Integrated study of secondary transformation (cavern porosity and fracturing) of carbonate platform rocks by seismic methods

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Summary

To examine the pore & cavern capacity volume, the technique of geostatictical partial stack inversion was used; and for delineation of fractured corridors, a new type of 3D pre-stack depth migration called duplex wave migration (DWM) was utilized. Comparison of the obtained data has shown that zones of the reservoirs having high capacity revealed by geostatistical inversion correspond to linear amplitude anomalies in the DWM data cubes, which were interpreted as fractured corridors. The play concept that higher production rates are related to the linkage between highly cavernous reservoirs and manifold fractured systems developed along the carbonate platform edge has been confirmed.

Introduction

The Upper Devonian carbonate platform revealed at the depth 3.5-4.0 km in the Timano-Pechersky basin was studied by 3D seismic. By traditional methods of structural interpretation, the two partly spatially coinciding chains of marginal reefs of different age were revealed, and the steep deep-water slope was mapped. Two prospecting wells were drilled in similar seismic-facial conditions, but the difference between their yields was 30 times.

To study the formation reservoir properties of the deuterogene carbonate sediments, two modern methods of seismic interpretation processing, geostatistical inversion of partial stacks, and DWM were used. It was shown that zone of the secondary reservoir capacity are linked to linear fractured corridors, along which the meteor streams were circulating. The fractured corridor follows the carbonate platform edge, and this is a manifestation of the nature of the gravitational settling of the platform edge as a result of differential compaction of underlying rocks.

Method

Four basic inversion techniques can be singled out:

- deterministic inversion of full stack seismic data;
- simultaneous deterministic partial stacks inversion;
- geostatistical inversion of full stack seismic data;
- simultaneous geostatistical partial stack inversion.

Reservoir identification is possible only in the Vp vs Vs domain. This means that we should a use pre-stack inversion algorithm for reservoir characterization. Reservoir thickness varies from 2 m up to 7 m in the target interval. Simultaneous geostatistical partial stack inversion was chosen for reservoir properties prediction.

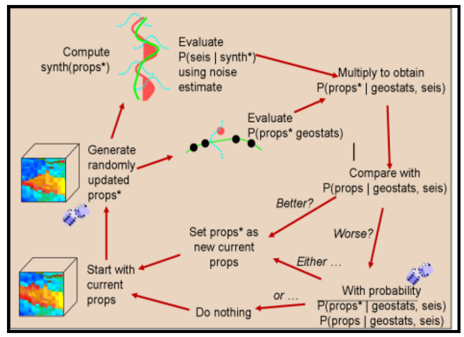

Figure. 1: Geostatistical inversion algorithm

The geostatictical partial stack inversion algorithm [Fransis A. ,2006, Sams M.S. et al, 1999], used in a study combined ideas from traditional geostatictics with simultaneous partial stack inversion and Bayesian analysis. The key inputs for this inversion technique are partial stacks (in this case study 6 stacks were used) and their associated wavelets. Prior statistical information (lithotypes, porosity) corresponding with elastic properties is also required, which were generated from available well information. The statistics with a set of partial stacks were input for this inversion process. 20 realizations of lithotypes distribution (reservoir and non-reservoir) with jointly inverted elastic properties (Vp, Vs and Density) were obtained from simultaneous geostatistical partial stack inversion. Reservoir and non-reservoir probability volumes were calculated based on multiple realizations of lithotypes volumes. The reservoir probability volumes provided an evaluation of net thicknesses using P10, P50, P90 risk analysis techniques.

DWM represents a technique differing principally from the traditional seismic methods evaluating behavior of P-waves.

The duplex waves reach the observation surface due to several reflections, and one of such reflections is caused by a sub-vertical boundary. There are two types of duplex reflections: VH and HV. For the first one, the initial reflection is caused by a sub-vertical target boundary, and the second does with a sub-horizontal one (key boundary); the second type has an inverted sequence.

Fig.2 shows an example of a sub-vertical boundary created by using synthetic gathers (Fig. 3 upper right) obtained by full-wave modeling. The zero-amplitude disjunctive in the formation between two key horizons was modeled (Fig. 2 upper left), which could not be obtained by the phase shift of a sub-horizontal reflection boundary (Fig.2, lower left). At the same time, the DWM results (Fig.2, lower right) show this disjunctive located at a correct place and having correct slope.

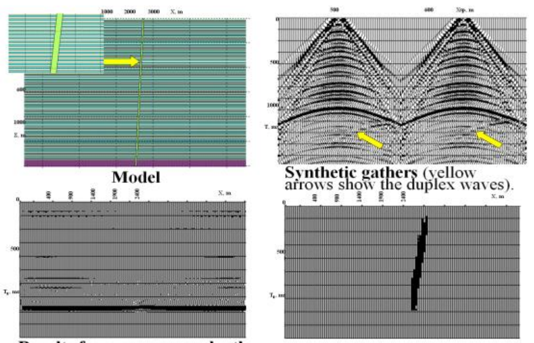

Figure 2: Seismic imaging of low throw faults in a horizontally layered medium.

DWM, apart from the medium velocity model standard for depth migration, also uses the key boundary, which represents the base of the target interval. As a rule, several key boundaries are used, and then the joint interpretation of the sub-vertical objects' cubes obtained from the related reference boundaries is carried out.

As against the standard Kirchhoff migration, during DWM the transformation aperture is shifted outside the interval between the receiver and the source. The apertures are considered, which are located both left and right of the receiver-source couple; they are used for creation of images depending on location of the couple related the sub-vertical object and type of the duplex waves.

The source-receiver offset value determines location of the formed reflection point of the sub-vertical object. The bigger if the offset the more far away from the key boundary the reflection point is located. As against the techniques forming sub-vertical objects by backward refracted waves (Hail et al., 1992), here the large offsets are not needed. The experience shows that it is enough to have the 1000-1500 m offsets for depths of the target objects reaching 4000 m or more.

Due to the fact that the DWM operator is turned round practically by 90˚ (Marmalyevskyy N at al., 2006) relative to the standard migration operator, the horizontal resolution of the DWM is higher than resolution of standard migration, and it gives the possibility to increase the spatial localization accuracy for sub-vertical boundaries.

Examples

Geological history of the Late Devonian of Timano-Pechora Basin relates to wide development of reef complexes of different ages, chains of edge-reef of which is freakish serpentines and shifts eastward following the Ural Ocean. One of the areas of such carbonate platforms built by the two chains (Late Frasnian and Early Famennian-Zadonsky generations) studied by 3D seismic are described here. The first prospecting well A was drilled into the large reef body which turned into one built of fragments of the two changes having different ages, by results of detailed seismic-facial analysis. These chains overbuild one another in a short interval, and northwardly part to the Frasnian reef turning westward and the Famennian one, which continue to go northward along the bend are of the prograding clinoform filling series (Fig.3).

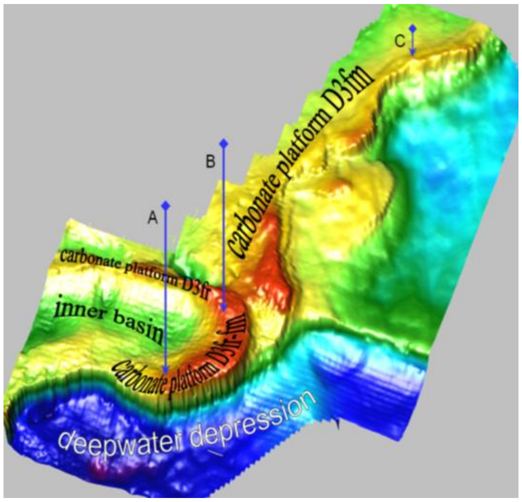

Figure 3: Axonometric projection of top of multiple-aged Frasnian - Famennian carbonate platform

Well A has high yield; the production is stable and reaches 5600 BOPD; the well section is characterized by high cavern porosity (Fig.4). Another well B was drilled for the northern part of the backreef hallow-shelf zone of the Frasnian reef, which is characterized by the well A. However, well B has low yield, and its production even after intensification methods applied is not higher than 140 BOPD. The conclusion was drawn that the primary properties of carbonates caused by facial conditions of sedimentation, are completely missed, and the main role in creation of the modern capacity volume is played by the secondary processes: fracturing, desalination, and cavern forming.

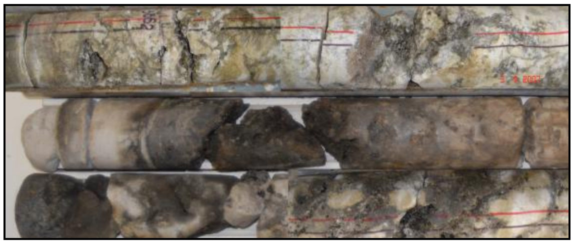

Figure 4: Photo of core from Well A

For examination of the pore & cavern capacity volume, the technique of geostatistical inversion of partial stacks was used, and the fractured corridors were located using the DWM technique. These interpretive processing procedures were carried out simultaneously but independently by Fugro Jason and Tetrale Technologies Inc respectively. During the final interpretation stage, the results were compared. It was found that the reservoir zones of high net pore volume (the effective thickness multiplied by porosity) correspond well to the DWM amplitude anomalies (Fig.5).

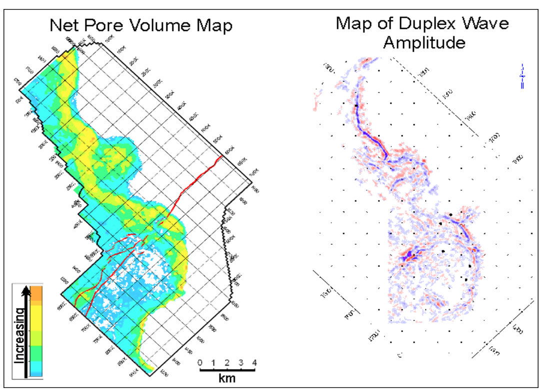

Figure 5: Net pore volume map obtained from geostatictical inversion and the map of DWM amplitudes.

The characteristic peculiarity of the object is the fact that the DWM amplitude anomalies and the accompanying zones of the prospective reservoir rocks carefully follow the carbonate platform edge. However, the bend of the DWM anomalies covers not only the crown part of the platform but also its slopes. The first impression was that the duplex waves were reflected from the sub-vertical slope, or cliff of the platform. Comparison with the known outcroppings described in publications (Kosa E. and Hunt D.W. 2006, Kerans C. and Harris P.M. 2007, Harris P.M., 2008, Frost E.L. and Kerans C., 2009,) provided the justification for interpreting of the DWM anomalies as zones of open fracturing breaking the platform slope. The genesis of the zone is not tectonic; the reason of the rocks fracturing is the gravitational settling of the solid carbonate platform edge as a result of differential compaction of softer underlying rocks. This is so called syndepositional fracturing (Fig.6).

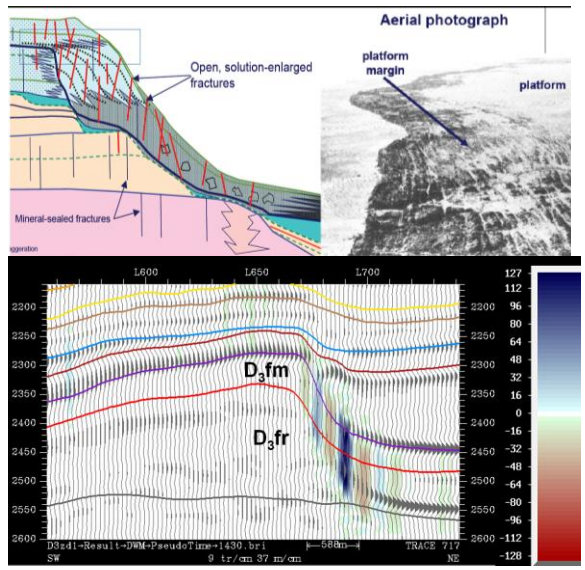

Fig 6: Top left – the principal model of the carbonate platform edge with network of syndepositional fractures (Narr W. et al,. 2008). Top right – photo of an outcropping (Playford P.E et al., 1984), below – the color-coded section of the duplex wave amplitudes' field with conventional seismic in wiggle.

Additional evidence that the DWM amplitude anomalies are a direct indication of the location of open fracturing was obtained when the drilling results of well C were analyzed. During well C drilling active drilling mud loss was observed. The initial yield of oil reached 2520 BOPD, but during the well tests the water inflow was determined. This means that there is a high level of probability that the DWM anomalies are associated with the zones of opened fracturing. Reservoir zones with larger net pore volume accompanying the DWM anomalies may be caused by zones of increased cavernosity or karst forming. Such matching of seismic anomalies obtained by two independent techniques and describing different properties of rocks, which have at a first glance different physical nature, in reality shows the close link between fracturing and increased cavern porosity of the reservoir.

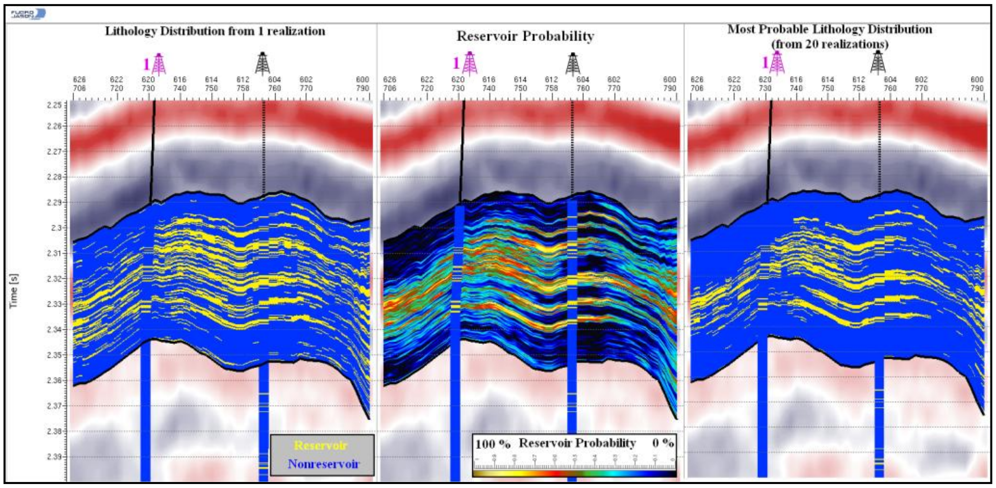

Figure 7. Section of predicted lithology types obtained from geostatistical inversion with lithology log in newly drilled well 1 overlaid (reservoir in yellow color, non-reservoir in blue).

The secondary processes of desalination caused the appearance of rocks with high cavern porosity and karst were developed along the open fractures, where active meteor water could move freely.

The fracture maps obtained using DWM, and the effective thicknesses and linear capacity of reservoirs obtained by geostatistical inversion were integrated with results of 5 initial exploration wells. This integrated interpretation process was used to justify the location of 5 new exploratory wells. Within a year after the interpretation was finished, the 5 new wells were drilled in the field. The results of the new drilling were carefully analyzed and compared with the forecast. The predicted lithology distribution at the newly drilled well locations was verified by petrophysical interpretation results ('lithology type' log) illustrated in Figure 7. Table 1 presents quantitative estimates of reliability of reservoir property prediction. This comparison was based on the following reservoir parameters: net pay, hydrocarbon pore volume (HCPV, net pay times porosity). For all of the above parameters, absolute and relative prediction errors were also calculated. Average reliability of prediction for net pay is 92%, and for hydrocarbon pore volume is 91.5 %.

Conclusions

Using the results of two independent methods of interpretative processing (geostatistical partial stack inversion and duplex wave migration), a substantiated geological model of the carbonate reservoir was obtained, the pore volume of which was formed by secondary desalination processes. The reliability of the geological model has been verified by drilling and can be successfully used for planning production wells spacing.

Well 1	***Drilling***	***Geostatistical Inversion***
Net Pay, m	18.7	15
HPV , m	1.7	1.5
Well 2	***Drilling***	***Geostatistical Inversion***
Net Pay, m	32	30
HPV , m	2.5	2
Well 3	***Drilling***	***Geostatistical Inversion***
Net Pay, m	18.5	17
HPV, m	0.87	0.8
Well 4	***Drilling***	***Geostatistical Inversion***
Net Pay, m	8.3	11
HPV , m	0.6	0.8
Well 5	***Drilling***	***Geostatistical Inversion***
Net Pay, m	31.9	36.2
HPV , m	2.4	3

Table 1. Comparison of reservoir properties obtained from simultaneous geostatistical partial stack inversion with data from newly drilled wells (HPV - hydrocarbon pore volume).

Acknowledgment

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