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Research paper

From mechanical modeling to seismic imaging of faults: A synthetic workflow to study the impact of faults on seismic

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A B S T R A C T

Although typically interpreted as 2D surfaces, faults are 3D narrow zones of highly and heterogeneously strained rocks, with petrophysical properties differing from the host rock. Here we present a synthetic workflow to evaluate the potential of seismic data for imaging fault structure and properties. The workflow consists of discrete element modeling (DEM) of faulting, empirical relations to modify initial acoustic properties based on volumetric strain, and a ray-based algorithm simulating prestack depth migration (PSDM). We illustrate the application of the workflow in 2D to a 100 m displacement normal fault in a kilometer size sandstone-shale sequence at 1.5 km depth. To explore the effect of particle size on fault evolution, we ran two DEM simulations with particle assemblages of similar bulk mechanical behavior but different particle size, one with coarse (1–3 m particle radii) and the other with fine (0.5–1.5 m particle radii) particles. Both simulations produce realistic but different fault geometries and strain fields, with the finer particle size model displaying narrower fault zones and fault linkage at later stages. Seismic images of these models are highly influenced by illumination direction and wave frequency. Specular illumination highlights flat reflectors outside the fault zone, but fault related diffractions are still observable. Footwall directed illumination produces low amplitude images. Hanging wall directed illumination images the shale layers within the main fault segment and the lateral extent of fault related deformation. Resolution and the accuracy of the reflectors are proportional to wave frequency. Wave frequencies of 20 Hz or more are necessary to image the different fault structure of the coarse and fine models. At 30–40 Hz, there is a direct correlation between seismic amplitude variations and the input acoustic properties after faulting. At these high frequencies, seismic amplitude variations predict both the extent of faulting and the changes in rock properties in the fault zone.

1. Introduction

Faults play a key role in restricting or enhancing fluid flow in reservoirs. Although commonly represented as 2D surfaces in reservoir models, faults are actually narrow zones or volumes of highly and heterogeneously strained rocks, with petrophysical properties differing from those of the host rock (Faulkner et al., 2010 and references therein). Faults are complex and their 3D structure and rock properties distribution depend on factors such as host lithology and stratigraphy (Davatzes et al., 2005; Eichhubl et al., 2005; Bastesen and Braathen, 2010), depth of burial at time of faulting (Fisher and Knipe, 1998), initial fault array geometry and structural evolution (Childs et al., 2009), and diagenesis (Solum et al., 2010). Figure 1a illustrates the differences between an actual fault (Fig. 1a, left), and its standard 2D reservoir model representation (Fig. 1a, right). The structures and rocks inside the fault volume affect reservoir connectivity, and can either stop or allow fluid flow depending on their 3D geometry, distribution, and petrophysical properties. 3D fault structure and internal petrophysical properties are therefore primary controls on fluid flow in faulted reservoirs, determining fault-sealing capacity over geologic and production time scales (Faulkner et al., 2010 and references therein). This has major implications in hydrocarbon exploration and production, CO_2 storage, hydrogeological and geothermal systems (e.g., Wibberley et al., 2008).

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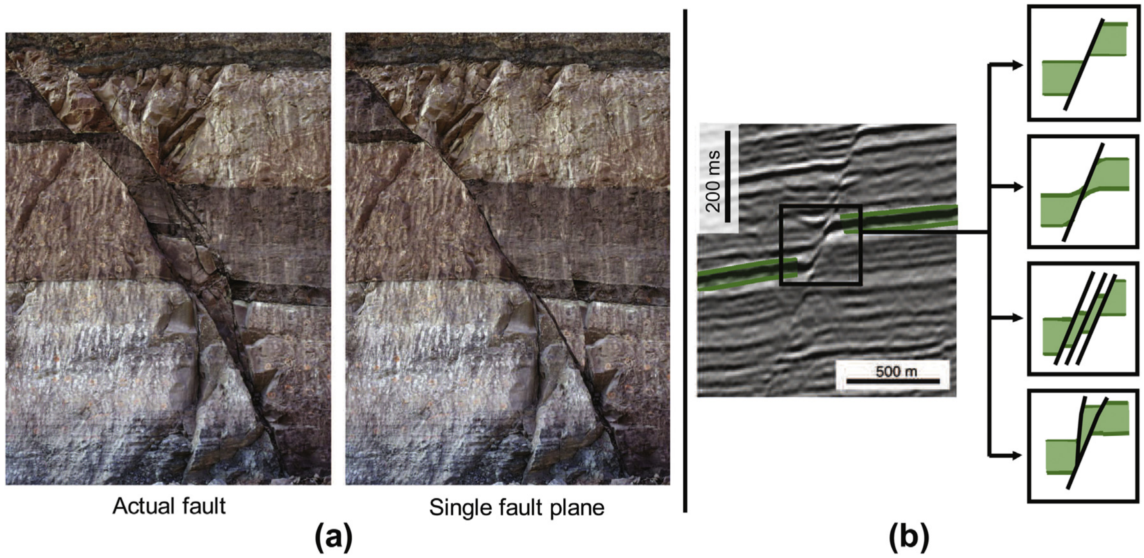

Figure 1. Examples of faults in outcrop (a) and seismic (b). (a) Actual fault (left) and modified picture with a single fault plane (right). This situation can be representative of scales going from m to km (actual and modified pictures from Haakon Fossen, http://folk.uib.no/nglhe). (b) Seismic profile of a fault with four possible interpretations resulting in different assessments of reservoir connectivity (modified from Wibberley et al., 2008).

Despite the impact of faults on reservoir connectivity, we still lack the understanding to fully represent them in reservoir models (Manzocchi et al., 2010). Much of what we know about the structure and internal properties of faults comes from outcrop studies. Field studies of exceptional fault outcrops have given unprecedented detail of the structure and properties of faults in 2D (e.g., Eichhubl et al., 2005) and 3D (e.g., Foxford et al., 1998), as well as an understanding of the physical and chemical processes operating in faults. These studies have also highlighted the complexity of faults in 3D (e.g., Childs et al., 1996, their Fig. 3). Outcrop data, however, mostly consist of small-scale cm to tens of m displacement faults (e.g., Childs et al., 2009, their Fig. 4). For specific combinations of lithology and fault displacement there are a limited number of outcrops and sometimes only incomplete 2D sections. Relationships derived from this small-scale outcrop dataset are often extrapolated to larger scales, although there are some concerns about the validity of this extrapolation (Færseth, 2006). Faults exhibit high variability in 3D, but we still lack quantitative, statistical tools to predict this variability (Manzocchi et al., 2010).

Large-scale faults with hundreds of m to km displacement can be mapped with seismic data. In few exceptional cases there are even well core data across these faults (Aarland and Skjerven, 1998). Fault internal structure and properties, however, are at the limit of seismic resolution. Strictly speaking, fault sealing as a property over the fault volume cannot be mapped directly with seismic. One rather looks at the impact of the fault on the surrounding rock (e.g., across fault pressure differences) to infer something about the fault properties and its sealing capacity (Yielding et al., 2010). A single fault surface with fault sealing properties determined in this manner is a reasonable estimate of the flow properties across and along the fault. However, within the limits of resolution of seismic data, there is room for alternative interpretations, which are equally valid and result in different assessments of reservoir connectivity (Fig. 1b).

Most of the seismic interpretation studies target the recognition of fault networks and their organization, whilst there are not many examples in the literature examining the potential of seismic data to elucidate the complexity of fault structure and its properties in space and time (i.e., fault evolution). A few studies focus on existing 3D seismic data using a range of seismic attributes to resolve the fault seismic response. Townsend et al. (1998) use seismic amplitude anomalies to detect small-scale faulting. Koledoye et al. (2003) decompose a large, seismically resolvable fault into segments to determine shale smearing. Dutzer et al. (2010) estimate fault architecture and fault sealing using seismic attributes in fault volumes. Long and Imber (2010, 2012) map the spatial distribution of fault related deformation using a seismic dip anomaly attribute. Iacopini and Butler (2011) and Iacopini et al. (2012) describe the geometry of complex thrust belts and associated fault damage zones by combining seismic attributes and volume based image processing and visualization techniques. Other works focus on the response of trapped waves within large fault zones in order to relate the anomalous behavior of the seismic wavefield to a possible fault zone (e.g. Ben-Zion et al., 2003; Lewis et al., 2005; Shtivelman et al., 2005). These techniques are however not applicable to standard industry seismic data and faults at large depths. Seismic characterization of fractured reservoirs is well covered in the literature, and fracture recognition (e.g., azimuthal variation in P-field, Li et al., 2003) could to some extent be extrapolated to larger fault zones. Nonetheless, despite all these studies, there is broad skepticism about the use of seismic data to characterize faults, partly because faults are at the limit of vertical and horizontal seismic resolution (Fig. 1b), and partly because standard industry seismic data are not designed to deal properly with the non-specular, back-scattered energy from faults.

The main objective of this paper is to describe a synthetic workflow to assess the potential of seismic for imaging fault structure and properties. The workflow is based on a geomechanical discrete element method (DEM) of faulting (Hardy et al., 2009), simple empirical relations to modify the initial acoustic properties of the model based on fault related finite strain, and a ray-based prestack depth migration (PSDM) simulator (Lecomte, 2008) to produce seismic images of the modeled fault. As a proof of concept, the workflow is investigated here in 2D, although it is possible to extend it to 3D. The DEM models the rock as an assemblage of circular rigid particles in 2D, and its main