Seismogeological criteria for gas deposits forecasting in the north of Western Siberia

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Abstract. Seismogeological criteria for forecasting the gas content of the Aptian-Cenomanian sediments of Western Siberia are identified and substantiated in the study based on a comprehensive interpretation of seismic data, well log data, test results and petrophysical studies results. As a reference object we use the Jubilee oil and gas condensate field, which is located in the Nadym-Pur interfluve. The field contains the unique gas deposit in the Cenomanian reservoir horizon PK₁, the Albian sand layer PK₁₈ is productive too. Based on the results of the research, seismogeological criteria for the gas-bearing forecast are formulated. If there is a giant gas deposit in Cenomanian reservoir: 1) there is a reflectors formed on gas-water contacts (GWC) in seismic cross sections, amplitude characteristics of the reflector G, which is confined to the top of the Cenomanian complex, decrease; 2) time thickness (ΔT) increase, the interval velocities (Vint) decrease and amplitude-energy characteristics of the seismic record in the Aptian-Cenomanian complex decrease. The Aptian-Albian sheet gas reservoirs are displayed in seismic cross sections a jump in amplitudes of the seismic record, forming the "bright spot" anomalies in the time sections.

1. Introduction
The northern and arctic regions of Western Siberia, including the Yamal-Nenets Autonomous District and Kara Sea southern part, are one of the world's largest gas-bearing regions. In terms of oil and gas zoning within this territory five oil and gas bearing areas (OGA) have been allocated: Nadym-Pur, Pur-Taz, Yamal, Gydan and South- Kara (figure 1).

The main gas reserves in the north of the West Siberian oil and gas province are controlled by high-amplitude anticline structures and concentrated in the Aptian-Cenomanian sedimentary megacomplex [1-4]. In the Aptian-Cenomanian megacomplex two regionally gas-bearing macro reservoirs are distinguished: Cenomanian and Aptian, which are covered by transgressive clay beds that act as reservoir cap rock for hydrocarbon deposits.

In the southern part of the Yamal-Nenets Autonomous District, Nadym-Taz interfluve, there are such unique gas giant fields as Medvezhye, Urengoy, Yamburg, Yamsovey and others. In this area there are no regionally developed reservoir cap rocks within the Aptian-Cenomanian complex, and in this region fields the main gas reserves are concentrated in Cenomanian sand body PK₁, which is covered by a thick clay Turonian regional reservoir cap rock (Kuznetsov formation). The Cenomanian deposits are massive and they are controlled by large, high-amplitude anticline structures. Substantially smaller gas, condensate and oil deposits are concentrated in the Aptian-Albian, Neocomian and Middle-Upper Jurassic sand beds.
In Far North regions of West Siberia and in the southern part of the Kara Sea, in the section of the Aptian-Cenomanian megacomplex there is a thick clay Khanty-Mansiiisk (Yarongsky) reservoir cap rock lying in the lower part of Albian sediments. As a result, in the fields of the Yamal, Gydan and South Kara OGA, there are traditional Cenomanian deposits, but the main gas reserves are concentrated in the Aptian sandstones of the TP group that underlay the Khanty-Mansiiisk reservoir cap rock. This situation takes place in Kharasavey, Bovanenkovo, South-Tambey, Nurminskoye, Arctic, Srednyamalsk and other fields. As a rule, Aptian gas deposits are multi-layered, and are localized in a series of closely located, hydrodynamically unconnected sand beds lying in the upper part of the Tanopchin formation; the type is Layer-uplifted deposit.

Cenomanian and Aptian deposits differ not only in structure, but also in gas composition. The Cenomanian deposits contain only dry gas - methane, whose density by air is 0.554; Aptian deposits - rich gas, the density of which is 1.03 - 2.97.

2. Seismogeological criteria for gas deposits forecasting in the Cenomanian sediments

In the north of West Siberia, the Aptian-Cenomanian megacomplex in seismic time cross-sections is limited by the reflectors M and G, which are associated to the top of the Neitin clay unit (top of Barremian) and the bottom of the Kuznetsov formation (top of the Cenomanian) respectively [5-7]. The Neocomian (Berriasian-Lower-Aptian) sedimentary complex underlies Aptian-Cenomanian complex, it’s controlled by the horizon M in the bottom and the reflector B in top, which forms on the top of the Jurassic sediments.

2.1. Physical nature of seismic level reflector confined to «GWC»

In this region, gas-water contacts (GWC) can be frequently identified in seismic cross-sections on large positive structures, to which the unique Cenomanian deposits are confined, because an intense reflected wave forms on the contact of natural gas and water-saturated sandstones of PK1 (figure 2). On such objects, there are locally developed seismic reflectors under anticline structures in the reflector G relief, which merge with G horizon in the direction of the positive structures slopes. The reflectors associated with the GWC are usually traced quasi-horizontally or have a convex downward form.

Reflected seismic waves are formed on the boundaries of environments characterized by different physical properties. To form reflected waves, such characteristics of rocks as the density and velocity model for the sediments are determinative. The product of these parameters is the acoustic impedance and the differences in the acoustic impedance at the geological boundaries define the reflection coefficients and, as a consequence, the energy level of the seismic horizons formed on the boundaries.

The cross-section of the Cenomanian complex and the productive horizon PK1 (as a part of the complex) is represented by interbedding of siltstones, argillites and sandstones with a sandstones
predominance. The sand layers of the sand body PK\textsubscript{1} are good reservoir rock which porosity coefficient is about 30-35%, but separating them silty clay beds, on the one hand, are characterized by low filtration and capacitance properties, on the other - are not effective impermeable rock. As a result, the Cenomanian gas reservoirs are massive and have bottom water-drive.

Analysis of acoustic logging data for hydrocarbon fields in the north of Western Siberia showed that the Cenomanian section , in general, is poorly acoustically differentiated - the p-wave velocity differences at the boundaries between different lithological rocks do not exceed 100-150 m/s, as a rule. At the same time, the presence of a reflector at the GWC level indicates that at this boundary there is a drop in the acoustic impedance. The reflector forming on the GWC is not isochronous and "cut" the different-age layers within the structure, which are parts of a single productive horizon.

It is known from published materials that in terrigenous rocks at depths of up to 1-1.5 km, p-wave velocities in water- and gas-saturated reservoirs differ by 15-25% [8]. The analysis of the results of tests and well-log data for a number of fields in the north of West Siberia which was carried out at IPGG of the SB RAS showed that the fluid in the sand beds of the TP, XM and PK bodies, separated in the Aptian-Cenomanian section, significantly affects the acoustic characteristics of rocks: the p-wave velocity in gas-saturated reservoirs are 2100-3000 m / s, in water-saturated reservoirs - 2500-3800 m / s [9]. On the average, the velocity difference at the boundary between gas and water-saturated sandstones is of the order of 500-600 m / s. Densities behave in a similar way. The density of methane is 0.00072 g / cm\textsuperscript{3}, Cenomanian water is 1.01-1.03 g / cm\textsuperscript{3}.

The synchronous decrease in the velocities and densities of the gas-saturated part of the section leads to a sharp drop in the acoustic impedance at the GWC and is the reason for the formation of an intense reflected wave on this physical boundary.

It should be noted that not all Cenomanian gas deposits generate reflectors associated with GWC in time cross-sections. This may be due to both the quality of the seismic material and the limited seismic resolution.

2.2. Interval velocities
The gas-saturated intervals of the Cenomanian section are characterized by underspeed of p-waves. When reservoir altitude is sufficiently high this factor will lead to interval velocities (V\textsubscript{int}) decrease and, as a consequence, time thickness (\Delta T) increase of the entire Aptian-Cenomanian seismic megacomplex.

Figure 2. Time cross-sections along the profiles, crossed gas fields. Legend: 1 - reflector, 2 - seismic complex.
Figure 3 shows the dependences of $\Delta T$ on $\Delta H$ for the Turonian-Cenozoic and Aptian-Cenomanian megacomplexes constructed from the Nadym-Pur interfluve wells data. We can see the standard distribution for West Siberia in the Turonian-Cenozoic complex, which is located in the upper part of the sedimentary cover and does not contain oil&gas pools. Figure 3A shows the observation times of the reflector $G$ (the depth of occurrence of the Kuznetsov formation) are increased in the direction of the depression zones, as the thickness of the megacomplex increases. In the Aptian-Cenomanian inverse dependence takes place caused by the velocities drop in the gas-saturated part of the section.

![Figure 3](image)

**Figure 3.** Dependence of time thickness ($\Delta T$) on thickness ($\Delta H$) for the Turonian-Cenozoic (A) and Aptian-Cenomanian (B) megacomplexes (Nadym-Pur interfluve).

![Figure 4](image)

**Figure 4.** Map of the amplitudes of the reflector $G$ in the interval -5 + 15 ms (A); map of modulus mean amplitudes of the seismic record of the Aptian-Cenomanian complex (B), the map of time thickness between reflectors M and G (C); map of the interval velocity in Albian-Cenomanian megacomplex (D) (Jubilee field). Legend: 1-wells, 2- Cenomanian deposit outline.

The effect of velocity drop is also reflected in paleoreconstructions. In seismic time paleosections flattened on reflector $G$ local depressions in M and B reflectors paleoreliefs conform to the large anticlinal structures controlling huge Cenomanian gas deposits. Formation of these depressions is due
the decrease of p-wave velocities in Cenomanian gas deposits, not to the geological structure of the objects (figure 3).

2.3. Amplitude attributes of the reflection record

1. Loss of densities and p-wave velocities leads to a decrease in acoustic impedance of the entire gas-saturated layer and, as a result, to a change in the reflection coefficients not only on its bottom but also on its top - at the boundary between the clays of Kuznetsov formation and the Cenomanian sandstones. The reflector G, which controls the top of the Cenomanian complex, is formed on the bottom of the Kuznetsov formation clays, p-wave velocity in which is about 2000 m/s. In the development zone of the hydrocarbon deposit at the "fluid-reservoir" boundary, the reflection coefficient and, as a consequence, the energy of the reflected wave, decrease since acoustic impedance decreases in the gas-saturated rocks.

2. As noted above the Cenomanian reservoirs filled with natural gas are characterized by reduced velocities and densities. At the same time, gas-saturated rocks have an increased absorptive capacity. Seismic waves passing through the gas-saturated part of the section, significantly lose energy, that leads to a drop in the amplitude waves characteristics within the entire Aptian-Cenomanian megacomplex and in the underlying Neocomian and Jurassic sediments.

The seismogeological criteria for gas deposits forecasting in the Cenomanian sediments were tested on seismic materials for a number of fields in the north of Western Siberia. As an example, in figure 4 the results of a comprehensive analysis of geological and geophysical materials for the Jubilee field, where a unique gas pool is concentrated in the Cenomanian reservoir, are given.

The results of these studies showed:

1. In the gas-saturated part of sand body PK1, the interval velocity is 2200-2300 m/s, in the water-saturated part - 2800-2900 m/s; the difference in velocity characteristics of the section is about 500-600 m/s, that predetermines the formation of a reflector associated with the GWC at this boundary (figure 2).

![Figure 5](image-url)

**Figure 5.** Parts of seismogeological cross-sections along profiles crossed Kruzenshtern and South-Tambey fields. Legend: 1 – reflector, 2 – “bright spot”, 3 - seismic complex.
2. The contour of the Cenomanian gas reservoir is characterized by:

- lowered (less than 8000 cu) amplitudes of the reflector G (figure 4A) and low values of the modulus mean amplitudes of the seismic record (less than 5000 ms) inside the entire Aptian-Cenomanian megacomplex (figure 4B).

- Increased (more than 860-870 ms) ΔT between the reflector M and G (figure 4C) and lower values (less than 2150-2200 m / s) of Vint (figure 4D).

3. Seismogeological criteria for gas deposits forecasting in the Aptian-Albian sediments

In principle, gas pools in Aptian-Albian sand layers, which are associated with the main gas reserves in the north of the West Siberian oil and gas province - Gydan, Yamal and South Kara OGA, affect the nature of the wave field [10]. In these regions, sand beds of the TP group, containing significant gas reserves, can be displayed in time cross-sections by jump in the amplitudes of the seismic record - a "bright spot" [6,7]. As an example, figure 5 shows the time sections crossing the Kruzenshtern and South-Tambeyskoye fields located in the Yamal OGA. In sections above the reflector M, confined to the Neitin clay unit, which lies in Aptian-Cenomanian megacomplex bottom part, there are local high-amplitude seismic records anomalies that characterize gas pools.

Figure 6. Seismogeological sections along Leningrad field profiles Legend: 1 – reflector, 2 – “bright spot”, 3 - seismic complex.

As noted earlier, in the West Siberian oil and gas province the Aptian-Cenomanian complex, composed of sandstones, siltstones and argillites, is characterized by weak acoustic differentiation. The Khanty-Mansiysk reservoir cap rocks developed in the northern part of the Yamal-Nenets Autonomous District and in the southern part of the Kara Sea, and the host rocks are characterized by the very close p-wave velocities, and reflector is not formed on it.

Under conditions of weak acoustic differentiation, only high-velocity thin calcareous sandstones and low-velocity gas-saturated sand beds have anomalous acoustic characteristics in this part of the section. Analysis of acoustic logging data showed that in productive wells where PK beds are gas-saturated, they are characterized by anomalously low p-wave velocities of the order of 2200-2400 m/s. In wells with water-saturated sandstones of PK beds, these strata do not differ in acoustic characteristics from overlying and underlying rocks, the p-wave velocity of which is 2800-3000 m/s. Thus, on the top and bottom of the Aptian-Albian gas-saturated sandstones, significant jumps of acoustic impedance take place. As a result high energy reflections form at these boundaries. The mathematical modeling results of wave fields show when the thickness of low-velocity gas-saturated sandstone exceeds 15-20 m, resonance summation of the waves from its top and bottom take place,
which leads to an increase in energy of the interference signal and the effect "bright spot" generates. A similar effect is observed in the case of multi layered reservoir, when the formation of an interference wave happen on a series of closely located thin gas-saturated sandstone beds.

The anomalies of "bright spot" are reliably mapped over the area, it allows us to outline the contours of the gas pools from the interpretation of the seismic data. As an example, figure 6 shows two time cross-sections along profiles crossing the Leningrad field located in the Kara Sea, where seismic anomalies are not difficult to identify. Calculation of amplitude characteristics of seismic recording in the interval of productive layers allows contouring of gas pools. It should be borne in mind that in the case of multi layered reservoirs concentrated in close beds, this contour will be integral character.

Seismogeological criteria for forecasting gas deposits in the Aptian-Albian and Cenomanian reservoirs formulated in the paper are reliably confirmed by the results of two-dimensional mathematical modeling of wave fields.

4. Conclusion
The study aims to develop seismogeological criteria for the gas deposits forecasting in the Aptian-Cenomanian deposits in the north of Western Siberia. The research was carried out on the basis of a comprehensive scientific analysis of seismic data, well-log data, test results and lithologic-petrophysical studies.

As a result we determine a series of seismogeological criteria allowing to forecast of gas deposits in the Aptian-Cenomanian sediments of the north of Western Siberia.

If there is Cenomanian gas deposit, in wave seismic fields we can see:
- the presence in the relief of the reflector G anticlinal structures, in the base of which reflectors, associated with gas-water contacts, are identified in time sections;
- Increase in $\Delta T$ (time thickness) and decrease in interval p-wave velocity ($V_{int}$) in the Aptian-Albian-Cenomanian megacomplex;
- the drop in amplitude characteristics the reflector G confined to the top of the Cenomanian reservoir, and the decrease in the amplitude-energy characteristics of the seismic record within the entire Aptian-Cenomanian megacomplex.

The Aptian-Albian bedded gas deposits are displayed in time cross-sections by a sharp increase in seismic record amplitudes and the seismic anomaly "bright spot" formation.

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