Seismic Imaging of Fractures – A Feasibility Study

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Summary

The seismic imaging of fractures represents a very important yet difficult problem for petroleum exploration and production in overthrust areas. We address many of the issues associated with seismic resolution when dealing with these 3-D problems, including the collapsing of Fresnel zones and the use of horizontal depth slices. Although the size of typical fractures is below the spatial resolution capabilities for typical seismic frequencies, the 3-D modeling and migration of foothills prototypes shows encouraging results for the possibilities of detecting fractured zones. We illustrate the challenges of these problems using synthetic modeling studies, and make recommendations for future research into the analysis of model and real seismic data.

Introduction

The permeability of petroleum reservoirs is greatly influenced by the presence and connectivity of fractures. Lamb and Spratt (2006) have shown that borehole data can be used to determine fracture orientations and density. Their results have been very encouraging and significant. Another piece of the "fracture imaging puzzle" could certainly come from the use of seismic data to map fractures between wells.

Given the size of fractures compared with seismic wavelengths, seismic imaging is an extreme challenge. Possible answers may come from the characterization of azimuthal anisotropy. In this area, Alford (1986) showed that the characterization of shear wave splitting in anisotropic media can be used be used to classify both the density and orientation of fractures. Subsequent research on anisotropic fractures has been presented by Thomsen (1995) and by Talinga and Lawton (2005). In much of this seismic research, the small size of the fractures requires that we treat the earth as an equivalent anisotropic medium. For typical seismic wavelengths, an equivalent anisotropic medium model represents fractured heterogeneous rock, with subseismic wavelength fractures, by a homogeneous medium with properties that differ from a homogeneous unfractured medium. We shall explore the necessity for doing this, but first of all, we examine the challenges that fractures pose for seismic resolution.

Spatial Resolution and Fresnel Zones

The traditional analysis of spatial resolution deals with Fresnel zones, the measure of resolvable anomalies. For the purposes of describing spatial resolution limits, we recall a lucid heuristic description of Fresnel zones by Lindsey (1989) which was later included in discussions of resolution by Lines and Newrick (2004). Migration can significantly reduce the Fresnel zones Depending on the depth and wavelength of the reflector, there is generally a significant improvement in resolution as a result of migration.

Methodology and Results

We examine the effects of 3-D reverse-time migration, illustrated by employing simple models with orthogonal fractures. We illustrate by that the fracture's Fresnel zones are significantly reduced – by nearly an order of magnitude in some cases. We demonstrate that 3-D depth migration can be an effective tool for spatial resolution. However, a key issue becomes that of reducing the Fresnel zone to a dimension that is comparable to the dimensions of the fractures. For typical seismic frequencies and wavelengths, the resolution of individual fractures is practically impossible.

Nevertheless, resolution aside, our migrated models indicate that the detection of fracture zones is feasible. A comparison of 3-D depth migrations does show detectable differences between fractured anticlines and unfractured anticlines.

Conclusions and Future Research Directions

It is apparent from both theoretical and modeling considerations that depth migration will effectively reduce Fresnel zones and thereby enhance spatial resolution. From the use of 3-D modeling and migration for a fractured fault propagation fold model, we also note that fractured zones are difficult to distinguish on migrated cross sections. It does appear that depth slices may hold some promise for distinguishing the boundaries of the fractured zones. The best diagnostic comes from differencing the cross-sectional profiles of normalized depth images. Given the size of fractures relative to seismic wavelengths, the problems must be examined with equivalent media anisotropic models. Azimuthal anisotropy may play a key role in this analysis. In this area, shear-wave anisotropy (especially shear-wave splitting) has proven to be successful in detecting fracture density and direction. For future research, the following methodologies will be pursued.

1. Enhancement of high-frequency energy prior to 3-D depth migration.
2. Elastic modeling and imaging of fractured models
3. Examination of anisotropic effects, especially the possibility of the detection of shear-wave splitting.

Fractures remain an important but extremely challenging problem in exploration seismology. Although the resolution of individual fractures may be practically impossible at normal seismic frequencies, we need to pursue methods which will delineate zones of fractures and fracture permeability.

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