W042

Fracture Delineation in a Carbonate in the Case of Signal Distortion from Overlying Sediments

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SUMMARY

The use of DWM in the oilfield in the Timan-Pechora gas & oil province, present in the Lower Devonian carbonates, allowed us to obtain information about previously unknown zones of fracturing. Analysis of the DWM transformation procedure using different apertures has shown that these areas have various different systems of fractures, and their superposition leads to an increase in the absolute amplitudes of the DWM data cubes. These amplitude anomalies are closely correlated with the potential productivity of wells within this oilfield. Fracture azimuths delineated on the basis of DWM in the proximity of the wells are in good agreement with XMAC data and passive seismic data after fracking operations were conducted.

Introduction

The fractured carbonate oil play described in this paper is located in the Timan-Pechora Basin in the Varandey-Adzvinskaya structural zone. The reservoir resides in an anticline trap at a depth of 3100m to 3200m within a carbonate reservoir of Lower Devonian age. The reservoir rock has very low porosity and permeability and its total thickness is 80 metres.

The field is located well above the Arctic Circle which greatly increases the development costs and therefore the E&P Company must find ways to limit drilling risks and optimize well productivity. All of the high production wells are associated with the presence of significant fracturing. The most direct evidence of the criticality of fracturing for well productivity is the fact that the permeability at the well locations (calculated from hydrodynamic studies) is on average 16 times higher than the permeability of the rock matrix as measured from cores. In some cases this factor increases to as much as 70 times permeability at the very productive wells. Therefore, the key to risk mitigation during the development of this field is the ability to delineate the location of the fracture systems and if possible to predict the relative permeability of the different fracture systems.

The prerequisites for the development of intensely fractured zones within the producing interval are that the carbonate matrix rock has relatively high density and is brittle and therefore tends to fracture when the carbonate rocks are bent due to tectonic forces. The earth's crust in the Varandey-Adzvinskaya structural zone has had an active tectonic history. It has undergone numerous periods of tectonic activity for most of its geologic history.

The anticline trap is located in Paleozoic carbonate plates that have been thrust faulted over Mesozoic clastic sediments. The underlying sediments show the characteristics that result from intensive and multidirectional tectonic stresses. The uneven loading of the Paleozoic thrust sheets led to the formation of subsidence troughs beneath the thrust zones. Salt deposits of Silurian-Ordovician age deformed to salt pillows and these salt pillows played a crucial role in the development of tectonic faults in the thrust sheets of the Lower Devonian carbonates.

The influence of fracturing on the productivity of the field is supported by the presence of wells with sharply differing rates of productivity. Fig. 1 shows a graph that ranks the wells based on the magnitude of their productivity coefficient.

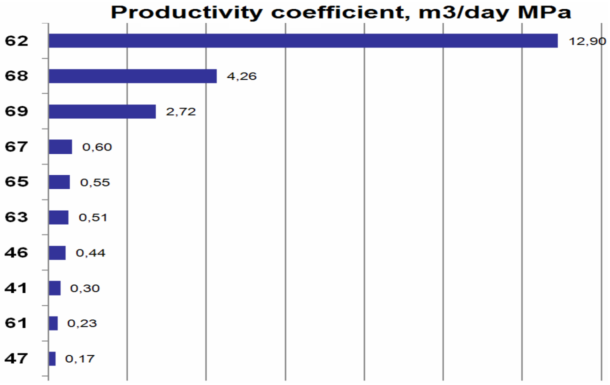


Figure 1. *Chart showing ranking of wells by productivity coefficient.*

Previously, conventional seismic based fracture detection methods such as coherency cubes, curvature attributes, etc were not effective partially due to complications caused by overlying Carboniferous carbonate deposits characterized by deep incisions filled with low-velocity rocks. This situation led to phase shifts on the seismic data at the zone of interest which could easily be mistaken as indications of faults when in fact they were simply distortions in the seismic wave field response.

In this situation, it became necessary to utilize a method for fracture detection that was not associated with the measurement of phase shifts on the horizons in the zone of interest. These methods include Duplex Wave Migration (DWM) (Marmalyevskyy et al., 2006). This paper presents the results of a fracture detection and delineation study based on DWM technology applied to this carbonate fracture oil play.

Method

Duplex Wave Migration (DWM) is designed for the imaging of sub-vertical boundaries within the reservoir interval that have zero or near zero vertical throw. McMechan (1983) was first to illustrate the imaging of a vertical boundary using duplex wave (DW) reflections. Recently, DW reflections were widely used for imaging of the salt dome walls (Broto et al., 2001, Marmalyevskyy et al., 2005, Farmer et al., 2006), and fractured zones (Link et al., 2007, Khromova et al., 2010) and others.

Duplex wave energy is the result of two reflections that include a sub-horizontal boundary and then a sub-vertical boundary (or vice versa) prior to being recorded at the surface. The Duplex Wave Migration method presented in this paper is based on the Kirchhoff transform in which the Green's function is calculated based on the kinematics of duplex wave energy propagation. The user provides the horizon in depth of a base boundary that is assumed to be the sub-horizontal reflector along with the depth model used for conventional PSDM to define the kinematics of the DW reflections from vertical boundaries above the base boundary.

The use of Kirchhoff migration to image vertical boundaries enables the user the flexibility to experiment with various types of apertures to illuminate fracture systems with different characteristics. The use of asymmetric apertures (left-sided or right-sided) or symmetrical (including variations with different surface offset ranges) enables the ability to identify multiple fracture systems that have dips that deviate from vertical. This capability is particularly important if the reservoir zone is quite thin and therefore the vertical height of the actual fracture systems is quite small.

DWM raw data cubes are sometimes contaminated by noise that can be characterized as being low, medium and high frequency, and the amplitude of this noise is comparable to or sometimes greater than the amplitude of the DW signal from sub-vertical boundaries. Fortunately, we can differentiate between the noise and the DW signal on the basis of their spatial characteristics. The low frequency noise is characterized by large-scale, slowly varying amplitude heterogeneity and it is mainly caused by reflections from sub-horizontal boundaries not completely suppressed by the DWM summation operator. Mid-range frequency noise is characterized by regularity and parallelism to the receiver line geometry and is the result of the 3D acquisition footprint problem. High-frequency noise is characterized by small continuities with a random, isometric pattern.

These three noise types are attenuated by a post processing workflow that is characterized by noise filtering and a sub-vertical boundary extraction methodology.

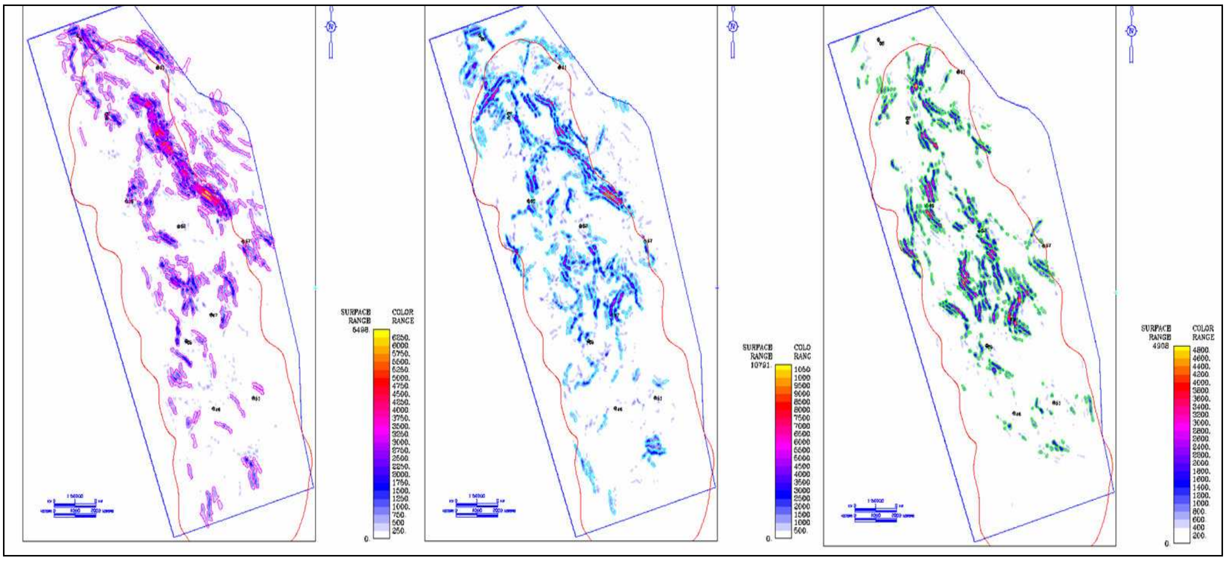
The results of the work

Three cubes of DWM images were obtained for the zone of interest under study; with a left-sided, symmetrical (hexagonal) and right-sided apertures. Symmetric aperture contains pair of asymmetrical apertures, summed with the proper sign for each of them. A joint analysis of these images leads to the following options for interpretation:

- each cube with an asymmetric aperture describes a single system of fractures with a corresponding dip of the fracturing plane (deviation from vertical) and those systems in space are not the same for different cubes;
- the coincidence of fracture systems which are obtained with left-sided and right-sided apertures at the same spatial location is interpreted as vertical fracture zone or two independent systems of fractures with the different dips;
- if a significant difference exists between a cube with a hexagonal aperture (approximation to circular) and a cube representing the sum of two cubes with asymmetric apertures

(rectangular aperture shape), this indicates the presence of sub-vertical boundaries with large angles of deviation from the vertical (this case was not observed for this study area)

The analysis of DWM amplitude cubes reveals that the most productive wells are associated with fracture zones of a certain intensity and length. Similarly, low-productivity wells are associated with areas of very weak and discontinuous DWM amplitude response. If no actual fracturing exists then the DWM signal amplitude response is zero. Consequently, the sub-vertical boundary extraction criteria were set such that if an event was below a defined minimum amplitude, and minimum spatial size, it was excluded from the post-processed DWM amplitude cube. Fig. 2 shows the stratigraphic depth slices of DWM cubes parallel to the bottom of the carbonate deposits for different migration apertures: (a) left-sided , (b) hexagonal and (c) right-sided .



a b c

Figure 2: *Stratigraphic slices of DWM cubes parallel to the bottom of the carbonate deposits obtained using different migration apertures: (a) left-sided, (b) hexagonal and (c) right-sided.*

The depth slices clearly show that the anomalies revealed by the left-sided aperture cube are characterized by having azimuth mainly in the northwest direction. The right-sided depth horizon slice is enriched by anomalies with north-east azimuth, and the hexagonal aperture slice includes both directions which are sometimes even more pronounced in amplitude intensity. A joint analysis of all three cubes has also shown that the most productive wells are located in areas of intersection or combination of anomalies derived using different apertures. In this regard, the most informative form of presentation of the DWM results is a map of the total absolute amplitudes of duplex waves built using the different migration aperture cubes; hexagonal, left- and right-sided combined with a set of selected polygons, as shown in Fig 3.

The robustness of this interpretation is illustrated by an analysis of the correlation between the potential productivity of the wells (as measured by hydrodynamic well studies) and the amplitude of the DWM data cube images. A graph that shows this linear relationship is presented in Fig. 4. The high mathematical correlation coefficient (R = 0.88) shows the close and robust relationship between DWM cube amplitudes and actual measured well productivity coefficients.

The azimuths of fractured zones delineated by DWM amplitude cubes within the well proximity are in good agreement with the XMAC well data. Also there is good agreement with passive seismic monitoring study results conducted after fracking operations. These results will be illustrated in the presentation.

Conclusion

The use of DWM in the oilfield in the Timan-Pechora gas & oil province, present in the Lower Devonian carbonates, allowed us to obtain information about previously unknown zones of fracturing. Analysis of the DWM transformation procedure using different apertures has shown that these areas have various different systems of fractures, and their superposition leads to an increase in the absolute amplitudes of the DWM data cubes. These amplitude anomalies are closely correlated with the potential productivity of wells within this oilfield. Fracture azimuths delineated on the basis of DWM in the proximity of the wells are in good agreement with XMAC data and passive seismic data after fracking operations were conducted.

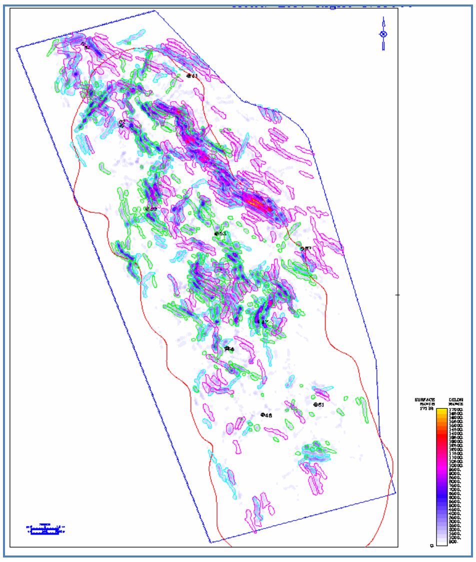


Figure 3. *Map of the total absolute amplitudes of duplex waves derived from different apertures used for DWM: hexagonal, left and right, with the combined set of selected polygons.*

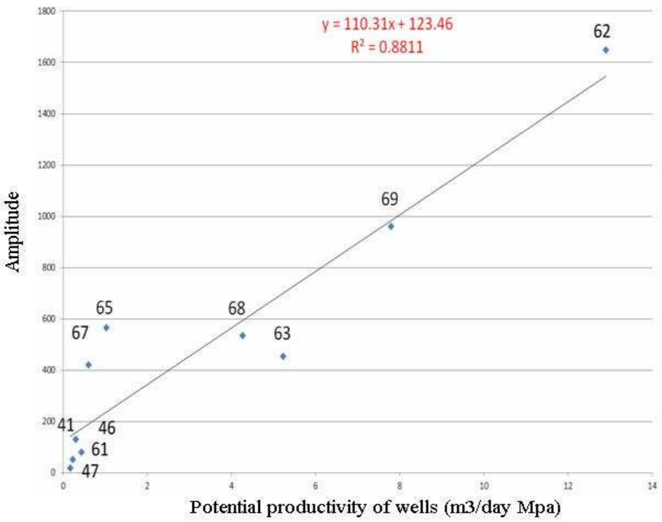


Figure 4. *The relationship between the amplitudes of DWM seismic images and the potential productivity coefficients determined by hydrodynamic studies at each well.*

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