Introduction

The Tiguentourine field is a Cambro-Ordovician gas condensate field that lies in the Southern part of the Illizi Basin in Eastern Algeria and is operated by the In Amenas Association, a joint venture between BP, Sonatrach and Statoil. Over 40 exploration, appraisal and development wells have been drilled since the field was discovered in the 1950's. These wells provide an extensive data set and include evidence of fractures present in core data and positive productivity assistance resulting from the presence of fractures (Figure 1). Where the fracture productivity index (FPI), the ratio of well test permeability to that derived from core/log correlation, is greater than unity this suggests an enhancement to the productivity from that predicted from log data, which we attribute to presence of open fractures.

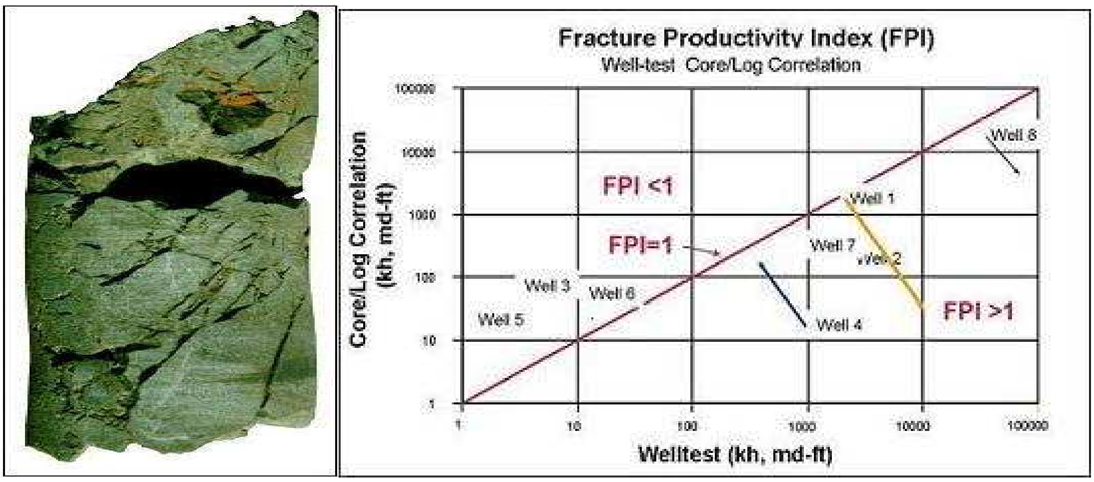

Figure 1. Evidence of open fracturing seen in core data and fracture productivity assistance in well test data.

Fracturing originates in rocks from a number of geological processes, of which tectonic stress is particularly important. The resulting fracture distribution will depend upon both the mineralogy and grain orientation within the rock. The fracture orientation distribution may be anisotropic, as a result of anisotropic stresses. A non-isotropic stress applied to the rock will result in preferential fracture closure. The greater the alignment between the fracture normal and the principal directions of the stress, the less the stress needed to close any given fracture. The resulting fracture distribution will exhibit further anisotropy.

The presence of fractures in matrix rock will influence the mechanical properties, such as velocities, of the rock. Anisotropic fracture distributions will give rise to anisotropic velocities within the fractured medium that will impact seismic reflection data; seismic reflection data recorded at differing azimuths will experience differing velocities within the fractured medium and give rise to different interpretation of the subsurface structure.

A conventional three dimensional seismic survey samples the Earth at what is essentially a single azimuth. A true wide azimuth seismic survey contains many more receivers lines live at any recorded shot point such that the sampling of the Earth occurs equally over all azimuths. Seismic processing techniques exist to make best use of this 'additional dimension' of the seismic data, the azimuth, to estimate the anisotropic properties associated with the rock (Rüger, 1998; Williams and Jenner, 2002). Correctly accounting for these anisotropic variations is crucial to enhancing image quality and reducing the likelihood of mis-positioning errors. The interpretation of anisotropic measurements made from seismic reflection data requires theoretical models that relate material parameters to macroscopically determined properties (Tod, 2003).

In 2004 both walk-around and walk-away VSP’s were acquired that proved that anisotropy could be measured within the bandwidth of seismic reflection data and so a true wide azimuth P-wave seismic survey was then acquired over a small section of the Tiguentourine field. The area was chosen for its flat topography, to coincide with known fault patterns and with wells with image logs or other fracture indicators, for use as calibration tools in interpreting the estimates of anisotropic parameters resulting from the processing of the seismic data.

Well Based Fracture Data

Within the area covered by the wide azimuth seismic survey lie a number of wells, from some of these we have core data and from others image logs from either FMI or GVR tools. As can be seen from a typical FMI image log (Figure 2), the interpreted open fractures lie predominantly in a roughly NNW-SSE orientation and have a near vertical dip. This azimuth of orientation is consistent with estimates of the regional stress direction.

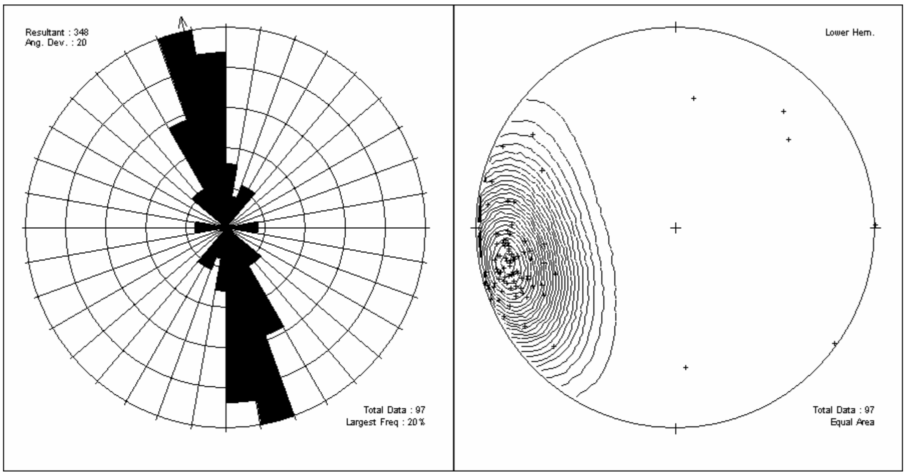

Figure 2. A rose diagram, left, and Schmidt projection polar plot, right, indicating the azimuth and dip of open fracture interpreted from an FMI log in a single well.

Dynamic data, in the form of a PLT, and image log data is only available in combination in a single well to correlate zones of productivity with the presence of open fractures (Figure 3).

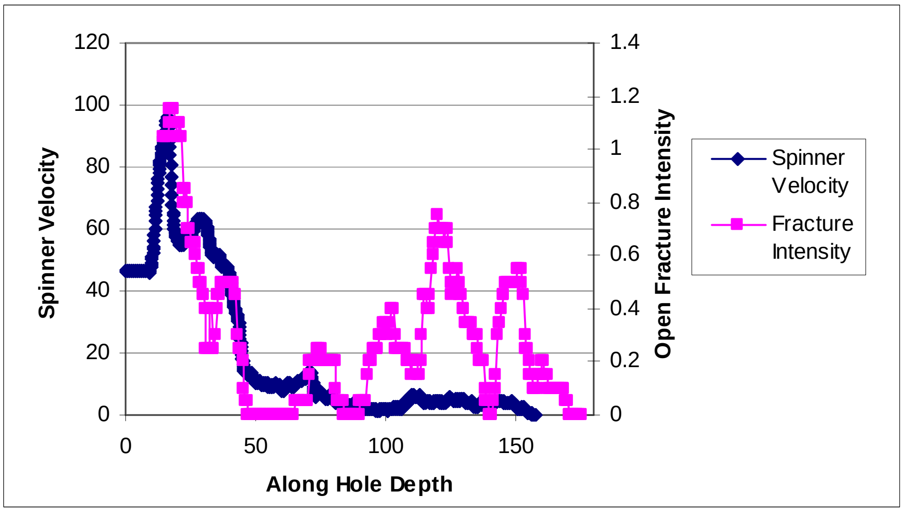

Figure 3. PLT spinner velocity and (rolling average) open fracture intensity variation with measured depth along well bore.

Clearly, not all fracture zones produce; while the (rolling average) open fracture intensity curve suggests that there are two distinct fractured zones within the logged interval, the spinner velocity clearly indicates that only one of these zones contributes to the fluid flow. The level of fracturing varies considerably with measured depth along the well bore and shows no clear correlation with the mechanical or hydraulic properties of the rock. This lack of lithological control is consistent with the hypothesis that the fractures are either fault related or distributed in swarms.

Wide Azimuth Seismic Data

The seismic data was recorded with a high density of source and receiver lines; the source lines were oriented perpendicular to the receiver lines. With a large number of receiver lines active for each source point, the acquired data was of a high nominal fold of 240, with an equal distribution of azimuths (Figure 4). The striping on the fold map due to an acquisition footprint was kept to a minimum by this design.

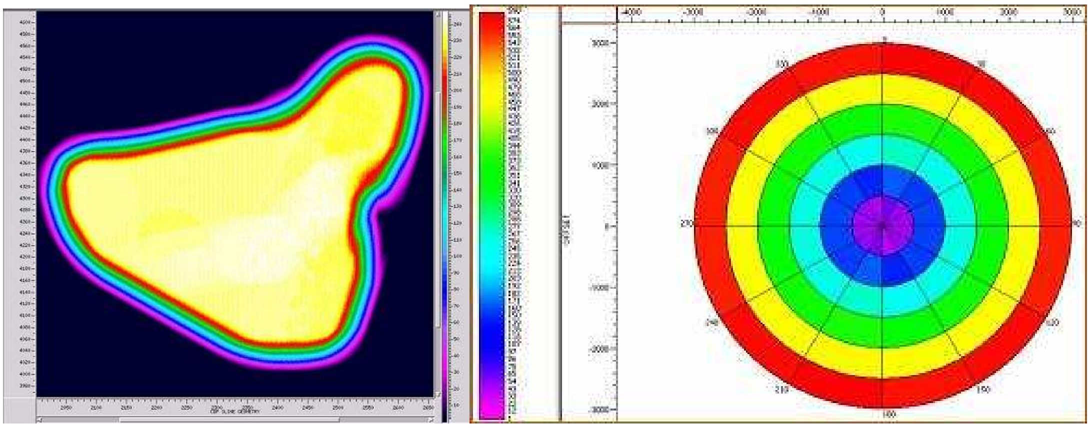

Figure 4. Nominal fold map, left, and offset and azimuth distribution for a single CMP point, right.

The data was processed by GX Technology using a surface consistent approach (Williams and Jenner 2002). The uplift in the resolution and imaging from the wide azimuth seismic data in comparison with the exploration 3D seismic survey acquired in 2000 was significant, but it is the azimuthal attributes of the data that are of primary interest to us here and their potential to indicate regions of higher fracture density. Examining a number of azimuth sorted far offsets from across the survey area (Figure 5), it becomes clear that at a number of these locations the gather remains flat in the overburden section while become sinusoidal shortly after, as marked, indicates an isotropic overburden and an anisotropic reservoir section.

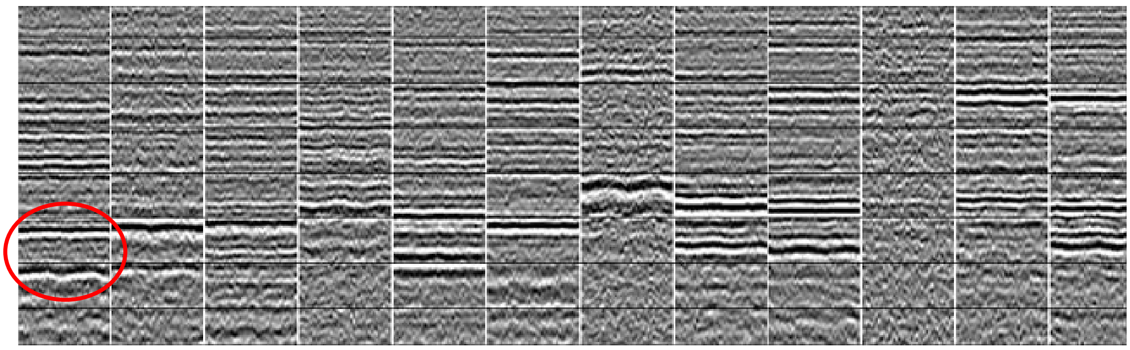

Figure 5. A series of azimuth sorted far offsets showing a range in sinusoidal motion associated with azimuthal anisotropy.

Correlation of well to seismic data

Processing of the wide azimuth seismic data yields estimates of fracture intensities and their orientations using both variations in amplitude (AVOA) and velocities with azimuth. These two techniques have differing approaches to estimating the anisotropic parameters; while the former has the potential benefit of vertical resolution by not being restricted by the averaging involved in using a rolling window for the velocity estimation, it makes an assumption of an isotropic over anisotropic layer interface at every point so is unable to deconvolve the effects of stacked anisotropic layers. In the case of an anisotropic overburden, determining the contribution to the amplitude anisotropy specific to the reservoir interval of interest becomes a considerable challenge. Extracting a trace at two well locations from the interval anisotropy volume and overlaying open fracture intensity logs (Figure 6) indicates peaks and troughs in the log curves broadly coincident with the higher and lower regions of seismic anisotropy, respectively. That the seismic attribute data shows a significantly lower frequency of variation than the log data limits the resolving power of the attribute data to see all of the detail of the variation in the log data, but the broad trend does, however, appear to be captured.

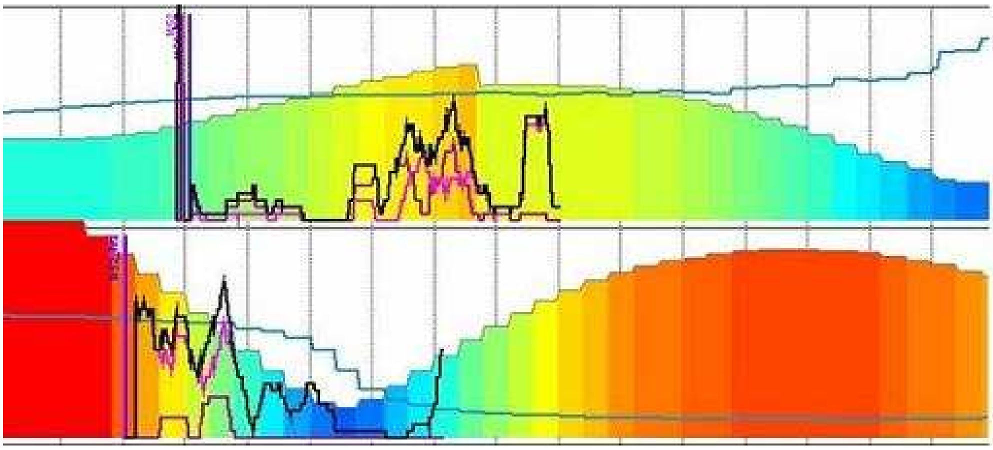

Figure 6. Trace extracted at well locations from interval velocity anisotropy volume (low frequency filled curve) overlain with open fracture intensity curve in dark purple.

Conclusions

We have successfully acquired and processed a full azimuth seismic survey. The raw data indicates evidence of anisotropy, and estimates of the magnitude of that anisotropy from interval velocities show broad correlation to image log data. This provides us with the opportunity to locate future wells in regions favourable to fracture enhanced fluid flow.

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