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Analysis of Migration Effects on Anisotropy Estimation for Shale Gas Reservoir - A Case Study from Northern Poland

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SUMMARY

The paper presents the results of anisotropy analysis of seismic data from a 3D project, aiming at mapping the Old Paleozoic formations in Northern Poland, with expected shale gas deposits. The geology of the area, together with 3D project parameters, have been discussed. Three types of migration Kirchoff PreSTM, Kirchoff PreSDM and CRAM (Common Reflection Angle Migration) were applied to the 3D data, being divided into six azimuthal sectors. For each of six migrated datasets, acoustic inversion has been carried out, resulting in inversion velocity volume. Those volumes have been analyzed via sinusoidal function fitting, which have yielded the most important anisotropy parameters (intensity and direction). The study results are presented and compared in a graphical way. It has been shown that for such an analysis, the application of depth migration (instead of time migration) can significantly improve the quality and reliability of the outcome.

Introduction

Poland has presumably the Europe's largest known shale gas reserves, as a result, north-eastern part of the country is currently being thoroughly explored in search for unconventional gas. Recognition and development of shale gas in Europe is now in its initial stage. Due to still unrecognized geology and insufficient amount of suitable well data (i.e. modern geophysical measurements and geochemical data), the exact evaluation of the shale gas reserves is impossible. Therefore, the reserves in Poland, estimated by different companies, range from 346-768 bilion m3 (Polish Geological Institute) to 5.29 trilion m3 (U.S. Energy Information Administration).

The largest share among the companies, being awarded the shale gas exploration licences, belongs to Polish national company PGNiG SA (POGC). PGNiG SA licences, covering an area of nearly 13 thousand square kilometres, are placed within major Paleozoic sedimentary basins e.g. Lublin Basin, Podlasie Basin and Baltic Basin. According to the current state of knowledge, Ordovician and Silurian shales are the target formations, due to sufficient content of organic matter and thermal maturity (Nowakowski and Kaczorowski, 2012).

Geological setting

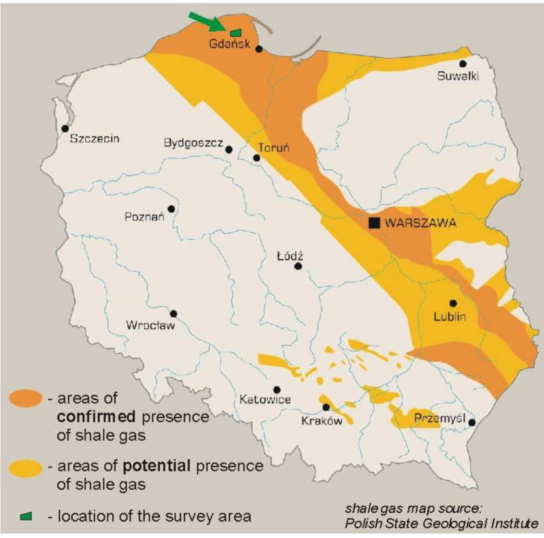

Figure 1. Location of 3D seismic data, acquired for the purpose of unconventional gas exploration.

The area of study, as shown in Figure 1, is located in the Baltic Basin, in the northern part of Poland.

The geological structure of the region is not very complex with two main structural levels: Old Paleozoic (Cambrian to Silurian sediments) and Permian-Mesozoic. Mentioned stages are separated by Variscan hiatus (Devonian and Carbon), when Old Paleozoic deposits were significantly eroded. In Old Paleozoic and basement formations, two dominant, mutually perpendicular fault systems are present. The older one, to some extent parallel to the Teisseyre-Tornquist Zone (NW-SE strike), cuts through the top of Ordovician horizon. This principal tectonic zone, located in the SE part of the area, is a large, reversed fault, that divides the whole region into two blocks: N (hanging wall) and SE (footwall). Analysis of the existing data indicates, that Old Paleozoic structural level, was under the compressive stress field. Beginning from Lower Silurian formations, tectonic complexity significantly decreased. In Silurian interval, different tectonic style with low-throw faults was observed. Nevertheless, due to the lack of well-defined reflections, seismic data didn't bring enough information about the structural style in mentioned formation. Most probably, the stress field was rebuild, what resulted in creation of oblique-slip fault zone, noticed on 3D seismic data. The Permian-Mesozoic level is characterized by monoclinal structure, gently dipping in the South. This structural stage is of no interest for shale gas exploration (Makarewicz et al., 2012).

Data acquisition

Shale gas reservoir characterization, structural interpretation and described here anisotropy analysis was based on 3D seismic data acquired in 2011 and 2012 within one of the most promising PGNiG SA licenses. The location of the 3D seismic survey was chosen after careful examination of the results of two regional 2D surveys and also the first vertical exploration well. The well, ended up in Cambrian deposits, drilled 1843.5 m of Silurian and 63 m of Ordovician strata, brought a significant amount of core, geochemical, petrophysical and geophysical data, which confirmed the presence of unconventional gas (Nowakowski and Kaczorowski, 2012).

The 3D seismic survey generally followed "wide-azimuth" geometry, having the following parameters: source area 33 sq km, orthogonal layout, receiver interval 40 m, receiver line interval

200m, source point interval 40 m, source line interval 280 m, symmetrical split spread, active channel per line 154, live channels 4620, patch length 6120 m, patch width 5800 m, maximum offset 4285 m, bin size 20x20 m and nominal fold 165 (Makarewicz et al., 2012).

Methodology

To evaluate anisotropy in Silurian and Ordovician formations, careful preparation of the input data was carried out. Taking into account, that every processing procedure may have an impact on the final results, several different methods were applied. The project included application of various types of migration techniques, including pre-stack time migration and depth migration. Before launching time migration several key processing techniques must be performed, such as: subdivision of the full-azimuth volume into azimuthal sectors (here 30° each), VTI anisotropy model building, grouping the data in Offset Vector Tile (OVT) domain and creation of HTI anisotropy model. Alternative solution is to make use of depth domain, in which OVT grouping is not required. In addition, modern geophysical software packages, such as EarthStudy 360 from Paradigm Geophysical, allows to use full-azimuth information instead of sectors to compute anisotropy parameters. Obtained results showed, how crucial the data preparation is, while studying such subtle features like HTI anisotropy.
Evaluation of HTI anisotropy in Silurian and Ordovician shales of the Baltic Basin is in its opening stage. Results of joint interpretation of crossed-dipole sonic tool and XRMI in the first shale gas exploration well showed, that the intensity of anisotropy is relatively small, with the average values between 5-6%. In examined formations, there are two main sources of anisotropy. The presence of carbonate and pyrite concretions is a dominant factor in Wenlock and Ludlow, while in Llandovery, anisotropy is clearly related to fractures. Statistical analysis of 700 meter thick Silurian and 50 meter thick Ordovician sediments indicated the existence of two major fracture sets, having the strikes of 15°-30° and 100°-120°. Interpreted directions are in agreement with two main fault zones. What is important, the well study also showed that more than two fracture sets are present in the intervals of interest. The above, made the seismic data-based calculations even more challenging.
Anisotropy analysis applied in this study takes into account the results of acoustic inversion performed on each of six azimuthal sector volumes separately. Therefore, for every location and every layer of interest, there are six values of inversion velocity (V_{inv}). Each velocity corresponds to distinct azimuthal sector (0°-30° and so on). Studying the values of V_{inv}, with the respect to the central sector azimuth (15, 45,...), it is possible to determine their relative difference, as well as the direction of maximum (or minimum) V_{inv}. The analysis can be done, by fitting a sinusoidal curve (function) of a period of p to the vector of six V_{inv} values. As a result of fitting (by the least squares method), parameters of the function fitted (amplitude, phase, offset from X axis) are recovered, and further related to the local anisotropy features (anisotropy intensity, direction of minimum/maximum V_{inv}). This methodology is graphically explained in Figure 2.

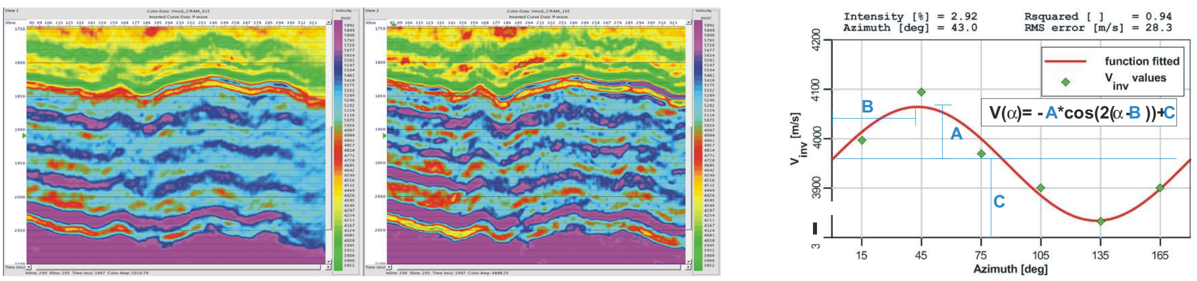

__Figure 2.__ Sample results of inversion process for two different azimuthal sectors for the same location (left, middle), together with sketch explanation of the adopted methodology

The above described procedure was applied to the inversion results of the data after three types of migration: PreSTM Kirchoff migration, PreSDM Kirchoff migration and Common Reflection Angle Migration (CRAM). The results (for an Ordovician layer of interest) are shown in Figure 3. In order to reject noisy data, a treshold for R^2 (goodness of fit) of 0.4 was applied. The quality of analysis, as indicated by the R^2 distribution, is slightly better for data after PreSDM CRAM migration,

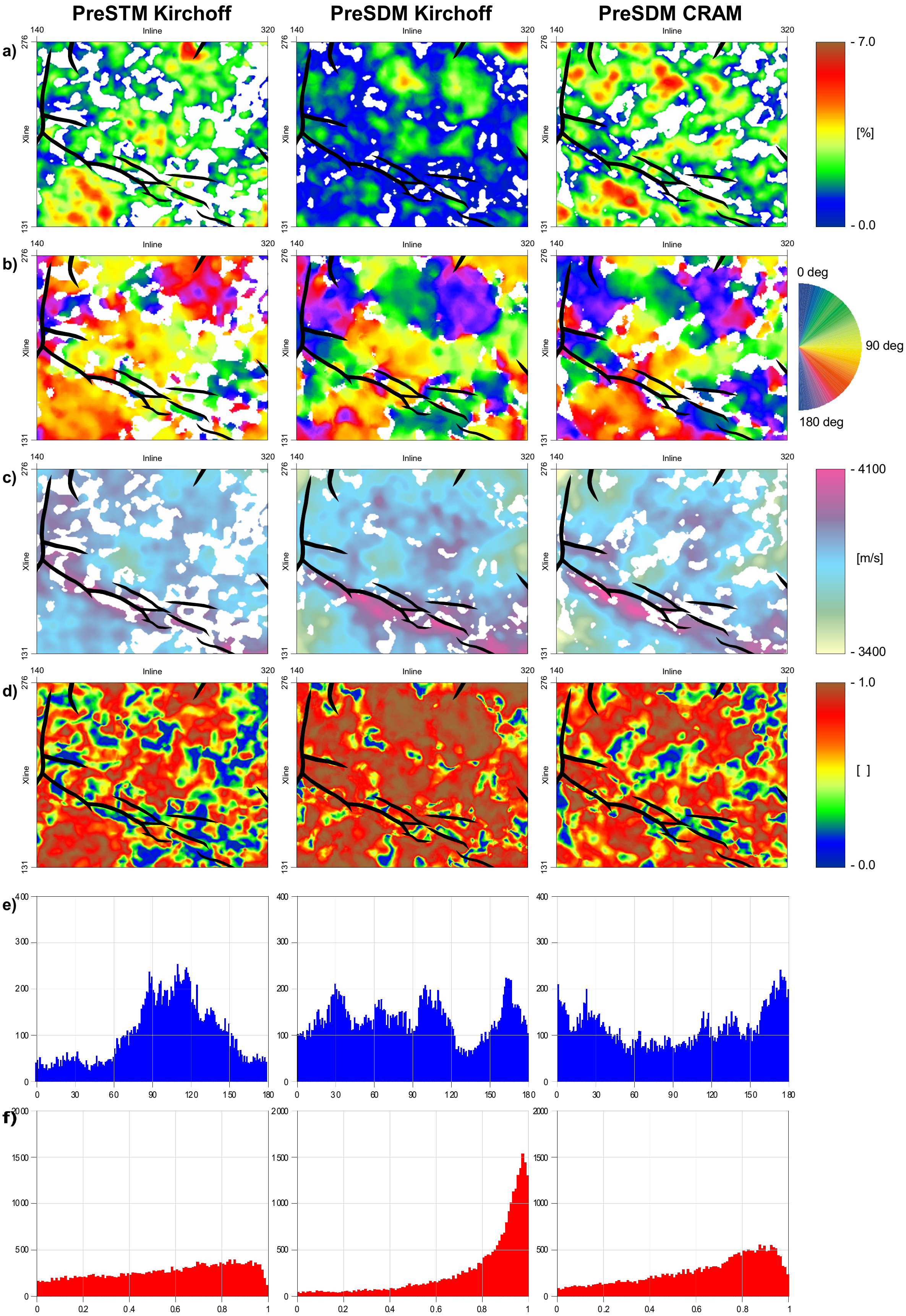

Figure 3. *Results of anisotropy analysis for the three types of migration applied (see text): anisotropy intensity (a), direction of maximum Vinv (b), mean Vinv (c), sinusoidal function fitting error (d), Vinv direction distribution (e), fitting error histogram(f).*

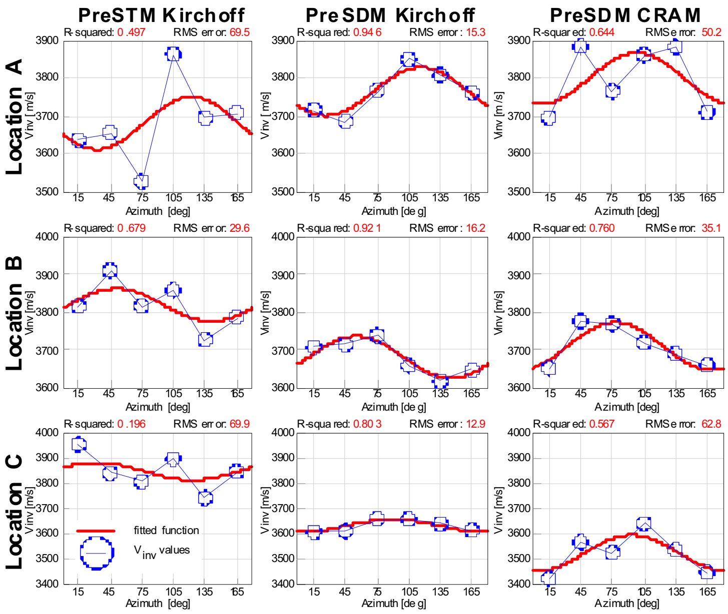

Figure 4. *Examples of the sinusoidal function fit*

and much better for data after PreSDM Kirchoff migration, than for data after PreSTM Kirchoff migration. In order to enhance the signal-to-noise ratio, a 7 by 7 boxcar filter was applied to the data prior to curve fitting procedure. In general, the results for the data after both types of PreSDM migration are in greater agreement (in terms of anisotropy direction and, to lesser extent, of anisotropy intensity), while the results for data after PreSTM direction appear to differ more significantly.

Figure 4 presents three examples (different locations) of fitting of the sinusoidal function to the inversion results, for the data after three different types of migration. For the locations A and B, a similarity between the analysis results (anisotropy intensity and direction) can be seen, while for the location C greater discrepancy (especially in the anisotropy direction) exists. Typically, the highest amount of noise can be observed for Kirchoff PreSTM data. It is interesting to note that even for the data with significant noise amount (e.g. data after PreSTM migration), the anisotropy direction seems to be evaluated quite reasonably (locations A and B). This conclusion justify the use of data, for which the values of R2 are quite low (0.4 to 0.7), in the creation of maps such as those on Figure 3, and their subsequent interpretation.

Conclusions

Examination of anisotropy on described 3D dataset was done by utilizing several methods of data processing such as PreSTM Kirchoff migration, PreSDM Kirchoff migration and Common Reflection Angle Migration. The main conclusion was that seismic anisotropy image obtained after the depth migrations, in which it was possible to incorporate small velocity heterogeneities into the velocity model, showed a significant improvement over the pre-stack time migration. Careful preparation of VTI and HTI models and its application during processing stage allows us to obtain consistent anisotropy estimation even under the condition of small scale anisotropy.

Acknowledgements

We would like to thank Paradigm company for allowing us to use their products such as CRAM - Common Reflection Angle Migration along with the package EarthStudy 360 – a brand new invention designed to image and interpret the total seismic wavefield, that provide us with the opportunity to properly process the data for the purpose of anisotropy analysis. We acknowledge colleagues from Geofizyka Torun S.A., especially Jakub Makarewicz, Piotr Godlewski and Wojciech Kobusinski for numerous discussions, data preparation and their contribution to the project.

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