Fracture identification based on remote detection acoustic reflection logging*

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Abstract: Fracture identification is important for the evaluation of carbonate reservoirs. However, conventional logging equipment has small depth of investigation and cannot detect rock fractures more than three meters away from the borehole. Remote acoustic logging uses phase-controlled array-transmitting and long sound probes that increase the depth of investigation. The interpretation of logging data with respect to fractures is typically guided by practical experience rather than theory and is often ambiguous. We use remote acoustic reflection logging data and high-order finite-difference approximations in the forward modeling and prestack reverse-time migration to image fractures. First, we perform forward modeling of the fracture responses as a function of the fracture–borehole wall distance, aperture, and dip angle. Second, we extract the energy intensity within the imaging area to determine whether the fracture can be identified as the formation velocity is varied. Finally, we evaluate the effect of the fracture–borehole distance, fracture aperture, and dip angle on fracture identification.

Keywords: remote detection, acoustic wave, reverse-time migration, finite difference, wave equation, reflection wave imaging

Introduction

Fracture identification is important for the evaluation of carbonate reservoirs. Both logging and seismic techniques are commonly used and often in combination. Typically, image logging is the most reliable method for fracture identification and can be used as reference to check the results of other methods. In seismic techniques, P-wave anisotropy has been widely used to predict fractures, particularly steeply dipping fractures. However, image logging has high vertical resolution but poor lateral resolution and can only probe a limited area around a borehole. Remote acoustic reflection logging is a new technique that images the wave reflections and detects fractures and other structures around a borehole. The method scans much deeper than conventional acoustic logging techniques that rely on the wave propagation along a borehole and has superior vertical resolution to seismic techniques, as shown in Figure 1. This new method bridges the magnitude gap in geophysical prospecting (Chai et al., 2009; Tang et al., 2013; Li et al., 2014). Remote acoustic reflection image logging (RARL) detects P- or S-waves from monopole
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or dipole sources. The most important step in the process of remote detection of acoustic data is migration imaging. It is better to use the most advanced prestack reverse time migration technique in seismic processing (Li et al., 2014). Inverse time migration is based on the complete wave equation, where there is no dip limit, not only for a wave imaging, but also on the rotating wave, prism wave, ghost wave and other multiple wave imaging. In addition, compared with the Kirchhoff integral and one-way wave equation migration, RTM imaging accuracy is higher, and the signal to noise ratio is higher, and the boundary of complex geological body is more clear (Guo et al., 2008; Zhang et al., 2009).

Hornby (1989) was the first to use f–k filtering and generalized Radon transform to extract and image waves reflected from oblique bed boundaries using full-wave logging data. Wang et al. (1998) used reflected signals from full-waveform logging data to locate cracks and estimate dip angles. Chabot et al. (2001, 2002) used the ProMAX software to process acoustic reflection logging data based on the equivalent-offset method (EOM) and imaged the dip angles of the bed boundaries around the borehole. Tang and Patterson (2006) and Tang et al. (2009, 2013) used dipole array acoustic logging data to determine the azimuth of a reflecting boundary and concluded that conventional array acoustic logging data could be used to evaluate the structures around the borehole. Based on the 2-kHz low-frequency cutoff of the flexural wave, Wei et al. (2013) showed that dipole acoustic waves are excited below the cut-off frequency and simulated the acoustic wave field. Su et al. (2014) used a neighboring well for testing the remote detection imaging. Xiao et al. (2014) introduced the split-step Fourier migration in remote acoustic reflection data migration and imaging and numerically simulated the responses of parallel fractures outside the borehole. Wang et al. (2014) correlated the reflected energy and productivity to predict the oil/gas potential of carbonate reservoirs. Gong et al. (2015) recorded signals with three-component sensors and inverted the horizontal and vertical components via reverse-time migration (RTM) and addressed the issue of determining the azimuth of a reflector. Li et al. (2014) performed migration imaging of remotely detected acoustic logging data using prestack RTM. However, in practice, there are problems in processing and interpreting logging data because of the lack of quantitative data on the investigation depth and fractures. In this study, we set up forward models of fractures and correlate the fracture aperture, dip angle, and fracture–borehole distance with logging data using numerical simulations.

Reverse-time migration

Reverse-time migration (RTM) is based on the accurate solution of a two-way wave equation that models the wave propagation in any direction and is suitable for any type of wave. RTM comprises three steps. First, we choose a suitable numerical method to solve the two-way wave equation and follow the source wave field as a function of time. Second, we extrapolate the receiver wave field in reverse time and save the wave field values. Finally, based on the source and receiver wave fields, we extract and stack the imaging data to obtain the final imaging profiles. Compared with ground seismic data, well logging produces higher precision data for reservoir identification. The RTM method is simple in principle, it has no angle limits, and it can be used to build complex velocity models. Based on these obvious advantages, we selected the prestack reverse RTM method despite the large computational cost; however, the remote detection of acoustic reflection wave data is less computationally costly than handling ground seismic data and the use of microcomputers is thus permissible.

Prestack RTM cannot be used to directly image remotely detected acoustic reflection data; thus, some modification is necessary. Figure 1 shows the remote acoustic reflection logging tool. The 2D single-side seismic geometry was rotated 90° and all recording parameters were mapped by the logging geometry.

Remote acoustic imaging uses seismic prestack RTM, which may result in data dispersion and computational instabilities owing to the difference between the seismic dominant frequency of about 30 Hz and the acoustic