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Fluid flow numerical experiments of faulted porous carbonates, Northwest Sicily (Italy)

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ABSTRACT

A methodology to assess the effects of structural heterogeneities below seismic resolution in porous carbonate grainstones on reservoir performance during production is developed by integrating structural analysis, power law distributions, up-scaling, and numerical techniques. The novelty of the methodology consists of accounting for the buffering effects on permeability caused by compactive and cataclastic deformation bands. By using this methodology, a 3D deterministic field analogue and a 3D Discrete Fracture Network (DFN) representations of the reservoir/aquifer were built first, and then single-phase, steady-state fluid flow numerical experiments in an equivalent porous medium framework were performed. The field analogue is located along the Northwestern coast of Sicily (Italy) where Lower Pleistocene porous carbonate grainstones are crosscut by a strike-slip fault system. This fault system is made up of two conjugate sets of strike-slip shear structures recognized as single compactive shear bands (CSB), zones of compactive shear bands (ZB) and well-developed faults (DF), with discrete slip surfaces and cataclastic material. The permeability of these structures is up to three orders of magnitude less than the surrounding porous carbonate rocks. The fluid flow numerical experiments have been performed on the two aforementioned reservoir/aquifer descriptions to assess the effect of Sub-Seismic Resolutions Faults (SSRF), such as those observed in the outcrops, on fluid flow during production from a well, injection production in Enhanced Oil Recovery (EOR), and up-scaling to large cell size for regional flow simulation. Comparison of draw-down modeling in the DFN and the deterministic models show that results are similar with the exception of wells located in areas of intense strain localization with ZB and DF. The use of the DFN model is therefore an acceptable representation of the heterogeneities induced by SSRF in a reservoir/aquifer. Results of numerical computations show that, in structurally complex areas, SSRF-related ZB and DF might represent a drilling risk because they can enhance draw-down during production and EOR activities.

1. Introduction

Sub-Seismic Resolution Faults (SSRF), also called sub-seismic faults, are small offset faults that cannot be imaged on seismic reflection profiles processed with standard and enhanced techniques (Childs et al., 1990; Walsh et al., 1998). The maximum vertical resolution obtained nowadays by seismic line processing is in the order of 5–10 m (Hustoft et al., 2007). Despite their elusive characteristics, SSRF may have a strong impact on fluid flow and sealing within a reservoir due to their geometry, high density, and connectivity (Agosta et al., 2010; Ambrose et al., 2008; Ballas et al., 2013; Cello et al., 2001; Damsleth et al., 1998; Esposito et al., 2010; Maerten et al., 2006; Manzocchi et al., 2008; Walsh et al., 1998; Yielding et al., 1992). According to kinematics, amount of offset, deformation mechanisms, burial conditions and diagenetic evolution that characterize these features, SSRF may enhance (when associated to predominant dilational fracturing), buffer (cataclasis) or prevent (clay smearing, compaction) fluid flow in a reservoir (Agosta et al., 2012; Antonellini and Aydin, 1995; Ballas et al., 2013; Fachri et al., 2013; Faerseth et al., 2007; Fossen and Bale, 2007; Yielding et al., 1997; Manzocchi et al., 2008; Morris et al., 2012; Rotevatn et al., 2009; Tondi, 2007; Walsh et al., 1998). Different

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strategies have been adopted to image SSRF from seismic data; they include the use of seismic attributes such as coherency or curvature (Astratti et al., 2012; Lohr et al., 2008; Pearce et al., 2011), analysis of amplitude variations in 3D seismic models (Lohr et al., 2008), the use of stochastic techniques to extrapolate the SSRF from seismic resolution faults (Marrett and Allmendinger, 1992), and interpretation of the fault traces from seismic profiles and logs (Lohr et al., 2008). Non-geophysical techniques employed to image SSRF are based on paleo-stress analysis, structural restoration, studies of outcropping analogues and fractal/stochastic analysis of fault attributes (Agosta et al., 2010; Cello et al., 2000, 2003; Kattenhorn and Pollard, 2001; Maerten et al., 2002; Maerten and Maerten, 2006; Maerten et al., 2006; Roberts, 2007; Saillet and Wibberley, 2013; Schultz et al., 2008, 2013; Shipton et al., 2002). Since the late 90s, a large number of studies on SSRF have been produced after analysis of, mainly, sandstone and siliciclastic rocks (Fossen and Bale, 2007; Morris et al., 2012 and references therein). Some studies have also been presented for carbonate rocks (Farran et al., 2005; Morris et al., 2009; Penney et al., 2005; Putz-Perrier and Sanderson, 2010), and for the effects of fault geometry, damage zones and SSRF on fluid flow (Matthäi et al., 1998; Fossen and Bale, 2007; Rotevatn et al., 2009; Fossen et al., 2010).

Besides the inherent risk or advantages that SSRF cause during oil exploration in terms of migration, fault sealing, top-seal breaching, and reservoir quality enhancement/degradation (Manzocchi et al., 2008; Walsh et al., 1998), SSRF may play an important role during the phase of oil production, Enhanced Oil Recovery (EOR), and geologic CO_2 sequestration (Ambrose et al., 2008; Damsleth et al., 1998; Esposito et al., 2010). Antonellini et al. (1999) have shown that deformation bands faults in the oil field of Arroyo Grande (California, USA) were controlling the efficiency of the steam injection production scheme employed for EOR. Structural heterogeneities and SSRF have also been shown to affect the water circulation in aquifers within siliciclastic (Haneberg, 1995; Rawling et al., 2000) and carbonate rocks (Celico et al., 2006).

Focusing on deformation bands, characteristic structural features of porous rocks that deform like granular media (Aydin et al., 2006), they have been a matter of interest due to their pronounced control on fluid flow in reservoir rocks (Nelson, 2001). The literature characterizing the petrophysical properties of deformation bands in siliciclastic rocks is rather extensive (Antonellini and Aydin, 1994; Faulkner et al., 2010; Flodin et al., 2001, 2004; Fossen and Bale, 2007; Fowles and Burley, 1994; Lothe et al., 2002; Main et al., 2000; Ngwenya et al., 2003; Shipton et al., 2002; Sternlof et al., 2004; Taylor and Pollard, 2000). Conversely, only in recent times some work has been done for deformation bands in carbonate rocks (Cilona et al., 2012; Micarelli et al., 2006; Rath et al., 2011; Rustichelli et al., 2012; Tondi et al., 2006b, 2012; Tondi, 2007). Field, numerical, and theoretical studies investigated how deformation bands may affect the subsurface fluid flow, and at what scale their effect is most influential (Ahmadov et al., 2007; Antonellini and Aydin, 1994, 1995; Jourde et al., 2002; Manzocchi et al., 1999; Sternlof et al., 2004; Manzocchi et al., 2008; Matthäi et al., 1998).

In siliciclastic rocks, the permeability values of deformation bands measured normal to the plane of the band range from less than 0.1 mD to a few tens of mD (Antonellini and Aydin, 1994; Fossen and Bale, 2007). The aforementioned values are consistent with the deformation bands decreasing the host rock permeability by one to four orders of magnitude. In carbonate rocks, Rath et al. (2011) documented that permeability is reduced as much as three orders of magnitude in the direction normal to the band with respect to the host rock. Slip surfaces associated to thick zones of deformation bands are discontinuities in the rock that may act, in a way, similarly to an open fracture enhancing the permeability in the direction parallel to its plane (Antonellini and Aydin, 1994, 1995).

Excellent rock exposures located along the Northwest Sicily shoreline provide a unique opportunity to study in detail the fluid flow properties of a high porosity, Pleistocene carbonate grainstone rock crosscut by a strike-slip faults system (Fig. 1). The outcrops allow investigating the effects of small offset sub-vertical faults on an aquifer/reservoir-scale permeability analogue during production by designing accurate numerical experiments for single-phase fluid flow. The strike-slip faults nucleated from compactive shear bands (*sensu* Aydin et al., 2006). Single compactive shear bands represent the incipient stage of faulting in porous rock (Aydin, 1978; Aydin and Johnson, 1978; Aydin et al., 2006). These structures evolve forming zones of compactive shear bands, which have offsets <0.5 m, well below the limit of seismic resolution. Eventually at an offset larger than 0.5 m, according to fault/rock type, lithologic characteristics, and stress state (Aydin et al., 2006), zones of compactive shear bands become well-developed faults (*sensu strictu*) containing discrete slip surfaces along which cataclasis occurs. It follows that many faults formed by the aforementioned process fall below the limit of seismic resolution in the outcrops of Northwest Sicily (Tondi, 2007; Tondi et al., 2012).

The objectives of this paper are the following. (1) Characterize in the field the sub-seismic resolution strike-slip fault network by means of structural mapping, scan lines/areas surveys and mini-permeametry. (2) Define methodologies to up-scale and/or elaborate the structural and permeability properties measured in the field, so that they can be imported in a standard single-phase fluid flow simulator (i.e. MODFLOW 2005) used in ground water modeling under an equivalent porous medium approach. (3) Compare two methodologies, one based on a deterministic fully descriptive approach (field maps), the other one on a Discrete Fracture Network (DFN) obtained with a stochastic approach (MOVE™), to describe both structural and petrophysical properties of the network of structures (i.e. compactive shear bands, zones of compactive shear bands, and faults). The comparison will be done by testing the same field area with the two aforementioned methods and using simple boundary conditions in the fluid flow numerical experiments. (4) Evaluate the importance of the sub-seismic resolution strike-slip fault networks on single-phase flow during well production at a reservoir-scale.

2. Study area

The studied outcrops, located in Northwest Sicily (San Vito lo Capo peninsula and Favignana Island) are roughly oriented north–south (see Fig. 1 for location). The northwestern corner of Sicily represents the most external sector of the Sicilian orogenic belt, which is mainly comprised of south-verging, Neogene fold-thrust tectonic elements (Giunta et al., 2000). The most recent faults outcropping in the area form a system comprised of high-angle, strike-slip structures oriented either W–NW or N–NE (Abate et al., 1993, 1997; Giunta et al., 2004; Nigro et al., 2000; Tondi et al., 2006a). The former faults are characterized by a right-lateral kinematics, the latter by a left-lateral one. The kinematics of such a fault system is compatible to the current regional stress field, which is made up of an NW–SE oriented principal horizontal compression direction (Giunta et al., 2009).

In the study area, deformed Triassic to Miocene platform carbonates, which pass upwards into deep-water marls and limestones, are the basement units underlying Plio-Pleistocene marine deposits comprised of Upper Pliocene shales overlain by 20–30 m thick, Lower Pleistocene carbonate grainstones (Abate et al., 1993, 1997). The latter rocks include beds, characterized by a thickness ranging between 20 cm and 100 cm, made up of eroded carbonate