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Converted Shear-Wave Anisotropy: New Technology for Fractured-Reservoir Management

Abstract

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 seismic surveys, where compressional waves generate shear-wave reflections (PS-waves), can provide complimentary surface-seismic information to help identify fracture properties early in the production history of a reservoir. Based on measurements of shear-wave azimuthal anisotropy, PS-waves can identify fracture density and strike, and because of their asymmetry they are also sensitive to fracture dip. Examples from both land and marine 3D PS-wave surveys demonstrate the potential of using these attributes to characterize subsurface stress variations that are important for open fracture development. The intermediate-scale seismic anisotropy properties obtained from PS-waves 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 PS-wave surveys prevent a small fraction of unproductive wells, 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 velocity 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 of total porosity and permeability (Figure 1). These two important parameters range in percent due to matrix versus percent due to

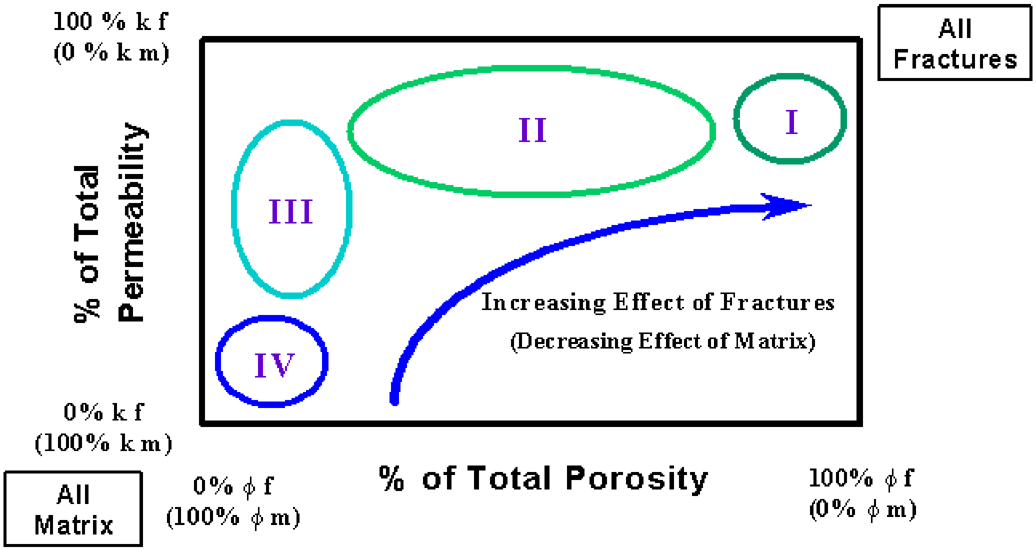

Figure 1. This shows a fractured reservoir classification (after Nelson, 2001) based on percent of total porosity and permeability in terms of percent due to matrix versus percent due to fractures. Type I reservoirs are heterogeneous and anisotropic, where fractures dominate porosity and permeability. Fractures control and assist permeability in Type II and Type III reservoirs, respectively, where more reserves are stored in the matrix. In Type IV reservoirs, fractures provide no additional porosity or permeability, but are still anisotropic and can create barriers.

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 has proven useful in quantitatively characterizing many reservoirs, based on traditional borehole methods of identifying fractures such as core and well-log analyses. 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 and 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. It is well known that fracture properties are fractal in nature (Figure 3). Identifying small-scale fracture properties from image logs and cores 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 large-scale faulting and heterogeneity in the inter-well spaces. Geomechanical modeling typically fills the gap between these scales; however, we can use anisotropy measurements that are sensitive to fracture scales below seismic wavelengths. 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

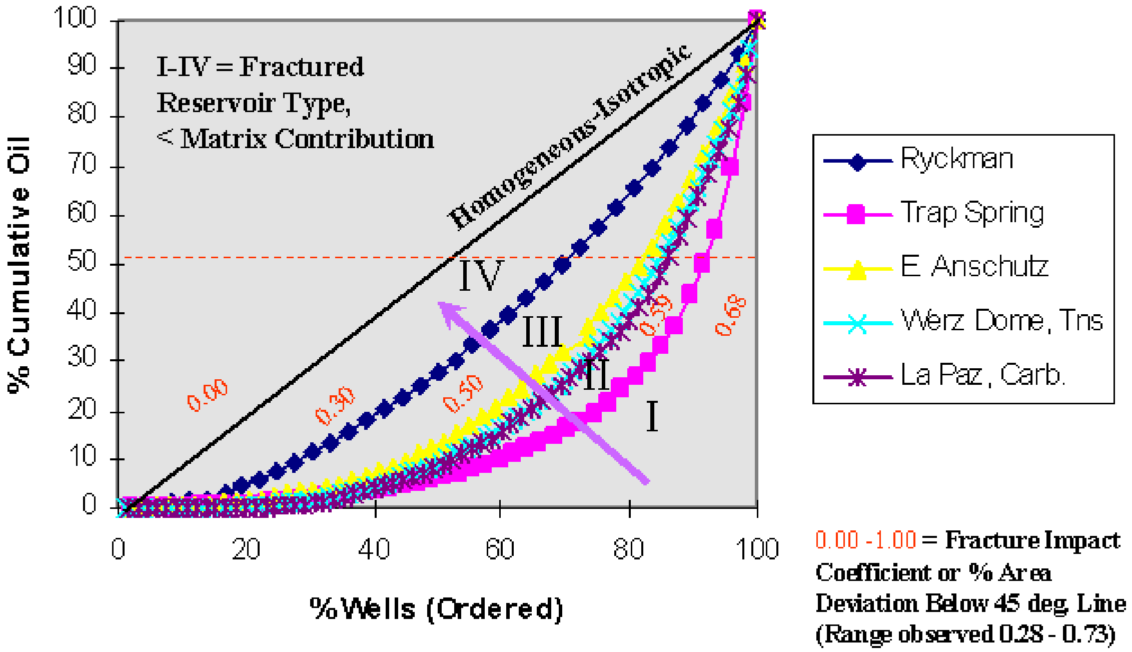

Figure 2. Percent cumulative oil versus percent wells (ordered from least to most productive) is cross-plotted for various fractured reservoirs along with reservoir Type I through IV (after Nelson, 2001). Fracture impact coefficient is the percentage of the area below the homogenous-isotropic line, and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

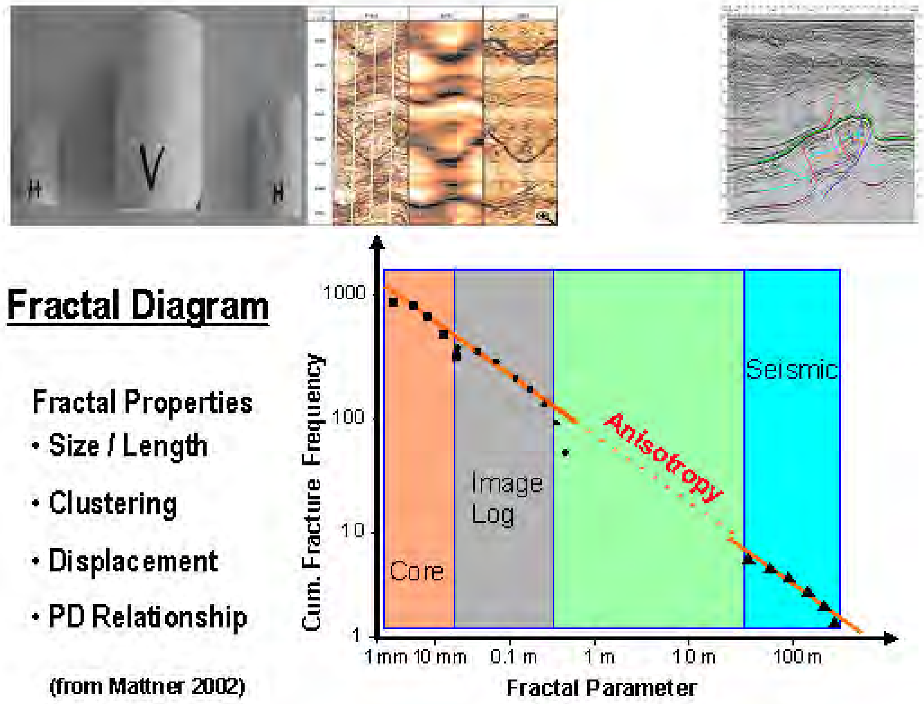

Figure 3. Fracture properties are fractal in nature. Cores and image logs provide the small-scale features of the reservoir and seismic data can provide large-scale features. Geomechanical modeling of paleo-strain fields is typically employed to fill the intermediate scale range, however, there is a tremendous opportunity to fill this range with anisotropy measurements from seismic data. PS-waves can provide fracture orientation and density at scales below seismic wavelengths.

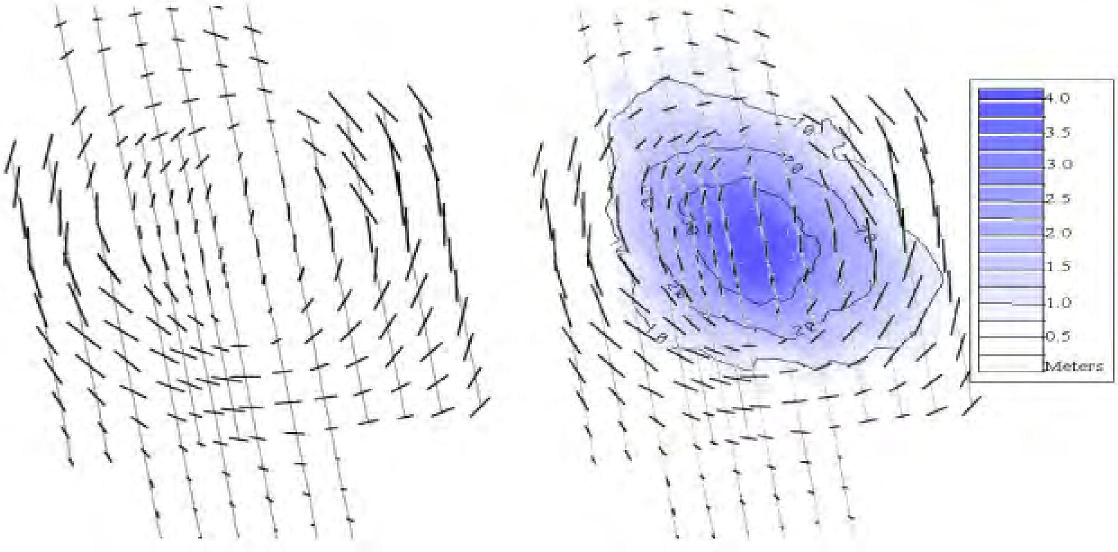

Figure 4. At the left is a vector plot of the fast S-wave orientation (small lines) and amount of anisotropy (length). At the right, these are superimposed on subsidence contours centered on the platform at Valhall field in the North Sea. S-wave polarization directions and amount anisotropy correlate nicely with the orientation and magnitude of this subsidence, and indicate they are very sensitive to these induced changes in the horizontal stress field.

velocity and amplitudes to help quantify fracture orientation, traveltimes of P-waves and PS-waves provide Vp/Vs measures for lithological discrimination and can help in the petrophysical description of the fractured reservoir.

More importantly, PS-waves yield traveltime differences between the fast and slow S-waves in addition to the fast S-wave polarization direction. These S-wave properties are very sensitive to stress variations as shown in Figure 4. Here the fast S-wave direction (short vectors) and amount of anisotropy (length) provide near-surface stress characteristics where they form a concentric pattern around the production platform at the Valhall field in the North Sea. This correlates nicely with sea-floor subsidence that has resulted from the collapse of the reservoir. Figure 5 shows an example of S-wave information obtained from the Gessoso formation just above the top-Paleocene target at the Emilio field in the Adriatic Sea (Gaiser et al., 2001). Note the clearly defined compartments and fault control where fast S-wave polarization and percent anisotropy change. Within the Emilio survey and at the target (not shown) the fast S-wave direction agrees well with the maximum horizontal stress obtained from borehole data: breakouts and induced fractures. Finally, the asymmetry of PS-waves (only upgoing S-waves) provides a unique ability to characterize fracture dip, 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.

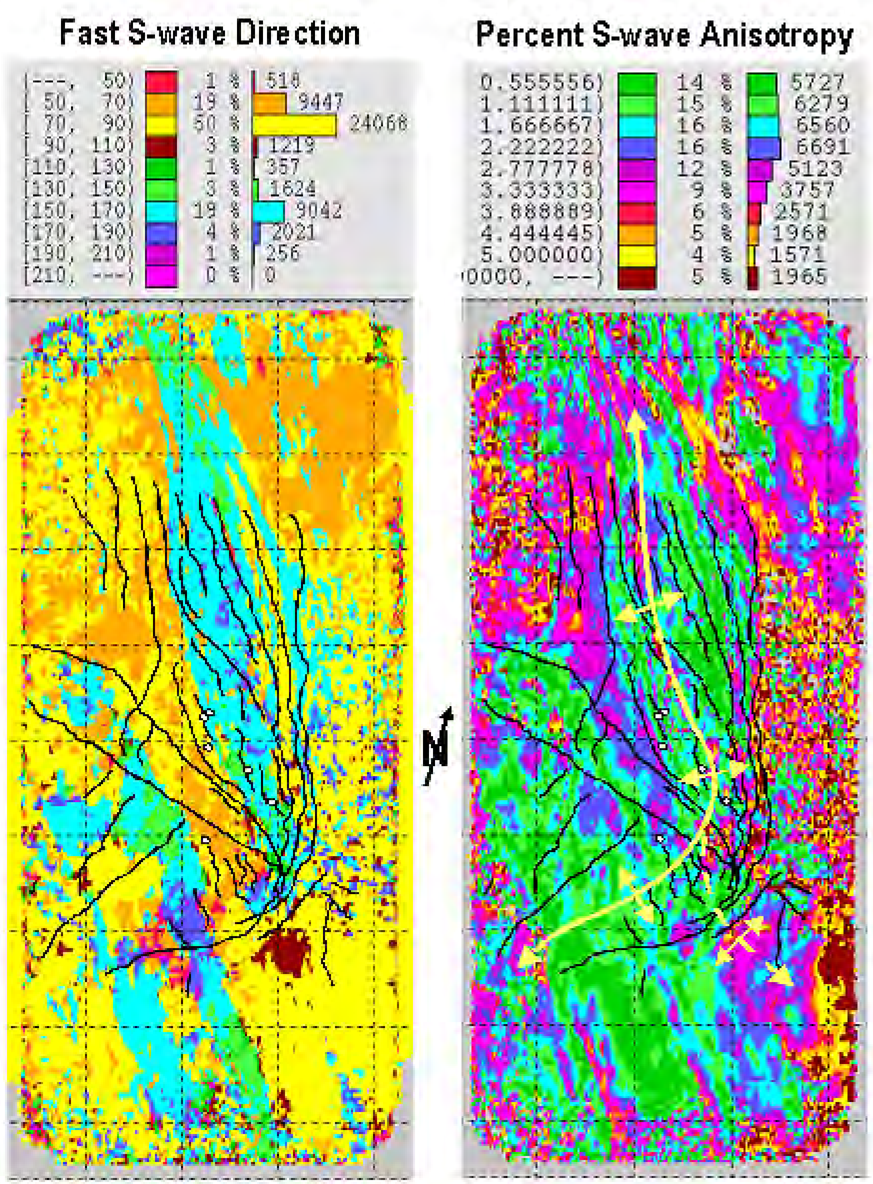

Figure 5. Fast S-wave polarization direction (degrees) and percent S-wave anisotropy from the Gessoso layer above the top-Paleocene target at the Emilio field in the Adriatic Sea. Note the clearly defined compartments related to faulting and where fast S-wave polarization changes direction towards the south. Also, percent anisotropy variations follow the structural high that occurs along the northern part of the trend.

Economic benefits

As described above, the fracture-impact coefficient in Figure 2 correlates with fractured reservoir type. However, it is important to reiterate 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. The fewer non-productive wells drilled, the more the cost savings. As a reservoir matures, repeat surveys are essential for quantifying large-scale fluid-flow mechanisms within the reservoir. There will be a trade-off, of course, between seismic costs and total production costs as a reservoir becomes depleted.

Conclusions

S-wave azimuthal anisotropy appears to be highly sensitive to the maximum horizontal-stress direction. Including 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, and including fracture dip.

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