Modelling Faults in Carbonate Rocks using the Discrete Element Method and the Impacts on the Seismic Image

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Abstract

Faults are structures typically interpreted in two dimensions, such as surfaces, in seismic data and are similarly represented in geological models of oil reservoirs. However, faults are three-dimensional complex zones that represent regions of weakness that concentrate fractures and highly deformed rocks. Therefore, the adequate representation of these zones is important for the management and economic evaluation of an oil field, with an impact on the areas of drilling, completion and location of wells, strategies for increasing the recovery factor and even on estimating the recoverable reserve. The proposed work aims at the structural modelling of a fault using the Discrete Method Element and a seismic simulation of this fault using the algorithms based on RTM (Reverse Time Migration) and Kirchhoff migration methods. The work also addresses the impacts of the spatial resolution of seismic data on the interpretation of these structures. The studies showed that although the volumetric interpretation of these structures through interpretation methodologies based on seismic attributes are possible, there is a considerable limitation due to the spatial resolution and the inadequacy of the seismic data to adequately deal with the lateral contrast of acoustic properties present in areas close to the fault zones.

Introduction

In recent years, many works have investigated the potential of seismic data to characterize the properties and architecture of fault zones (Townsend et al., 1998; Koledoye et al., 2003; Cohen et al., 2006; Long and Imber, 2010, 2012; Hale, 2013; Botter et al., 2014, 2016, 2017). Many of these studies use workflows based on seismic attributes. Dutzer et al. (2010) estimates fault architecture and sealing properties through a combination of geometric seismic attributes that capture the lateral contrasts of acoustic properties. Iacopini et al. (2016) applied seismic attributes to define unsupervised seismic facies of a fault zone. Botter et al. (2014, 2017) used a combination of geometric seismic attributes to volumetric extract a fault from a 3D synthetic seismic from an outcrop relay ramp model. Torabi et al. (2016a, b) used a series of geometric attributes to quantify the relationship displacement and fault zone length. The results of these studies show the importance and feasibility of interpreting faults as a representative volume of the fault zone through seismic data.

However, despite all these studies, there are doubts about the use of seismic data to characterize fault zones, because faults are at the limit of horizontal and vertical seismic resolution, around 30 meters for investigations depths of 2 and 4km, and because industry standard seismic data are not designed to adequately handle the lateral properties contrasts of found in fault zones (Botter et al., 2016). For typical investigation depths of 2 and 4 km, the seismic hardly capture faults with displacements smaller than 12 and 25 meters (Botter et al., 2014). The horizontal resolution in seismic data is highly dependent on many factors, including noise, and is generally less than or at best equal to the vertical resolution (Sheriff and Geldart, 1995). Noise is often present in seismic data, due to the acquisition techniques and complex 3D structures encountered. All these factors must be considered in order to obtain a correct representation of the faults and their associated deformations (Botter et al., 2014).

The objective of this work is to use the technique of the discrete element method to produce a strain field and geometry consistent with complexity of the fault zone. From the strain field, produce seismic images of the modeled fault to evaluate the image on aspects of seismic resolution and on the different seismic migration methods.

The results of this work can be used to define strategies of seismic interpretation and seismic processing with a focus on the investigation and characterization of geological faults in carbonate rocks.

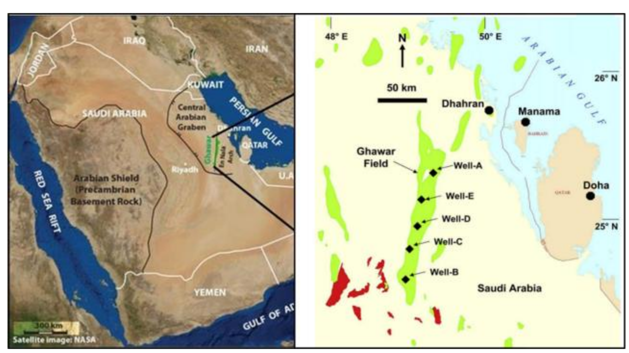

***Figure 1** – Gawar field location map. Adapted from Ameen et al. (2009).*

Method

The work applies a methodological adaptation to the workflow developed by Botter et al. (2014). A geological fault is created using the discrete element method

(DEM) introduced by Cundall and Strack (1979). DEM is a suitable technique for studying problems where discontinuities are important, as they allow for deformations involving relatively large movements of individual elements. The strength and deformability parameters for fault modeling in carbonate rocks were obtained from the work of Ameen et al. (2009) from the field of Gawar in Saudi Arabia (Figure 1). The PSDM simulator, developed by Zhu et al. (2015), which forms the seismic image of the fault, will consider different algorithms, Kirchhoff and RTM (Reverse Migration in Time), and aspects of spatial resolution will be studied through variation of the seismic pulse. The methodology used in this work is illustrated in Figure 2.

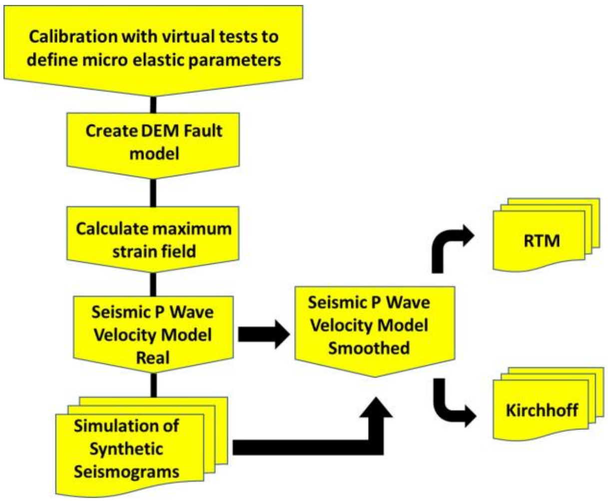

Figure 2 – *Workflow to create geological fault in seismic data using the discrete element method.*

Results

Figure 3a shows the DEM fault model for crystalline carbonate rock. The model is 1000 meters height and 2500 meters width and is composed of > 12500 particles, the normal fault was imposed at the base of the model with dip of 70º degrees and a maximum throw of 100 meters. The fault was formed under the confining stress state of 25 MPa.

Discrete Element Models (DEM) consist of an assembly of individual particles of finite size, each of these particles having its own translational and rotational degrees of freedom. According to Bagi (2006), it is essential to interpret the results of the DEM model from a macro level context, to establish a relationship between displacements at the particle level and deformations at the macro level.

There are different ways to calculate the strain field. In this work, the best fit method developed by Cundall and Strack (1979) was used where only the translation of the centers of the particles is considered. For a better representation of the strain field, a regularly spaced grid is created with the Grid Nearest Neighbor method presented in the work of Cardozo and Allmendiger (2009). Figure 3b presents the calculated maximum shear strain field for the presented DEM model.

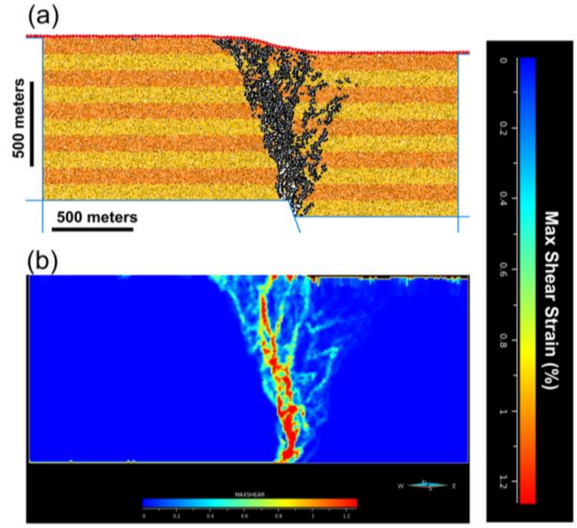

Figure 3 – *(a) DEM fault model for crystalline carbonate rock. (b) Maximum shear strain field calculated with the best fit method developed by Cundall and Strack (1979).*

The fault geometry is established by the largest strain values. Therefore, the highest strain values are related to the compressional wave velocity values for the rock present in the fault zone. The velocity values of the fractured carbonate rock, present in the fault zone, and of the intact rock were obtained from the work of Ameen et al. (2009). Figure 4a shows the velocity model used for seismic simulation. For seismic migration, the velocity model created was smoothed and the fault zone removed, Figure 4b.

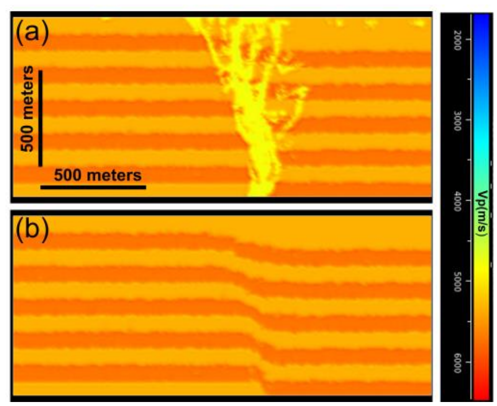

Figure 4 – *(a) Compressional velocity model used for seismic simulation. (b) Compressional velocity model smoothed used for seismic migration.*

The simulation consisted of seismic acquisition with a distance between the receiver and the source of 10 meters and used a wavelet with a peak frequency of 10 Hz and 20 Hz. Figure 5a and 5b show the seismic data migrated with Kirchhof algorithm. The results show that in the fault zone it is possible to observe artifacts with hyperbolic geometry, that is, the diffractions produced by the lateral velocity contrast of the fault zone were not collapsed in the migration. Migrating the data with a 10 Hz, the artifacts are attenuated, and it is possible to recover part of the fault geometry.

Figure 6a and 6b show the data migrated with the RTM algorithm. RTM data recover part of the geometry of the fault zone, no features that compromise the fault interpretation are observed.

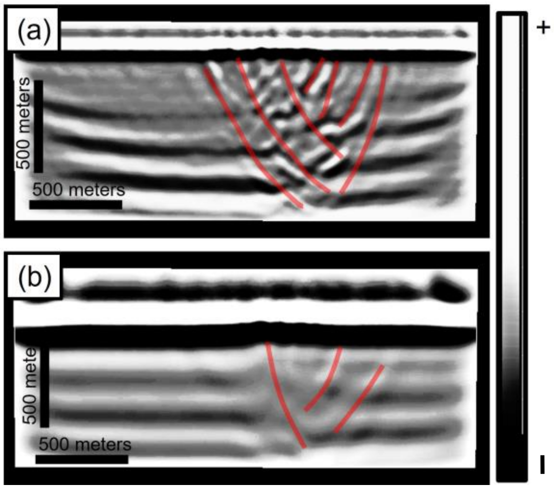

Figure 5 – *(a) Stacked Kirchhoff depth migration with 20 Hz wavelet. (b) Stacked Kirchhoff depth migration 10 Hz wavelet. The red lines are the interpretation of discontinuities.*

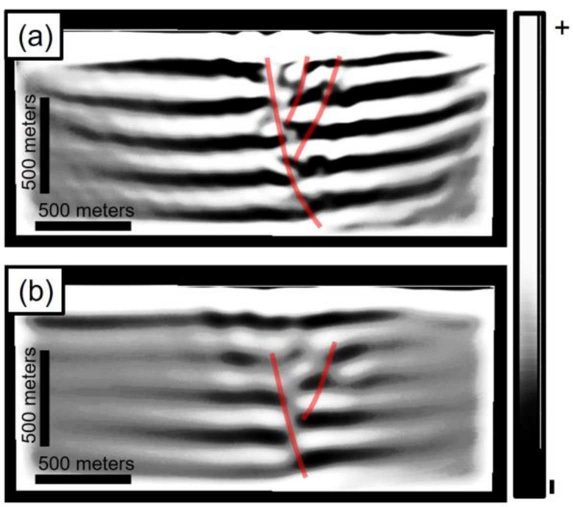

Figure 6 – *(a) Stacked RTM depth migration with 20 Hz wavelet. (b) Stacked RTM depth migration with 10 Hz wavelet. The red lines are the interpretation of discontinuities.*

Conclusions

The numerical modeling of faults from the discrete element method (DEM), together with the modeling of seismic data, proved to be an adequate tool for studying the impact of fault zones on the seismic image. Therefore, it is a methodology that can be applied in the fields of geomechanics, seismic acquisition and processing, and seismic interpretation.

However, there are limitations in the adopted methodology. DEM modeling of seismic scale fault zones, with throw of tens of meters, does not model microscopic effects that occur in carbonate rocks during the fault formation, such as, for example, the formation of a fault core with cataclastic rock. Therefore, the characterization of the fault zone through this methodology captures only the region related to the damage zone, not being considered the fault core. Diagenetic effects such as dissolution and precipitation along the fault zone were also not modeled.

Regarding the seismic images, the results showed that for higher frequencies the complexity of the field reflected in the damage zones is not resolved in the migration process, recommending the use of filters that cut the high frequencies in order to properly interpret the fault zone. Furthermore, RTM data is more suitable for fault interpretation even in the wavelet model with a peak frequency of 20 Hz.

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