Fractures and Fracture Networks in Carbonate Reservoirs: A Geological Perspective*

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Abstract

Fracture (networks) play a key role in the development of naturally fractured reservoirs. Present knowledge is insufficient to predict the 3D architecture of fracture networks in buried reservoirs and permeability and flow patterns. This is particularly true for carbonate rocks, which typically lithify close to the Earth surface and experience fracturing very early in their geological history. Detailed quantitative analysis of outcropping successions coupled with mechanical studies provides significant predictive tools and, thereby, minimizes exploration and production risks. New acquisition, processing, and interpretation tools are presented in this article with results from Cretaceous to Tertiary shallow-water limestone of the Potiguar Basin (Brazil) and of the Gafsa Basin (Tunisia). Carbonates of these two case studies experienced very early diagenesis and were lithified when they began their subsidence towards maximum burial depths. Subsidence took place in a stress regime characterized by a sub-horizontal tectonic stress. The first episode of fracturing occurred at depths of 500–1000m and led to the formation of sub-vertical stylolites and veins organized in conjugate sets with a sub-vertical intermediate principal stress σ_2. Opening of fractures reduced pore pressure, thereby favoring pressure solution and activated the long range circulation of fluids, allowing for the arrival of meteoric waters in the buried carbonates and associated dissolution/cementation. With proceeding subsidence little deformation took place in the form of small normal faults. Carbonates of the Gafsa Basin were folded during and following subsidence, thereby experiencing stresses resulting from the interaction between the fold-related and the regional stress fields. The type, position, and architecture of syn-folding fractures critically depend on the mechanical stratigraphy of the folded sedimentary succession. In packages where layers are separated, low-friction surfaces, new sets of conjugate fractures are formed in the hinge zone with an overall trend parallel to the fold axis. Layers which are thick and cannot easily slip with respect to each other are affected by fracturing controlled by flexural slip resulting in fractures ad stylolites oblique to bedding and concentrating away from the hinge zones. Outcrop models can then be translated in permeability and, eventually, in flow models to test flow scenarios and sensitivity.

General Comments

Present knowledge of fracture (networks), which play a key role in the development of naturally fractured reservoirs, is insufficient to predict the 3D architecture of fracture networks in buried reservoirs and permeability and flow patterns. Carbonate rocks, in particular, exemplify this relation, due to their common lithification close to the Earth surface, and they experience fracturing very early in their geological history.

In a fairly representative scenario where tectonic stresses are present, the position in space and magnitude of the principal stresses as well as the intensity of the deviatoric stress are predicted to change with depth (Figure 1). Therefore, rocks will potentially experience different deformation episodes during and following their subsidence. Depending on the depth at which fracturing occurs, strain will be accommodated by fractures of different modes and with different positions in space. In addition, folding can affect the considered rocks during and following subsidence, thereby generating "local" stress fields, which will interact with the regional one determining spatially variable conditions. Surprisingly enough, fracture patterns in rocks are commonly less complex than what one would predict. It seems that not all possibilities potentially available are used.

The theoretical knowledge we have on the relevant processes is incomplete and, for instance, little is known on the generation and development of stylolites, on the factors controlling the depth of the transition from mode I to mode II fracturing and on the interactions between fluids and fracturing. Because of their spatially continuous exposure, outcrops can be of great help in quantifying the geometries of fracturing, characterize their type and interactions and, eventually, develop an evolutionary model.

In this article we perform a comparative analysis of fractures developed during subsidence affecting two carbonate formations, the Lower Cretaceous Jandaira Formation (Potiguar Basin, Brazil) and the Upper Cretaceous Berda and Eocene Kef Eddour formations (Gafsa Basin, Tunisia).

Carbonates of these two case studies experienced early diagenesis and were lithified when they began their subsidence towards maximum burial depths. Subsidence took place in a stress regime characterized by a sub-horizontal, tectonic-related maximum principal stress. Assuming a simplistic stress scenario characterized by tectonic stress constant with depth and an overburden column with single density rocks (Figure 1), we estimate that the first episode of fracturing took place at effective stresses of 10-30MPa, which would correspond to a depth of 500-1150m in a fully dry scenario (Figure 1). Obviously, with a less strong tectonic stress, the depth interval with vertical σ_2 would become shallower. Deformation led to the development of sub-vertical stylolites with sub-horizontal peaks and veins organized in conjugate sets with a sub-vertical intermediate principal stress σ_2.The angle between conjugate faults is typically 15^o-25^o, that is, substantially less than what predicted by Andersonian theory. These very low values are rather typical for hybrid fractures; that is, fractures which form at the transition between mode I and mode II fractures (Hancock, 1985; Sibson, 1998). Not coincidentally, fractures both in Brazil and Tunisia are filled with calcitic cement, suggesting that they had a component of opening (Figure 2).

Opening of fractures reduced pore pressure, thereby favoring pressure solution and activated a long–range circulation of fluids, allowing for the arrival of meteoric waters causing dissolution/cementation.

Case Study: Shallow-Water Limestone of Potiguar Basin (Brazil)

In Brazil, fluid chemistry and O and C isotopes from calcite cements and fluid inclusions in veins suggest that fluids were of meteoric nature, flowed through the Açu Formation underlying the carbonates (Maraschin et al., 2004) and then through the carbonates of the Jandaira Formation precipitating calcite in the (mainly open at that time) veins. Fairly constant isotope values suggest that cementation occurred in one single episode. In a poorly defined time, possibly during exhumation to the surface, veins and stylolites were selectively reactivated, resulting in a network of open fractures longer than the original discontinuities but preserving the same orientations.

Case Study: Carbonates of Gafsa Basin (Tunisia)

Carbonates of the Gafsa Basin were folded during and following subsidence, thereby experiencing stresses resulting from the interaction between the fold-related and the regional stress fields. The type, position, and architecture of syn-folding fractures critically depend on the mechanical stratigraphy of the folded sedimentary succession. Where layers are separated by low-friction surfaces, new sets of conjugate fractures are formed in the hinge zone with an overall trend parallel to the fold axis. Layers which are thick and cannot easily slip with respect to each other are affected by fracturing controlled by flexural slip, resulting in fractures and stylolites oblique to bedding and concentrating away from the hinge zones.

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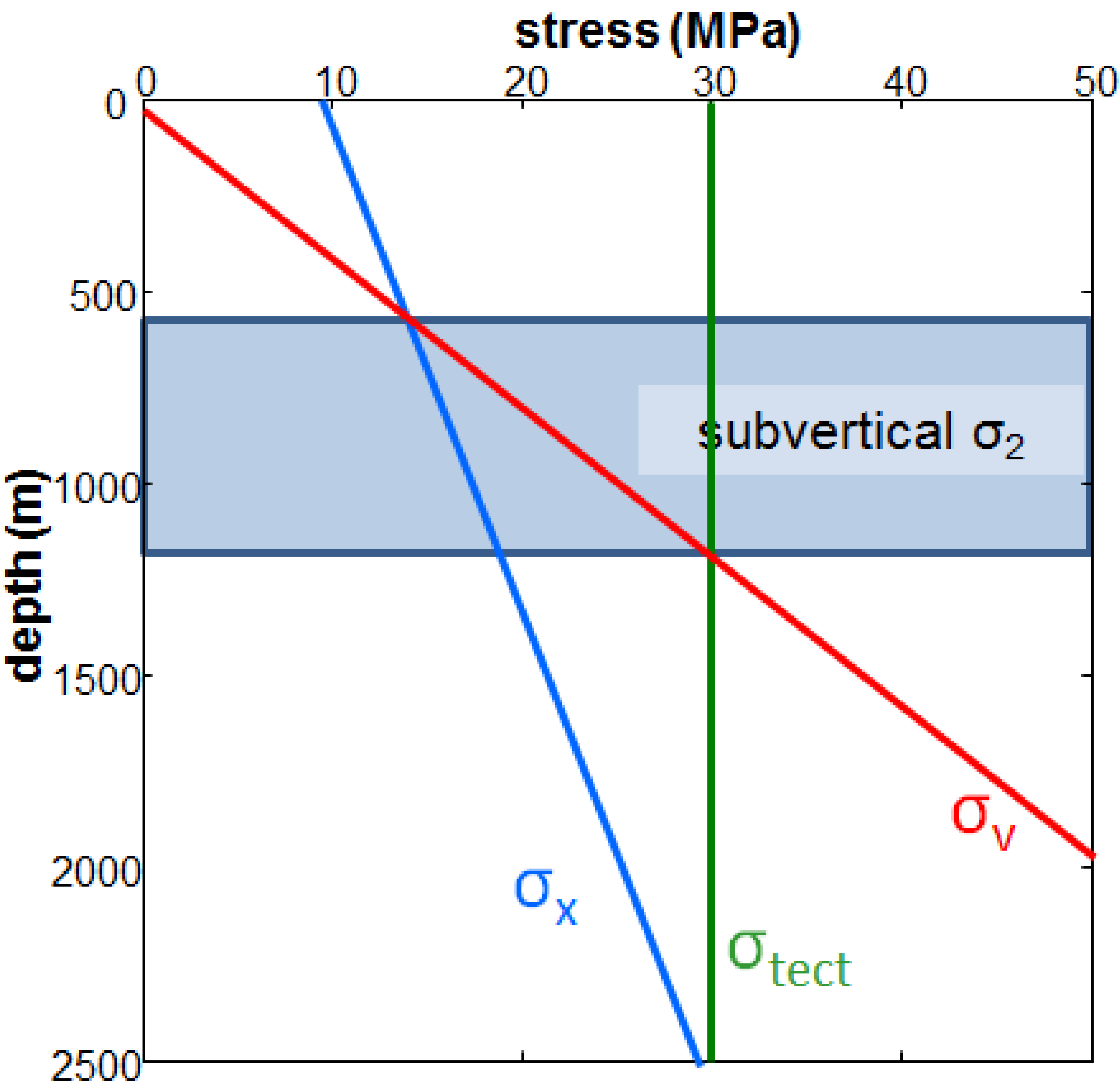

Figure 1. Values of vertical and horizontal stresses with depth assuming a constant tectonic stress in the y direction.

Figure 2. Hybrid vein in the carbonates of the Jandaira Formation, Potiguar Basin (Brazil).