Permeability Multiplier Prediction Utilizing Wide Azimuth 3D OBC Seismic Data*

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Abstract

This work describes an approach in characterizing fractured reservoir of upper Jurassic Carbonate using seismic azimuthal anisotropy. The ultimate objective of this study was to attempt to map permeability multiplier inter-well for the contribution to the simulation model and the subsequent development plan of an oil field offshore Abu Dhabi. The azimuthal seismic anisotropy for fracture prediction method showed fractures that are similar to those indicated by well methods and therefore seismic could be used to detect natural fractures between wells. The confidence in the seismic fracture prediction method's ability to capture information about fracture in Carbonate reservoir has increased if the well data are accurately integrated. The study interval exists in the dense zone of the Upper Jurassic reservoir with total thickness of 120 ft. The fractures evidence have been compiled from well data, such as Core, FMI, orthogonal shear sonic, production test, multi-arm caliber….etc. Present day stress is captured from induced fractures direction, borehole breakout, offset field stress map, Eocene structure map and world stress map. All compiled information has indicated maximum horizontal stress of N10°-30°E direction. The four sectored wide azimuth seismic data set have been fitted to an ellipse to find out the fast and slow velocity direction and the difference between those velocities. The Interval Velocity is sensitive to Lithology, porosity, pore fill; the Vint Slow is sensitive to the minimum horizontal stress. The lower the VINT Slow, the less the minimum horizontal stress, which allows the fracture apertures to be more open.

It is observed that the seismic anisotropy map for fractures showed a dominated direction (NNE-SSW) that match with present day stress field. The azimuthal Vint records current day stress field, not paleo-stress field. Good correlation between well permeability multiplier and the fractures map, particularly at the two reference wells. Following the analysis of the azimuthal seismic anisotropy maps such as azimuthal amplitude and interval velocity, a good correlation has been observed between the seismic anisotropy components and the production well test. The two seismic anisotropy components that showed a great deal of link with the computed well permeability multiplier are the computed slow interval velocity and the anisotropy azimuth deviation from the known present day stress. Therefore, the following equation has been written to invert those azimuthal seismic components into permeability multiplier. The resulted map showed match at both input wells and one blind well.

$$\text{Perm. Mult.} = (X * \text{Vint Fast-Slow}) + (Y / \text{Vint Slow}) + \cos(\text{Ref. AZ} - \text{Seis. AZ})$$

Introduction

The subject structure is an undeveloped and located about 120 km offshore of Abu Dhabi. The structure is a North-South elongated anticline, approximately 15 km by 7 km in size and covered by orthogonal wide azimuth OBC. The subject reservoir is 450 ft thick coarsening upward carbonate and considered as the main hydrocarbon container. The subject carbonate reservoir lies immediately below 250 ft thick of heterogeneous dolomitic reservoirs (each 15-25 ft thick) intercalated in anhydrite thin layers and is divided into upper (porous) and lower (dense). Reservoir overburden layers; the thick solid anhydrite layer and the thin intercalation of dolomite and anhydrite are one of reasons energy attenuation, multiple diffraction and wavefield deformation in the underlying seismic image for the subject reservoir.

The study interval exists in the dense zone of the Upper Jurassic reservoir with total thickness of 120 ft. The study interval covers both UJ-DM1 and UJ-DM2. Well methods confirmed that both layers are fractured. The occurrence and distribution of fractured corridors is one of the main subsurface uncertainties affecting the development plans and its production. The study area is only 6 km by 6 km and located at the structure crest where the 3D seismic data were pre-stack migrated after sectoring into four azimuths. In low primary permeability reservoir layers of Upper Jurassic, production of oil and gas is expected to depend on natural fractures and / or induced fractures created by high-pressure injection of fluid. The horizontal extent and azimuth of these fractures depend on present horizontal stress fields.

Anisotropy can be defined as the value of measurement does vary in different direction of measurement. The routinely encountered anisotropic quantities are velocity, amplitude, attenuation and permeability. The seismic wave propagation in anisotropic heterogeneous media can be simplified in two types of anisotropy and they are Vertical Transverse Isotropy (VTI) for characterizing horizontal layers and Horizontal Transverse Isotropy (HTI) for characterizing vertical fracturing. Ordered heterogeneity such as fractures and stress variation can give rise to azimuthal anisotropy (HTI). This study is focusing on horizontal transverse isotropy to try to understand the relationship between the seismic azimuthal anisotropy and the observed well permeability multiplier.

Methodology

Azimuthal Seismic Anisotropy Analysis for Fracture map computation

The four azimuth sectors were chosen so that the expected Maximum horizontal stress azimuth is in the middle of one of the quadrants. This type of Azimuthal analysis presumes that flat layers and vertical cracks is the summary of the rocks. Stacking velocity (Figure 1) and Amplitude were used for azimuthal anisotropy analysis. In case of unequal stress (anisotropy) exists in the overburden layers, then the azimuthal variation in stacking velocity and reflection amplitude at the deeper reservoir level for both staking velocity and amplitude will have the overburden anisotropy interference. In order to remove the overburden anisotropy effect, a time window for anisotropy analysis was selected to cover only the fractured layer with few milliseconds above and below the window. Therefore, anisotropy analysis was conducted utilizing layered interval velocity and widow of RMS Amplitude is expected to remove the overburden anisotropy effect.

With Four Azimuth Sectored seismic 3D dataset, we desire to determine the azimuthal variation in a measurement. To do so, we fit an ellipse to four values. The ellipse fit exercise was conducted for RMS velocity and RMS amplitude. The transformation of these RMS velocity attributes into Interval Velocity attributes is performed by use of a Dix-like equation that incorporates ellipse coefficient, and output the fast interval velocity, slow interval velocity and the azimuth of the fast one. The four azimuthal values at each point have been fitted to an ellipse for both interval velocity and RMS amplitude. “To fit an ellipse” is equivalent to fitting a cosine 2-theta curve. The ellipse, or cosine 2-theta, is the mathematical designation of a measurement that has its Maximum value and its Minimum value at 90° to each other (Figure 2). The outcome of the ellipse fit computations is the azimuth of the fast velocity; fast and slow velocity values.

The interval velocity is sensitive to lithology, porosity and pore fill. The Slow interval velocity (Vint Slow) (Figure 2) is sensitive to the minimum horizontal stress. The fast direction of the P interval velocity is interpreted as parallel to the open fracture network and the maximum horizontal stress (Lynn, 2010). The ellipse fit for both Azimuthal Seismic Velocity and Amplitudes have been utilized to compute the maximum and minimum values that are 90° apart.

Then the output of the ellipse fitting and computed interval velocities are used to make an Icon Map (Figure 3). It is necessary to have an Icon (a symbol) that holds three numbers: a length (always a positive value), an azimuth (always the Fast Direction or the Bright amplitude direction), and a color (the velocity or the amplitude value). By choosing to process four azimuth sectors, we obtain data sensitive to any azimuth of fracture (or max horizontal stress). It is worth to mention that, It is very important to not interpolate beyond one bin when gridding the AZIMUTH values. The reason is that, the average N179°E with N01°E, the answer is N0°E, but the computer will determine the average as N90E WHICH WILL MAKE THE AZIMUTH TURN OUT WRONG.

The interval velocity anisotropy is known to be good predictors of fracture orientations. The lower the VINTslow, the less the minimum horizontal stress, which allows the fracture apertures to be more open. If there are pre-existing structural features (faults, flexures, etc. (Figure 3)) that occurred in the geologic past, we anticipate the P-wave anisotropy to be influenced by these pre-existing zones of weakness. In the pilot study area, either these pre-existing structures are a single set of vertical aligned fractures or multiple sets of vertical fractures (see Figure 2). The UJ-DM1+2 Velocity anisotropy icon map displayed with the top UJ-D twt structure map. The length of the vector is proportional to the degree of anisotropy while the direction indicates the azimuth of maximum anisotropy. Multiple sets of vertical cracks appear as random azimuths, low interval velocity fast-slow, and low maximum interval velocity. For simplicity, I assume that if there are more than one fracture set, only one will be parallel to the maximum horizontal stress and open now, which is the NNE-SSW trend. When interval velocity fast minus slow (Vint Fast-Slow) is large and interval velocity maximum (Vint Fast) is high this is indicative of one set of cracks; but when Vint Fast-Slow is large and interval velocity is low it is indicative of two sets of orthogonal cracks; see the magenta polygon in Figure 3. Multiple sets of vertical cracks appear as random azimuths, low interval velocity fast-slow, and low maximum interval velocity.

The resulted azimuth of Vint Fast has shown a spatially variant maximum horizontal stress only at the structure crest (see Magenta outlined polygons of Figure 2). However, the dominant direction based on the statistics of the azimuth of Vint Fast is NNE-SSW and minor small component in the NW-SE (Figure 2 rose diagram). The pilot study area is small, covering only the structure crest, which is severely faulted and showed some influence of the paleo-structure to the anisotropy azimuth. The results at the structure crest should be checked against the multi-arm caliper logs of the future development wells to try to understand how the maximum horizontal stress changes across the area. In addition, the Vint-Slow icon map, co-rendered with the fault interpretation and structure map, clearly shows how fault compartmentalization in the stress field can be mapped (the Magenta outlines of Figure 2 illustrate the point). The results were not only geologically consistent but also geophysical and geomechanically consistent so that it can be used to forecast the behavior and performance of fractured reservoirs.

In addition, we obtain a “goodness of fit” or RMS (root mean square) error between the model (the ellipse) and the data. Therefore, that goodness of fit can be called Reliability. “Reliability” = (Max-min value) / RMS error. “Reliability” has been used to only show on the map the “Reliable” values, particularly with the anisotropy results from azimuthal RMS amplitude data. For the RMS amplitude maps, we posted data that were greater than three. The error map for the azimuthal amplitude showed less reliable maps compared to the azimuthal velocity results.

Computing Permeability multiplier map from seismic azimuthal anisotropy results

In the map of Figure 2 there is indeed a low Vint Slow anomaly west of W-9 , that would be interpret that area as prospective for finding open fractures that will flow fluids. For W-9, the maximum horizontal stress from well methods matches the computed Vint Fast azimuth of N10-20E. Therefore, the azimuth of Vint Fast is also sensitive to the maximum horizontal stress direction, which is parallel to the open vertical aligned fractures that are flowing fluids. The open fractures expected there is the N-S azimuth (azimuth of Vint Fast) which is parallel to the regional maximum horizontal stress. West of W-9 there is a combination of both Vint Slow and high anisotropy. Development wells are selected to test that anomaly which is envisaged to have good production of oil from fractures UJ-DM1+2.

For W-7 well in the vector map of Figure 2, the Vint Fast-Slow (anisotropy=icon size) is small and E-W / NW-SE icons (the stiff direction) are the well local maximum horizontal stress. Also at W-7, the Vint Slow is relatively larger than Vint Slow at W-9. Concerning W-9, the N-S approximate direction of Vint Fast is the stiff direction, or maximum horizontal stress direction, and that correlates with the well methods maximum horizontal stress. The computed azimuths at W-7 are almost perpendicular to the present day stress. Therefore, the fractures that are filled with fluid in W-7 are likely fewer conduits compared to those at W-9.

Following the analysis of the azimuthal seismic anisotropy maps of azimuthal interval velocity and azimuthal amplitude, a good correlation has been observed between the seismic anisotropy components and the production well test (Figure 2 cross-plots). The two seismic anisotropy components that showed a great deal of link with the computed well permeability multiplier are the computed slow interval velocity and the anisotropy azimuth deviation from the known present.

The simulation modelers normally would compute the permeability scalar or multiplier to come up with a match between the core permeability and the well test permeability (Table 1). The above detailed azimuthal interval velocity analysis concluded a good correlation observed visually between the Slow Interval Velocity (Vint Slow); azimuth of the fast interval velocity (azimuth Vint Fast) and the permeability multiplier at W-9 and W-7 wells.

Currently it is almost impossible to derive permeability from seismic data, but three seismic components were observed after the azimuthal velocity analysis and found responsible for the excellent match of the seismic azimuthal Velocity map and the production well test results. Those three components were combined in a brilliant method with well data to derive inter-well-region permeability multiplier map (see Figure 4). The estimated permeability multiplier was blind tested with field data and reasonable correlation coefficient was achieved at W-5 blind well.

The computed permeability multiplier map can guide modeler's to forecast behavior and performance of fractured reservoirs. This type of work if conducted to the full field scale, it can contribute to the subsequent development plan and drilling risk mitigation.

Therefore, the following equation has been written to invert those azimuthal seismic components into permeability multiplier. The resulted map showed match at both input wells and one blind well.

$$\text{Well Perm. Mult.} = (X * \text{Vint Fast-Slow}) + (Y / \text{Vint Slow}) + \text{COS}(\text{Ref. AZ} - \text{Seis. AZ})$$

The initial permeability multiplier map has been computed only with the first two seismic components (above equation) where Vint Slow does exist as follows:

Extract seismic component values at both wells, and then substitute in the above,

> W-9 Perm. Mult. 10 = (X * 339.78) + (Y / 5162.77)
> W-7 Perm. Mult 5= (X * 95.032) + (Y/ 5240.54)
> Solve Y @ W-9, and then substitute Y for W-7 equation to get X value.

Now the values for the two unknowns to convert seismic to permeability scalar are X = 0.020241462 and Y = 16120.00609

Assumption: VintFast-Slow and VintSlow has equal contribution to permeability scalar.

The permeability scalar of 10 for well 9 can be interpreted as arising due to:

1) The larger magnitude anisotropy (VINTfast-slow) at well 9, ~340 m/sec difference in the interval velocities [when compared to well 7, where it is ~ 95 m/sec difference, a lower magnitude anisotropy]. When one set of vertical aligned fractures are present, then the greater the VINTfast-slow, the greater the fracture density;
2) The local max horizontal stress at well 9 is parallel to the regional max horizontal stress, N-S.

The permeability scalar of five at well 7 is agreeing with the seismic that the effective open fracture density is less at well 7, compared to well 9. The magnitude of the anisotropy (VINTfast-slow) is larger at well 9, and smaller at well 7. This positive and important result has been achieved with this analysis.

Conclusion

It is observed that the seismic anisotropy map for fractures showed a dominated direction (NNE-SSW) that match with present day stress field. The seismic azimuthal interval velocity and azimuthal amplitude should be considered for full field analysis after the reasonable results for fractures mapping. Good correlation between well permeability multiplier and the fractures map, particularly at the two reference wells.

Therefore, the derived seismic anisotropy components were used to write two equations for two unknown's multipliers to invert the slow interval velocity and the Vint slow-fast (anisotropy) into permeability multiplier at each individual grid point. The resulted map showed match at both input wells and one blind well. The anisotropy from amplitude-based maps has been generated, but unfortunately, the amplitude data quality showed high rms error in ellipse fit. In addition, the computed azimuth of the bright amplitude did not show a good match with the well methods present day stress. However, the azimuthal amplitude maps can be co-rendered with the azimuthal velocity to derive more interpretation.

Acknowledgments

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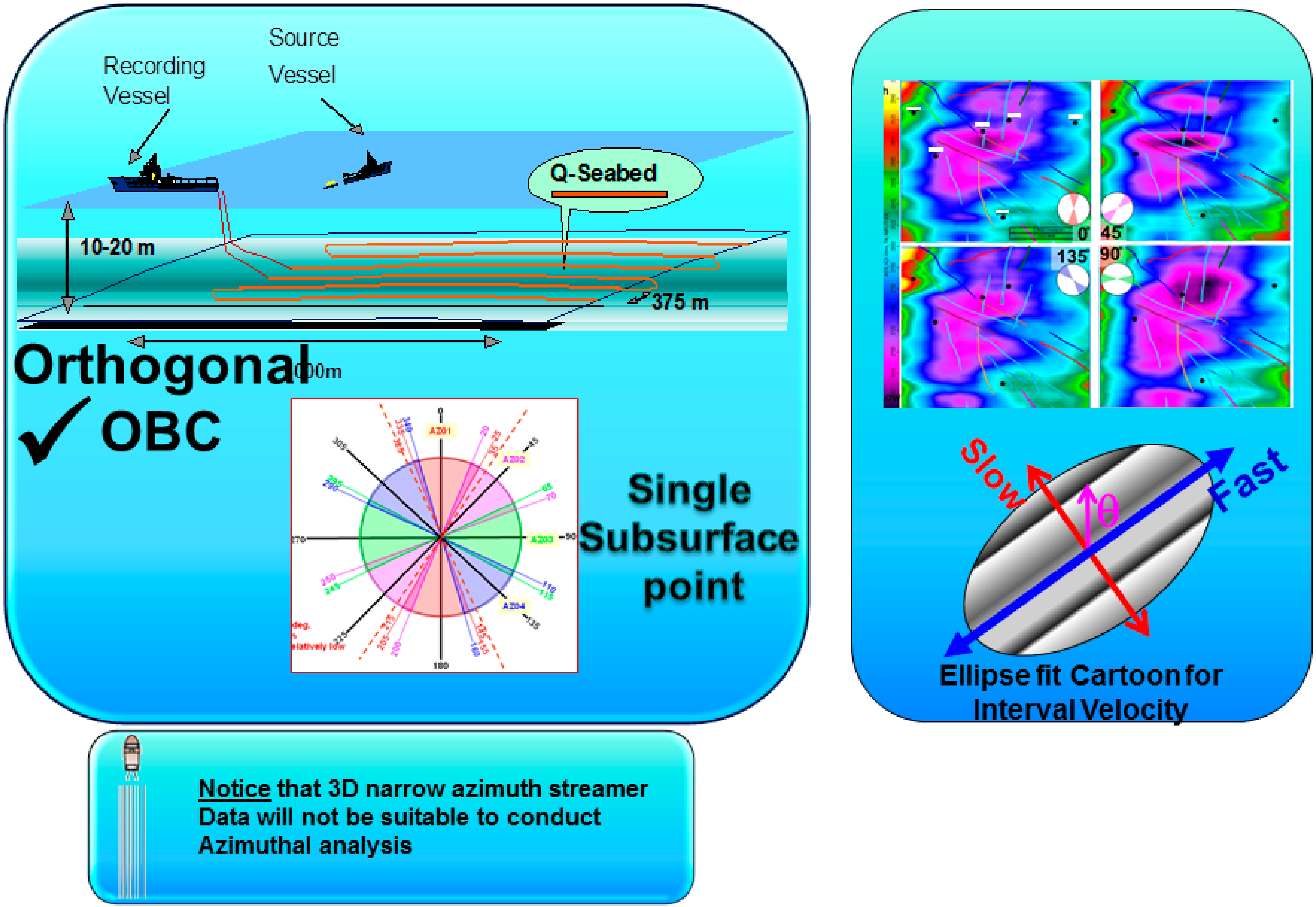

Figure 1. Orthogonal wide azimuth OBC (left); Azimuthal RMS velocity (right).

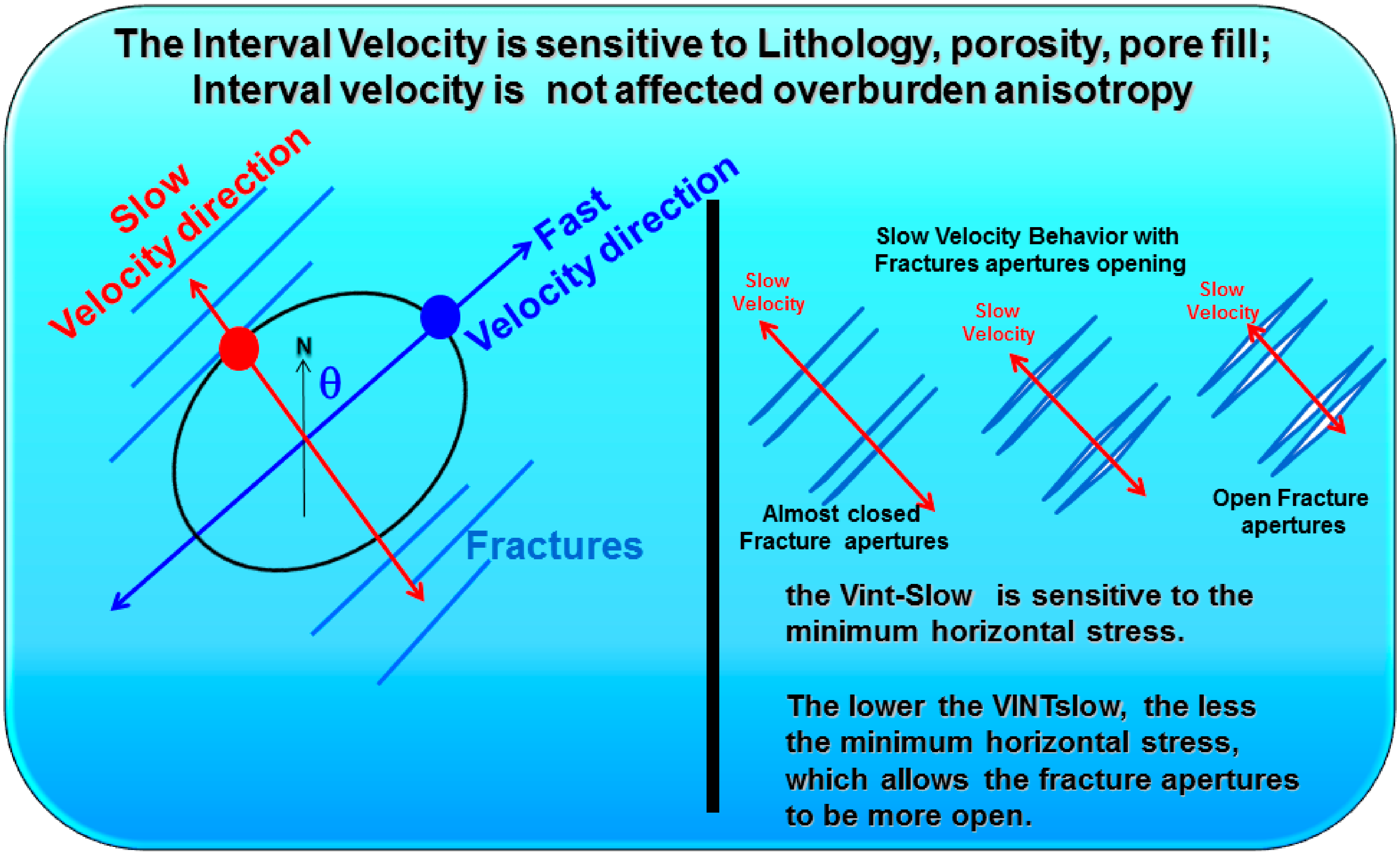

Figure 2. Interval velocity responses with fracture presence.

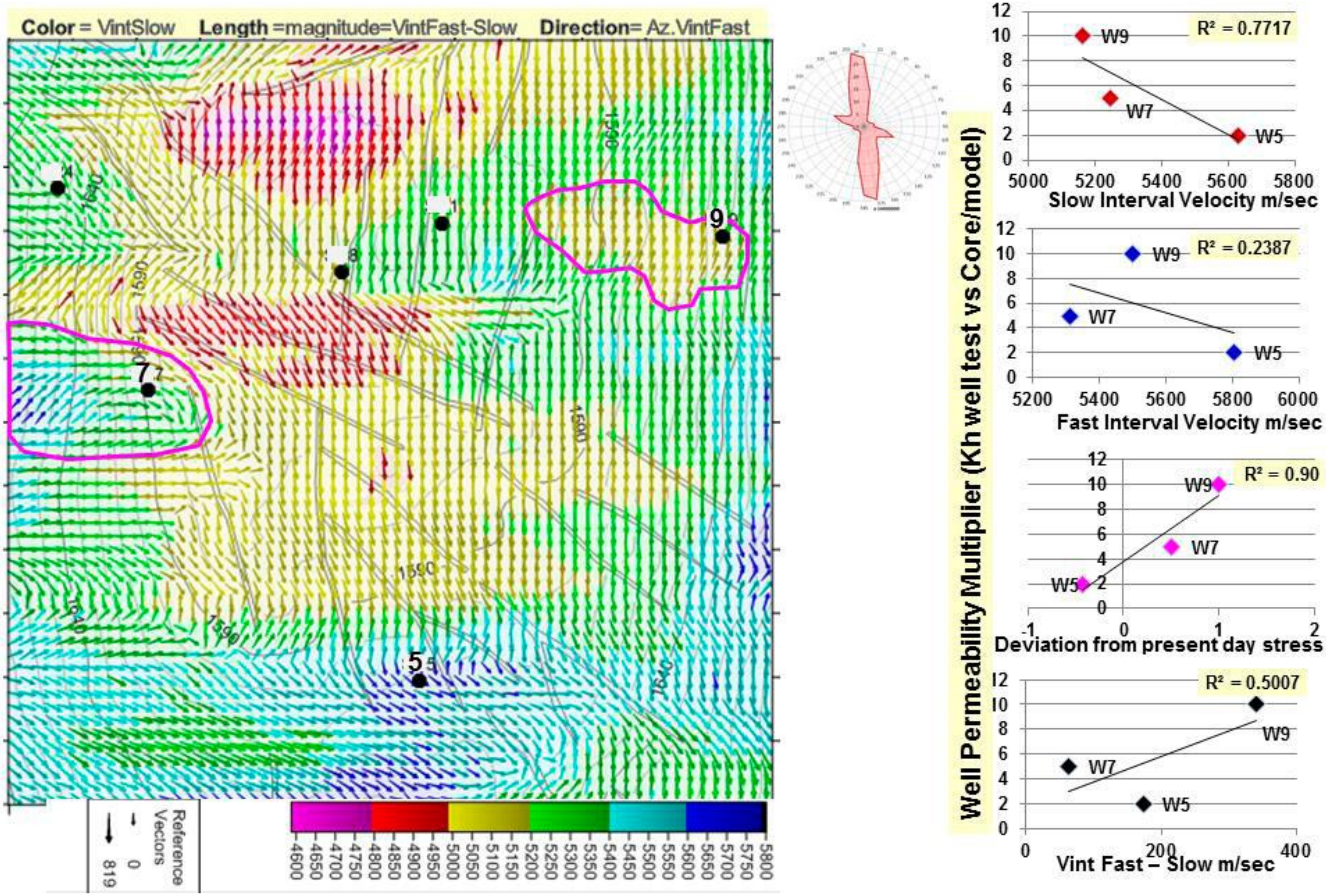

Figure 3. Fracture map (left) and cross-plot of well(s) permeability.

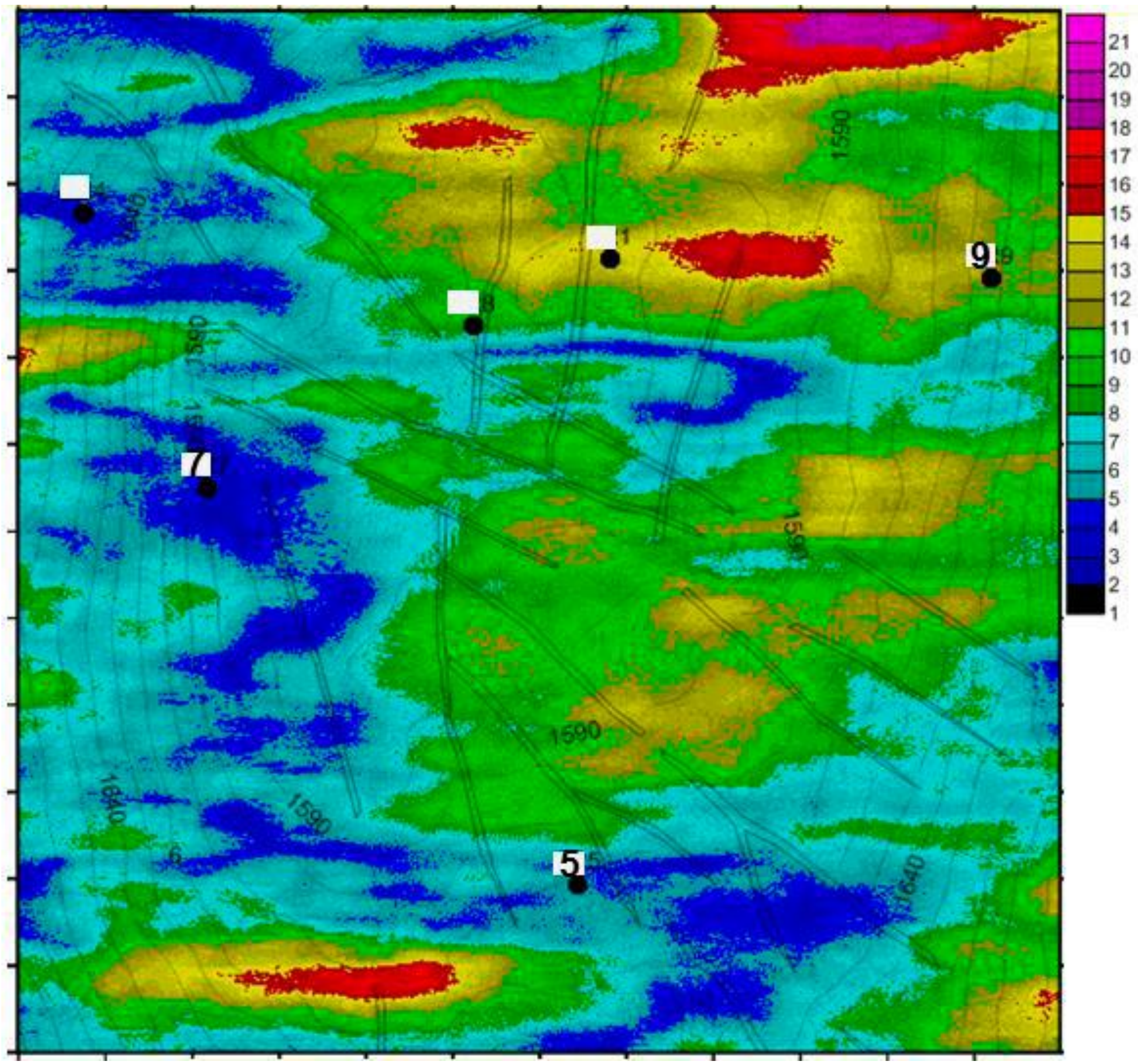

Figure 4. Permeability Multiplier map.

Well Perm. Multiplier		
W-7	UJ-DM2	4.39
W-9	UJ-DM1	11.64
W-5	total D	1.93

Table 1. Well Permeability Multiplier.