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Geophysical Corner

The Importance of Fracture Toughness

And its azimuthal variation for fracability analysis

Shale resource plays are associated with low permeability, so hydraulic fracturing is required for their stimulation and production. In order to enhance the flow of fluids with hydraulic fracturing, it is vital to understand the stress field distribution. The efficiency and effectiveness of a hydraulic fracture stimulation are predicated on adequate horizontal well placement in the subsurface. For that purpose, the horizontal wells are usually drilled in the direction of minimal horizontal stress so that hydraulic fracturing takes place in the direction of maximal stress that ensures better reservoir contact and production, which also depends on how a complex fracture network is created by induced fractures.

The complexity of induced hydraulic fractures is a function of in-situ stresses. In an isotropic in-situ stress field, a complex fracture network can probably occur, increasing the contact area and thus the induced permeability, resulting in higher production. While the direct detection or determination of the stress field from seismic data is not possible, indirect methods are usually used for the purpose of extracting such information. These methods are based on the fact that earth becomes anisotropic in the presence of varying in-situ stress fields and fractures, which can be observed seismically.

It is worth mentioning here that the fracture-induced anisotropy and stress-induced anisotropy are closely related and may not be differentiated easily while these two play their individual roles at different stages of hydraulic fracturing. Consequently, few assumptions are introduced in order to address such complexity. In this context, the existence of a single set of vertically aligned fractures in the subsurface is usually considered for deriving the fracture orientation and their intensity from seismic data. Furthermore, an isotropic rock under ambient stress with randomly-oriented and distributed cracks, the shapes of which get changed due to the differential principal stresses, are believed to be the source of stress-induced anisotropy and can be used to extract information about the pattern of induced fractures.

Defining Fracture Toughness

In this article, we propose an alternative approach for extracting the maximum stress orientation and the intensity of stress-induced anisotropy using fracture toughness, which is defined as "the ability of a rock to resist fracturing and propagation of pre-existing fractures." Rocks with low fracture toughness promote fracture propagation. It is common knowledge that the orientation and propagation directions of hydraulic fractures are controlled by in-situ stresses. Being tensile in nature, hydraulic fractures open in the direction of minimum stress due to least resistance offered by a formation in this direction. Therefore, as per the definition of fracture toughness, it must be minimum in the direction of minimal horizonal stress and maximum in the direction of maximal horizonal stress. This suggests that, the azimuthal variation of fracture toughness should allow us to extract the maximal stress direction and thus a workflow is proposed as shown in figure 1. As per this workflow, simultaneous inversion (discussed in the June 2015 Geophysical Corner) is carried out first

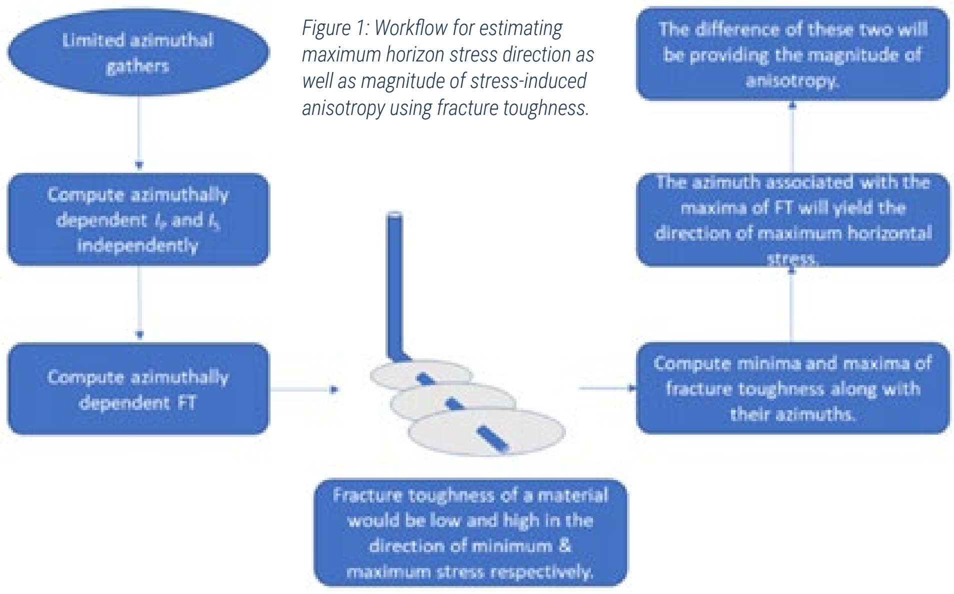

Figure 1: Workflow for estimating maximum horizon stress direction as well as magnitude of stress-induced anisotropy using fracture toughness.

on preconditioned azimuth-sectored gathers by following the proper inversion parametrization. Once simultaneous inversion is done, the fracture toughness volumes for individual azimuths are computed using the P-impedance and S-impedance volumes. To analyze the azimuthal variation of fracture toughness, the simultaneous inversion must be executed on prestack seismic data of individual azimuths in such a way that its azimuthal variation is preserved. Knowing that initial low frequency models, angle dependent wavelets and inversion parameters are key elements of simultaneous inversion, their consistency must be preferred in executing the inversion on prestack seismic data of individual azimuths. As fracture toughness of a material would be low and high in the direction of minimal and maximal stress, respectively, the maxima and

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minima of fracture toughness along with their azimuth are computed first. Thereafter, the azimuth corresponding to the maximum fracture toughness is selected as the direction of maximum horizontal stress. Furthermore, the difference between minimal and maximal fracture toughness will provide the magnitude of stress-induced anisotropy and can be used in estimating the pattern of hydraulic fracturing as discussed next.

Fracture Toughness for Estimation of Hydraulic Fracture Patterns

It is anticipated that fracture toughness will allow us to get information on the pattern of fracture network, whether it is for aligned fractures or a complex network. From the definition of fracture toughness, it is intuitive that a complex fracture network would be formed, if fracture toughness is the same in all directions, i.e. difference between maximal and minimal FT is low and induced fractures can propagate in any direction. However, if the difference is large then fractures are likely to follow a particular direction and will tend to create a planer fracture. Based on these arguments a new attribute is introduced, which is named differential horizontal fracture toughness ratio (DHFTR) defined as

$$DHFTR = \frac{FT_{max} - FT_{min}}{FT_{max}},$$

where FT_{min}, FT_{max} represent minimal and maximal fracture toughness. Hydraulic fractures will be parallel if DHFTR is low, otherwise, the pattern will be complex. Following the workflow mentioned above, the maximal and minimal FT can be computed and used in the estimation of DHFTR. Once it is done, the DHFTR can be crossplotted with HFC (a replacement of brittleness index) for identifying the favorable zones for hydraulic fracturing.

Determining Maximal Stress Direction

For implementation of the FT workflow, a dataset from the WCSB is picked up where the Montney and Duvernay formations represent the zones of interest. As per the proposed workflow, simultaneous inversion was performed on the individual azimuth-sectored gathers. Such inversion yields P- and S-impedance volumes for all the azimuths. Thereafter, fracture toughness volumes are also determined for different azimuths using impedances volume. Having computed these volumes, their maxima and minima corresponding to different azimuths are computed. As fracture toughness would be maximal in the direction of maximal horizontal stress direction, the azimuth associated with the maximal FT value at each time sample is computed and exported as a 3-D volume which is taken as the orientation of maximal stress. Figure 2 shows the vector display of stress induced anisotropy (the length of needles) and maximal stress orientation (needles direction) extracted from the azimuthal variation of FT. Notice a consistent general trend appears to be northeast-southwest on this display. Consequently, the orientation of minimal stress is northwest-southeast, which matches very well with the orientation of horizonal wells placed in the area to the left in the figure. Such a resemblance between the orientation of horizontal wells drilled in the area and orientation of minimal stress is encouraging. However, in the absence of direct stress measurement in the area it is challenging to authenticate such estimation of stresses orientation.

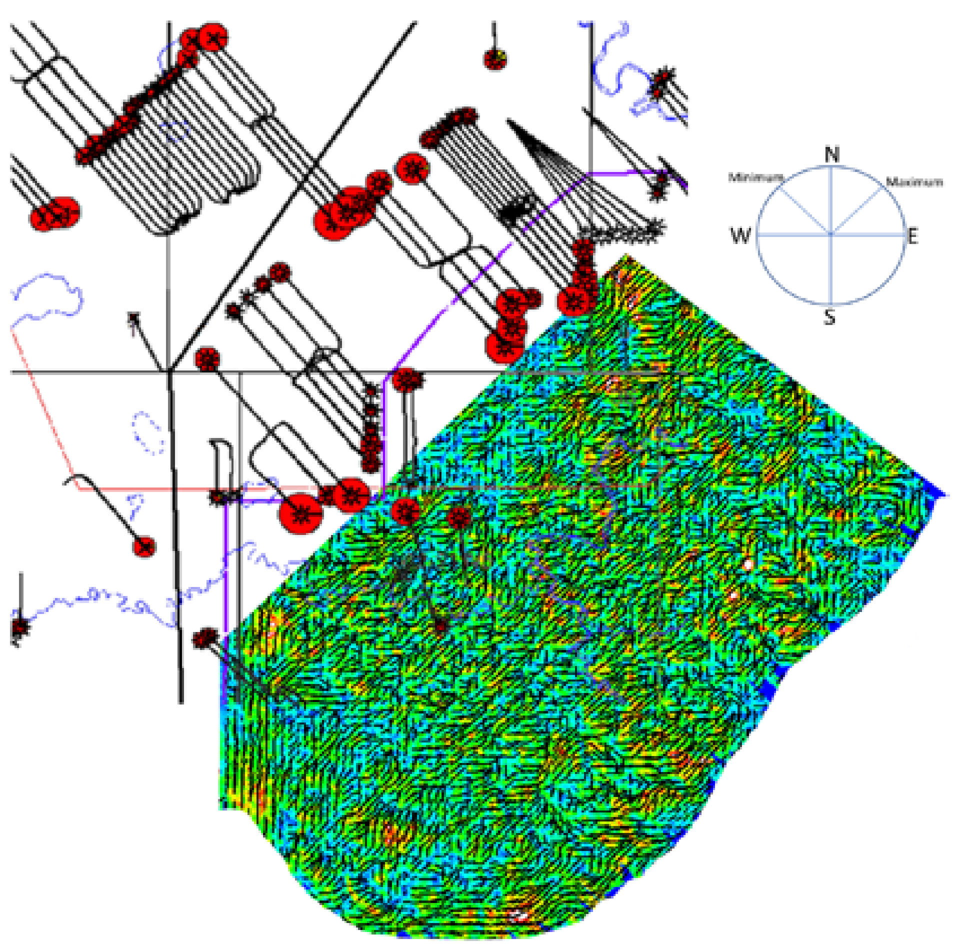

Figure 2: The consistent trend of minimum stress orientation (NW-SE) extracted using proposed fracture toughness (FT) approach seems to correlate well with the direction in which horizonal wells have been drilled in the area of study. Such a resemblance lends a confidence in the extraction of maximal stress orientation using the proposed approach.

Identifying Patterns of Induced Fractures

As mentioned earlier, identification of the favorable zones for hydraulic fracturing can be accomplished in the crossplot domain of DHFTR and HFC. While azimuthal variation of FT carried out on the azimuthal sectored prestack seismic data makes it possible to compute the former attribute, the latter attribute is a function of Poisson's ratio and Young's modulus, and hence is computed from the prestack seismic data generated after stacking all the azimuthal sectored data. Having all these attributes, horizon slices from the HFC volume and the DHFTR volume over Duvernay interval were extracted and are shown in figures 3a and 3b. Hot colors

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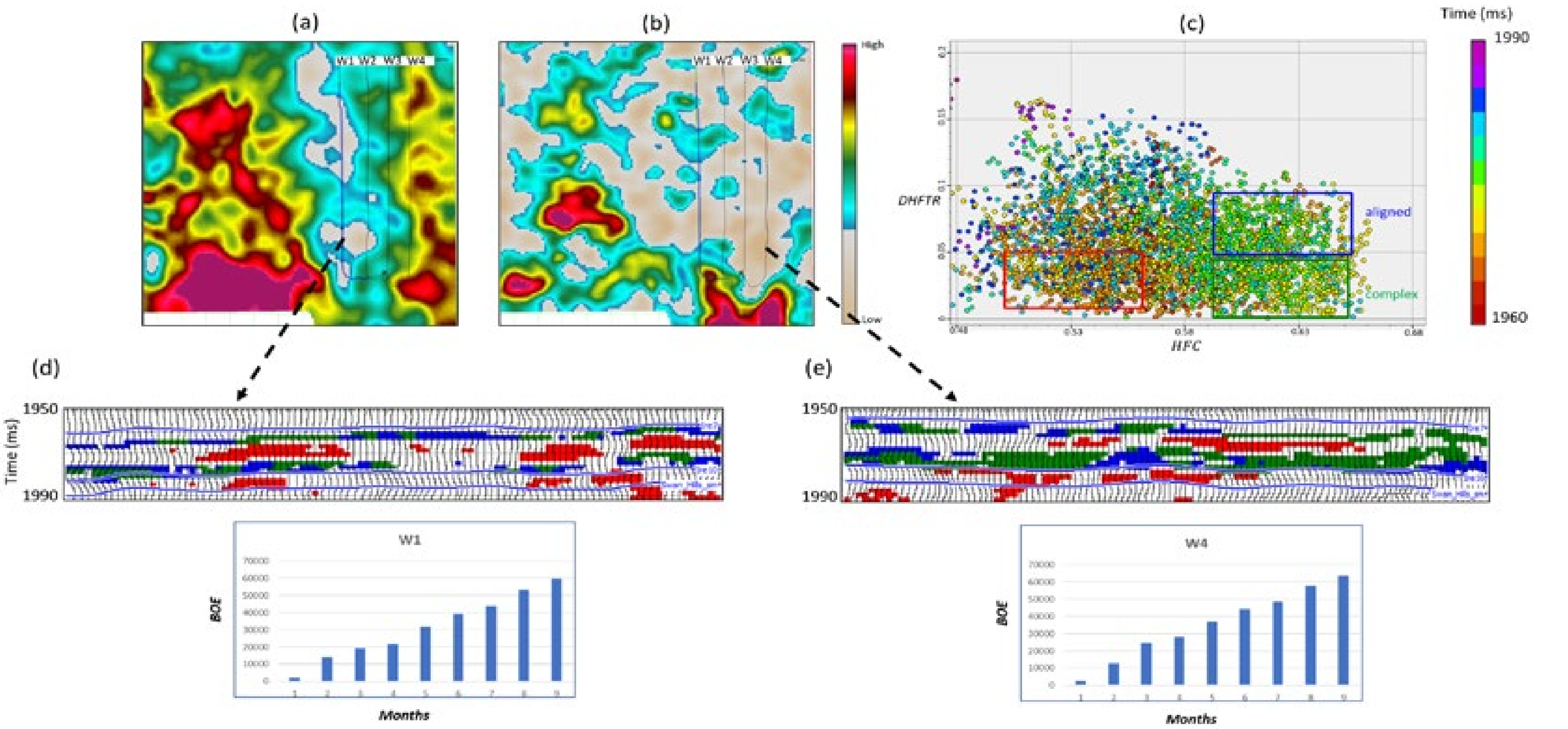

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represent high values of displayed attributes. On these slices, four different horizontal wells that have been drilled from the same pad are overlaid. While a transition in HFC values (low to high) is evident, the changes in DHFTR are not so obvious as we go from left to right. Thus, a crossplot of these two attributes is generated as shown in figure 3c. As per the interpretation of these two attributes, data points enclosed by green and blue rectangles are likely to be coming from a formation that is favorable for a complex and aligned fracture network, respectively. The points enclosed by the red rectangle are not favorable for hydraulic fracturing. To validate this statement, one could make use of production data as ultimately, all these parameters contribute to production data in one way or another. Figures 3d and 3e show the back projection of data points enclosed by different polygons shown in figure 3c on the seismic section along the path of wells W1 and W4, respectively.

The nine-months cumulative production BOE of these wells are also shown as bar charts. Notice, a higher production (>60,000 BOE) for well W4 than of well W1 (<60,000 BOE) as data points corresponding to the path of W4 well are exhibiting higher and lower values of HFC and DHFTR, respectively, which are favorable for a complex fracture network that leads to better production. E

Figure 3: Horizon slice extracted from the (a) HFC, (b) DHFTR volume over the Duvernay formation. Hot colors represent the high values of HFC in (a), i.e. better fracability zones, and stress induced anisotropy in (b). A variation in the fracability is evident as we go from left to right for the wells drilled from the same pad. (c) Crossplot of HFC and DHFTR over an internal that includes the zone of interest along the path of four different wells drilled. Points enclosed by blue and green rectangular indicate the areas of aligned and complex fractures while poor areas for hydraulic fracturing are highlighted by red rectangular. The back projection of the data points enclosed by different polygons on the seismic section along the path of wells W1 and W4 are shown in Figures 3d and e respectively. The nine-months cumulative production BOE of W4 well is greater than of well W1. This variation can be supported with the interpretation of the crossplot as data points preferable for hydraulic fracturing are coming from well W4.