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Sensitivity of fluid flow to deformation-band damage zone heterogeneities: A study using fault facies and truncated Gaussian simulation

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We demonstrate that truncated Gaussian simulation (TGS), which is typically used for modeling of sedimentary rocks, can be employed to reproduce detailed damage zone structure as observed in outcrops. The basic modeled units employed are fault facies classified according to deformation density. Published damage zone field maps are re-drawn as fault facies maps and used for deriving geostatistical descriptions of model input parameters. We apply the modeling method for damage zones related to three scenarios: an isolated fault, branching faults and double-tip interacting faults. Constrained by the resulting TGS models, a series of damage zone permeability models are generated by systematically modulating five modeling factors related to different heterogeneity scales. Single-phase flow simulations reveal that fault facies proportion and damage zone width are the most influential factors, followed by deformation band frequency. Deformation band permeability and fault facies extent are the least important factors. Modifying fault facies proportion and damage zone width mainly change the flow retardation/enhancement in the models, whereas modifying deformation band frequency, deformation band permeability and fault facies extent mainly change the flow tortuosity in the models. Finally, we examine hierarchical modeling and upscaling procedures to incorporate our fine-scale models into flow simulation models.

1. Introduction

Damage zones form the volumetrically largest part of deformation-band faults (Aydin and Johnson, 1978) and are characterized by coupled heterogeneity and anisotropy properties that in many cases impede fluid flow across the zone (Antonellini and Aydin, 1994). Depending on their internal configuration and the presence of high permeability structures such as slip surfaces, deformation-band damage zones may also enhance fluid flow parallel to the zone (Antonellini and Aydin, 1994; Shipton et al., 2002; Eichhubl et al., 2010), and hence they form combined barrier-conduit systems. Assessment of damage zone impact on fluid flow within hydrocarbon reservoirs and groundwater aquifers calls for robust description of their characteristics and accurate representation of their upscaled properties, specifically permeability, in flow simulation models. Addressing these challenges, detailed outcrop-based deterministic models have been used to develop permeability upscaling techniques for complex fault zones (e.g. Jourde et al., 2002; Flodin et al., 2004). Stochastic models of damage zone and fault core shapes based on field observations by Caine et al. (1996) are presented in O'Brien et al. (2003), but this study does not address the internal heterogeneity within the fault zone elements. Modeling methods using implicit approach (Manzocchi et al., 2008), surface representation of deformation bands (Hollund et al., 2002; Harris et al., 2003; Odling et al., 2004) and combined geomechanics and discrete fracture techniques (Paul et al., 2011) address the characterization of deformation band spatial distribution for obtaining upscaled permeability in flow simulation models. However, these methods have limitations with respect to reproducing models that can be compared directly with field observations.

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In recent years, the fault facies approach (Tveranger et al., 2005; Braathen et al., 2009) has been proposed for modeling fault zones. Fault facies modeling involves populating volumetrically expressed fault envelope grids with features originating from tectonic deformation of the host rock (fault facies). The concepts' emphasis on employing 3D fault zone elements has spurred the development of classification and systematization of structural observations (Braathen et al., 2009; Bastesen and Braathen, 2010) along these lines allowing systematic collection of field data, easy comparison between different localities and statistical analysis of 3D fault zone structure for modeling purposes. The feasibility of this approach, using a combination of fault envelope grid, fault facies description, conditioning factors and conditional simulation techniques to model fault zones, has been demonstrated by Syversveen et al. (2006), Skorstad et al. (2007), Soleng et al. (2007), Fredman et al. (2008), and Fachri et al. (2011). However, these studies employ relatively simple fault configurations and focus on conditional simulation techniques that include object-based and sequential indicator simulation.

In this paper, we investigate another conditional simulation technique, i.e. truncated Gaussian simulation (TGS) (Journel and Isaaks, 1984; Matheron et al., 1987), for modeling damage zones described by using fault facies. The output of a TGS is geological facies which are derived by discretizing a continuous Gaussian field. This discretization is based on user-defined facies proportions (i.e. at a particular location, which facies has a higher occurrence probability) and proportion trends (i.e. in which direction a facies occurrence increases/decreases), whereas the Gaussian field is computed based on user-defined variogram ranges which in turn control the resulting facies cluster size. We have tested this approach for damage zone models related to three scenarios:

- Scenario A: an isolated fault segment
- Scenario B: single-tip interacting faults (branching of two fault segments)
- Scenario C: double-tip interacting faults forming a relay ramp

The aim of this paper is twofold. First, to demonstrate the capability and flexibility of TGS to reproduce detailed damage zone structure as observed in outcrops. This demonstration is carried out using 3D grids with 25 cm × 25 cm × 25 cm resolution and involves the definition of fault facies groups according to structural sets and modulation of two TGS attributes: fault facies proportion and fault facies cluster extent.

Our modeling approach involved specifying modeling factors related to different scales of damage zone heterogeneity. *Damage zone width* represents the largest heterogeneity scale; it delineates host rock and damage zone regions in the grids. Within the damage zone region, the TGS attributes (*fault facies proportion* and *fault facies cluster extent*) define heterogeneities on a smaller scale related to the grid resolution (i.e. 25 cm). Heterogeneities related to damage zone width and TGS attributes are considered to represent m-scale and dm-scale heterogeneities, respectively. In addition, two other modeling factors were specified to provide inputs to damage zone permeability modeling: *deformation band frequency* (dm-scale heterogeneity) and *deformation band permeability*. Deformation band permeability is a factor representing mm-scale heterogeneity which is below the grid resolution. Hence, the effect of this factor was captured by upscaling procedures.

The second aim of this paper is to investigate the influence of the damage zone modeling factors on fluid flow. For this purpose, a series of permeability models of Scenario A damage zone were generated by systematically modifying the five modeling factors. Data from published field studies were used to constrain these factors. Finally, flow simulation outcomes of the permeability models were statistically analyzed to reveal the sensitivity of fluid flow to deformation-band damage zone heterogeneities.

2. Field-based maps of fault facies

A deformation-band fault in porous sandstone is typically comprised of a thin, highly strained fault core and surrounding, wide and mildly strained damage zone (Clausen et al., 2003; Berg and Skar, 2005; Flodin et al., 2005; Wibberley et al., 2008; Braathen et al., 2009). The fault core accommodates most of the fault displacement and is characterized by a combination of structural elements such as slip surfaces, host rock and fault rock lenses, and other fault rock layers and pockets (or membranes; Braathen et al., 2009). Where porous sandstone is interbedded with clay-rich layers, shale smears may also constitute a hydraulically important structural element.

The damage zone is typically much more volumetrically extensive than the core (e.g. Beach et al., 1999; Berg and Skar, 2005). Intrinsically, damage zones are characterized by relatively small, discrete structures and a more distributed deformation in otherwise basically intact host rocks. Lower porosity host rocks offer fractures and sometimes dissolution structures; whereas porous rocks such as sandstone commonly develop damage zones of deformation bands. Deformation bands are millimeter-thick tabular zones where primary characteristics, such as porosity, grain sorting, grain packing and grain angularity have been altered. Deformation bands display a range of geometries, from single isolated structures to clusters of bands. Commonly they accommodate offset on mm- to cm-scale, however, truly dilational and compactional bands can also be found (Fossen et al., 2007; Eichhubl et al., 2010). Based on internal characteristics resulting from differing deformation mechanisms, deformation bands are commonly divided into two end members: cataclastic and disaggregation types. Cataclastic bands are characterized by significant grain crushing and more or less porosity loss, whereas disaggregation bands show intact grains rearranged by grain boundary sliding (e.g. Torabi et al., 2007). Cataclastic bands offer in most cases reduced permeability, in contrast to disaggregation bands that tend to have limited impact on flow behavior (Tueckmantel et al., 2010; Torabi et al., 2013). Most deformation bands are striking parallel to subparallel to the main orientation of the fault, although oblique orientations may occur locally, and exhibit both synthetic and antithetic orientations in cross-section (e.g. Johansen et al., 2005; Johansen and Fossen, 2008). Deformation band frequency generally increases toward the fault core (Beach et al., 1999; Berg and Skar, 2005). In the present study, geometry and permeability characteristics applied are those commonly found for cataclastic deformation bands. Another structural component of some damage zones is slip surfaces, in this case with relatively minor offset compared to the principal slip surface(s) of the fault core (Aydin and Johnson, 1978; Shipton and Cowie, 2001). Slip surfaces typically have cataclastic wall rocks ("wall rock cataclasites" of Tueckmantel et al., 2010), and the combination of slip surfaces and their wall rocks have been termed "slip zones" (Foxford et al., 1998). Slip zones are in most cases associated with deformation band clusters (Shipton and Cowie, 2001). However, slip surfaces can also occur within isolated bands (Rotevatn et al., 2008).

In previous modeling studies employing fault facies (e.g. Fredman et al., 2008; Fachri et al., 2011), individual structural elements such as single deformation band are not included explicitly. Instead, these studies define a series of fault facies based on deformation band frequency that include both deformation bands and interspaced un-strained sandstone facies. Fachri et al. (2011), for