Applications of stress polygon to constrain stress magnitudes and faulting style in Potiguar Basin, northeast Brazil.

Álvaro F. Campassi Reis PETROBRAS, Francisco Hilário R. Bezerra UFRN/PPGG, Joaquim M. Ferreira UFRN/PPGG, Aderson F. do Nascimento UFRN/PPGG and Cláudio C. Lima PETROBRAS.

Abstract

The construction of the stress polygon is based on the assumption that the admissible stress state on the crust, at any depth or pore pressure, is limited by the frictional strength of preexisting fractures and faults critically oriented to the present tectonic stress field. In this paper we use the stress polygons to constrain stress magnitudes in two different geological domains in Potiguar Basin. In the pos-rift sequence (Açu and Alagamar formations) a present normal faulting regime was observed from 0.5 to 2.0 km, a maximum horizontal stress (SH_{max}) gradient of 20 MPa/km and a S_{Hmax}/S_{hmin} ratio of 1.154. In the deeper rift sequence (Pendência Formation) a transitional (normal to strike-slip) present faulting regime was observed from 2.5 to 4.0km, which is characterized by a S_{Hmax} gradient of 24.5 MPa/km and a S_{Hmax}/S_{hmin} ratio of 1.396. The deeper regime in the Basin also takes place in the surrounding basement at 1-12 km depth, according to published focal mechanisms. We concluded that this dual stress regime is consistent with an incipient tectonic inversion in the basin.

Introduction

The knowledge of the present state of stress in a sedimentary basin is vital for petroleum industry, and it defines many aspects of drilling and production, such as borehole stability, water injection, sand production, reservoir stimulation among others (Moos et al., 2003; Zoback, 2003, 2007). The orientation and magnitude of the three principal stresses is also important for the understanding of fault style, fault reactivation potential and seismic hazard (Tingay et al., 2009; Sibson, 1994, Moeck and Backers, 2011).

In general, there are few available studies in the literature about the state of stress in the Brazilian sedimentary basins. In Potiguar Basin the published data are mainly composed of borehole breakout analysis (Lima et al, 1997) and earthquake focal mechanisms, which are concentrated in the crystalline basement around the onshore border of Potiguar Basin (Assumpção, 1992; Ferreira et al, 1998; Bezerra et al., 2007). These studies provided information about stress orientation. Little attention has been dedicated to the determination of a full stress tensor and a three dimensional stress variation across the Brazilian sedimentary basins. This study contributes to fill this knowledge gap about the present state of stress in these basins. We integrated log data (resistivity image logs, conventional sonic and density logs), rock strength laboratory analysis (unconfined and triaxial tests), and hydraulic fracture data to determinethe full stress tensor (least and maximum horizontal stresses and vertical stress) at different depths and geological domains in Potiguar Basin. The stress magnitude data were then plotted in stress polygons as proposed by Barton et al. (1988).

Stress field in the Potiguar Basin

The Potiguar Basin is located in the Borborema Province (figure 01), one of the most seismically active region in the South American stable continental plate. Lima et al. (1997) presented a detailed study concerning compressive stress orientation across several Brazilian sedimentary basins from borehole breakout analysis in dip-meter logs. These authors analyzed 541 wells, 481 of them in the continental margin. In the Potiguar Basin, the present state of stress is constrained by earthquake focal mechanisms determinations, borehole breakout analysis, fault slip data and anelastic strain recovery measurements (Bezerra et al., 2011). The orientation of compressive stress is margin parallel rotates from E-W to NW-SE in Potiguar Basin. A detailed description on stress data from resistivity image logs in Potiguar Basin onshore, both orientation and magnitude, can be found in Reis (2012). These studies show that the maximum compressive orientation (SHmax) tends to reproduce the margin parallel pattern found in the focal mechanisms in the crystalline basement nearby the basins of the equatorial margin.

Assumpção (1992), Ferreira et al. (1998) and Lima et al. (1997) concluded that flexural stresses, caused by sediment load offshore and density contrast, both local forces, control stresses along the continental margin of South America.

The stress indicators points to an overall strike-slip regime in the Borborema Province (Bezerra et al., 2011). The predominant regime is also strike-slip, according to earthquake focal mechanisms in the crystalline basement surrounding the Potiguar Basin (Bezerra et al., 2011). The two main characteristics of this seismicity around Potiguar Basin is a swarm-like activity which exhibits long duration (several months to 10 years) and shallow hypocentral depths (1 to 12 km), according to Ferreira et al. (1998).

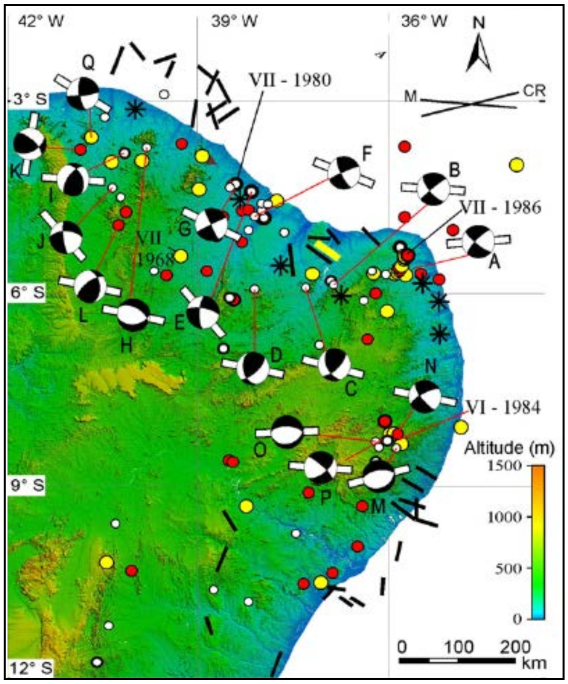

Figure 01: orientation of compressive stress (S_{Hmax}) in the Borborema Province. A to Q: focal mechanisms; white circles: earthquake magnitude m_b=2; red circles: earthquake magnitude m_b=3; yellow circles earthquake magnitude m_b=4 and 5; black lines: compressive orientation from borehole breakouts (Lima et al., 2007); yellow line: compressive orientation from anelastic strain recovery (Araujo et al., 2009). Modified from Bezerra et al. (2011).

Stress Polygon

In many parts of world stress magnitudes are constrained by the strength of pre-existing critically stressed faults (Zoback et al., 2003; Zoback, 2007). Assuming that condition, it is possible to constrain and reduce the uncertainty in stress magnitudes estimation, as the stresses in the crust are limited by Coulomb frictional sliding of faults(Moos et al., 1999). In addition, the stress magnitudes in the crust, in seismically active zones, are found in a state of frictional failure of equilibrium. This means that, in these active zones, even low pore pressure increments or perturbations in stress magnitudes can trigger earthquakes. It follows that in deep wells drilled in many parts of world, the Coulomb coefficient of friction (μ) is found to be within small a range between 0.6 and 1.0 (Barton et al., 1988; Zoback et al., 2003).

The condition of frictional failure equilibrium is given as follows (Jaeger et al., 2007):

$$\frac{\sigma_1}{\sigma_3} = \frac{S_1 - P_p}{S_3 - P_p} = \left[\left(\mu^2+1\right)^{\frac{1}{2}} + \mu\right]^2 ....(1)$$

Applying the Andreson`s faulting theory to relate S_{hmin} (least in situ horizontal stress), S_{Hmax} (maximum in situ horizontal stress) and Sv (vertical or overburden in situ stress) to S1 (maximum principal stress) and S3 (least principal stress), and assuming that one of the three principal stresses is vertical, the previous equation can be written as (Zoback et al., 2003; Zoback ,2007):

Normal faulting:

$$\frac{S_v - P_p}{S_{h\min} - P_p} = \left[\left(\mu^2+1\right)^{\frac{1}{2}} + \mu\right]^2 ....(2)$$

Strike-slip faulting:

$$\frac{S_{H\max} - P_p}{S_{h\min} - P_p} = \left[\left(\mu^2+1\right)^{\frac{1}{2}} + \mu\right]^2 ....(3)$$

Reverse faulting:

$$\frac{S_{H\max} - P_p}{S_v - P_p} = \left[\left(\mu^2+1\right)^{\frac{1}{2}} + \mu\right]^2 ....(4)$$

Where:
σ_1= maximum principal effective stress
σ_3= least principal effective stress
S_1= maximum principal stress
S_3= least principal stress
Pp= pore pressure
μ= Coulomb coefficient of friction
Sv= overburden stress
S_{Hmax}= maximum horizontal stress
S_{hmin}= least horizontal stress

These three equations above define the limits of a stress polygon (Figure 02) in a graphic S_{hmin} versus S_{Hmax} for a specific depth and pore pressure (Zoback et al., 2003; Zoback ,2007). The interior of the polygon represents the admissible state of stress for the three faulting regimes, assuming that the stress magnitudes are constrained by the strength of pre-existing critically stressed faults in the crust.

An additional constraint for the stress magnitudes is defined by drilled induced tensile fractures (DITF) in a borehole wall. The DITF are observed in image logs when the hoop stress is greater than the rock tensile strength. The hoop stress can be also plotted in the stress polygon and represents a lower boundary for the maximum horizontal stress

The hoop stress in a borehole wall is a function of the contrast between S_{Hmax} and S_{hmin}, pore pressure and mud pressure (Jaeger et al., 2007):

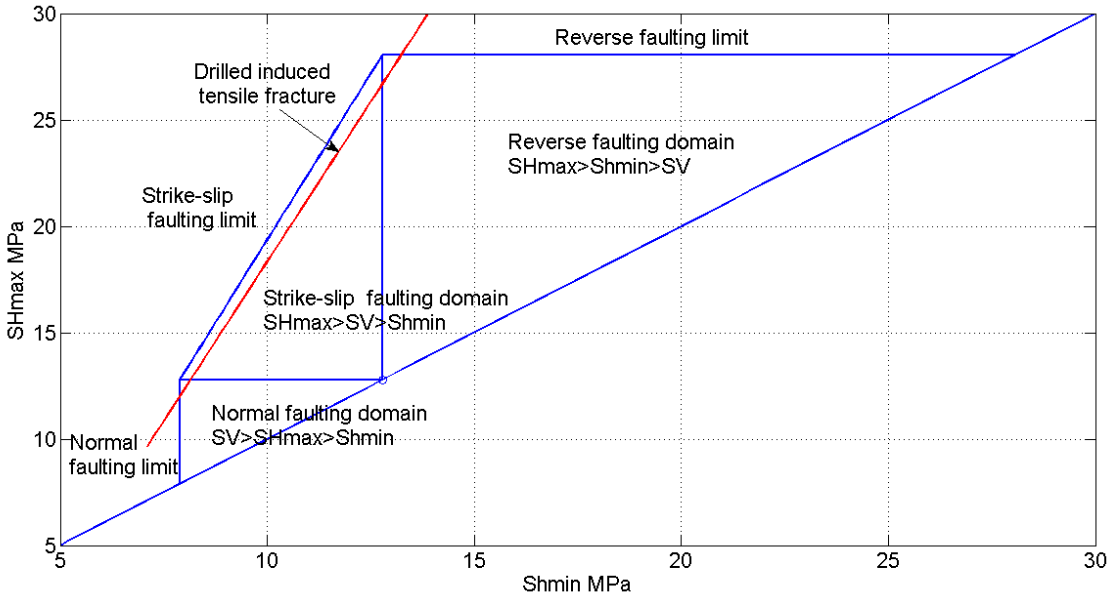

Figure 02: stress polygon plot as used in this study to represent the three faulting style domains. The external boundaries represent the state of frictional failure equilibrium for a specific depth and constrained by the Coulomb coefficient of friction of critically oriented fault and fractures.

$$\sigma_{\theta\theta} = S_{H\max} + S_{h\min} + 2(S_{H\max} - S_{h\min})\cos 2\theta - P_p - P_M - \sigma^{\Delta t} \quad (5)$$

Where:

$\sigma_{\Theta\Theta}$= hoop stress
θ= azimuth angle from the S_{hmin} orientation
Pm= mud pressure
$\sigma^{\Delta t}$= differential temperature stress

Results

We selected 10 well located in the western, southern and central parts of the onshore Potiguar Basin. The selection followed some criteria: (1) only vertical wells (deviation lesser than 10°); (2) original and no depleted pore pressure; (3) identification of borehole breakouts or drilled induced tensile fractures, which were used to analyze stress magnitude and orientation; (4) presence of mini fracture tests in the selected wells or in correlative intervals in nearby wells; (5) presence of uniaxial or confined rock strength tests, in order to provide the unconfined compressive strength and internal friction angle; and (6) minimum length of borehole breakout or drilled induced tensile fracture intervals of 1 meter.

The S_{Hmax} orientation ranged from 139° to 160° (borehole breakouts analysis) and 110° to 121° (drilled induced tensile fractures analysis), according to its location in the basin. The quality of the stress indicators, both breakouts and tensile fractures, was classified according to the criteria proposed by the *World Stress Map* (Heidbach et al., 2010). The quality of the stress indicators varies from A (S_{Hmax} orientation uncertainty between +/- 15°) to D (S_{Hmax} orientation uncertainty between +/- 25° to +/- 40°).

The mean overburden gradients, calculated through the integration of density logs, vary from 22.5 MPa/km to 23.8MPa/km.

The pore pressures were calculated directly from drill stem tests, injection tests and wireline formation tests. The mean pore pressure gradient vary from 9.81 MPa/km, in Açu and Alagamar Formations, to 12.22 MPa/km in Pendência Formation.

The least horizontal stress (S_{hmin}) gradients vary from 13.7 MPa/km to 18.5 MPa and the maximum horizontal stress magnitude (S_{Hmax}) gradients range from 20.7 MPa/km to 23.7 MPa/km. The maximum horizontal stress magnitudes were estimated through the analysis of borehole breakout widths, as proposed by Barton et al., (1988) and Zoback et al., (2003).

Discussion

The stress orientation found in this study is also consistent with the interpretation of earthquake focal mechanisms in the crystalline basement surrounding the basin. The predominant SHmax orientation is margin parallel and rotates 45° from E-W to NW-SE (Figure 01).

The margin-parallel SHmax orientation in Potiguar Basin, observed in this study, is controlled by a superposition of a roughly E-W regional compression, related to plate wide motion, along with a local margin-normal extension, related to density contrast between continental and oceanic crusts and sediment load (Assumpção, 1992 and Ferreira et al., 1998).

The stress magnitudes estimated in this study, at different depths and geological domains, point to a decoupling between the normal faulting regime found in the shallower wells and the transitional normal to strike-slip faulting regime found in the deeper wells. The strike-slip regime is predominant in the crystalline basement that surrounds Potiguar Basin (hypocentral depths 1 to 12 km). This extensional regime at shallower depths and the deeper transitional regime is consistent with an ongoing incomplete tectonic inversion in the basin (Lima, 2003).

The stress polygon boundaries define the frictional failure equilibrium, as proposed by Zoback et al. (2003) and Zoback (2007) and represent the maximum admissible effective stresses in the crust before failure. The stress magnitudes found in this study did not lay on the polygonal periphery, which is consistent with the absence of seismicity inside the sedimentary basin. However, the seismicity observed in the basement suggests that in this region the crust is at frictional equilibrium.

Acknowledgments

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References

Araújo, J., Vieira, M.M., Bezerra, F.H.R., 2009. Influence of tectonic stresses in the Permeability of Petroliferous Reservoir in Potiguar Basin, Brazil. Proceedings of the 2009 SPE Latin American and Caribbean Petroleum Engineering. Cartagena,Colombia, SPE 122075.

Assumpção, M. (1992), The regional intraplate stress field in SouthAmerica, J . Geophys. Res., 97, 11889–1 1903.

Assumpção, M. (1998), Seismicity and stresses in the Brazilian passive margin. Bull. Seism. Soc. Am., 88(1), 160–169.

Assumpção, M., G. Suarez, and J. A. V. Veloso (1985), Fault plane solutions of intraplate earthquakes in Brazil: some constraints on the regional stress field, Tectonophysics, 113, 283–293.

Barton, C. A., M. D., Zoback, and K. L. Burns (1988), In situ stress orientation and magnitude at the Fenton geothermal site, New Mexico, determined from wellbore breakouts, Geophys.Res. Lett., 15, 467–470.

Bezerra, F. H. R., M. K. Takeya, M. O. M. Sousa, and A. F. do Nascimento (2007), Coseismic reactivation of the Samambaia fault, Brazil, Tectonophysics, 430, 27–39.

Bezerra, F. H. R., A. F. do Nascimento, J. M. Ferreira, F. C. Nogueira, R. A. Fuck, B. B. B. Neves, and M. O. L. Sousa (2011), Review of active faults in the Borborema Province, Intraplate South America- integration of seimological and paleoseismological data, Tectonophysics, 510, 269–290.

Chang, C., L. C. Neil, J. C. Moore, W. Lin, M. Conin, and Y. Yamada (2010), In situ stress state in Nankai accreationary wedge estimated from borehole wall failures, Geochem. Geophys.Geosyst, 11, Q0AD04, doi:10.1029/2010GC003261.

Ferreira, J.M., M. K. Takeya, J. M. Costa, J. A. M. Moreira, M. Assumpção, J. A. Veloso, and R. G. Pearce (1987), A continuing intraplate earthquake sequence near João Câmara, northeastern Brazil - preliminary results. Review of seismicity and Neogene tectonics, Geophys. Res. Lett., 14, 1042–1045.

Ferreira, J.M., R. T. Oliveira, M. Assumpção, J. A. M. Moreira,R. G. Pearce, and M. K. Takeya (1995), Correlation of seismicity and water level in the Açu reservoir - an example from Northeast Brazil. Bull. Seism. Soc. Am., 85, 1483–1489.

Ferreira, J. M., R. T. Oliveira, M. K. Takeya, and M. Assumpção (1998), Superposition of local and regional stresses in northeast Brazil: evidence from focal mechanisms around the Potiguar basin, Geophys. J. Int., 134, 341-355.

Heidbach, O., M. Tingay, A. Barth, J. Reinecker, D. Kurfeß, and B. Müller (2010), Global crustal stress pattern based on the World Stress Map database release 2008, Tectonophysics, 462, doi:10.1016/j.tecto.2009.1007.1023.

Jaeger, J. C., N. G. W. Cook, and R. W. Zimmerman (2007), Fundamentals of Rock Mechanics, 4th ed., Blackwell, Malden, MA.

King, R. C., R. R. Hillis, M. R. P. Tingay, and A. R. Damit (2010), Present-day stresses in Brunei, NW Borneo: superposition of deltaic and active margin tectonics, Basin Res., 22, 236–247.

Lima, C. C. (2003), Ongoing compression across South American plate: observations, numerical modeling and some implications for petroleum geology, Fracture and in-situ stress characterization of hydrocarbon reservoirs, Geol. Soc., London, 209, 87–100.

Lima, C.C., E. Nascimento, and M. Assumpção (1997), Stress orientation in Brazilian sedimentary basins from breakout analysis - implications for force models in the South American Plate, Geophys. J. Int., 130, 112–124.

Moeck and Backers (2011), Fault reactivation potential as a critical factor during reservoir stimulation, First Break, 29, 73–80,doi: 10.3997/1365-2397.2011014.

Moos, D., P. Peska, T. Finkbeiner, and M. D. Zoback (2003), Comprehensive wellbore stability analysis utilizing quantitative risk assessment, J. Pet. Sci. Eng., 38, 97–110.

Reis, A. F. C. (2012), Orientação e Magnitude de Tensões na Bacia Potiguar: Implicações para evolução de bacias em margens passivas. Dissertação de Mestrado, PPGG-UFRN. Natal-RN, dez 2012.

Sibson, R.H. (1994), An assessment of field evidence for Byerlee friction, Pageophys., 142, 645–662.

Takeya, M.K., J. M. Ferreira, R. G. Pearce, M. Assumpção, J. M. Costa, and C. M. Sophia (1989), The 1986–1989 intraplate earthquake sequence near João Câmara, northeastern Brazil - Evolution of seismicity, Tectonophysics, 167, 117–131.

Tingay, M.R.P., R. R. Hillis, C. K. Morley, R. C. King, R. E. Swarbrick, and A. R. Damit, (2009), Present-day stress and neotectonics of Brunei: implications for petroleum exploration and production. Am. Assoc. Petrol. Geol. Bull., 93, 75–100.

Zoback,M. D. (2007), Reservoir Geomechanics, Cambridge University Press, New York, doi:10.1017/CBO9780511586477.

Zoback, M.D., C. A. Barton, M. Brudy, D. A. Castillo, T. Finkbeiner, B. R. Grollimund, D. B. Moos, P. Peska, C.D. Ward, and D. J. Wiprut (2003), Determination of stress orientation and magnitude in deepwells, Int. J. Rock Mech. Min. Sci., 40, 1049–1076.