Structural Analysis of a Core on Fractured Carbonate Reservoir, Brazil: Implications for Exploration and Reservoir Modeling*

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Abstract

Fractured Albian carbonate reservoirs, localized along eastern Brazilian marginal basins, have proven to contain important hydrocarbon reserves. The purpose of this paper is to discuss the structural analysis carried out on a selected oriented core, and its application for exploring and modeling fractured reservoirs. Attributes of fractures and faults measured on the core were correlated with depositional sequences, facies, and other petrophysical properties. We observe that the most deformed facies are mechanically soft, porous laminated mudstones. We suggest that this occurs due to flexural slip. We suggest that a clear, positive correlation between fracture density and some petrophysical parameters occurs when deformation results from wider wavelength structures in relation to thickness, like large folds.

Nevertheless, this correlation is not so obvious when restricted fault-related deformation occurs. Like sub-seismic faults, flexural slip zones are virtually undetectable by seismic imaging, and may connect different structural levels in the reservoir. The detachment horizons may also represent a decouple between distinct mechanical layers, and hence a boundary between zones with distinct stress axis orientation. It could be expected that in this case, the fracture systems could have distinct hydraulic properties from the decouple surface.

Introduction

Carbonate hydrocarbon reservoirs play an important role in storage and production of worldwide reserves. These reservoirs are frequently fractured, due to the more fragile rheology of carbonate rocks during deformation in upper crustal conditions. These rocks are also affected earlier by diagenetic events (e.g. recurrent dissolution and cementation), which can significantly change the hydraulic and mechanical characteristics of the system with time (Olson et al., 2007; see also Hesthammer et al., 2002). Hence the distribution of fractures in these rocks, although influenced by other factors such as composition, grain size, layer thickness, strain rate, structural position, depends upon the kind of chemical transformations they have suffered throughout their diagenetic history, in relation to the timing of deformation (see Nelson, 2001). The relative higher chemical mobility of these rocks leads to an additional complexity to the usual structural and geomechanical modeling, as it considers the diagenesis as a controlling factor of hydraulic characteristics of the system (Laubach, 2003).

The distribution of fractures and faults on rocks is heterogeneous and interdependent at a certain extent (Price and Cosgrove, 1991; Shipton and Cowie, 2003; Ortega et al., 2006; Micarelli et al., 2006) because faults control a fraction of the fracturing amount in most areas. The detection of faults is also critical in modeling the hydraulic behavior of fracture networks in reservoirs, because only larger structures are imaged by seismic data and much of the discontinuities may remain undetected. In this paper we shall present a description of the structure in an oriented core which reached the carbonate Albian reservoirs in the Campos Basin. We shall present and discuss the correlations between pattern of fracturing and petrophysical, seismic and compositional attributes. We also discuss the possible relations of the described fracture pattern with the proposed evolution for rift tectonics in the basin.

Fracture Distribution and Structure of the Studied Core

The core presents many types of structures such as joints and shear fractures (faults), brecciated zones, tension gashes and stylolites. Most fracture fillings are generally calcite. Some are filled by clay. Aperture values tend to increase because of decompression during the coring process. Some joints have vugs that may have been formed by calcite cement dissolution or by incomplete filling of large extensional fractures. Some vugs seem to be partially filled cavities as they have idiomorphic calcite crystals (semi-open fractures). Several vugs are filled with oil. The observed faults or shear fractures are straight or curved surfaces. Tension gashes occur sometimes associated with the faults. Stylolites are typical structures. Normally they are welded by clay films, but in some cases were found open with traces of oil. Horizontal and vertical stylolites were observed associated with the fractures. Slicks on the bedding planes are present at a specific stratigraphic level, restricted to the upper portion of the core interval in the laminated mudstones. Their direction is NNW-SSE.

The microstructural analysis evaluated the relations between the tectonic features, diagenesis and the migration of hydrocarbon, and determined the existence of a main cementing event followed by a partial dissolution and porosity production. Most of fracture planes are filled with carbonate (calcite) cement, with no evidence of dissolution. The cement fills the fractures totally or partially, constituting an important seal and damaging the connectivity among the fracture sets. In this context, planes are predominantly oriented to N60E/60NW (330/60°). The second context exhibits fracture planes also filled with carbonate cement, but dissolution features may be observed. The dissolution and production of secondary porosity occurs mostly in the fault plane edge. These fault planes, showing evidence of carbonate cement dissolution, tend to be oriented N27E/77NW (297/77°). The third context shows fractures with no occurrence of carbonate cement. In some cases, movement can be characterized (shear features), re-orienting and disrupting small grains due to small relative displacement between the fault walls. In this context, hydrocarbon filling was not observed, suggesting that the described fracture was nucleated after the hydrocarbon migration. This type of fracture tends to be oriented according to the direction N-S, dipping either to the east or to the west.

Fracture Parameters

The structural data obtained from the core analysis were presented as curves of fracture parameters, such as density, aperture and spacing. The data were compared with the data from conventional logging and from dynamic rigidity (Young modulus). Therefore, we intend to compare the special distribution of the parameters along the core interval, draw correlations with the described lithofacies and the well logs, and determine the main mechanical units.

Between 4049 m and 4100 m there are two grainstone intervals separated by a layers of packstone and wackestone. An interval between 4053.5 m and 4063.9 m was lost, probably due to the presence of very porous oolitical grainstones, similar to the beds containing oil found immediately below (Figure 1). From 4049 m packstone and wackestone intercalations occur again, with a tendency of thinning upwards up to 4035m. From this depth upward, fine grained facies are predominant (mudstones). The mudstones at this level are generally laminated. This facies corresponds to the base of the Middle Albian sequence. The remaining intervals below the laminated mudstones belong to the Lower Albian sequence (Figure 1).

The grainstones seem to contain fewer fractures than the other facies. This control is evident in the lower portion of the core below the lost interval. Most fractures are concentrated in the interval between 4070 m and 4080 m, composed of packstone, wackestone and mudstone intercalations. In the upper portion, a prevailing wackestone and mudstone interval was observed, which contains the highest concentration of fractures in the entire section. The whole interval is fractured with average density around 2 fr/m, except to the upper 5 meters, which do not contain fractures. The fracture peak coincides with a contact between the wackestone at the base and laminated mudstone at the top (~12 fr/m). This contact is related to the presence of slicks on the bedding plane.

Figure 1 shows that the fracturing tends to be more intense in the fine-grained facies, especially in laminated ones. However, some intervals do not follow this correlation. Concentrations of fractures in grainstones, observed at 4087 m and secondarily at 4052 m, can not be fully understood in a model in which fracture intensity is controlled only by the rock type. Both fracture populations are positioned immediately above the faults (hanging wall), probably associated with deformation concentration without clear lithological control. Furthermore, the interval between 4020 m to 4025 m is composed mainly by mudstones, but does not contain any fractures. Therefore, the relation between the facies and the fractures does not seem to be linear.
The gamma ray log is more influenced by the faciology and can be used to characterize the lithological types, which keep straight relation with the fracture. It can be ascertained that there is a tendency of direct relation between the gamma ray curve and the density of fractures. The density, neutron and sonic logs reflect the porosity of the rocks, which generally presents an inverse relation with the

fractures. Those curves show a similar behavior: Generally, where these curves are displaced to the left, indicating an increase of porosity, the fractures are rare or absent. This pattern is disturbed in the upper portion of the core, up to 4035 m, where laminated mudstone layers occur. This lithofacies provides a strong increase in the DT and neutron porosity values. When comparing these results with the porosity curve obtained with the petrophysical tests, it is observed that the less porous intervals coincide with the main fractured intervals.

Structural Model – Implication for Fracture Modelling

The results obtained with the inversion of fault/slick data, as well as the description of natural structures of the core, suggest a stress partitioning, or vertical stratification of stress in the structure, at least for some rift structures. In the overlapping sequence, relatively more anisotropic, the data from fault inversion suggests the presence of instantaneous maximum horizontal stretching ($\sigma3$), toward the SE. The $\sigma2$ is also horizontal and trends toward the SW. In the lower sequence, the fault and slick data suggest the maximum instantaneous stretching points to the NNE, while the intermediary axis points ESE, showing a shift between the minimal and intermediary axis of the vertical stress ellipsoid (Figure 2). For both inversions the maximum stress is vertical, showing an extensional regime. It is worth highlighting that by separating these domains, a bedding-parallel movement zone occurs where the slicks measured in the core are concentrated (Figure 3). These data is compatible with the genetic model of the rift structures, as presented by Gangá and Machado Jr. (2007) and Machado Jr. et al. (2007), and suggest that the orientation of the fractures which are most susceptible to be open may vary in a cross-section through the flexural fault zone (Figure 2 and Figure 3a).

Two models were assumed as possible (considering only the geometrical characteristics), for the production of flexural shear and fracturing associated with a rift structure: the first model is considered as being formed by the generalized sub-horizontal extension, accommodated by normal faults, layer rotation and flexural slip (Ferril et al. 1998 – see also Wernicke and Burchfiel 1982) (Figure 3b). The second model is associated with the arching of the structure, geometrically similar to what occurs in folding due to flexural slip (Ramsay 1967, Wilson and Cosgrove 1982). The main geometrical consequence for the exploration and production is that the full development of this system is placed at the flank of the arched structure, concentrating in the rheological interfaces of the main mechanical units (Stephenson et al., 2007). This may produce more fractured corridors parallel to the bedding surface, which may connect the upper and lower structural portions of the zone of interest, as well as more fracture-damage zones of contiguous faults or associated to the arched structures (Figure 3b). In the studied core, the intense cementation prevents an effective hydraulic connection.

The results of the structural analysis are also consistent with the previously proposed model for rift tectonics I the basin (see Figure 4). According to Gangá & Machado Jr. (2007) and Machado Jr. et al. (2007), rifts have been displaced mainly toward the southeast, but northeast-southwest extension was also present, as shown by the geometry of normal faulting (Figure 4). Hence, the obtained inversion of faults and slick data are consistent with the finite geometry pattern of normal faulting.

Discussion and Conclusions

The presented data suggest that the parameters of porosity composition, grain size, and thickness of layers are important in the modelling of fracture intensity and definition of mechanical stratigraphy of the system, notably for the structures which develop affecting a significant portion of the section. In the case of faults, the more intense deformation in the influence zone locally causes these parameters to have subordinated influence. This is fundamental for the activities of development and exploration, as it is expected that many faults in an area have sub-seismic dimensions, and that the sampling of fault and fracture data in the subsurface is problematic due to the heterogeneous distribution of fractures and scale problems.

In the studied case, the existence of faults associated with the movement on bedding planes are virtually untraceable by seismic imaging independently of its throw. These structures can connect different levels of the reservoir if the relation between the fracturing and the diagenetic modifications is favorable. The possibility of connection seems low due to the intense cementation. The presence of decoupling surfaces between the main mechanical units may favor a shift in the stress axis along a section normal to the surface. In these cases, the orientation of fractures which are more favorable to fluid flow may vary abruptly from this surface.

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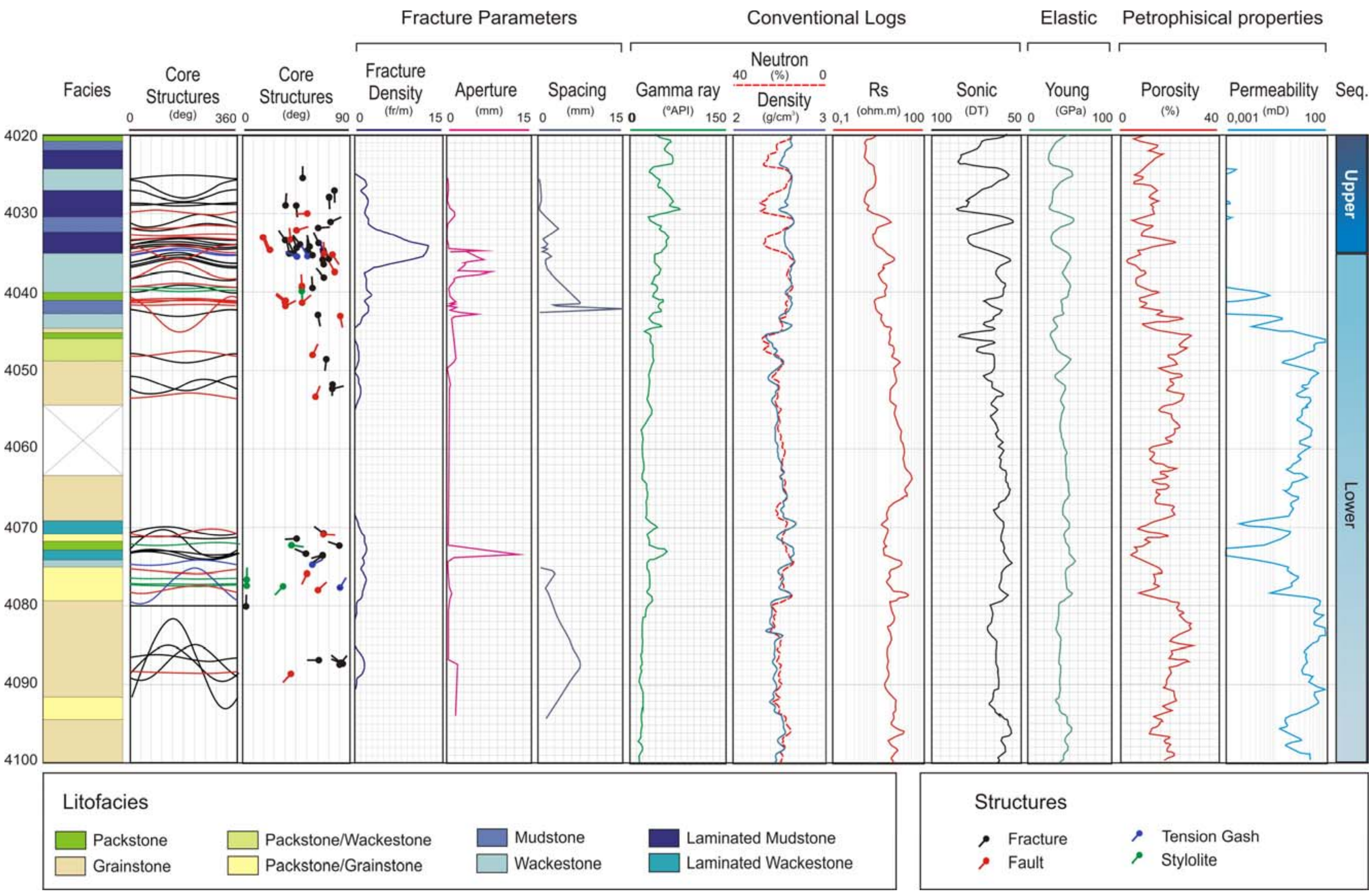

Figure 1. Sketch of the core showing facies distribution, fracture attributes, logs, petrophysical properties and depositional sequences. See text for discussion.

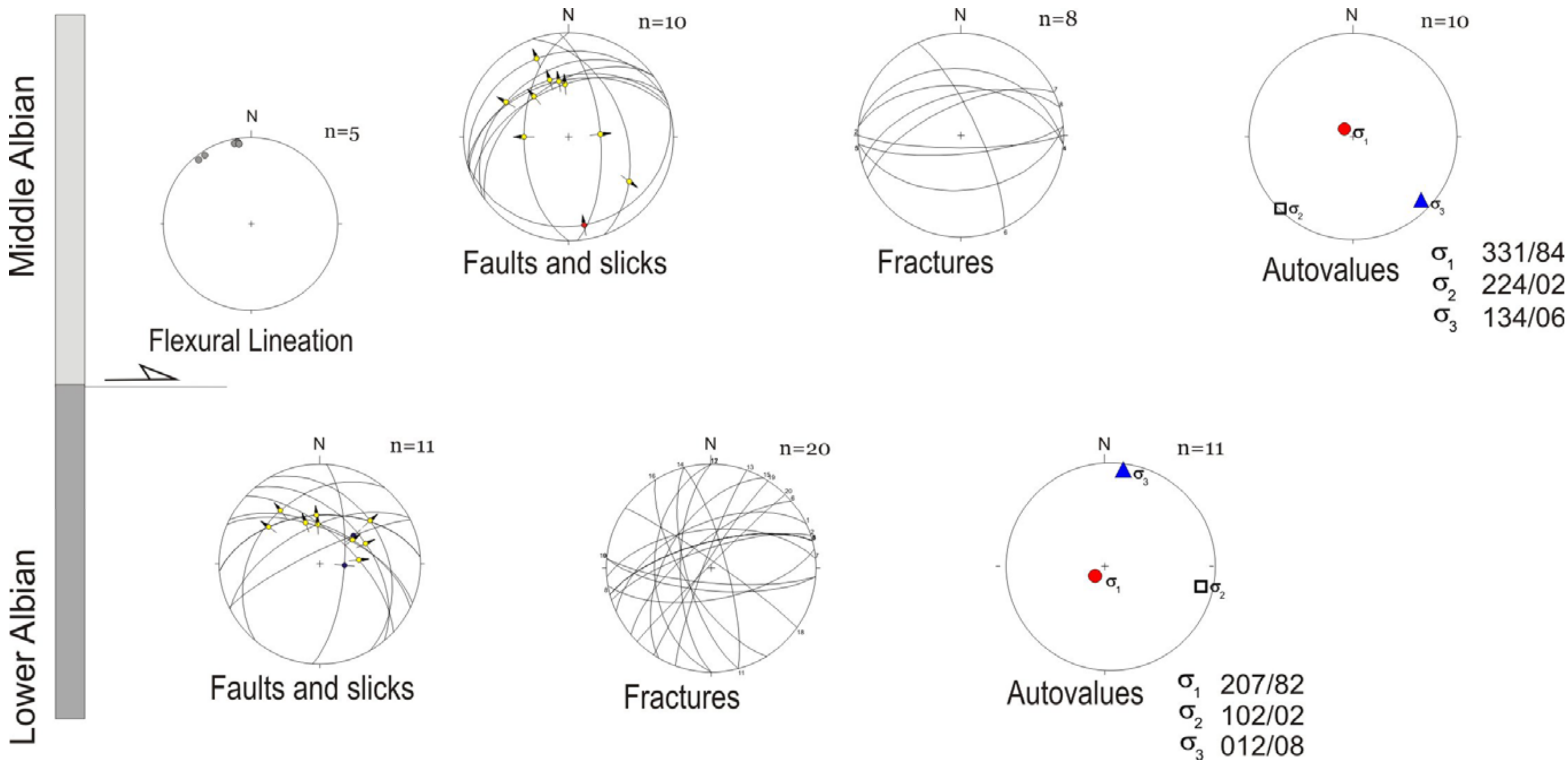

Figure 2. Stereoplots (lower hemisphere) of structures observed in the studied core and inversion of fault/slicks data. See text for further discussion.

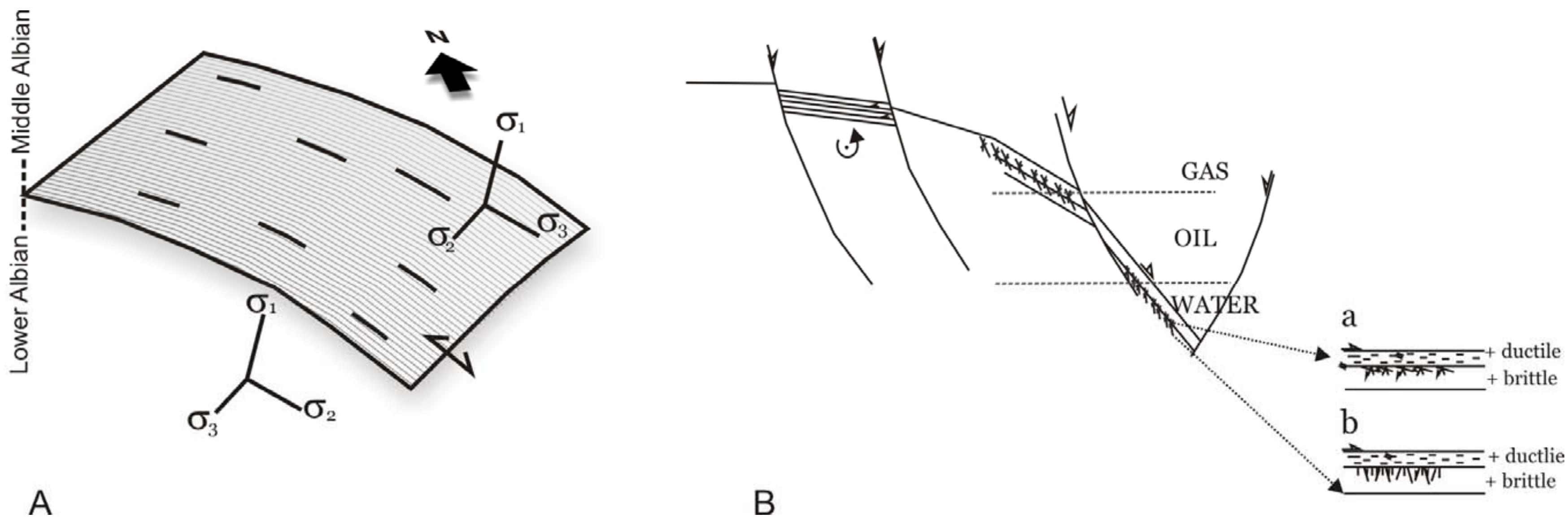

Figure 3. A) Dynamic/kinematic model derived from inversion data; B) Geometric model showing the possible connection between different reservoir levels due to flexural slip zones.

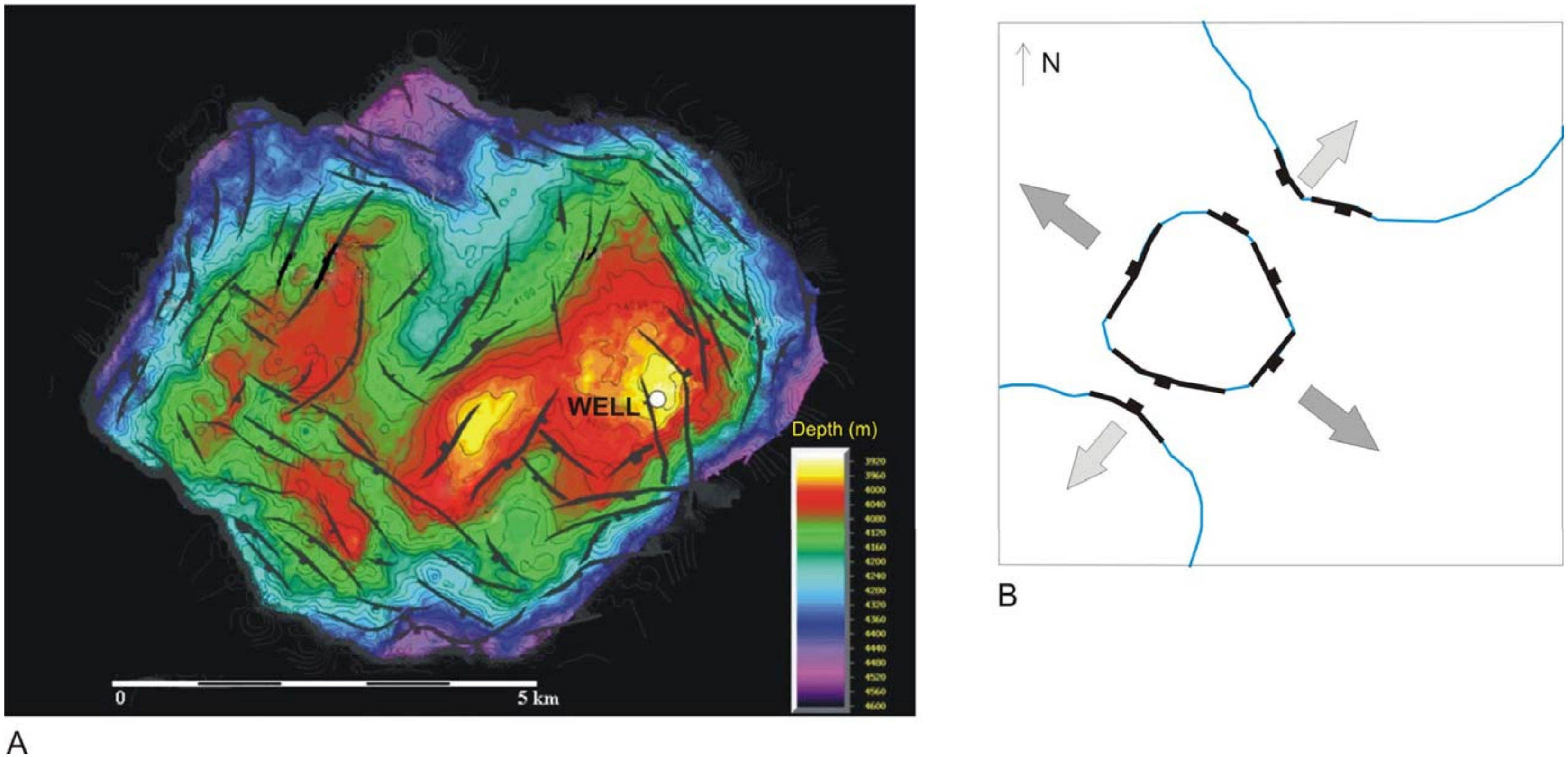

Figure 4. A) Structural map of the rift deformed by NE and NW trending normal faults (Extracted from Machado Jr. et al., 2007); B) Sketch showing interpretation of extension directions active during rift sliding.