# Case study: Paleokarst development zones in the Upper Devonian Domanik Group, Timan-Pechora basin

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**Abstract:** Paleokarst system structures form an important type of carbonate reservoir, and are product of surface karst processes, further sediment compaction and diagenesis, all of which can contribute to the heterogeneity development and compartmentalization of a carbonate reservoir. One of the most important conditions is when the cave is filled by solid minerals such as anhydrite. Filling of the cave by Minerals and further compaction during area subsidence can destroy much of the original cavern porosity and significantly decrease the reservoir quality of the formation. For this reason, during the design stage of exploration and production drilling, it is necessary to pay attention on the pattern and distribution of paleokarst systems, make an assessment of their impact on reservoir properties which might affect the reservoir quality.
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**Keywords:** Tight paleokarst zones, Timan-Pechora basin, seismic inversion.

## 1. Introduction

Karst systems are actively developed on the surface of carbonate platforms or islands, during partially or completely subaerial exposure in hot and arid conditions for a long period of time. Subaerial exposure is controlled by eustatic or tectonic change in sea level during geologic history. As a result, karst regions usually develop connected cavity systems with significant volumes. Paleokarst systems, in general, correspond to their modern analogues, but are complicated by mechanical compaction and diagenesis processes, that occurred during their subsequent geological history (Q. Dou et al, 2011).

Nowadays, identification and characterization of buried paleokarst structures is a new and big challenge for geologists and geophysicists. Many examples of modern karst systems are described on the basis of their outcrops, while buried paleokarst structures, which are important for determining sea level fluctuation and reservoir quality characterization haven't been sufficiently considered so far due to the lack of data and necessary technologies. Petrophysical data allows authors to make an assessment of paleokarst structures only in areas that have been drilled, but this information is not enough to predict the development of such zones in areas considered for further exploration drilling. Seismic data and analysis of geometric seismic attributes are useful tools to delineate the distribution of paleokarst structures in 3D space. On the other hand, the traditional seismic resolution is not enough to characterize some small scale structures.

This paper describes an approach, comprising the integrated use of seismic inversion, geometric attributes, core and well-log data analysis, which allows detection of tight paleokarst zones with low reservoir quality zones, as well as an assessment of their ability to inhibit migration of hydrocarbons. The study area is located in Schelyayur area, on the territory of the Timan-Pechora basin and covered by 3D seismic surveys.

## 2. Review of paleocave systems

Karst is defined as a comprising terrain with distinctive hydrology and landforms which arise from a combination of high solubility rocks and well developed secondary (fracture) porosity. Karst areas are characterized by sinking streams, caves, enclosed depressions, fluted rock outcrops, and large springs (Figure 1). Important factors in the formation of karst are rock structure and lithology such as massive, pure, and coarsely fractured rocks (K. Slotnæs, 2012).

Many sequences of carbonate rocks are found to contain or be terminated by unconformities that are karst solutional surfaces or cavities that are now inactive, these are called paleokarst. Paleokarst can be defined as a karstified surface and karst features associated with it, such as caves, which have been buried by younger rocks.

Classifications of cave products and of six common paleocave facies in Loucks (1999) and Loucks and Mescher (2001) can be found (Figure 2). To show the relationships between crackle breccias, mosaic breccias, chaotic breccias, and cave sediments ternary diagram was used.

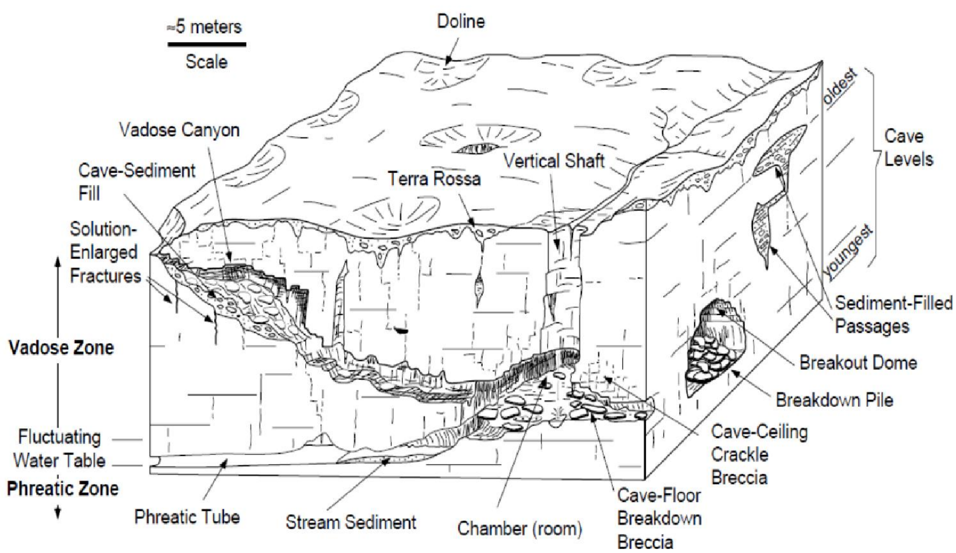


**Figure 1.** The block diagram shows near surface karst terrain with phreatic (below the water table) and vadose (above the water table) cave features. The figure is from Loucks and Handford (1992).

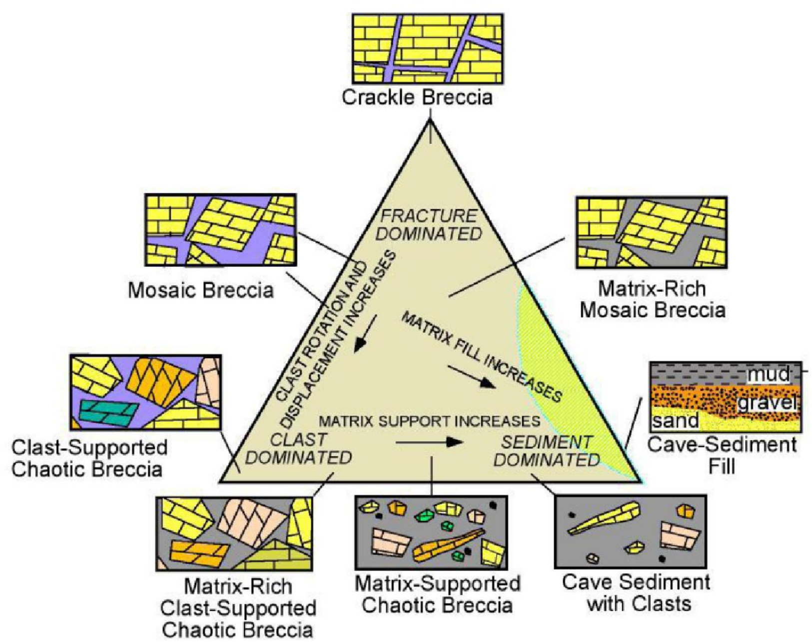


**Figure 2.** Triangle classification showing the breccia and clast deposits within a cave system. Originally from Loucks (1999), modified in Loucks et al. (2007)

Crackle breccia shows minor displacement between the separate rock fragments and are the product of fracturing due to stress relief in the cave ceiling and walls. Mosaic breccia is more displaced and rotated than crackle breccia, but can still be fitted back together. Chaotic breccia cannot be fitted back together and is composed of a mixture of clasts which originate from one or several sources. They have been transported vertically by collapse, or laterally by fluvial or density flow mechanism and they range from matrix-free to matrix-rich. Sediment fill indicates processes of suspension, traction and mass flow mechanisms and can therefore be of any material texture or fabric.

Due to differential compaction, crackle breccia with loosely fitted clasts are formed in the buried cave-roof. Due to further mechanical compaction, brecciation creates a chaotic breccia of smaller clasts as the voids are closed. In the subsurface, hydrothermal dissolution can give preferred mechanism for mineral deposits. Because of several episodes of rebrecciation and tectonic overprint it can be hard to distinguish between the caves related breccia and the tectonic overprint.

Karst brecciation is the controlling factor for a paleokarst reservoir`s quality and heterogeneity, and not the tectonic overprint. A model of karst facies is therefore important in order to understand the heterogeneity of the reservoir. Loucks and Mescher (2001) proposed a general classification of six common paleocave facies, described below, and is shown in Figure 2. Undisturbed strata, is characterized by undisturbed bedding with continuation ranges from tens to hundreds of meters. The strata can show minor deformation such as titling and fracturing and solution holes with breccia and /or sediment fill. Disturbed strata, is characterized by high continuity of the bedding with small scale folding and faulting that is commonly overprinted with crackle and mosaic brecciation. This facies are interpreted as disturbed host rock around collapsed cave passages. Highly disturbed strata are very discontinuously bedded strata with pockets and layers of chaotic breccia. Small scale folding and faulting are common with significant overprint of crackle and mosaic breccia. This facies are interpreted as lithified collapsed roof and wall rock at the top of the caverns. Coarse-clast chaotic breccia, is poorly sorted, matrix to clast-supported, granule- to boulder sized chaotic breccia that is 0.3 to 3 meter long. It is commonly clast supported, but can contain matrix material. It forms ribbon- to tabular-shaped body as much as 15 meter across and hundreds of meters long. The facies has been interpreted to be deposited in-situ as collapsed-breccia cavern fill which has not been transported by stream or mass-flow processes. Interclast pores in the matrix-free chaotic breccia have good reservoir quality when it is not cemented. Fine-clast chaotic breccia is poorly to well sorted matrix- to clast-supported, granule- to cobble-sized chaotic breccia with varying amounts of matrix. The clasts can be imbricated or graded and form ribbon- to tabular shaped body as much as 15 meters across and hundreds meter long. It consists mostly of cavern fill that has been transported either by mass flow or stream flow processes. Finer grained sediments consist of fine silt-to granule-sized sediments that contain less than 10 % granules, and are carbonate and/or siliclastic debris. Sedimentary structures can be common. The facies ranges from 0.3 to 0.8 meter in thickness and are interbedded with chaotic breccia facies. The fine grained material that makes up this facies is interpreted to have been transported by traction, mass-flow, and suspension mechanism.

It is important to understand the general processes that develop modern cave systems since the scale, geometries, and spatial complexities of paleocave systems are influenced by their initial near-surface scale, geometries and complexities. They are products of near-surface cave development, including dissolutional excavation of passages, breakdown of passages, and sedimentation in cave passages, and later burial cave collapse, compaction, and coalescence. Phreatic or vadose-zone dissolution causes passage development. Passages are excavated where surface recharge is concentrated by preexisting pore systems such as bedding planes or fractures that extend continuously between ground-water input, such as sinkholes, and ground-water output, such as springs. Cave ceilings and walls are under stress from the weight of overlying strata. A tension dome, or zone of maximum shear stress, is induced by the presence of a cavity. Stress is relieved by collapse of the rock mass in the stress zone. Major products of collapsed ceiling and walls are chaotic breakdown breccia on the floor of the cave passage. In addition, the stress release around cave passages produces crackle breccias in the cave-ceiling and cave-wall host rocks. Near-surface dissolution and cave sedimentation terminate as cave-bearing strata are buried into the subsurface. Extensive mechanical compaction begins.

Loucks (1999) noted that paleocave systems that form large hydrocarbon reservoirs are not a product of the collapse of isolated cave passages only meters across and tens to hundreds of meters long, but instead are a product of coalesced, collapsed-cave systems hundreds to several thousands of meters across, thousands of meters long, and tens of meters to more than 100 m thick (330 ft). Internal spatial complexity is high, resulting from the collapse and coalescing of numerous passages and cave-wall and cave-ceiling strata. The more extensive coalesced, collapsed-paleocave systems originated at composite unconformities where several cave systems may overprint themselves during several million years of exposure to karst processes.

Reservoirs in karstified carbonate rocks are usually heterogeneous. The heterogeneity is the result of the irregular distribution of porosity zones and complex nature of pore systems. The heterogeneity causes problems in reservoir development such as karst related dissolution that has overprinted pre-existing porosity systems complicates reservoir petrophysical characterizations.

Paleokarst is reworked carbonate and evaporite rock, and can therefore have induced porosity with a complex pore geometry configuration. This means that two or more pore systems may occur. The basic rock material is fine intercrystalline and referred to as the matrix, with one pore system consisting of uniformly small pores. Larger voids and pores are due to leaching or fracturing of the primary rock material, and can be variable in size and distribution. The secondary porosity can therefore be classified into several pore types.

## 3. Geological settings

The Shelyaur area is located in the Izhma district of the Komi Republic, 10 km south-west of the village of Shelyaur. According the oil and gas potential zoning, accepted in Russia, the area is located within the Tobyshsko-Neritskiy petroleum district of Izhma-Pechora petroleum region (Figure 4).

In terms of stratigraphy, the potential reservoir is Domanik-Tournaisian formation. The Frasnian (D3f) producing formation sits approximately 1900-2150 meters at depth and consists of Domanik (D3dm) organogenic limestone and interbedded dolomite and mudstone of Sirachoy (D3src) age (Figure 3). The Shelyaur field was discovered by the first well in 2001 and well test gave a commercial flow of oil. At present, over 11 prospect and exploratory wells have been drilled within the Upper Devonian formations, nine formations were penetrated and tested in open hole conditions during drilling. Of these five formations had oil flows. In the Upper Devonian the study area appeared as a zone of shallow shelf, with slope break in the northwestern part, which at the time divided the entire Timan-Pechora basin into deep and shallow marine environments, on the edge of which reef build-ups were actively forming (L. Azevedo et al, 2009). The Upper Devonian was a period of frequent fluctuations of the sea level. Shallow marine conditions alternated subaerial conditions after regression that could allow karst processes to operate.

During the seismic data interpretation process a large number of ring-shaped structures in the Upper Devonian interval were found (Figure 5), which in cross-section appear like low-amplitude faults formed due to difference in rock density between layers (Figure 5, 6). Such faults were found in the study area, and were also identified on single 2D seismic profiles in adjacent areas. However these structures have not been studied enough, and this gives this research a practical meaning and its importance to exploration is significant. These structures are mainly developed in Upper Frasnian part of the section and can be clearly distinguished within Sirachoy formation often appearing at the top of Domanik formation and usually die out in the bottom of Evlano-Livensky formation. In previous seismic interpretation reports of the study area, these structures were characterized as faults of sedimentary origin, i.e. faults associated with the differentiated nature of the compaction on the boundary between Domanik formation and Vetlasyan-Sirachoy formation.

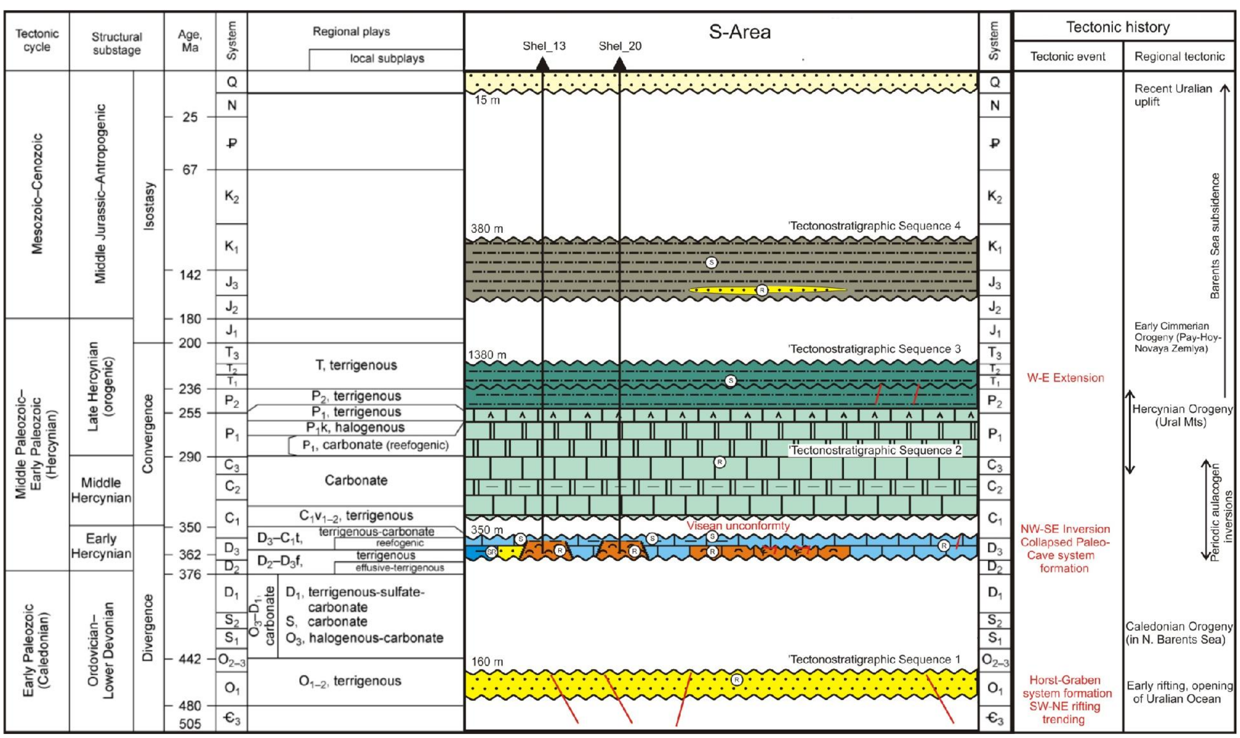


**Figure 3**. Chronostratigraphic chart of study area

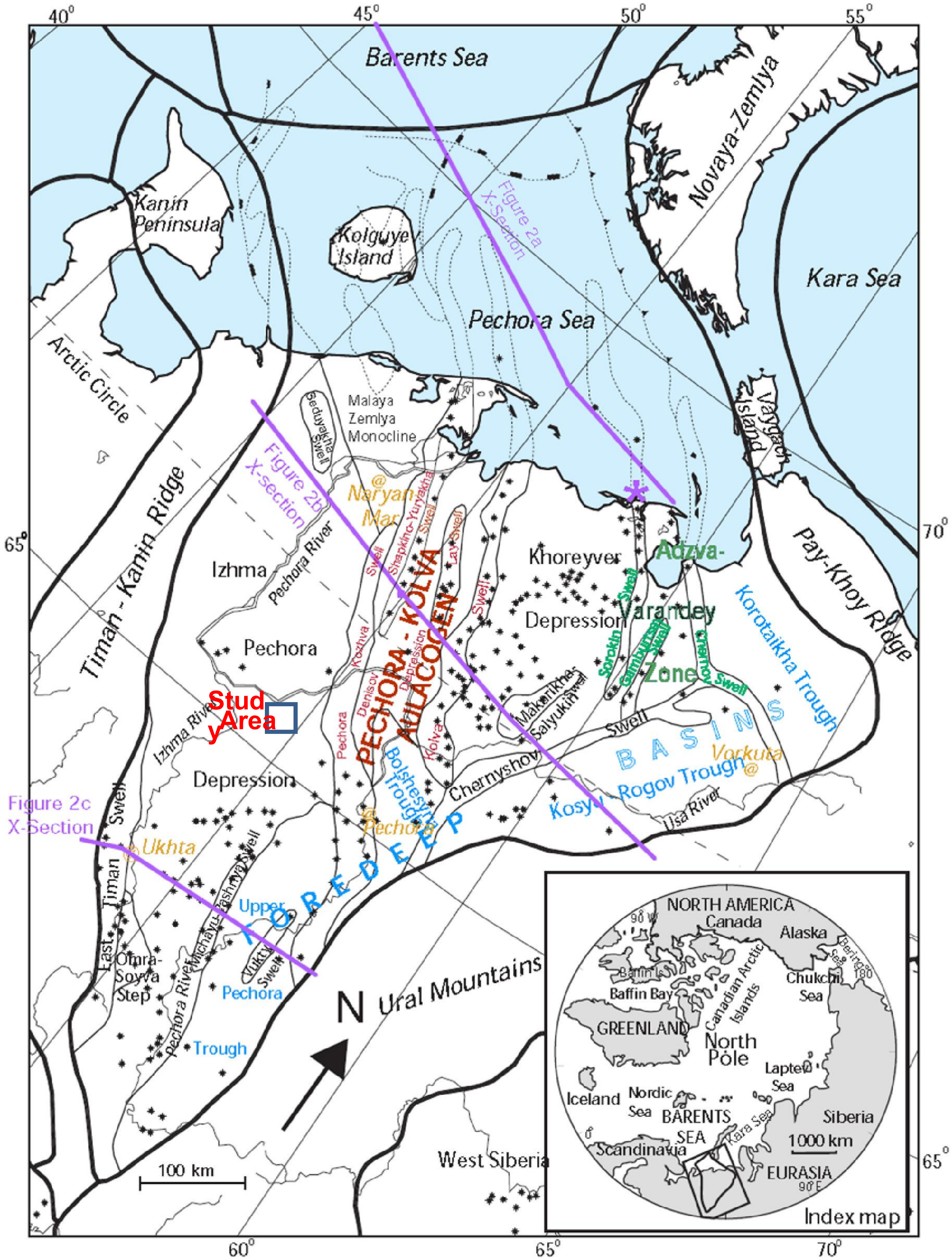


**Figure 4.** Location map for Timan-Pechora basin and province (After Sandra J. Lindquist, 1999).

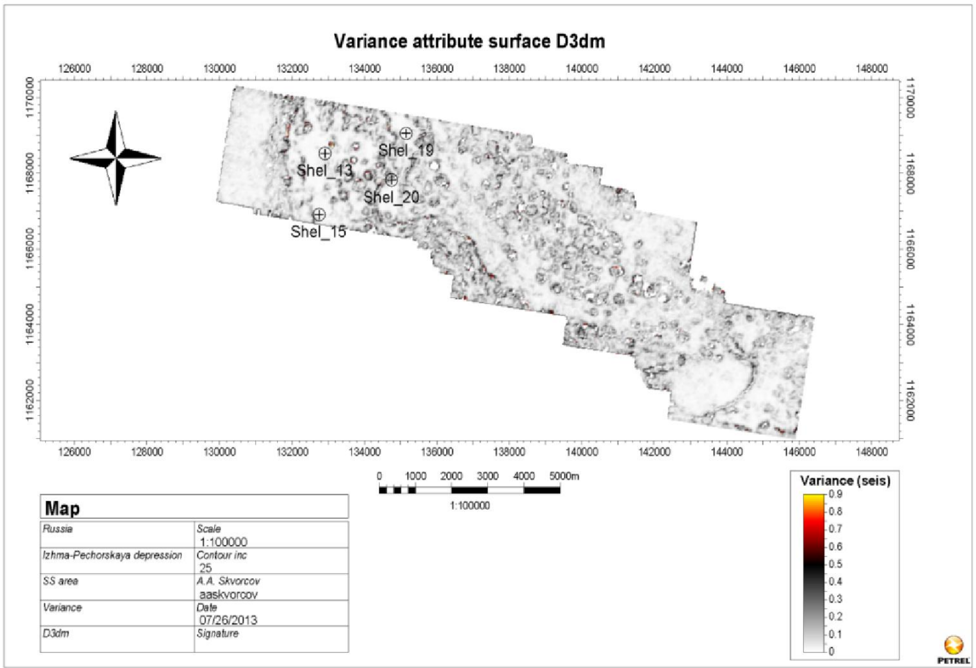


**Figure 5**. Variance attribute time slice showing ring-shaped structures in Domanik formation

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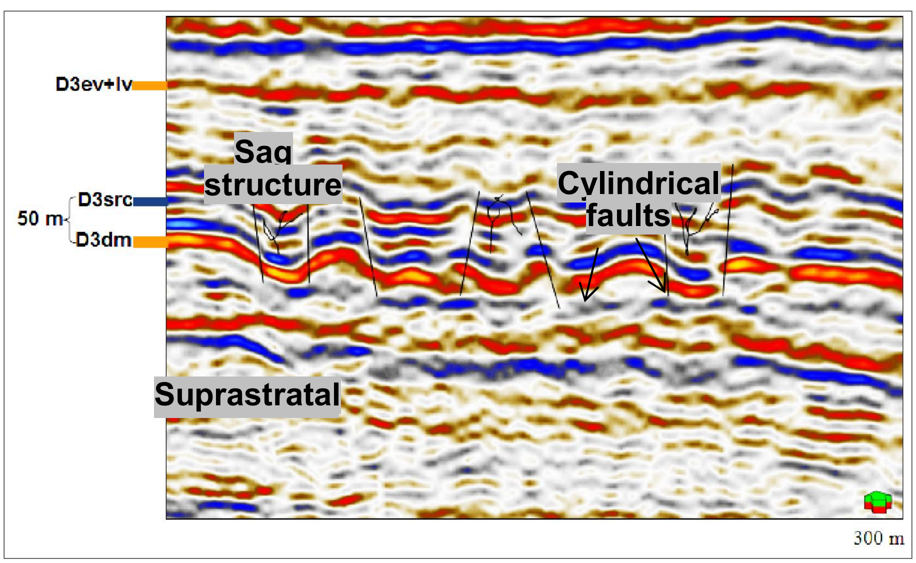


**Figure 6.** Seismic line showing missing sections (collapse in Domanik-Sirachoy section), cylindrical faults, and sag structures.

When study and comparison of structures with known analogue were done, alternative assumption was reached (Q. Dou et al, 2011). Features, marked at the seismic profiles and Variance attribute maps, indicate that paleokarst structures were widely developed in this area. Intervals in which the structures are concentrated indicate that these processes occurred predominantly during Upper Devonian time, in which the area was subjected to dry conditions, hydrothermal brecciation during diagenesis, and possible tectonic movements, or various combinations of these processes.

Considering that the paleokarst systems within the area are developed in an oil producing interval, and as noted above, this could adversely affect the reservoir quality, it is necessary to analyze their impact on the local oil-production. Extremely different efficiency of existing wells within the area suggests that the effect of paleokarst structure can be negative due to crack-filling by anhydrite (Figure 7), which reduces the pore space or creates a hydrodynamic barrier between two adjacent traps, thereby blocking hydrocarbon migration, which could lead to negative drilling results. Also, the considered paleokarst structure systems deserve an attention in terms of identifying and tracing organogenic structures and could be used as indicators of significant variations in sedimentary regime. It should be noted, that this analysis is carried out for the first time in the Timan-Pechora basin, and can be used in the future as an integrated approach to study similar structures. In regard to the above stated, a special algorithm of actions was selected, which allows identification of paleokarst systems, assessment of their size, number and degree of influence on reservoir properties within sites unstudied by drilling. This algorithm was selected by analysis of existing methologies and has been replicated in Shelyaur area.


**Figure 7.** Representative cores from paleocave facies.

## 4. Data and methodology

Seismic surveys used for this study were carried out on Schelyayur area from 2002 to 2004 by several seismic crews. Seismic data processing was completed by PetroAlians Service Company. The area covered by 3D seismic surveys area is 266 km2. In this work 3D seismic cube was used, and after deconvolution, common-midpoint and stacking methods, and in combination with well-log data to create structure maps for D3dm and D3src horizons Variance and Coherence geometric attributes maps were also calculated (O.M. Prischepa et al, 2011). Seismic and well-log log interpretation, as well as calculation of attributes was carried out in Petrel software of Schlumberger. The most informative and useful tool for the analysis of the spatial propagation of paleokarst structures is acoustic impedance, which was also created by PetroAlians experts. The results of acoustic impedance calculation are the product of the dynamic parameters of seismic data linking with an acoustic subsurface model in the wells.

First phase of project was considered to be a gathering of information concerning texture of the rocks and their petrophysical features in paleokarst systems development intervals using available core material was completed. Later on, comparing the information obtained from the core with well-log data, typical responses of the various well-logging tools for intervals that have reservoir properties and impermeable intervals with anhydrite filled cracks were obtained.

Well-seismic tie was also carried out in special plug-in of Petrel software. For that purpose the acoustic log and vertical seismic profiling data were used as input data. Then, the analysis of the seismic signal was completed. The next step, based on the acoustic log, is a calculation of the synthetic seismic traces, after which comparison and degree of convergence with observed traces need to be assessed as well. After well-seismic tie is established, correlation of the Domanik and Sirachoy horizons on a scale of 1:50000 was completed. Then, for these surfaces using structural maps and cubes of variance and coherence as input data, attribute structural maps were calculated, which allowed mapping of zones of development large-scale paleokarst structures. Size of paleokarst structures related anomalies of the wave field and geometric attributes resolution depends on the seismic data resolution and acoustic contrast between zones of paleokarst development and surrounding layers, and also to a certain extent depends on the inversion method used. In this case, the geometric attributes were used to characterize the large scale paleokarst structures recognized on seismic section as small faults, sags of amplitude or discontinuity of the seismic reflections.

The acoustic impedance cube, which was calculated primarily for facies analysis and prediction of reservoir properties of Upper Domanik deposits by PetroAlians specialists especially through the inversion, had different purpose in this study, with the aim of extracting information about the spatial distribution of small-scale paleokarst structures throughout the area, using the obtained information from core and well-log data. In comparison with traditional seismic interpretation, seismic inversion can convert seismic reflections in to quantitative evaluation of the rocks properties and thus allows prediction of the paleokarst systems development in undrilled areas. Acoustic impedance is widely used approach of seismic inversion, which gives a more detailed understanding of the lithology, fluid type and properties of reservoir porosity, moderately increasing resolution by removing the source pulse effect. The data used for the calculation was obtained from well #14, which is located the north-west of area. After testing, acoustic impedance cube was calculated by a model based algorithm of seismic impedance inversion. When first working with this algorithm, the geological model is created, and then it is compared with the real seismic data. This comparison is used to allow multiple updates of the original model, to achieve better compliance with the seismic data.

Upper Devonian sediments within the study area were discovered at the depth of 2 kilometers. The central frequency, which was derived from the seismic data, is about 45-55 Hz with useful high-frequency content up to 75 Hz, which is very important and allows a high resolution to be obtained in further research. Through core data and petrophysical data analysis, paleokarst zones were discovered in two wells with thicknesses of 14 and 29 meters respectively. Assuming an average velocity of the wave within the zone of paleokarst development about 6.5 km/s and average frequency of the seismic data 50 Hz, the average wavelength is, therefore, 115 m. Theoretical seismic resolution for the Upper Devonian sediments, assuming that the limit of the seismic resolution is about 1/8 of the predominant wavelength under favorable conditions is 14 meters. According to the petrophysical, data average paleokarst thickness is about 20 meters and thus most of such structures will be identifiable on seismic. Seismic resolution of geometric attributes is the same as the seismic data resolution.

In order to obtain additional information attribute and amplitude analysis were carried out. Prediction of reservoir parameters was performed on the basis of well-log data cross-correlated with values of various seismic attributes (amplitude-frequency attributes). The attribute maps with the highest correlation level were used. The analysis was performed by using the available set of seismic attributes in Petrel 2008.1 software.

The available seismic attributes are divided into volume and surface attributes. Each process has the available attributes organized by several libraries which attempt to group attributes with similar outputs. Volume attributes are those computed from an entire 3D seismic cube resulting in a new seismic cube containing the attribute information. Surface attributes are the value of the computed attribute from a seismic cube in one surface, created from seismic interpretation, or in between two surfaces, or between a surface and a constant time window. Volume attributes are divided into five libraries and within each library several attributes can be chosen among of 29 in total. Surface Attributes have an extensive list of 50 attributes which are categorized into four libraries depending on how they are computed: Amplitude, Statistical, Signal Shape and Measurable Interval. Depending on the algorithm for their calculations, seismic attributes may have, or don’t have, user-defined parameters which will be taken into account when the algorithm is applied, in order to achieve the desired output data with the best quality possible. In all user-defined parameters Petrel always suggests a value by default which in many cases is suitable for the expected result. Apart from the catalogued attributes, a myriad of attributes can also be calculated with Petrel’s Seismic Calculator. This tool allows the user to create new versions of seismic cubes by user-defined formulas. The new attributes seismic cubes are generated based on already existing and realized cubes.

Correlation quality is controlled by the set of statistical indicators. The figure 8 shows the scatter plot of correlation coefficient against statistical connection probability for the defined number of wells. For the areas with a 4-5 wells probability of statistical connection (conventionally corresponding a moderate degree of confidence) is achieved with a correlation coefficient of 0.65 and above. Accordingly, this coefficient was assumed as a threshold to obtain informative attribute map.

When all calculations were done and when threshold requirements for the interpretation of attributes maps were taking into account, maps with following parameters were selected:

- Highest quality of geological structure visual displaying of the formation
- Highest correlation coefficient with predicted well data and minimum error (standard deviation, local estimate of uncertainty);

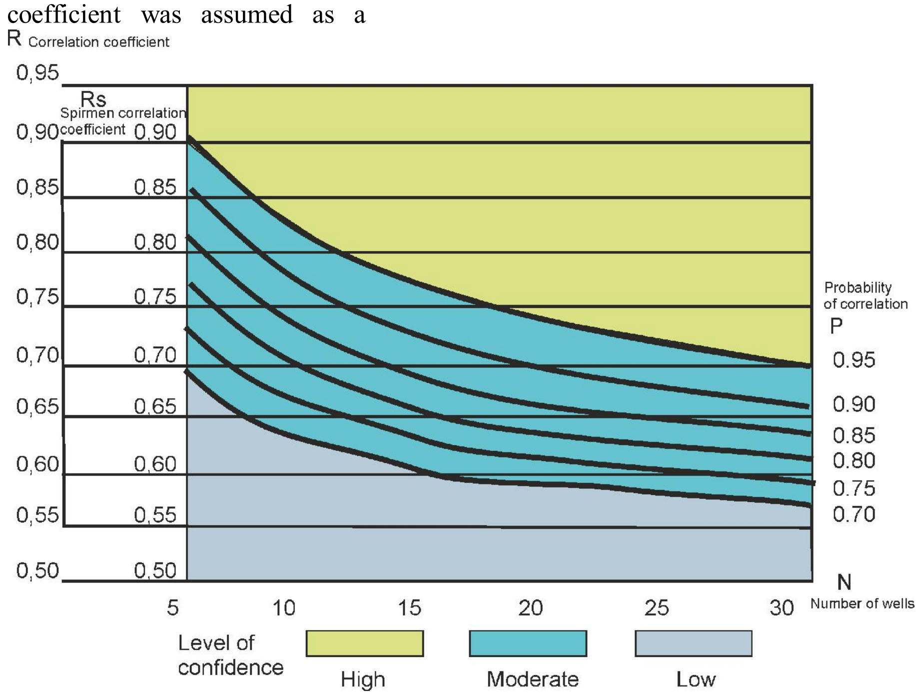


**Figure 8.** The scatter plot of correlation coefficient against statistical connection probability

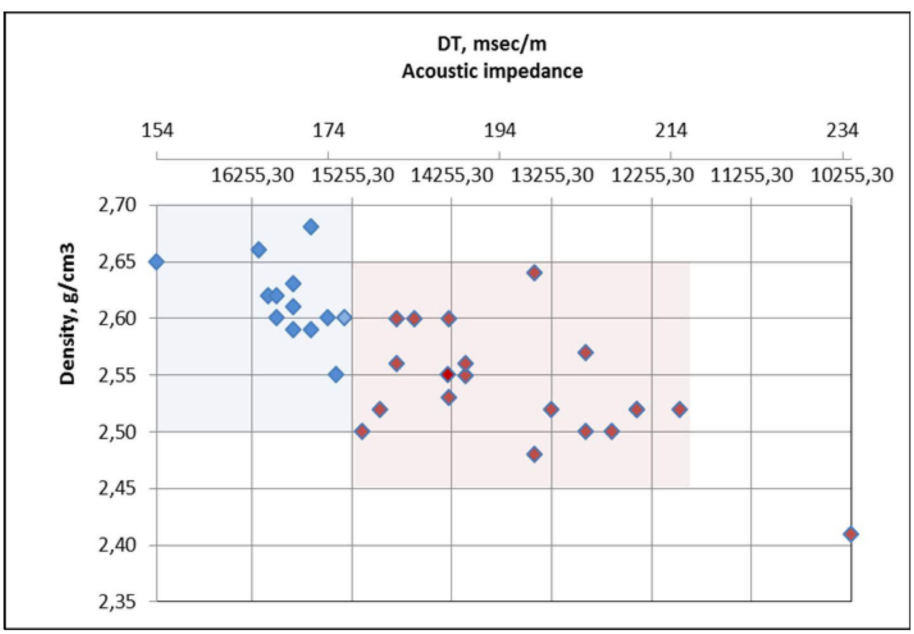


**Figure 9.** Cross-plot of the transit time-density. Blue: tight paleokarst-zone; red: non-paleokarst zones.

## 5. Results

Within the paleokarst structures pore space includes caverns and intergranular pores, as well as cracks and breccias. Except for a few open fractures with oil shows the rest of the pore space is filled by anhydrite. A clear petrophysical difference between paleokarst and non-paleokarst zones, identified through well-log data analysis, allows the use seismic inversion to be used as a tool for the delineation of lateral and vertical extent of paleokarst zones within the study area.

Well-log data analysis showed that the paleokarst development zone has abnormally high velocities, density and resistivity, as well as low neutron porosity in comparison with non-paleokarst zones. The average neutron porosity of paleokarst zones is less than 4%, while for non-paleokarst zones it ranges from 4 to 25%. Average values of velocity and density is higher than 6.1 km/sec and 2.59 g/cm3 respectively, for the paleokarst zones these parameters were measured directly from core. The density log shows values for non-paleokarst zones less than 2.59 g/cm3. It scatter plot of estimated densities against acoustic logs for the intervals, where coring has been done, is presented in Figure 9. The blue points corresponds to the paleokarst development zones, and therefore do not have the good reservoir properties. Acoustic impedance of the paleokarst development zones exceeds 15,255 m/s, and the zones in which the acoustic impedance exceeds this limit, on the acoustic impedance model are distinguished as paleokarst zones with reduced permeability and porosity, and thus are excluded from the prospective areas for exploration drilling (Figure 10).

Intensive anhydrite filling significantly reduces primary and secondary porosity, associated with karst processes, as well as disrupting the hydrodynamic connection inside the reservoir. Core data analysis shows the average core porosity and permeability of paleokarst zones less than 2% and 1 mD. These conditions correspond to paleokarst zones with non-reservoir properties. It is known that for a potential reservoir the porosity and permeability must be higher than 10% and 30 mD.

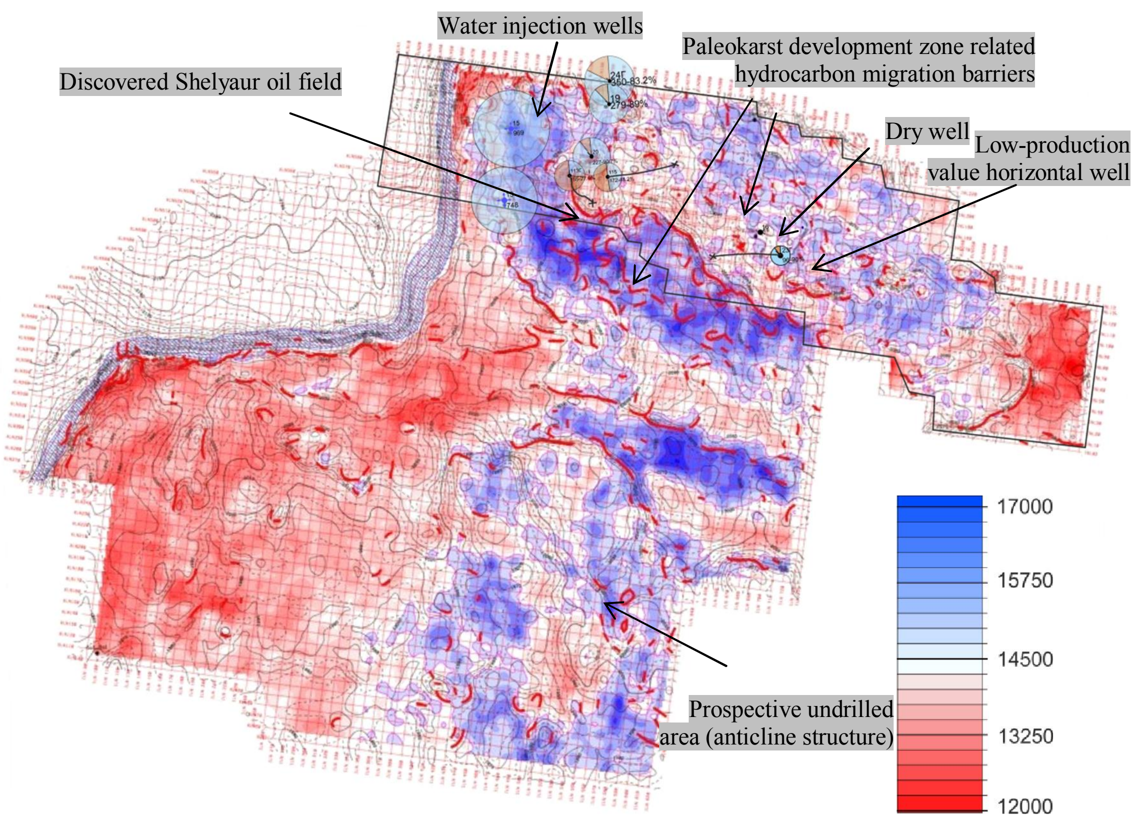


**Figure 10.** The impedance time slice at 15 ms below the top of Domanik formation.

The presents of paleokarst systems may be the reason for the extremely variable productions of wells within the study area. Tracer and pressure analysis data also shows that the paleokarst system control compartmentalization of the carbonate reservoir in the study area.

The calculated maps of seismic attributes fulfilling the correlation coefficient conditions generally confirm the obtained from acoustic impedance analysis results. The most productive wells are located in areas with a range of instantaneous frequency values from 40 to 45 Hz (Figure 11). Paleokarst structure development zones have values of frequency above 50 Hz, water-injection wells are also located in areas with relatively high frequency values, it is worth noting that initially these wells were planned as oil producing, but tests during drilling have shown that Domanik formation is water-bearing this may indicate the presence of barrier for hydrocarbon migration due the development of paleokarst structures.

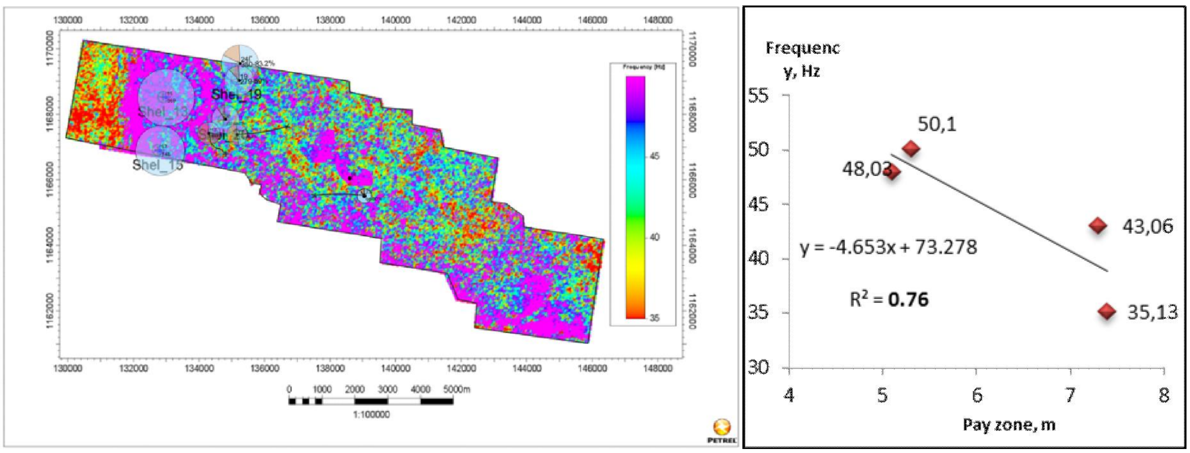


**Figure 11.** The instantaneous frequency time slice at 10 ms below the top of Domanik formation

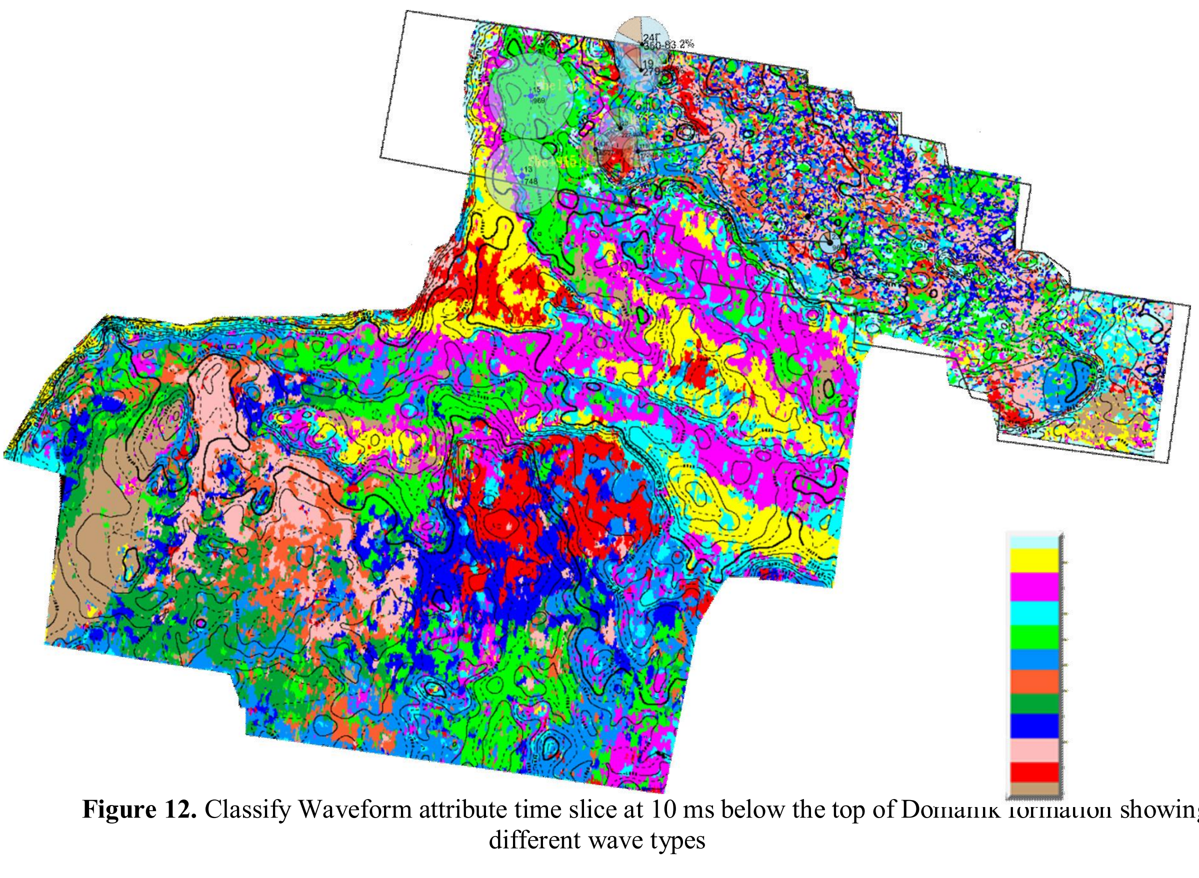

**Figure 12.** Classify Waveform attribute time slice at 10 ms below the top of Domanik formation showing different wave types

Wavelet shape analysis which were carried out by using "Classify Waveform" seismic attribute significantly expand the understanding of the Domanik formation facies composition and paleokarst structures development within the area (Figure 12). Algorithm of calculation allows detecting arbitrarily or on a given pattern, in a certain time window, zones with similar types of reflections. Total for Domanik interval 11 main types of waves was allocated. "Classify Waveform" attribute map shows that the types of waves in paleokarst zones are widely developed on the Northern part of an area, but also can be found in the West-North and central parts. When comparing this map with the Variance attribute map it can be seen that zones of these wave types distribution coincide with areas of ring-shaped structures concentration (which has been interpreted as paleokarst structures).

**Conclusions**

This paper presents the experience of using a complex method for the recognition of paleokarst systems by combining the core and well-log data analysis, seismic inversion and geometric seismic attributes and amplitude analysis. This method allows the delineation of distribution of the collapsed paleokarst system in three-dimensional space within the study area, as well as determination of their influence on carbonate reservoir compartmentalization.

Small-scale paleokarst systems with non-reservoir properties, developed in the study area, demonstrate high acoustic impedance due to high content of anhydrite compared to non-paleokarst with more uniform porosity. The results from seismic inversion and well-log data interpretation, which were used for mapping paleokarst systems showed the anhydrite contents in reservoirs. The applied seismic inversion method revealed itself as a useful tool for the characterization vertical and lateral distribution of the small-scale paleokarst systems. For the large-scale paleokarst systems, geometric seismic attributes analysis is most appropriate tool for mapping propagation anomalies that have been created by the structures on seismic data.

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