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PS-wave azimuthal anisotropy: benefits for fractured-reservoir management

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Summary

Fractured reservoirs have been encountered worldwide and in general they are profitably produced, however it is safe to say that none of them have been depleted efficiently. As the seismic industry focuses more on production and development it is becoming more important to recognize the presence of fractures for optimal reservoir management. Fractures can significantly influence the behavior of reservoir porosity and permeability, resulting in numerous dry wells and higher production costs. A key strategy for fractured reservoir management is a quantitative description of the geology, geophysics and petrophysical attributes. 3D converted-wave (PS-wave) surveys provide complimentary surface-seismic information to help identify fracture properties early in the production history of a reservoir. Based on azimuthal anisotropy measurements, PS-waves indicate fracture density and strike, and because of their asymmetry they are also sensitive to fracture dip. These large-scale properties will be critical for solving specific production problems associated with different fractured reservoir types, and could improve reservoir modeling: production-history matching, and fluid-flow simulation. From an economic point of view, if multicomponent surveys prevent a small fraction of unproductive wells, then they are worth the expense.

Introduction

Many fractured reservoirs have been profitably produced, but few of them have been depleted in an efficient manner. Nelson (2001) points out the importance of classifying fractured reservoirs based on the amount of heterogeneity and anisotropy observed in the porosity and permeability. Quantifying this anisotropy with surface seismic data should provide an optimal strategy for fractured reservoir management by integrating the geophysical data from all scales with the engineering data.

P-wave AVO/AVA and azimuthal anisotropy analyses can be important for inferring fracture properties (e.g., Hall et al., 2000). However, amplitudes provide only second-order measurements of fracture properties and are sensitive to thin-bed effects. In addition to these analyses, pure S-wave modes can be exploited for their birefringent properties or S-wave splitting (e.g., Potters et al., 1999), however at great acquisition expense. PS-waves have a number of advantages for identifying the large-scale effects of fractures on seismic anisotropy. This paper discusses the geophysical and economic benefits of PS-waves to provide solutions for fracture characterization with an emphasis on reservoir management. Both land and marine studies (Gaiser et al., 2001; Van Dok et al., 2001) indicate the potential of PS-waves to impact the geological and petrophysical description of fractured reservoirs.

Fractured-reservoir classification

Understanding the nature and distribution of the pore space within a reservoir is essential for optimal recovery of hydrocarbons. Nelson (2001) describes a fractured reservoir classification that is based on percent reservoir porosity and permeability (Figure 1). These two important parameters vary in percent due to matrix versus percent due to fractures. In type I, fractures dominate porosity and permeability. Reservoir porosity is very heterogeneous and localized, while reservoir permeability is very anisotropic and directionally controlled by fracturing. In type II reservoirs, fractures control essential permeability, and in a type III reservoir, fractures assist permeability. In type IV reservoirs, fractures provide no additional porosity or permeability but, just the opposite, can create anisotropic barriers.

This classification, based on traditional borehole methods of identifying fractures such as core and well-log analyses, has proven useful in quantitatively characterizing many reservoirs. Figure 2 shows various fractured reservoirs where wells, ordered from least to most productive, are cross-plotted against percent cumulative oil (Nelson, 2001). The fracture-impact coefficient is the percent of the area below the diagonal line and provides a quantitative measure that correlates with reservoir type. For example, type I reservoirs have a large fracture-impact coefficient and a larger proportion of unproductive wells. At the other end of the fracture-classification spectrum the coefficient becomes smaller and approaches zero for homogeneous, isotropic reservoirs where each well would provide equivalent production. It should be pointed out that the fracture-impact coefficient is not really a property of fractured reservoirs but rather an indicator of *fracture denial* (Nelson, 2001). Unproductive wells result from not recognizing the significance of fractures early in the development of a field. Many wells are drilled assuming reserves are evenly distributed, where the porosity and permeability are controlled only by rock matrix.

Fracture characterization using PS-waves

To avoid fracture denial, a quantitative description of a new reservoir is needed soon after the first discovery of hydrocarbons. Identifying fracture properties in the borehole is the first key step to characterize a reservoir; however, these are only local observations. Surface seismic methods provide a means to investigate the heterogeneity and anisotropy on a larger scale in the inter-well spaces. Multicomponent seismic methods using PS-waves contribute added value to compliment conventional P-wave methods and are typically higher resolution than S-wave source methods. Aside from obtaining azimuthal S-wave velocity and amplitudes to quantify fracture orientation, traveltime differences between the P-wave and PS-wave provide Vp/Vs measures for lithological discrimination and can help in the petrophysical description of the fractured reservoir. More importantly, the traveltime differences between the fast and slow S-waves and the fast S-wave polarization direction yield fracture density and orientation information. Figure 3 shows an example of this type of S-wave information obtained from the Gessoso formation just above the top-Paleocene target at the Emilio field (Gaiser et al., 2001). Note the clearly defined compartments and fault control along the axis of the structure where fast S-wave polarization and percent anisotropy change. Finally, the asymmetry of PS-waves (only upgoing S-waves) provides a unique ability to characterize fracture dip that is not available from symmetric modes.

Along with stratigraphic, structural, and P-wave fracture information, PS-waves have the potential to solve problems associated with fractured reservoirs. For example, Nelson (2001) points out these problems for different reservoirs: in type I to define the drainage area, calculate reserves, and identify early water encroachment, in type II to identify fracture intensity, geometry (dip), and fracture closure in overpressured reservoirs, and in type III to quantify highly anisotropic permeability and unusual responses in secondary recovery (elliptical drainage area). In type IV reservoirs, it is important to identify reservoir compartmentalization where permeability anisotropy can be opposite to the other fracture types.

Many of these problems have been examined with time-lapse seismic data (Lumley et al., 1999), another area where PS-waves can be beneficial and should play a more strategic roll in fractured reservoir management. They can help quantify the geologic and petrophysical description of the reservoir to improve production history matching, reservoir modeling, and fluid-flow simulations.

Economic benefits

As described above, the fracture-impact coefficient in Figure 2 correlates with fractured reservoir type. It is important to understand that this coefficient is not a physical property of the reservoir, but is rather a measure of the learning curve for developing complex fractured reservoirs. More importantly, it is a direct measure of the increased production costs associated with the lack of large-scale geological and petrophysical properties of the fractured reservoir. Unproductive wells are drilled in a trial-and-error process based on local borehole information without the benefit of adequate seismic data.

Ideally, the fracture-impact coefficient should be zero for all reservoirs. If we can reduce this number by performing cost-effective multicomponent (P-wave and PS-wave) surveys, there is a tremendous potential to produce fractured reservoirs more efficiently. 3D seismic surveys often cost much less than a single well, and 3D PS-wave surveys are economically affordable in both the land and marine environment as compared to the use of S-wave sources. If a survey results in one less non-productive well, there can be a cost savings, if several wells are affected the potential savings are significant. As a reservoir matures, repeat surveys are essential for quantifying large-scale fluid-flow mechanisms within the reservoir. There is a trade-off, of course, between seismic costs and total production costs as a reservoir becomes depleted.

Conclusions

Using PS-wave surveys to identify fractures early in the production history of a reservoir makes economic sense for any type of fractured reservoir and has the potential to significantly reduce production costs. 3D converted-wave data, which are affordable in today's market, provide an additional tool to assess the azimuthal anisotropy associated with fracture density and strike, including fracture dip.

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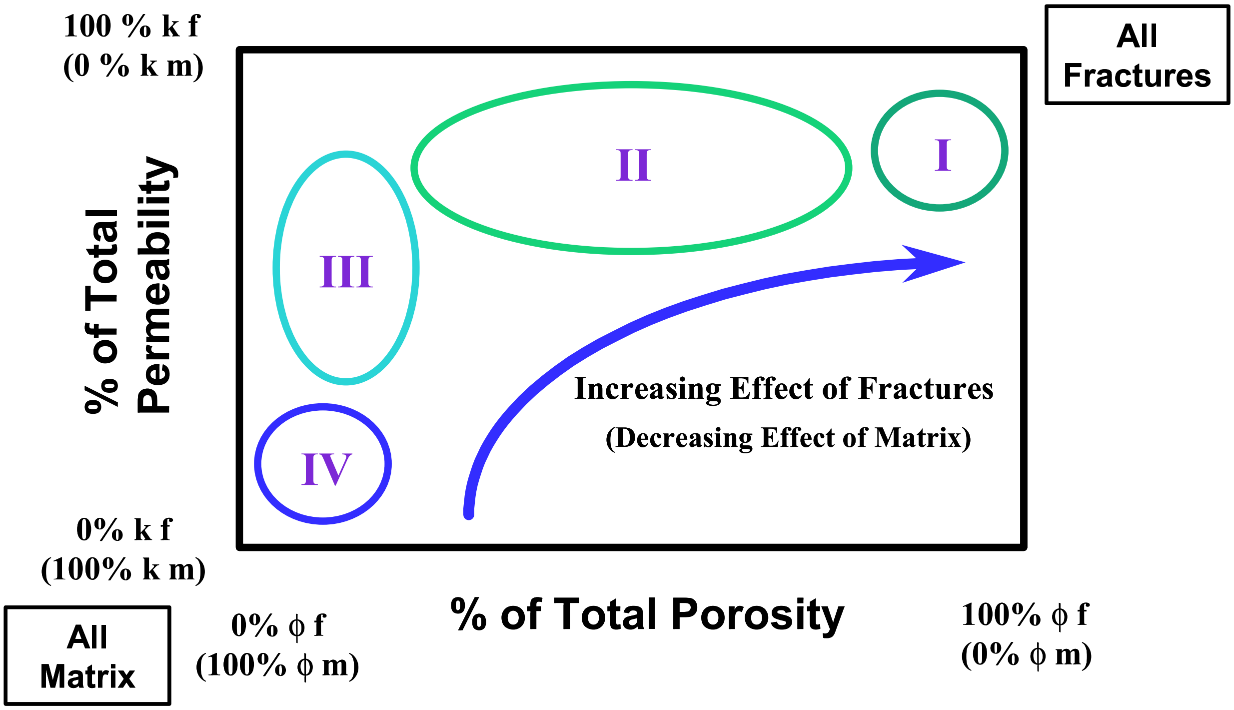


Figure 1. Reservoir classification (after Nelson, 2001) based on percent reservoir porosity and permeability in terms of percent due to matrix versus percent due to fractures. Type I reservoirs are heterogeneous and anisotropic, where fractures provide the essential reservoir porosity and permeability. At the other end of the spectrum, type IV reservoir fractures provide no additional porosity or permeability, but are still anisotropic and can create barriers.

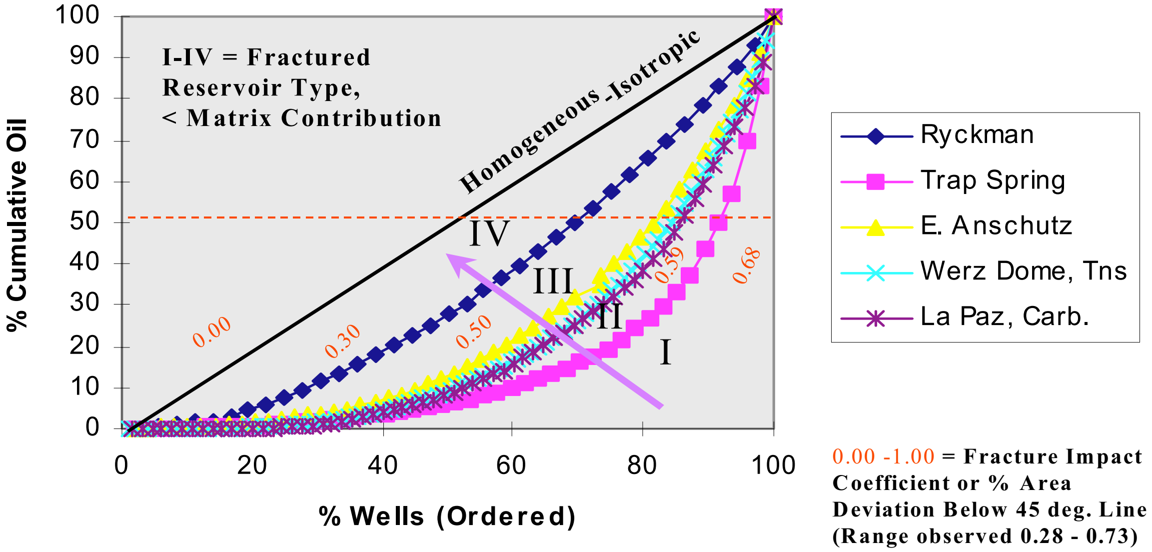
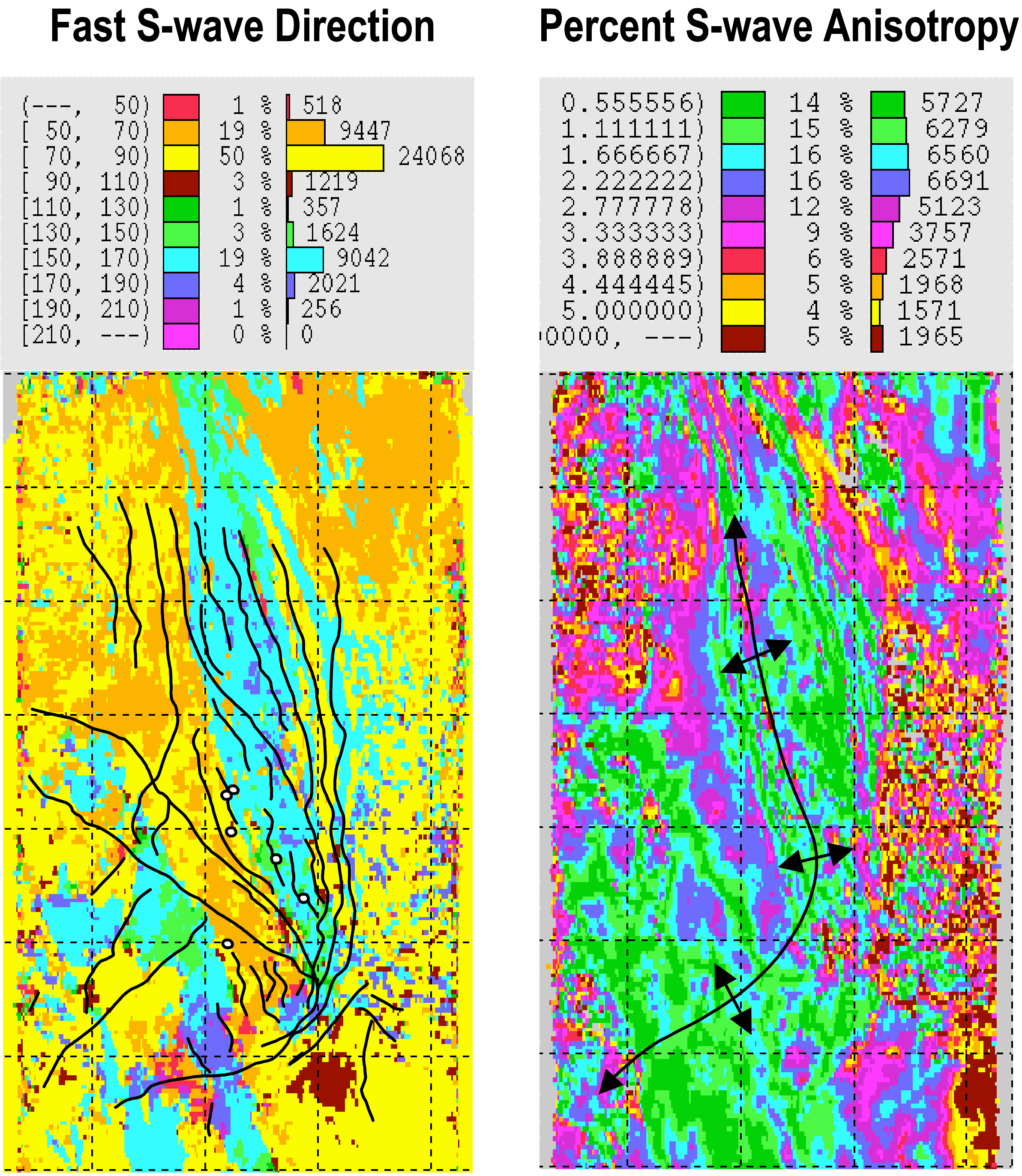


Figure 2. Percent cumulative oil versus percent wells (ordered from least to most productive) is cross-plotted for various fractured reservoirs along with reservoir type I through IV (after Nelson, 2001). Fracture impact coefficient is the percentage of the area below the homogenous-isotropic line, and provides a quantitative measure of increased production costs and fracture denial.


Fast S-wave Direction

Percent S-wave Anisotropy

Figure 3. Fast S-wave polarization direction (degrees) and percent S-wave anisotropy from the Gessoso layer above the top-Paleocene target at the Emilio field. Note the distinct influence of northwest-southeast trending faults and compartmentalization along the axis of the structure.