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Evidence of hydraulic connectivity across deformation bands from field pumping tests: Two examples from Tucano Basin, NE Brazil

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ABSTRACT

It is assumed that deformation bands may compartmentalize aquifers or hydrocarbon reservoirs because these low-permeability structures may behave as barriers to fluid flow. To address the question whether there is, at a reservoir scale, hydraulic connectivity across a damage zone dominated by cataclastic deformation bands, we present results of two pumping tests carried out in a fluvial-deltaic phreatic sandstone aquifer from the Ilhas Group at Tucano Basin (NE Brazil) where intense concentration of deformation bands occurs. Both test sites are associated with macroscopic damage zones that are approximately 1 km in length and 15 m thick. In situ permeability measurements show values of 2000 mD for host rock and 0.1 mD for deformation bands. GPR profiles reveal good continuity of the primary sedimentary structures with almost no deformation band vertical offsets (less than 10 cm). The well locations for the pumping tests were chosen so that the damage zone is located between pumping and monitoring wells. Pumping tests in both cases revealed hydraulic connectivity across the damage zone since the observed stationary drawdown at monitoring wells was a considerable fraction of the drawdown observed in the pumped well. In one experiment using eight monitoring wells the drawdown cone is evolving through the damage zone instead of contouring it. Local deviations in the natural groundwater flow allow to say that the damage zone dimensions are quite large both in horizontal and vertical directions compared to the distances among the wells. The interpretation of all experimental results is that deformation bands do not fully compartmentalize the aquifer. Generalization of this result to hydrocarbon reservoirs has to take into account capillary effects which are not present in the studied case.

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1. Introduction

Deformation bands (Aydin, 1978; Antonellini and Aydin, 1994) are one kind of frictional deformation structures found in the uppermost Earth's crust. They may be defined as tabular structures of finite width resulting from strain localization commonly found in very porous (15–25% of porosity) granular material such as sandstones. Commonly, deformation bands exhibit localized porosity reduction that lack shear offset (Du Bernard et al., 2002). Based on microstructural analysis, Antonellini et al. (1994) classified the deformations bands in three main groups: (i) deformation bands without cataclasis: characterized by the almost complete lack of crushed grains. They can exhibit positive or negative volume variation; (ii) deformation bands with cataclasis: characterized by intense grain size and volume reduction, and (iii) deformation bands with clay smearing or localized shear zones. For a comprehensive review on deformation bands see Fossen et al. (2007).

Deformation bands are thought to baffle fluid flow during oil production (e.g. Knipe et al., 1997; Gibson, 1994) and to act as seal for hydrocarbon accumulations (e.g. Ogilvie and Glover, 2001) because they tend to have lower permeability than their host rock (e.g., Pittman, 1981; Jamison and Stearns, 1982; Antonellini and Aydin, 1994; Knipe et al., 1997; Gibson, 1994; Fisher and Knipe, 2001; Lothe et al., 2002; Shipton et al., 2002). Tindall (2006) argued that when connectivity across deformation bands (or damage zone) is detected it is interpreted that this is due to open joints. However,

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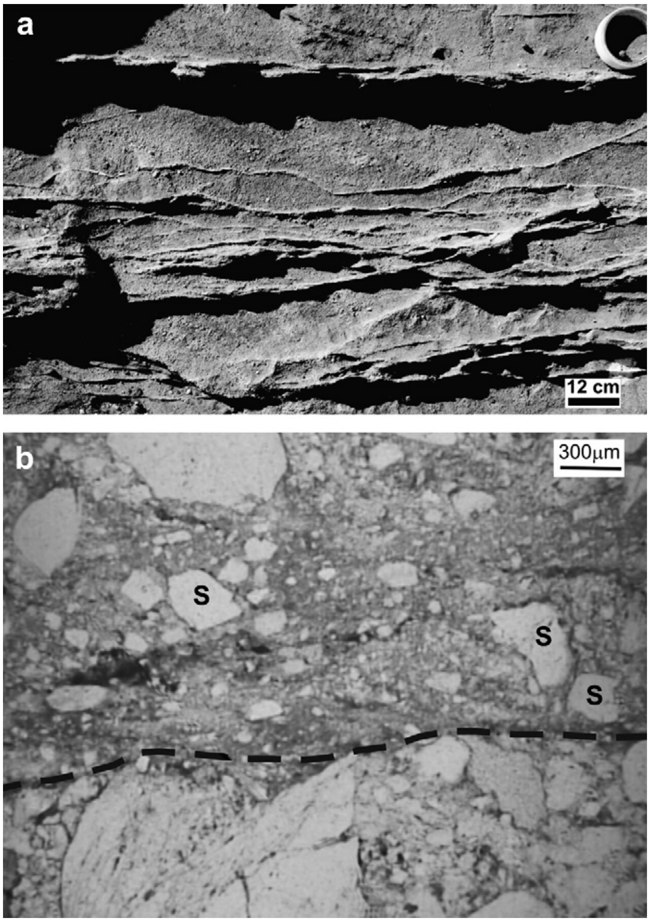

Fig. 1. Deformation bands in outcrops at Site 1: (a) Mesoscopic aspect of the deformation band. Note the positive relieve of the structures due to their greater resistance to erosion. (b) Microscopic view of a deformation band exhibiting evidences of cataclasis. The lower contact is sharper than the upper one and is shown by a dashed line. Note the great reduction of grain size in the tectonic matrix. Some survivor grains (S) are still seen along the deformation band.

Fossen and Bale (2007) suggested that the impact of deformation band on reservoir production is small or negligible in most cases based on observation of paleofluid fronts seen in the field and on mathematical considerations on the average permeability of rocks affected by deformation bands.

In order to address the question whether there is, at a reservoir scale, connectivity across damage zones dominated by deformation bands in porous sandstone, we show here results of two pumping tests of a phreatic sandstone aquifer where intense concentration of deformation bands occur. In both studied sites, because deformation bands are more resistant to erosion than the host rock they show a typical positive relief at the mesoscopic scale (Fig. 1a). Microscopically they are characterized by cataclastic processes with grain size reduction (Fig. 1b). The degree of cataclasis showed by the deformation bands of the Ilhas Group can vary from moderate to high (Alves da Silva et al., 2005). Sometimes they exhibit strong comminution with production of gouge-like material in discontinuous stripes; in other occasions survivor grains can be visualized within a finer tectonic matrix as show in Fig. 1b. The deformations bands limits can be sharp or gradational in respect to the normal sandstone and sometimes one can find both types of limits in the same structure, as also shown in Fig. 1b.

Both test sites are associated to faults with a length of 1 km. The associated damage zones have a thickness of approximately 15 m. As a general rule, the well locations were chosen so that the deformation bands are located between pumping and monitoring wells. We stress that the results of our pumping tests must be interpreted in terms of piezometric head connectivity between the wells and not in terms of mass transfer between them.

We are going to present strong evidence that there is hydraulic connectivity across the deformation bands/damage zones on a reservoir scale. In the following sections we present the regional geographical and geological contexts of the test sites, petrophysical and geophysical characterization of the aquifer sandstone where the tests were performed, description of the pumping tests methodology and their results and finally discussions and conclusions.

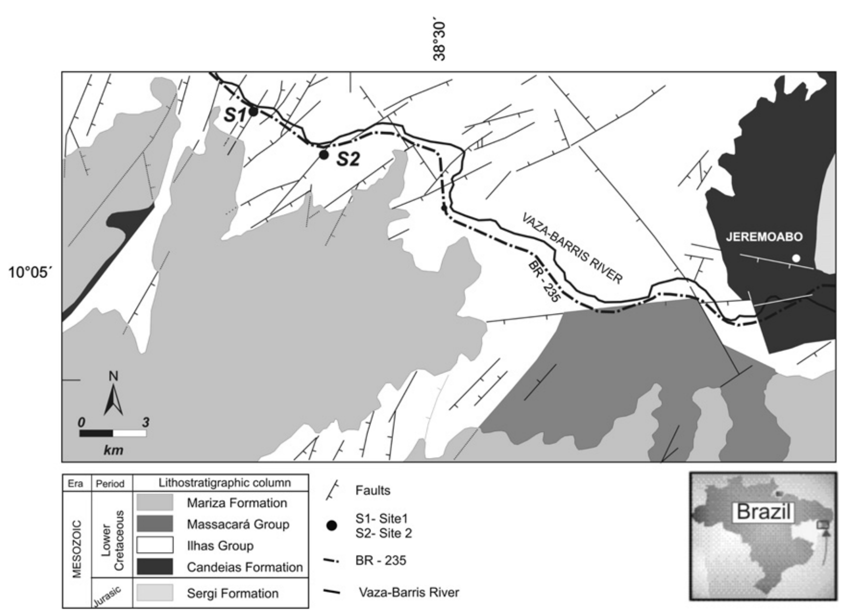

Fig. 2. Geological sketch of Sites 1 and 2 (S1 and S2 respectively) in Tucano Basin, Bahia State, NE Brazil.

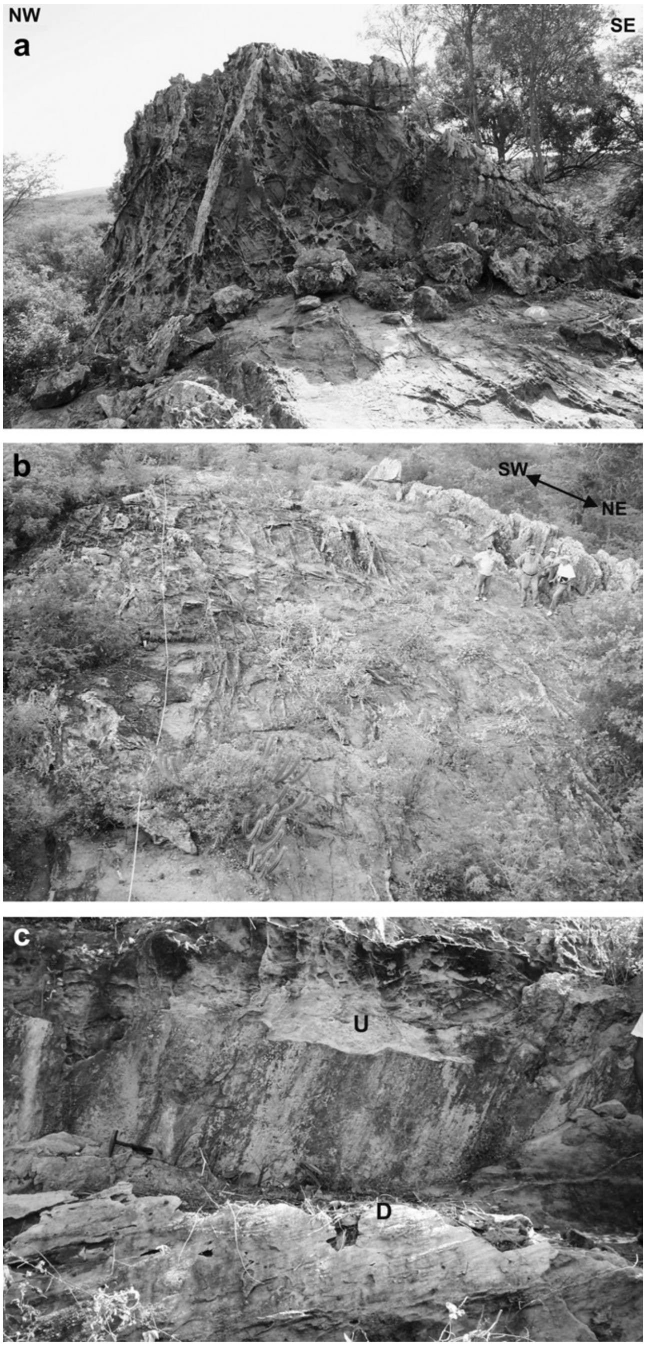

Fig. 3. (a) Outcrop showing deformation bands in different orientations in Site 1. (b) View of the damage zone in the Site 1 showing a swarm of deformation bands. (c) Fault plane with part of the associated damage zone (upper part of the picture) in the Site 2. The hammer handle points towards the North. "U" and "D" identify the foot wall and hanging wall respectively.

2. Tucano Basin, NE-Brazil: geographical and geological contexts

In Tucano Basin (Bahia State, NE Brazil), porous sandstones exhibit abundant deformation bands and related fault outcrops. This basin is the central part of the intracontinental Recôncavo–Tucano–Jatobá rift (RTJ) which is composed by N-S and NE-SW half grabens with upper Jurassic to lower Cretaceous sedimentary infillings. Regionally speaking, the RTJ shows a N–S trend related to the stress field that stretched the continental lithosphere in association to the Gondwana break-up and formation of the South Atlantic Ocean to the east of the rift system (Magnavita and Cupertino, 1987; Magnavita, 1992).

The Tucano Basin is characterized by sets of NS trending normal faults that tilted the sedimentary strata eastward displaying a domino-like structural style (Magnavita and Cupertino, 1987; Magnavita, 1992). The basin sedimentary infillings can be related to distinct tectonic stages: deposition of the Brotas Group (Aliança and Sergi Formations) and the basal portion of the Santo Amaro Group (Itaparica Formation) represent the pre-rift stage whilst deposition of Candeias Formation (Santo Amaro Group), Ilhas and Massacará Groups, and Salvador Formation are associated to the rift phase (Caixeta et al., 1994).

The pumping tests described hereafter were done in sites dominated by the sandstones of the Ilhas Group (Fig. 2). A fluvial-deltaic sedimentation is proposed to this group (Cupertino, 1990). The two chosen sites are located near the south margin of the Vaza-Barris River (Fig. 2). Although the Vaza-Barris River is the main river of the region it is intermittent because the climate in the area is dry. The main rain season usually occurs from May to August.

In outcrops at the studied sites (Fig. 3a–c) the normal faults trend NNE (Fig. 3c) and dip steeply to the ESE (Figs. 3b and 4). In the damage zone of such faults three main sets of deformations bands are intensely developed (Fig. 4).

3. Petrophysical and geophysical characterization of the Ilhas Group sandstone

Because of the excellent visual exposure, Site 1 was chosen for conducting GPR (Ground Penetrating Radar) and in situ permeability measurements. Fig. 5 shows the location of the GPR and permeability measurement profiles. This excellent visual exposure makes Site 1 as a type-outcrop and a lot of care had to be taken to preserve it, thus posing operational problems in particular for well drilling.

Fig. 6 shows a GPR section transverse to the main deformation bands. The survey was done using a 200 MHz antenna connected to a GSSI SIR-System 2. The data processing (Miranda, 2004) was done in such a way to highlight the deformation bands. The GPR processing flow begins with a trace editing to remove anomalous amplitudes and signal sampling errors. Afterwards, a zero-offset correction was done by removing aerial and direct wave arrivals. Then, low frequency electromagnetic induction effects between pairs of antennae were removed with a high-pass band filter. After this preliminary processing spherical and exponential correction together with spectral balancing were applied to the traces to restore amplitude and frequency content due to attenuation (Xavier Neto and Medeiros, 2006). Because noise content is also enhanced in this operation, a low-pass filter was applied. Finally, migration and topographic correction was done.

In Fig. 6, we interpret the abundant white subvertical stripes as deformation bands. We indicate some of them by a black ellipsis. We think this interpretation is correct based on two facts: (i) correlation between scan line and GPR profile (Miranda, 2004) and (ii) grain reduction associated to deformation band would change porosity and water adsorption thus changing the GPR response. Note that despite the pervasiveness of the interpreted deformation bands they are poorly interconnected evidencing that the undamaged portion of the sandstone remains interconnected regardless the presence of a complex set of deformation bands. Additionally, the GPR section reveals good continuity of the primary sedimentary structures showing that there is almost no vertical offset of the deformation bands. These two observations are corroborated by field data. We are confident that if we show this section to an interpreter without telling him/her

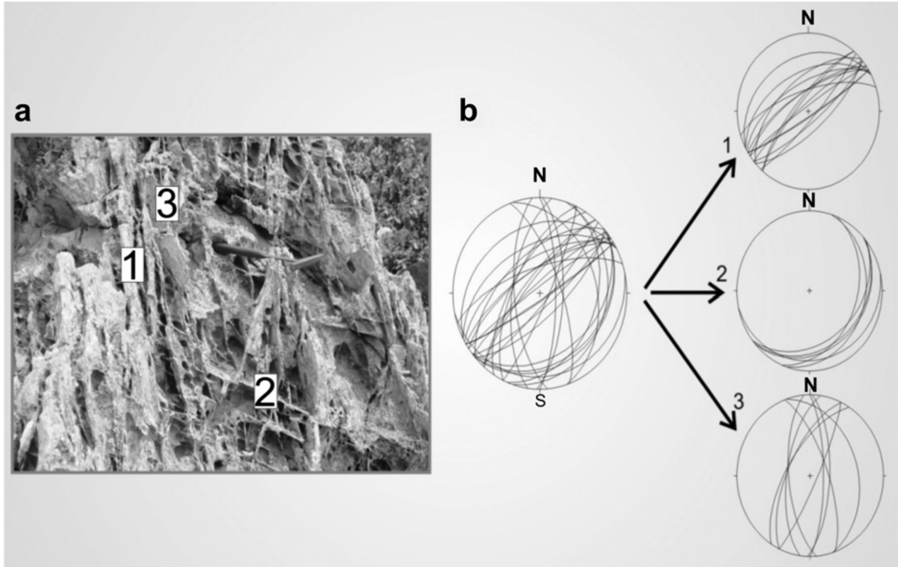

Fig. 4. (a) Photo and (b) stereograms showing the three main sets of deformation bands in Site 1. Two sets are subvertical (1 and 3) and the other one (2) is subhorizontal. The hammer points towards the North.

about the presence of the deformation bands, chances are that the interpreter would not infer these deformation bands. The difficulty to image the deformation bands was quite surprising for us since we expected they would have a higher impact in the image. Probably, the reason for that is twofold: (1) the deformation bands are dominantly subvertical with no offset and (2) they occur in rocks of the same lithology. Certainly a similar effect occurs with seismic data in reservoir scale. If that is the case, conventional processing and/or interpreting seismic data would not

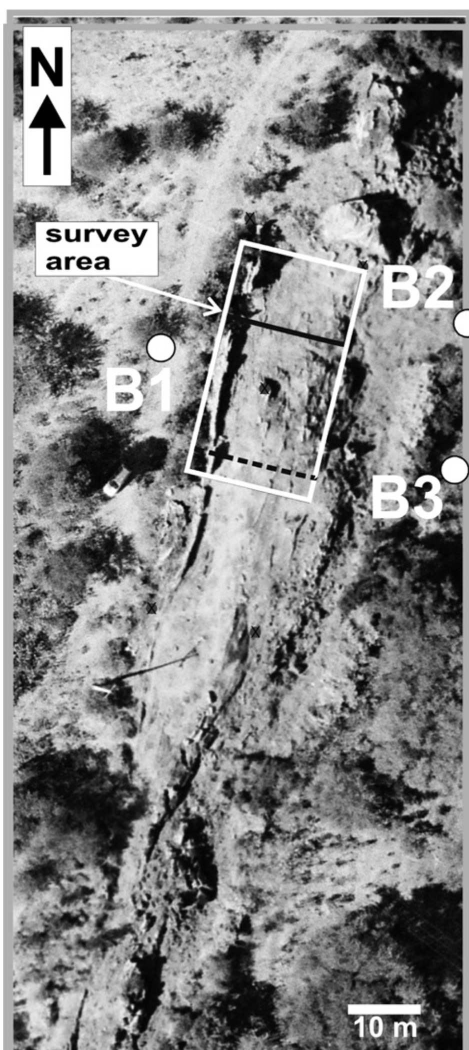

Fig. 5. Aerial photo of Site 1 showing the location of the GPR and permeability measurement profiles (continuous and dashed black lines, respectively) and pumping well locations (B1, B2 and B3).

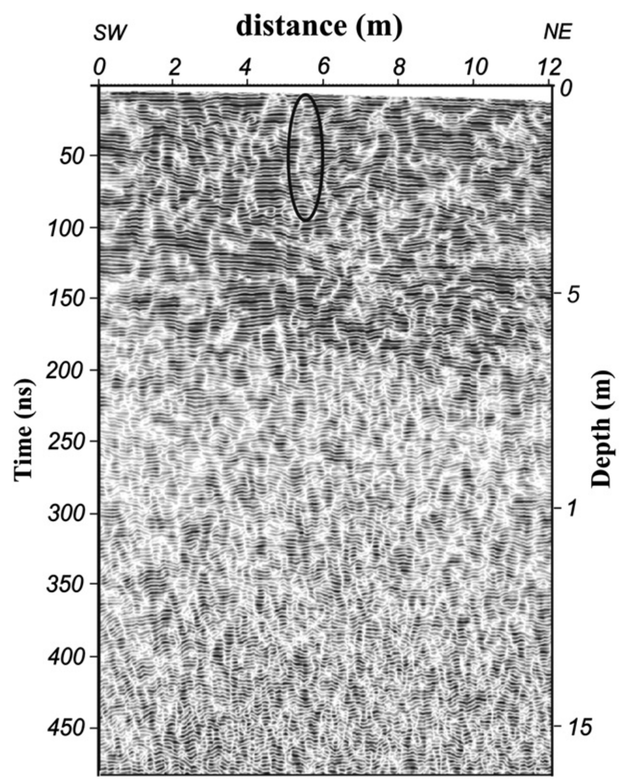

Fig. 6. Ground Penetrating Radar section (200 MHz) transverse to the deformation bands in Site 1. Pervasive white stripes are interpreted as deformation bands, as shown by the black ellipsis.

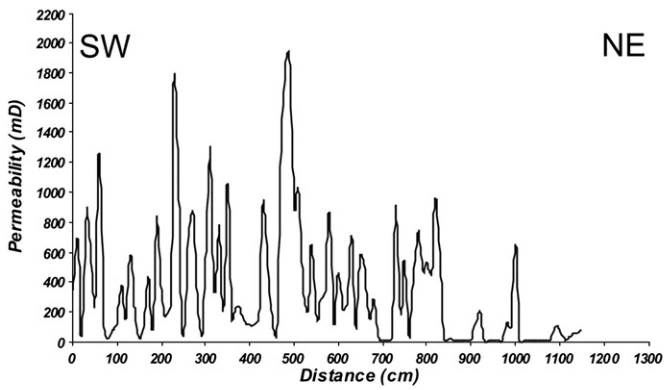

Fig. 7. Scan line of in situ permeability measurements transverse to the deformation bands in Site 1.

straightforwardly identify deformation bands. Therefore, even when their presence is suspected, the impact of the deformation bands in seismic data would potentially be better evaluated with very specific data processing maybe similar to fracture and joint detection (e.g. Liu et al., 2005).

In situ permeability measurements were done using a portable PPP-250 minipermeameter from Core Laboratories Company. The working principle of this device is based on the diffusion of an air pulse injected into the rock (Goggin et al., 1988). According to Antonellini and Aydin (1994) the sampled rock volume with this device is about $5\pi r^3$ where r is the radius of the cylinder (gun) from where the air pulse is injected. In our case, this volume is around 0.25 cm^3. To assure reliability of the measurements, we checked regularly the device using a ceramic sample with known permeability provided by the manufacturer. For example, in one of these tests, the known value of 7.5 mD of the ceramic sample was reproduced with average 7.43 mD and standard deviation 0.39 mD after 100 measurements. During the permeability measurements on the rock, approximately one check of the device with the ceramic sample was done at every 30 measurements. Fig. 7 shows a typical permeability scan line measurement transverse to the deformation bands. The location of the scan line is shown in Fig. 5. Before measurements the rock surface was prepared to remove a thin weathering layer and to allow better coupling between the minipermeameter and the rock surface. Permeability measurements on the rock surface were done at every 0.2 m and every value shown in Fig. 7 is the mean of three measurements done in the same point. The high values of permeability (up to 2000 mD) are associated to the host rock whilst low values (down to 0.1 mD) are associated to deformation bands. The high variability (up to four orders of magnitude) revels that a single scan line crosses many deformation bands at this scale.

4. Pumping tests

4.1. Site 1

Site 1 exhibits an excellent visual exposure of deformation bands, especially on the horizontal cross section (Fig. 3b). Because two dominant sets of deformation bands in the area are subvertical (Fig. 4), the outcrop floor shows the horizontal cuts of the deformation bands revealing a great amount of their intersections and complexity (Fig. 3a, b). However, the wall of the main deformation band (fault?) is not visible so that subvertical offsets could not be measured and/or inferred. Judging also from the GPR data, there is no significant vertical offset.

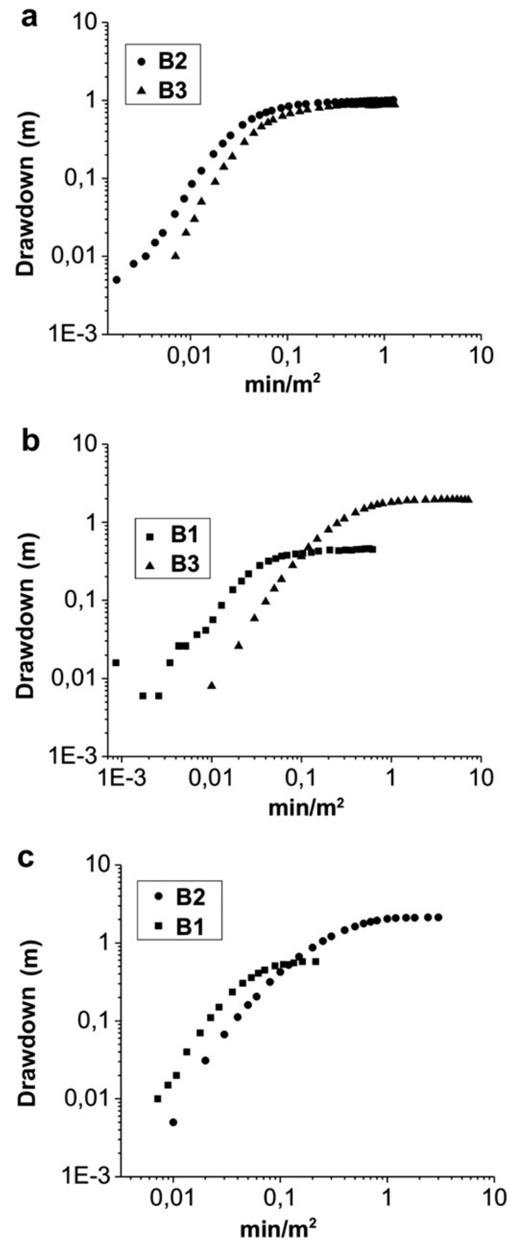

Fig. 8. Observed drawdown curves for pumping tests in Site 1. (a) At B2 and B3 when pumping from B1. (b) At B1 and B3 when pumping from B2. (c) At B1 and B2 when pumping from B3.

Three wells were drilled around Site 1 (B1, B2 and B3 in Fig. 5). All three wells were drilled and cased in the same manner so that any of them could either be used to pump water from or to measure the drawdown. The wells are 30 m long and are cased with 6'' diameter steel tubes. The steel casing is hydraulically opened from 12 to 28 m deep so that filters could be installed in this depth range. The remaining parts of the wells are not connected to the aquifer.

Static water levels were measured in all three wells. They were the same within 0.2 m. This difference is due to the natural piezometric head. The local topography is flat (maximum difference of 0.4 m) and the water table is in average 7 m deep. From the hydrogeological view point, the aquifer in the area may be assumed as phreatic.

All pumping tests were done in December 2005 (the dry season in the area) using the same equipment, technical team and following similar procedures. While one of the wells was pumped,

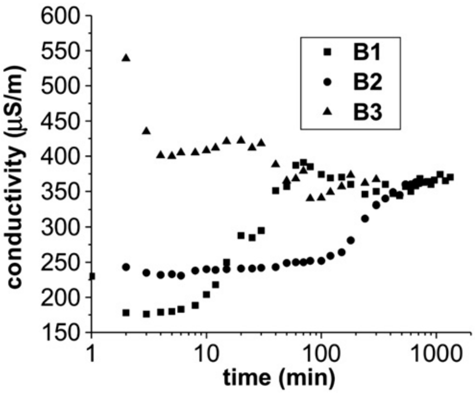

Fig. 9. Electrical conductivity measurements of the waste water from tests in Site 1.

the observed drawdowns in all three wells were monitored. All drawndown measurements were done with either automatic or manual level loggers. Three constant flow rates of 1.60, 1.13 and 1.38 m^3/h were used during the tests for B1, B2 and B3, respectively. These values were determined with pre-tests in order to attain stationary conditions. B1 and B2 were pumped during 24 and 12 h followed by 12 and 6 h, respectively, of recovery in order to reestablish the natural piezometric head. The pumping test from B3 was scheduled to occur in the same manner as pumping test from B2 but due to operational problems, the test was interrupted after 6 h of pumping and the piezometric head reestablishment was not achieved. Adequate disposal of the waste water was done in order to avoid its influence on the aquifer recharge.

Results of the pumping tests for each pair of monitoring wells are shown in Fig. 8a–c (Alves da Silva and Destro, 2008). Each of these figures shows the drawdown measured in the two monitoring wells while pumping from a third one. As usual, the x-axis variable in each of these plots is expressed as [time/distance^2] in order to take into account the combined effect of pumping time and distance between pairs of pumping and observation wells (de Marsily, 1986). In addition, the maximum drawdowns observed in the pumping wells were 14.0, 6.5, and 16.5 m when pumping from B1, B2, and B3, respectively.

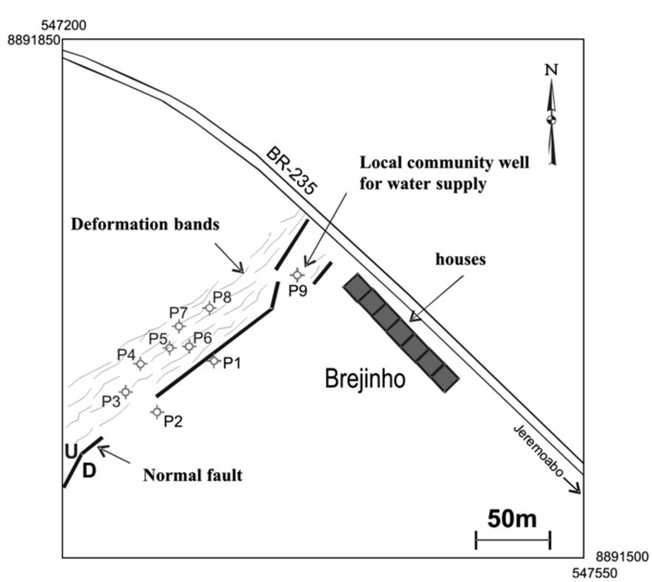

Fig. 10. Sketch map of Site 2 showing fault and damage zone, the Brejinho village and the well locations (P1–P9). "U" and "D" identify the foot wall and hanging wall, respectively.

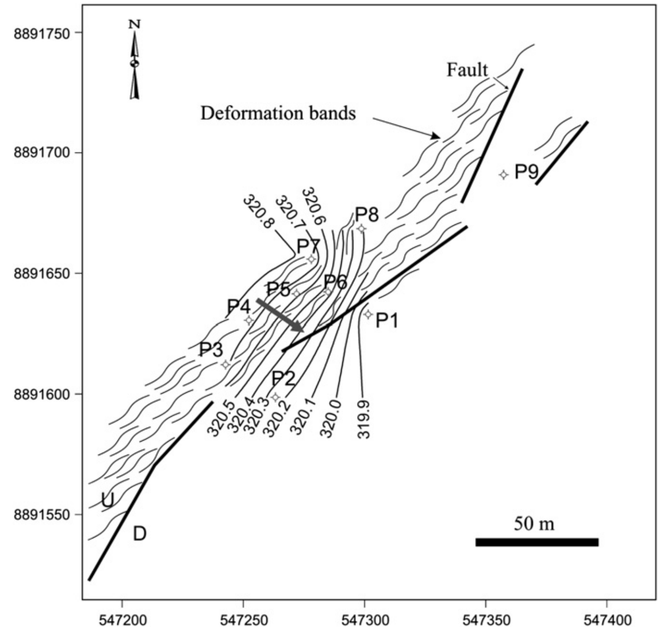

Fig. 11. Natural piezometric head (cm) in Site 2. Black arrow shows the inferred main direction for the groundwater flow. "U" and "D" identify the foot wall and hanging wall, respectively.

According to local farmers, similar wells typically show yields higher (~40 m^3/h) than the ones obtained in our tests. This fact reveals that the macroscopic values of the permeability and transmissivity of the aquifer at the test site are relatively low because of the presence of the deformation bands. Fig. 8a–c reveals hydraulic connectivity across the damage zone since the observed stationary drawdowns at monitoring wells were considerable fractions of the drawdowns observed in each pumped well.

In all pumping tests, samples of the waste water were collected in order to measure their electric conductivity. Fig. 9 shows in a single plot these values measured in the three different tests (Alves da Silva and Destro, 2008). It is important to bear in mind that these measurements were not simultaneous and the time in the *x*-axis refers to the pumping interval time in each test.

Fig. 9 shows that the initial values for water conductivity are quite different for the three wells. However, as pumping continues, there is a tendency that water electric conductivity values reach a common value around 360 µS/m. We give below an interpretation of this fact based on simple fluid flow simulation in an equivalent isotropic homogeneous aquifer with similar flow rates as those obtained in the pumping tests. This simulation reveals that fluid particle motion near the pumping wells are limited to a radial distance of about 3 m after 24 h of pumping. Thus, given that after

Table 1
Information about the pumping tests in Site 2.

Pumping well	Flow rate (m^3/h)	Pumping time (h)	Time to reestablish the natural piezometric head	Monitoring wells during pumping time	Monitoring wells measuring the time to re-establish the natural piezometric head
P1	5.45	48	24 h	All wells including P1	P2, P3, P4, P6, P7 and P8
P2	6.14	24	Ranging from 1 h 40 min to 2 h	All wells including P2	P1, P3, P4, P5, P6 and P8
P5	4.64	24	10 h	All wells including P5	P1, P3, P4, P7 and P8

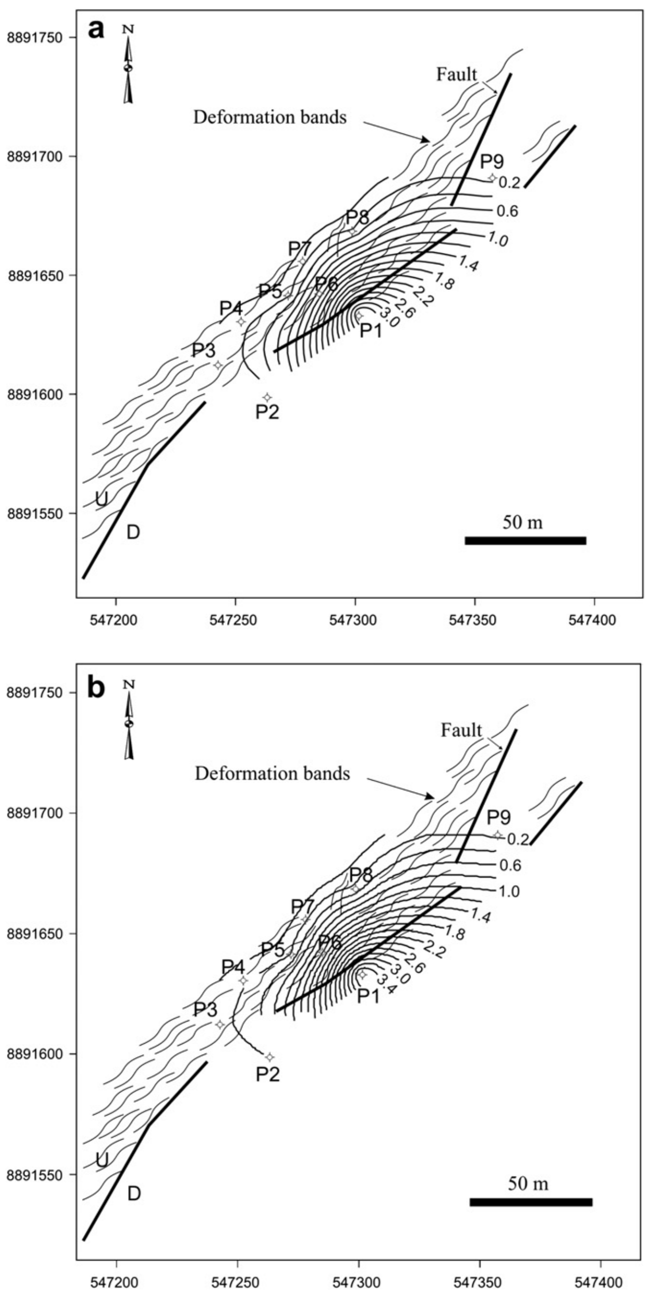

Fig. 12. Piezometric head maps (m) after 24 (a) and 48 h (b) of pumping from P1 in Site 2. "U" and "D" identify the foot wall and hanging wall respectively.

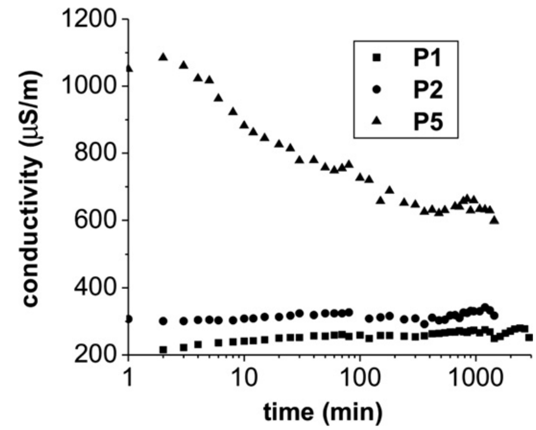

Fig. 13. Electrical conductivity measurements of the waste water from tests in Site 2.

24 h of pumping the water electric conductivity reaches the same value (~360 μS/m), a volume of around 3^3 m^3 is a fair estimate of the representative elementary volume (REV) for the entire aquifer. Note that this REV is much larger than the usual values for homogeneous and isotropic aquifers (~10^{-3} m^3). So, this is evidence that there is difficulty for water circulation and mixing inside the aquifer due to the presence of the deformation bands and the REV is comparatively larger to take into account the high heterogeneity due to the deformation bands.

Pumping test results from Site 1 suggest that deformation bands do not fully compartmentalize the aquifer. Some issues may be raised regarding this result:

1. At a meso-scale, the fault zone (and consequently its damage zone) is not exposed 100 m away (northwards) from the wells (Fig. 5). If the outcrop absence represents a termination of the damage zone, where the intensity of the deformation band is expected to diminish, the piezometric head connection between pairs of wells in each side of the damage zone would occur by contouring this termination. Because physical integrity of Site 1 was a major constraint, we could not drill wells between B1 and B2 in order to monitor the drawdown cone evolution so that this possibility could not be ruled out in this test.
2. The damage zone could have a small vertical extent when compared with its horizontal dimension. Therefore, analogously to the previous issue, piezometric head connectivity would occur by contouring the hypothetical in-depth vertical termination.
3. And isolated macroscopic subvertical fracture transverse to the deformation bands was observed thus posing the possibility that the observed piezometric head connectivity could be due to (or enhanced by) this fracture.

Because these issues could not be addressed with the pumping tests in Site 1, we decided to choose another site, for a second test, carefully selected in order to honour two additional criteria in relation to Site 1: (i) fracture absence at least from a visual inspection view point in the site of the new test, and (ii) possibility to drill a group of wells so that the cone of depression could be better monitored and we could be more confident that the drawdown is evolving through the damage zone instead of contouring it. Site 2 (Fig. 2) fits both additional criteria above described. Regarding the vertical dimension issue we raised above, we can assert for now that the likelihood of this being the dominant factor in two tests is reduced.

4.2. Site 2

Eight vertical wells were drilled on Site 2 (P1–P8 in Fig. 10). In addition, a pre-existing well (P9) that supplies water for the local Brejinho community was used as a monitoring well. Wells P1–P8 were drilled in the same manner with depths ranging from 30 to 35 m and only P1, P2 and P5 were fully cased with a 4½" diameter PVC tube because they were chosen to be pumping wells. The remaining ones, used only for drawdown monitoring, were cased only on their top 5 m to avoid collapse. PVC tubes in P1, P2 and P5 were open from approximately 15 to 27 m to allow hydraulic connectivity to the aquifer. Regarding P9, unfortunately no information on how this well was drilled and constructed was available.

All pumping tests were done using the same equipment, technical team and following similar procedures to those described in

Site 1. All tests were done in January 2007 still within the dry season in order to maintain natural conditions similar to those at the time of the tests in Site 1. The natural piezometric head is shown in Fig. 11. One can observe that the piezometric head gradients are small (around 1.6 cm/m) and that the main natural water flux is towards the ESE direction. There are, however, important deviations in direction resembling wave refraction, indicating that the fault zone is large both in horizontal and vertical directions. As consequence, the issue 3 raised above may be ruled out. The water table static level is nearly the same as that found in Site 1, which corroborates the hypothesis that a phreatic aquifer model is valid in the region.

Table 1 shows pumping test information that has been gathered. As in the previous tests in Site 1, adequate disposal of the waste water was done. Despite the fact the flow rates are around four times greater than those obtained from tests in Site 1, they are still small when compared to typical yields in the region. For the sake of clarity, we are presenting piezometric head maps after 24 and 48 h of pumping from P1 only (Fig. 12a, b); results obtained when pumping from P2 and P5 are similar.

Both piezometric head maps in Fig. 12a, b show that the drawdown cone is indeed evolving through the damage zone instead of contouring it. Moreover, the drawdown cone shapes reveal the presence of a highly anisotropic structure. For instance, in Fig. 12b, after 48 h of pumping from P1, the isovalue line of 0.2 m reaches P5 and P9 despite the fact that the distance from P1 to P9 is more than twice the distance from P1 to P5. Since P1 and P9 are at the same side of the fault/damage zone, this is consistent with our expectation that the drawdown cone will reach more easily P9 for a given value of drawdown.

As in previous tests in Site 1, samples of the waste water were collected in order to measure their electric conductivity (Fig. 13). Regarding the measurements of electrical conductivity of the waste water, the observation time was not enough to draw similar conclusions to those described for the pumping tests in Site 1. However, the fact that the initial values for the water electrical conductivity observed in different wells may be different is also valid here. If the hypothesis we raised about the local fluid mobility around the pumped wells is correct, we could say that for the case of Site 2, the mobility is far less than the one inferred from the data in Site 1. In fact, if convergence to a single background level of electrical conductivity is to be attained in Site 2, the estimated pumping time is 10^6 min (approximately 2 years).

5. Discussion and conclusion

Regarding the confidence of the assertion that deformation bands/damage zones do not fully compartmentalize the aquifer, results from Site 2 fulfill some aspects that remained open after tests in Site 1. These open aspects are associated to the finiteness (compared to the distances among wells) either in horizontal or vertical dimension of the damage zones and also to the presence of open fractures. Results from Site 2 show that the drawdown is indeed evolving through the damage zone and is not contouring it. Additionally, local deviations in the natural groundwater flow are consistent with the fact that the vertical dimensions of the damage zone are large compared to the distances among wells. Finally, from field observations, there are no open fractures in Site 2.

We stress that the main strength of our results is that they are based on real tests where the pumped aquifer is at a similar scale of an oil reservoir. We are aware that in any real test it is impossible to have control in all aspects that eventually may influence the results. Additionally, in aquifers, capillary effects are not important whilst in hydrocarbon reservoir they play an important role on compartmentalization. For a comprehensive discussion on the effects of capillary pressure in sandstones containing deformation bands, please see Fossen and Bale (2007) and references therein.

The conclusion that deformation bands/damage zones do not fully compartmentalize the studied aquifer is supported by the inspection of the geometry of these structures. It is our experience that analysis of deformation bands from aerial photos, outcrops, GPR images and thin sections evidence that individually such structures present terminations in all scales although the dimension of a group of these structures may continue and be quite larger than individual structures. In other words, the undamaged portion of the sandstone remains three-dimensionally interconnected regardless the presence of an intricate set of deformation bands. Thus, a 'percolation core' of the undamaged reservoir rock is preserved allowing at least partial hydraulic connection through it. In fact, the hydraulic connection through the 'percolation core' of the undamaged rock is clear from the fluid flow simulation results presented by Lunn et al. (2008). As Lunn et al. (2008) state: '… it is the connected nature of highly tortuous high-permeability pathways that governs the bulk hydraulic properties of the fault zone'. Our main results are also in agreement with Fossen and Bale (2007) suggestion that deformation bands may not influence fluid flow in a production setting because, among other reasons, these structures may present low connectivity so that fluids are free to flow around and between bands. In this aspect, the deformation bands here play a similar role to faults that despite their local sealing nature may not fully compartmentalize a reservoir as demonstrated by Medeiros et al. (2007) for the case of a carbonate reservoir.

Nonetheless the above arguments concerning the possible general validity of our results, we are aware that at the moment they are limited to the case of cataclastic deformation bands occurring in sandstones of fluvial-deltaic origin, which is the case of the studied Ilhas Group sandstone. We propose that tests in aquifers containing deformation bands of other types should be carried out to verify if similar results are found.

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References

Alves da Silva, F.C., Destro, N., 2008. Falhas e fraturas naturais: aplicações na caracterização de reservatórios. UFRN/FINEP/Petrobras. Petrobras Internal Report No. 650-29397, 276 pp. (in Portuguese).

Alves da Silva, F.C., Ferreira, T.S., Costa, P.R.C., Guedes, I.M.G., Jardim de Sá, E.F., 2005. Aspectos microtexturais, geométricos e mecanismos de deformação de bandas de deformação e fraturas em arenitos porosos da bacia de Tucano (BA): influência na circulação de fluidos. In: XXI Simpósio de Geologia do Nordeste, Recife, 2005, Resumos Expandidos, pp. 194–198 (in Portuguese).

Antonellini, M.A., Aydin, A., 1994. Effect of faulting on fluid flow in porous sandstones: petrophysical properties. American Association of Petroleum Geologists Bulletin 78, 355–377.
Antonellini, M.A., Aydin, A., Pollard, D.D., 1994. Petrophysical study of fault in sandstone using petrographic image analysis and X-ray computerized tomography. Pure and Applied Geophysics 143, 181–201.
Aydin, A., 1978. Small faults formed as deformation bands in sandstone. Pure and Applied Geophysics 116, 913–929.
Caixeta, J.M., Bueno, G.V., Magnavita, L.P., Feijó, F.J., 1994. Bacias do Recôncavo, Tucano e Jatobá. Boletim de Geociências da Petrobras 8, 163–172 (in Portuguese).
Cupertino, J.A., 1990. Estágio Exploratório das Bacias do Tucano Central, Norte e Jatobá. Boletim de Geociências da Petrobras 4, 45–54 (in Portuguese).
de Marsily, G., 1986. Quantitative Hydrology. Academic Press, New York.
Du Bernard, X., Eichhubl, P., Aydin, A., 2002. Dilation bands: A new form of localized failure in granular media. Geophysical Research Letters 29, 2176. doi:10.1029/2002GL015966.
Fisher, Q.J., Knipe, R.J., 2001. The permeability of faults within siliciclastic petroleum reservoirs of the North Sea and Norwegian continental shelf. Marine and Petroleum Geology 18, 1063–1081.
Fossen, H., Bale, A., 2007. Deformation bands and their influence on fluid flow. American Association of Petroleum Geologists Bulletin 91, 1685–1700.
Fossen, H., Schultz, R.A., Shipton, Z.K., Mair, K., 2007. Deformation bands in sandstone – a review. Journal of the Geological Society 164, 755–769.
Gibson, R.G., 1994. Fault-zone seals in siliciclatic strata of the Columbus Basin, offshore Trinidad. American Association of Petroleum Geologists Bulletin 78, 1372–1385.
Goggin, D.J., Thrasher, R.L., Lake, L.W., 1988. A theoretical and experimental analysis of minipermeameter response including gas slippage and high velocity flow effects. In situ 12, 79–116.
Jamison, W.R., Stearns, D.W., 1982. Tectonic deformation of Wingate Sandstone, Colorado National Monument. American Association of Petroleum Geologists Bulletin 66, 2584–2608.
Knipe, R.J., Fisher, Q.J., Clennell, M.R., Farmer, A.B., Harrison, A.B., Kidd, B., McAllister, E., Porter, J.R., White, E.A., 1997. Seal analysis: successful methodologies, application and future directions. In: Møller-Pedersen, P., Koestler, A.G. (Eds.), Hydrocarbon Seals: Importance for Exploration and Production. Norwegian Petroleum Society (NPF) Special Publication 7, pp. 15–40.
Liu, E., Chapman, M., Hudson, J.A., Tod, S.R., Maultzsch, S., Li, X.Y., 2005. Quantitative determination of hydraulic properties of fractured rock using seismic techniques. Geological Society Special Publications 249, 29–42.
Lothe, A.E., Gabrielsen, R.H., Bjørnevoll-Hagen, N., Larsen, B.T., 2002. An experimental study of the texture of deformation bands: effects on the porosity and permeability of sandstones. Petroleum Geoscience 8, 195–207.
Lunn, R.J., Shipton, Z.K., Bright, A.M., 2008. How can we improve estimates of bulk fault zone hydraulic properties? In: Wibberley, C.A.J., Kurz, W., Imber, J., Holdsworth, R.E., Collettini, C. (Eds.), The Internal Structure of Fault Zones: Implications for Mechanical and Fluid-Flow Properties Geological Society, London, Special Publication, 299.
Magnavita, L.P., Cupertino, J.A., 1987. Concepção atual sobre as bacias do Tucano e Jatobá, Jatobá, Nordeste do Brasil. Boletim de Geociências da Petrobras 1, 119–134 (in Portuguese).
Magnavita, L.P., 1992. Geometry and kinematics of the Recôncavo–Tucano–Jatobá rift. NE Brazil. PhD thesis, University of Oxford.
Medeiros, W.E., Nascimento, A.F., do Antunes, A.F., Jardim de Sá, E.F., Lima Neto, F.F., 2007. Spatial pressure compartmentalization in faulted reservoirs as a consequence of fault connectivity: a fluid flow modelling perspective, Xaréu oil field, NE Brazil. Petroleum Geoscience 13, 341–352.
Miranda, H.C.B., 2004. Interpretação conjunta de dados de GPR e medidas de permeabilidade sobre um análogo de reservatório siliciclástico falhado na Bacia de Tucano. NE do Brasil. Universidade Federal do Rio Grande do Norte, MSc Thesis, in Portuguese.
Ogilvie, S.R., Glover, P.W.J., 2001. The petrophysical properties of deformation bands in relation to their microstructure. Earth and Planetary Science Letters 193, 129–142.
Pittman, E.D., 1981. Effect of fault-related granulation on porosity and permeability of quartz sandstones, Simpson Group (Ordovician), Oklahoma. American Association of Petroleum Geologists Bulletin 65, 2381–2387.
Shipton, Z.K., Evans, J.P., Robeson, K., Forster, C.B., Snelgrove, S., 2002. Structural heterogeneity and permeability in faulted aeolian sandstone: implications for subsurface modelling of faults. American Association of Petroleum Geologists Bulletin 86, 863–883.
Tindall, S.E., 2006. Jointed deformation bands may not compartmentalize reservoirs. American Association of Petroleum Geologists Bulletin 90, 177–192.
Xavier Neto, P., Medeiros, W.E., 2006. A practical approach to correct attenuation effects in GPR data. Journal of Applied Geophysics 59, 140–151.