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Constraints on bed scale fracture chronology with a FEM mechanical model of folding: The case of Split Mountain (Utah, USA)

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ABSTRACT

A technique is presented for improving the structural analysis of natural fractures development in large scale fold structures. A 3D restoration of a fold provides the external displacement loading conditions to solve, by the finite element method, the forward mechanical problem of an idealized rock material with a stress-strain relationship based on the activation of pervasive fracture sets. In this elasto-plasticity constitutive law, any activated fracture set contributes to the total plastic strain by either an opening or a sliding mode of rock failure. Inherited versus syn-folding fracture sets development can be studied using this mechanical model. The workflow of this methodology was applied to the Weber sandstone formation deformed by forced folding at Split Mountain Anticline, Utah for which the different fracture sets were created and developed successively during the Sevier and the syn-folding Laramide orogenic phases. The field observations at the top stratigraphic surface of the Weber sandstone lead to classify the fracture sets into a pre-fold WNW–ESE fracture set, and a NE–SW fracture set post-dating the former. The development and relative chronology of the fracture sets are discussed based on the geomechanical modeling results. Starting with a 3D restoration of the Split Mountain Anticline, three fold-fracture development models were generated, alternately assuming that the WNW–ESE fracture set is either present or absent prior to folding process. Depending on the initial fracture configuration, the calculated fracture patterns are markedly different, showing that assuming a WNW–ESE joint set to predate the fold best correlates with field observations. This study is a first step addressing the complex problem of identification of fold-related fracturing events using an elementary concept of rock mechanics. When tight to complementary field observations, including petrography, diagenesis and burial history, the approach can be used to better constrain fractured reservoir characterization.

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1. Introduction

Many sub-surface reservoirs (e.g. Asmari carbonate in South-West of Iran, Frontier sandstone Formation (Fm) in Colorado Plateau, Ordovician quartzite in South Algeria) are characterized by a low matrix permeability which could be compensated by the presence of natural pervasive fracture sets of "bedding scale" and heterogeneously distributed in space (Nelson, 1985). The knowledge of the distribution of these fractures is certainly crucial for the development strategy of the fractured reservoirs. For example, Hennings et al. (2000) illustrate the compartmentalization of a reservoir due to the fracture distribution within a fold. Moreover, since the pioneering works of Stearns (1964), Stearns and Friedman (1972), and Price and Cosgrove (1990), it is recognized that the small scale fracture networks could vary according to the structural location in a fold. For similar fold geometry, different fracture patterns are found depending on the deformation scenario, for example thick-skinned versus thin-skinned folding (Hennings et al., 2000; Cooper et al., 2006), and suggesting a dependency on the stress state evolution (Engelder et al., 1997; Engelder and Peacock, 2001; Silliphant et al., 2002; Mynatt et al., 2009). Because this heterogeneous distribution of fractures should be taken into account in addition to the heterogeneity in sediment facies distribution, the design of a production scheme for a fractured reservoir, either for hydrocarbon, CO_2 or water flow requires assessment by dedicated numerical modeling. The numerical models require information on the distribution of fractures in terms of orientation, size, conductivity and density (e.g. Bourbiaux et al., 2002). Obtaining such fracture parameters remains difficult because many fractures are discontinuities at sub-seismic scale, and because their distribution in space does not allow a simple mathematical expression to extrapolate the fracture parameters between data from different wells. To compensate for the lack of direct information on fracture populations, the reduction of uncertainty in the fracture characterization is currently obtained through geostatistical methods, which correlate the fracture distribution with available information on a large scale. This information can include sedimentary facies, as given

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by stochastic models or by deterministic sediment transport simulations. It can also include structural attributes derived from 3D seismic interpretation like the curvature of bedding horizons or the distance to identified faults (Gauthier et al., 2002; Garcia et al., 2007). Also, deformation obtained after a restoration, such as mathematical unfolding and unfaulting of a top layer surface (Bally et al., 1966; Dahlstrom, 1969; Moretti, 2007), may be used as another driver of the geostatistical extrapolation method (Hennings et al., 2000). Finally, in complement to the sediment distribution, the main geometrical patterns and the related seismic signal, an appealing attribute could come from the results of geomechanical simulations analyzing the fracture development with a scenario including the in-situ stress state evolution with the burial and tectonic history: see Guiton et al. (2003a), for a FEM example and Gauthier et al. (2002), for a geostatistical approach constrained by geomechanical results.

The choice of a numerical method to simulate the mechanical development of natural fractures stems from an assumption regarding the size distribution of the displacement discontinuities. A crucial question is whether this distribution in displacement discontinuities is continuous-regular or is discrete-irregular and over what extreme values. Many works based on syntheses of field data tend to favor the scale continuity, using in particular a power law distribution with fractal dimension (for a review see Bonnet et al., 2001). However, as pointed by these authors, this property is not clearly established due to limitation in the data acquisition and also because of the possibility of few characteristic dimensions inherited from the sedimentary stratification (Hegelson and Aydin, 1991). A second property of fracture data which should constrain the choice of the numerical model is the spatial distribution, distributed or localized at a given scale, as discussed by stereological analysis (Berkowitz and Adler, 1998; Darcel et al., 2003).

Modeling the development of natural fractures with the classical mechanics of continuum solids relies on the fundamental assumption of a Representative Elementary Volume (R.E.V.). When dealing with non-periodic but heterogeneous stochastic materials, the existence of a R.E.V. requires to satisfy several properties (Hill, 1963). Firstly its characteristic size should be smaller than the size of the macro structure. Secondly, its size should be large enough to contain all the statistical information of the displacement discontinuities it contains, that we will call later on meso-fractures for sake of brevity. This implies that a separation can be identified in the size distribution between the meso-fracture and the larger discontinuities, namely faults. It implies also that the spatial distribution of the meso-fractures is not localized within the R.E.V., so that the mechanical properties satisfy invariance by translation and ergodicity (Kröner, 1971). The latter point means that the mean of these mechanical properties over the R.V.E. is equivalent to the expectation of the statistical distribution. In the following of the paper, assuming such properties for the meso-fractures, we will call them pervasive fractures.

When one of the required properties regarding the distribution of fractures is missing to postulate a R.E.V., few authors argued that explicit representations of the fracture networks could alleviate these limitations. A similar discussion on the fracture upscaling problem has developed for fluid flow modeling in fractured rocks (see Chapter 6 of U.S. Nat. Comm. Rock. Mech., 1996 for more details). The impossibility to set a R.E.V. due to fluid percolation motivated the development and large utilization of Discrete Fracture Network built from estimate of the statistical distributions of fracture properties (e.g. Bourbiaux et al., 2002; Dershowitz and La Pointe, 1994; Long & Billaux, 1987). In parallel, mining engineering issues, like tunneling or slope stability, have also motivated the development of numerical methods where the fractures are seen as interfaces cutting the rock domain into blocks (Goodman and Shi, 1985). These numerical models follow the strategy of Discrete Element Method which was popular in soil mechanics (Cundall and Strack, 1979). The mechanical behavior is obtained by giving contact properties to the interfaces, possibly identified from laboratory experiments (Bandis et al., 1983), and the dynamic equilibrium of the blocks is iteratively computed to converge to a stabilized state satisfying the boundary conditions and the contact conditions.

In the field of hydrocarbon subsurface reservoirs mechanics, Boundary Element Models with explicit representation of discontinuities were popularized to investigate the perturbation of stress field around faults seen as dislocations in a medium idealized as elastic (Bourne et al., 2000; Maerten et al., 2006; Bellahsen et al., 2006b). When trying to extend the approach to the case of bed-scale joints, because of their heterogeneous distribution it is necessary to set a boundary value problem at the full field scale. An explicit representation of bed-scale fractures will then be limited if considering the huge number of bedding fractures (e.g. Sanz et al., 2008; for a Finite Element Method (FEM) model of the reactivation of few vertical joints during the folding of Sheep Mountain Anticline). For that reason, a homogenized approach assuming a R.E.V. is preferable for the pervasive fractures, keeping the explicit approach for macro-faults. This idea was explored by Mandl (1988), Nieuwland and Walters (1993), Mäkel and Walters (1993), with phenomenological plasticity models representing the irreversible deformation with one or few internal variables like the classical Drucker–Präger model.

As emphasized by many field investigations (Silliphant et al., 2002; Guiton et al., 2003a; Bergbauer and Pollard, 2004; Bellahsen et al., 2006; Ahmadhadi et al., 2008; Mynatt et al., 2009; Amrouch et al., 2010; Bazalgette et al., 2010; Casini et al., 2011; Lacombe et al., 2011; Quintà and Tavani, this issue), pre-folding fracture sets may constitute an initial mechanical anisotropy which can be reactivated during folding and which can influence the syn-folding fracture development. More generally, fracture sets can be seen as a stress induced anisotropy (Rudnicki and Rice, 1975). A way to take into account this anisotropy was proposed by Leroy and Sassi (2000), thanks to a multiplane plasticity model in which the irreversible deformation is accommodated by opening and/or sliding of pervasive fracture sets. This model originates from the plasticity models developed for polycrystalline metals (Koiter, 1960; Mandel, 1965) later generalized to include a rate-dependency of the plastic flow (Pan and Rice, 1983). Details on the associated algorithms can be found in Simo and Hughes (1998). The extension to pressure sensitive yield surfaces for rock mechanics was first proposed in Zienkiewicz and Pande (1977). FEM simulations of folding events with the Leroy and Sassi (2000) plasticity model were documented in Guiton et al. (2003a, 2003b), demonstrating that the resulting fracture sets development is strongly dependent on the definition of the initial anisotropy of the rock material, i.e. the existence of a given fracture set as a structural inheritance.

Validating the numerical model of fracture development for a real subsurface reservoir is a particularly difficult task, because of the limited access to the fracture data, and because only the present-day configuration of the reservoir is known. This well-known dilemma linking modeling results and quality of available data motivates the work presented in this paper, exploiting the exceptional exposures of the fractured and faulted Weber sandstones at the Split Mountain Anticline in northeastern Utah. This site was selected as a field analogue for the Weber Fm because it is located in the vicinity of the Rangely Giant oil field (Narr, 1996, 1998), and also because it is favorable for analyzing the history of fractures in relation to a folding event, as shown by Wilkins et al. (2001), Silliphant et al. (2002). In contrast with the two last cited works, which focused on the Cretaceous sandstones in the same area, the present paper documents observations for the Permian Weber sandstones which constitutes the main outcropping top surface of the anticline.

The content of this paper is as follows. The first section documents the field observations on the fracture and fault populations in the top of Weber sandstone Fm at Split Mountain Anticline, Utah. Despite field data do not enable to justify rigorously the existence of a R.E.V., many fractures of metric size are considered diffuse and their mechanical contribution to the fold deformation is represented by the constitutive law of a homogeneous equivalent material. In the second section, the methodology of the numerical modeling is detailed, including the