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Tectonophysics 400 (2005) 179–207

TECTONOPHYSICS

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Interpreting fracture development from diagenetic mineralogy and thermoelastic contraction modeling

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Received 1 March 2004; accepted 1 March 2005
Available online 9 April 2005

Abstract

Four sets of thin-section scale, Mode I (open mode), cemented microfractures are present in sandstone from the Eocene Misoa Formation, Maracaibo basin, Venezuela. The first set of microfractures is intragranular (F1), formed early during compaction and are filled with quartz cement precipitated at temperatures equal to or higher than 100 °C. The second set of microfractures (F2) is cemented by bituminite–pyrite, formed at temperatures between 60 and 100 °C, and are associated with kerogen maturation and hydrocarbon migration from underlying overpressured source rocks. The third set of microfractures (F3) is fully cemented by either quartz cement or calcite cement. The former has fluid inclusion homogenization temperatures between 149 and 175 °C. These temperatures are mostly higher than maximum burial temperatures (~160 °C), suggesting that upward flow, caused by a pressure gradient, transported silica vertically which crystallized into the fractures. Upward decompression may have also caused a P_{CO_2} drop, which, at constant temperature, allowed simultaneous carbonate precipitation into the third microfracture set. The fourth set of thin-section scale microfractures (F4) is open or partially cemented by siderite–hematite and other iron oxides. The presence of hematite and iron oxides in microfractures is evidence for oxidizing conditions that may be associated with the uplift of the Misoa formation. In order to time and place constraints on the depth of formation of the fourth set of microfractures, we have coupled published quartz cementation kinetic algorithms with uniaxial strain equations and determined if, in fact, they could be associated with the uplift of the formation. Our results suggest that thermoelastic contraction, caused by the formation's uplift, erosion, and consequent cooling is a feasible mechanism for the origin of the last fracture set. Hence, we infer that meteoric water invasion into the fractures, at the end of the uplift, cause the precipitation of oxides and the transformation of siderite to hematite.

Keywords: Sandstone diagenesis; Fracture formation; Veins; Thermoelastic contraction; Overpressure

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doi:10.1016/j.tecto.2005.03.002

1. Introduction

Reservoir and thin-section scale partially cemented fractures and veins represent examples of tensile failure and fluid/fracture interactions. Extension fractures exhibit simple power-law scaling across 3.4–4.9 orders of magnitude (Marret et al., 1999), but regardless of their scale, hydraulic fractures decrease pore fluid pressure *in the adjacent rock*. Furthermore, depending on their connectivity, frequency, and hydrologic regime they may facilitate mass transfer and heat advection. Over time, some fractures are cemented while others remain open, causing a host-rock scale porosity and permeability heterogeneity that ultimately affects fluid production. Microfractures are used to determine far field stresses (i.e., Laubach, 1989) and magnitude, direction, and scale of fluid movement (e.g., Laubach, 1988; Eichhubl and Boles, 1997). Geochemical studies of cemented fractures *in sandstone* are typically performed in tectonically deformed areas such as fault zones and folds (e.g., Hippler, 1993; Macaulay et al., 1997; Perez and Boles, 2004; Boles et al., 2004), but microfractures and veins are not restricted to deformed areas.

In the absence of tectonic stresses, compaction disequilibrium and quartz cementation can result fluid retention and pore pressure increase (Helset et al., 2002; Swarbrick et al., 2002), which may lead, in turn, to hydraulic fracturing (e.g., Laubach, 1988; Engelder and Lacazette, 1990). Uplift, erosion, and cooling can also cause significant pore fluid changes and thermoelastic stresses that subsequently lead to tensile failure (e.g., Suppe, 1985; Swarbrick and Osborne, 1998). Tensile failure produces, in turn, pore pressure changes, allowing fluid movement, and leading, ultimately, to vein formation (Eichhubl and Behl, 1998). In these cases, the formation and cementation history of veins indirectly reflect the host rocks stress history, fluid pressure, and fluid composition.

The Misoa Formation, the subject of our study, is present in the subsurface on the east side of the Maracaibo Lake, Venezuela. The Misoa Formation is one of the most prolific siliciclastic hydrocarbon reservoirs of the world (Higgs, 1996), and, in this paper we show microfractures provide avenues for aqueous and hydrocarbon flow as well as vertical connection between sandstone horizons. The Misoa Formation was deposited during Eocene time in a shallow marine-deltaic environment (Gonzalez et al., 1980), buried to more than 4 km under high sedimentation rates, subject to temperatures higher than 180 °C (Rodriguez et al., 1997), and uplifted more than 2/3 of its maximum burial depth. Because of the wide range of pressure and burial regimes, the formation is ideal for the recognition of compaction, and the study of inversion related fractures (Law and Spencer, 1998). Previous diagenetic studies (e.g., Ghosh et al., 1990; Perez et al., 1999b) and burial-thermal reconstruction (Rodriguez et al., 1997; Perez et al., 1999a) of the Misoa Formation provide input for our semi-quantitative thermo-mechanical analysis used to interpret fracture conditions during burial and uplift.

Our study describes the diagenesis of the Misoa Formation sandstone and the mechanisms of fracture development and cementation during burial and uplift. The timing of cementation and fracture forming-filling events are interpreted from fluid inclusion data and the application of the quartz precipitation kinetic model of Walderhaug (1996). Based on petrography and diagenetic cements we distinguish microfractures that originated during burial subsidence (fractures sets F1 to F3) from others *possibly* originated during uplift (fracture set F4). The origin of the fourth fracture set is difficult to ascertain. Combining, however, petrologic information and diagenetic-mechanical modeling we infer they have been formed and cemented in recent in time at shallow depth, and are associated with uplift.

Samples were collected from the Lagunillas, Bachaquero, and Motatan onshore oil fields and a wildcat exploration well, BA-1, which is located approximately 2 km to the northwest of the Bachaquero field (Fig. 1). No information on core or sample orientation was available. These localities provide, however, excellent chronology of fracture events. All fractures cements are monomineralic, which led us to group the structures in sets, based strictly on their mineralogy, depth of occurrence, orientation relative to bedding, and cross-cutting relations. The data and results that we herein present may characterize the general diagenesis, veining conditions, paleofluid composition, pore pressure,