stresses.

Flexural stresses in continental margins

Sediment loading at the continental shelf and continental rise can cause considerable flexural stresses in the upper crust. A line load on a thin elastic plate will cause bending stresses above the neutral plane that are compressive right under the load but change to extensional towards the peripheral bulge (Turcotte & Schubert 1982, chapter 3). The maximum peripheral extension occurs at about 300–400 km from the load axis for a 100 km thick continental lithosphere. For example, Cloetingh, Wortel & Vlaar (1984) modelled the evolution of a 100 Ma continental margin, subjected to a total sediment load of about 8 km, assuming a simple elastic behaviour for the upper part of the lithosphere, and a more ductile behaviour for the lower part. If no elastic stresses were released during the sedimentation history, the compressional bending stresses under the load would reach more than 1000 MPa. The peripheral extensional stresses in Cloetingh's model would be about 270 MPa a few hundred kilometres from the edge of the continental shelf. If allowance is made for the relaxation of stresses with faulting at the ocean/continent boundary during the evolution of the marginal basin, the extensional stresses in the continental upper crust will be smaller, maybe around 100 MPa (Turcotte, Ahren & Bird 1977), but still significant.

The peripheral extensional bending stresses are oriented normal to the coast, which makes the maximum horizontal compression parallel to the coastline. Accurate stress magnitudes due to sediment load are difficult to calculate because of the complex rheological properties of the crust and the faulting history of the marginal basin. Slow sedimentation rates on a viscoelastic lithosphere can reduce the flexural stresses by an order of magnitude compared to purely elastic models (Stein et al. 1989). Despite these uncertainties, it seems clear that flexural stresses have the same order of magnitude as those caused by lateral density contrasts and plate margin forces, and could contribute significantly to the observed pattern of coast-parallel $S_{\text{shmax}}$. Interestingly, coast-parallel $S_{\text{shmax}}$ was more easily observed towards the onshore part of the marginal basins, usually a hundred kilometres or more from the maximum sediment thickness of the continental shelf, consistent with the predicted distances for the peripheral extensional stresses.

Effect of the Tucano and Recôncavo basins

The Tucano Basin (Fig. 8), close to 100 km wide and about 10 km deep (Chang et al. 1992), has been interpreted as being the result of a lower-crustal east-dipping detachment fault that became active during the South Atlantic rifting (Ussami, Karner & Bott 1986). The gravity anomalies are extremely high, reaching $-140$ mGal (Bouguer) and about $-100$ mGal (free air), and are completely explained by the low-density sedimentary layers in the basin (Ussami et al. 1986). Because no compensating Moho topography under the basin was detected with the gravity data, a minimum value of 50–80 km for the effective elastic thickness of the continental lithosphere was inferred by Ussami et al. (1986). This negative gravity anomaly has about the same amplitude and width as the positive anomalies in the Middle Amazon Basin, and so should produce flexural stresses of the same order of magnitude as those determined by Zoback & Richardson (1996) for the Amazon basin, but of opposite sign, that is extensional stresses under the basin and compressional stresses towards the peripheral bulge.

The few breakout data in the middle of the Tucano Basin (Fig. 8) are consistent with roughly E-W extension (i.e. N–S $S_{\text{shmax}}$). The mean $S_{\text{shmax}}$ orientation in the Sergipe Basin, about 140 km from the Tucano Basin, is about NE–SW (Fig. 2), whereas that in the Alagoas Basin, about 260 km from the Tucano Basin, is roughly E–W. The continental crust beneath the Tucano Basin is part of the Lower Proterozoic SãoFrancisco craton. The nearby marginal basins overlie metamorphic rocks that were deformed mostly during the Brasiliano (Upper Proterozoic) orogeny. An effective elastic thickness of 100 km for this continental lithosphere, consistent with its age and the minimum value of 80 km determined by Ussami et al. (1986), will sustain upper-crustal E-W extensional stresses beneath the basement up to about 180 km from the main sedimentary (negative) load. This would place the Sergipe onshore basin in the E–W extensional domain and the Alagoas Basin in the E–W compressional domain towards the peripheral bulge. These flexural stresses are probably large enough to cause the observed rotations of the resultant $S_{\text{shmax}}$ orientations.

The discussion above of the Tucano Basin was based on estimates of flexural deformations of a homogeneous thin elastic plate, which is clearly an oversimplification. Sedimentary loads on the continental shelf should also contribute significantly to flexural stresses, although the free-air gravity anomalies in the continental margin are not as impressive as in the Tucano Basin, ranging from $-50$ to $+30$ mGal at the eastern margin (Molina 1996). Also, the effective elastic thickness in the extended crust beneath the continental shelf is usually smaller than in the normal continental crust, with values as low as 5–10 km (Karner & Watts 1982; Mello & Bender 1988): this implies higher flexural stress magnitudes but with a shorter
CONCLUSIONS
A detailed breakout analysis was carried out to evaluate regional stress directions. The original well log data involved a large number of samples (3.9 x 10^3); enlargements close to directions of the borehole deviations were systematically discarded, and only breakout intervals with well-defined orientations (std ≤ 12°) were considered. The new breakout data (136 A-C quality wells from a total population of 541 wells) cover a broad region of mid-plate South America where only 23 stress indicators (B-D quality) had been compiled in the World Stress Map Project. The breakout results are generally consistent with nearby focal mechanism solutions, especially in the Potiguar Basin in NE Brazil.

When the lateral density contrasts across the continental margins are taken into account, the stress models of Meijer (1995) and Coble and Richardson (1996) give a reasonable first-order fit to the observed data in the equatorial margin and in central Brazil. In areas where additional large-scale crustal structural variations are present, such as in the Middle Amazon Basin and near the Tucano Basin, large rotations of the Smax orientation were observed. Large rotations were also observed along the continental margin from 10 to 15°S where the Smax orientation are almost perpendicular to the predicted stress directions of both the M95 and the CR96 models (Fig. 2). We propose that flexural stresses caused by sediment load in the continental shelf can produce the observed coast-parallel stresses.

The newly increased observed stress data set should be helpful in constraining more detailed theoretical models of the forces that drive the South American plate.

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REFERENCES
Demerican, S., Sztach, P. & Cobbold, P.R., 1993. Style pattern of salt diapirs due to thin-skinned gravitational gliding, Campos and Santos basins, offshore Brazil, Tectonophysics, 228, 393–433.


Schlumberger, 1987. Log Interpretation Principles and Applications, Schlumberger Education Services, Houston, TX.


