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Integrating damage zone heterogeneities based on stochastic realizations of fracture networks for fault stability analysis

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ABSTRACT

In the domain of reservoir engineering, fault stability assessment is traditionally performed by assimilating fault systems to surfaces. However, faults are complex and heterogeneous geological systems, whose compartmentalized architecture generally corresponds to an inner core surrounded by outer, often fractured, damage zones (DZ). To date, few studies have assessed the potential role of the DZ characteristics (anisotropy, complex spatial distribution, etc.) on the shear behavior of the whole system, the main challenge being the proper (numerical) integration of fracture networks in reservoir simulators. The present study was motivated by the stochastically generated fracture networks representative of DZ investigated on outcrops (Cirques de Navacelles, South of France). We propose here a methodology relying on homogenization techniques for deriving the spatial distribution of effective anisotropic hydro-poro-elastic DZ properties from these stochastic fracture networks. Using them as inputs of 2D finite-element coupled hydro-mechanical models of a reservoir-scale fault zone, the key role of the spatially-varying DZ stiffness and Biot's coefficients are highlighted: neglecting them might lead to a high over-estimation of the maximum sustainable injection pressure (by nearly 50% in the considered cases).

1. Introduction

Fault systems can play a significant role regarding several risk issues related to massive fluid exploitation from porous sedimentary reservoirs (e.g., targeted for petroleum production or fluid storage like CO_2 or natural gas): fluid flow enhancement or compartmentalization within the reservoir,[1] loss of integrity of the reservoir–caprock systems,[2] fluid leakage,[3] and potential triggering of seismicity.[4]

In the domain of reservoir engineering, fault stability is traditionally studied by assimilating fault systems to 2D bodies, i.e. surfaces (an illustrative example can be found in Ref. 5). Yet, numerous outcrop surveys have demonstrated the complex and heterogeneous nature of faults' 3D architectures. Most of these studies have shown that a large variety of fault zones exhibit a "damage zone DZ – fault core FC" architecture at different spatial scales.[6,7] The inner core can be made of fine material, often impermeable, hence generally acting as a barrier to flow. Empirical relationships on the FC properties mainly linked to the clay content can be found in the literature.[8] The fault core is often surrounded by an outer damage zone (DZ) that often acts as a hydraulic pathway, because of the presence of a fracture network (especially in brittle sedimentary settings), whose characteristics (fractures' orientation, connectivity, lengths, density, number of fractures' families, etc.) depend on the distance to the core.[9]

To date, few studies have assessed the potential role of the DZ characteristics (anisotropy, complex spatial distribution, etc.) on the shear behavior of the whole system, one among the main challenges being the proper (numerical) integration of fracture networks in reservoir simulators. Existing studies often assume the relationship of such properties with distance to the FC, see for instance, Refs.10,11 Recently, a great effort has been made to collect and evaluate such data on site,[12] and to incorporate them in numerical code to get better insight in the fault behavior.[13] This characterization study is based on a large variety of combined techniques: core data, geotechnical index for rock masses description, electrical topographies, hydraulic injection tests, use of a Schmidt hammer, etc.

Yet, it should be recognized that such "rich" (though highly useful) data are not always accessible on site and are often restricted to characterization information of structural nature, i.e. statistical description of the fractures' families (length, orientation, infilling materials, etc.) and restricted to scan lines along outcrops. To overcome the lack of data, geostatistical tools have shown to be very powerful to stochastically generate fracture networks'

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realizations, which are representative of the field observations.[14,15]

In the present study, we investigate how to manipulate and synthetize information provided by geostatistical simulations of DZ fractures' networks in the view to incorporate them in geomechanical simulators for fault stability analysis. This study was motivated by the outcrops surveys carried out at the Cirques de Navacelles (South of France), which allowed defining such a geostatistical model.[16]

A brief description is provided in Section 2. Details on the development of the stochastic model are given in the appendix. We then concentrate on the use of such data as inputs for geomechanical analysis. In the present work, we focus on homogenization methods for integrating such data through the derivation of the effective properties of fractured media. Section 3 summarizes the current methods. The numerical strategy to apply homogenization methods and its application to this case study are described in Section 4. Empirical relationships are then derived to link effective quantities with characteristics of the fracture network. Section 5 focuses on a simulation-based study to improve the understanding of the influence of DZ heterogeneities on fault shear reactivation during fluid injection.

2. Motivating case study

In this section, we briefly describe the surveys on fault zones' outcrop carried out at the Cirques de Navacelles, South of France, which initiated the present study. Based on the data collected on the fractures' characteristics of the damage zones (DZ), a geostatistical model was defined (Section 2.2) to stochastically generate fracture networks representative of the onsite observations.

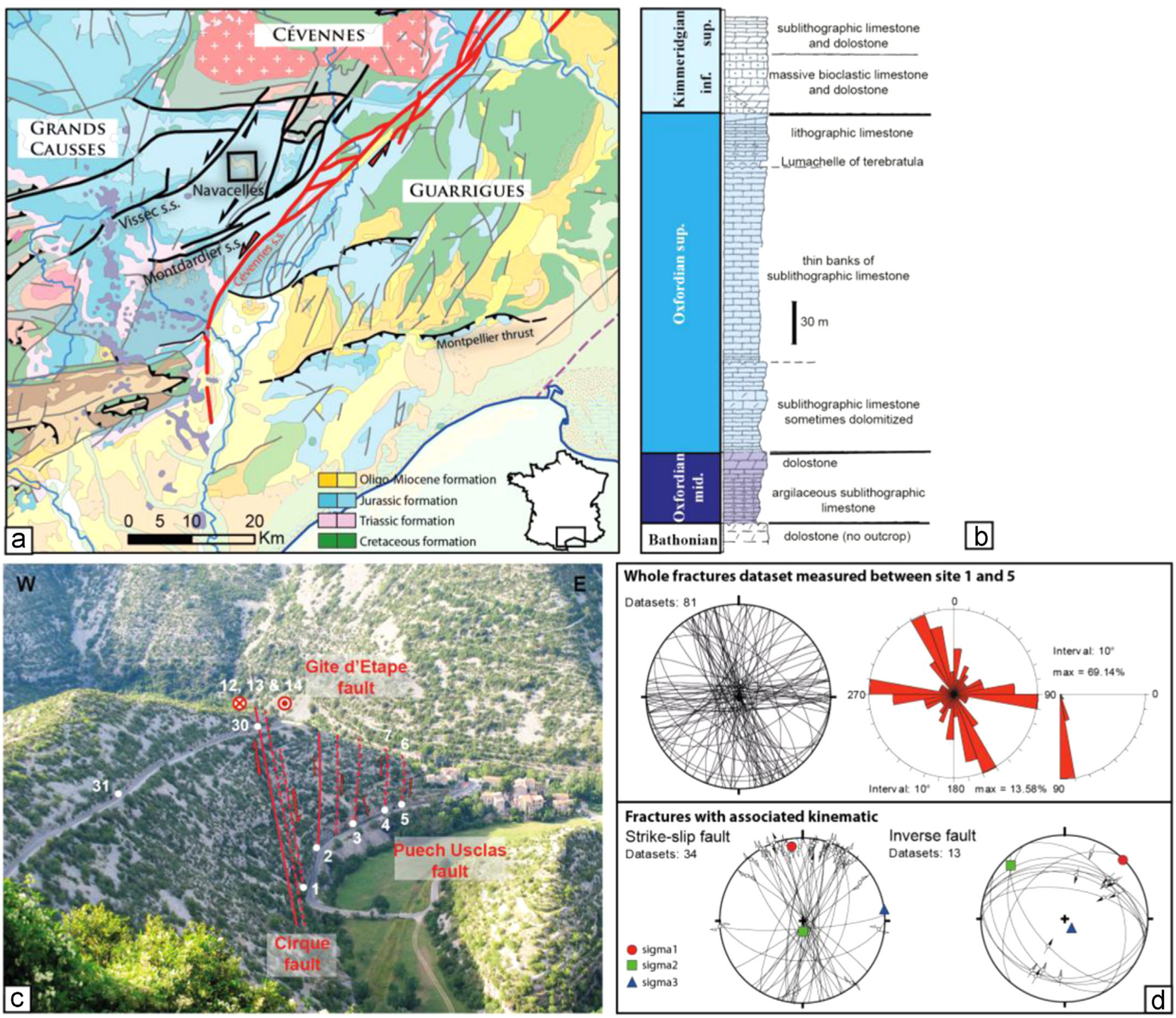

Fig. 1. (a) Regional geological and tectonic setting of the studied site "Cirques de Navacelles" in the south of France (inset at the bottom). the main strike-slip tectonic features are highlighted. (b) Details of the stratigraphic column on the site modified from Bodeur [19] (c): View toward the north of the fault corridor (in red) associated to the dextral strike-slip Cirques fault and sites of measurements (white). (d)-top: the whole dataset of fractures measurements Is represented in stereographic projection (lower hemisphere) (left) and rose-diagram for azimuth (middle) and dip (right). (d)-bottom: among the whole dataset, some sets of fault/strike have been measured and are represented in stereographic projection (lower hemisphere) for the strike-slip family (left) and the inverse family (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)