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POSSIBILITIES OF SEISMIC EXPLORATION FOR CRYSTALLINE BASEMENT STUDY

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Possibilities of seismic methods of reflected and refracted waves have been examined for the purposes of detailed study on crystalline basement structure. Investigation of depth and structure of the basement plays an important role in the exploration of various deposits. Sedimentary cover is usually associated with oil and gas reserves. Ore deposits are formed in the basement rocks, basement splits and structure of its surface have a genetic relation not only to ore minerals, but also to oil resources. Reflection seismology is one of the main seismic methods of investigating structural geometry of the sedimentation mass, forecasting its material composition and possible hydrocarbon reserves. However, its possibilities for investigating crystalline basement are limited. Basing on many years' experience of reflection seismology and physical modeling it has been identified that actual roughness of basement surface limits the obtainable amount of waves reflected from it. Possibilities of reflection seismology for basement structure study are mostly related to investigation of discontinuous faults as diffraction objects using diffracted waves. Method of refracted waves combined with modern procedures and material processing aimed at getting dynamic seismic sections holds much significance for the basement study, especially in the process of surface mapping and, to a lesser extent, in investigating discontinuous faults. Combining seismic methods of reflected and refracted waves in basement study increases reliability of forecasting its geological structure: in particular, its surface can be well defined by means of refraction seismology, and zones of discontinuous faults are identified from diffraction objects using both reflection and refraction methods. As a result of applying both reflection and refraction seismology, an opportunity arises to carry out detailed analysis of basement structure and to predict its oil and gas content.

***Key words*:** reflected and refracted waves, seismic data processing, determination of basement surface, discontinuous fault study

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Introduction. The basement is normally composed of metamorphosed rocks of complex dislocation, formed at the pre-platform stage of earth crust development, and its surface is a denudation sheet of consolidated crust. Basement structure is often complicated by numerous intrusions of various composition, split zones and discontinuous faults. Structure of the upper basement is close to the vertical fault model.

The range of geological problems that require basement investigations is quite wide. It includes mapping of basement surface, forecasting of its material composition and conditions of ore deposit formation, identification of discontinuous faults and split zones, estimation of sedimentation cover thickness and analysis of prospects of oil and gas occurrence.

In the recent years many oil formations have been discovered in fractures and faults of crystalline basement [3, 5, 6, 14]. With this in mind, it is important to assess possibilities of seismic exploration to investigate structure of crystalline basement and to search for oil deposits in it.

Application of reflection seismology. The key seismic method of oil and gas exploration in sedimentary rocks is reflection seismology. The method, processing of materials and interpretation of results are well developed to investigate sedimentary structures and to forecast oil and gas resources in them [1, 7, 13].

Interpretation of reflection seismology results is carried out using kinematic (arrival time) and dynamic (amplitude) parameters of reflected waves. Application of kinematics and dynamics of reflected waves is based on repeated tests (method of common depth point – CDP), i.e. on the possibility to obtain wave dynamics, caused by changes in elastic properties on the reflection boundary – on the effective reflecting area, under various positions of source and receiver. Wave kinematics allows to define geometry of potential traps for the formation of oil and gas reserves, and dynamics – to forecast reserves basing on changes in elastic properties. Moreover, possibilities of wave dynamics to estimate elastic properties and to forecast potential oil and gas deposits are expanding quickly. In the latest 50 years not a single oil and gas well has been drilled in sedimentary rocks without prior application of reflection seismology.

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However, results of reflection seismology are limited when it comes to investigation of crystalline basement surface and its tectonics (discontinuous faults, down- and upthrown blocks). Basing on many years' experience of seismic works using methods of reflection and refraction waves and physical modeling, it has been identified that roughness of basement surface limits possibilities of reflection seismology, as waves reflected from its surface often cannot be registered, at the same time there is no problem in registering refracted waves. In practice it is usually considered that basement surface is located «lower than the last reflection boundary» in the sedimentary rocks.

It happens for two reasons: first of all, reflected waves have higher frequencies compared to refracted ones and, consequently, they are more sensitive to roughness of the boundaries; secondly, formation and distribution of reflected and refracted waves is different. Reflection from the basement surface is influenced by its roughness – a dispersion of waves takes place, whereas refracted waves spread within refracting bed and exit through its surface. For optimal registration of reflected waves in sedimentary rocks it is enough to set maximum distance between source and receiver, approximately equal to total thickness of prospective section. In existing systems of reflection seismology tests, when investigating sedimentary rocks, refraction waves from basement yield underburden are not normally registered [11, 12].

Possibilities of reflection seismology for basement structure study are to a great extent associated not with the waves reflected from its surface, but rather with diffracted waves and assessment of discontinuous faults as diffraction objects. With this in mind, special processing of seismic data is needed basing on migration of original records for relative gain in diffracted waves compared to reflection boundaries. As an example, consider processing results of seismic data, obtained in the course of physical modeling of horizontal reflection boundaries, disrupted by a vertical zone of irregularities in the shape of short steeply inclined reflecting areas (Fig.1).

Fault zone is modeled using steeply inclined reflecting areas (Fig.1, *a*), reflections from the areas themselves are not registered, but their upper and lower edges serve as objects of diffraction, which produce relatively strong diffracted signals. In case of normal migration of time section,

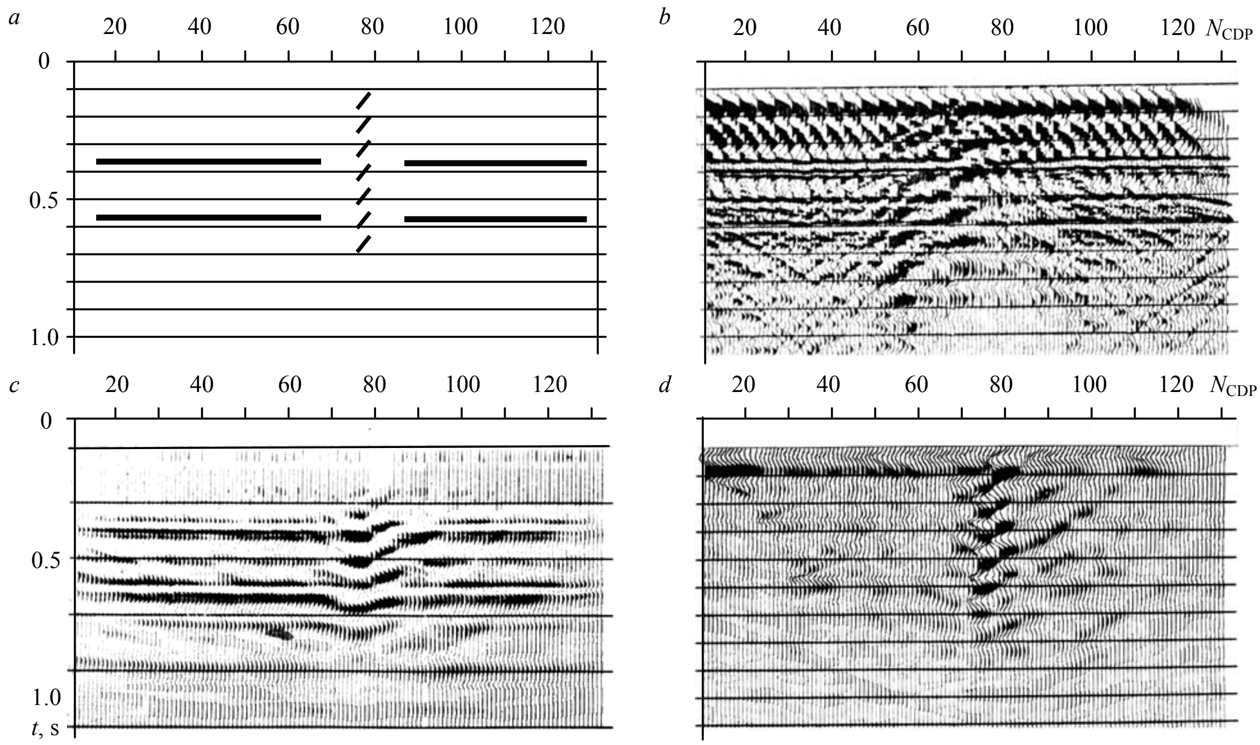

Fig.1. Special processing of physical modeling data from reflection seismology to identify diffraction objects:
a – physical model of discontinuous fault; *b* – CDP time section; *c* – migration of CDP section; *d* – section after processing, aimed at identification of diffraction objects. All the sections are presented in the scale of vertical time of wave distribution.
N_{CDP} – number of the point

horizontal reflection boundaries and weak diffraction objects can be identified (Fig.1, *c*). In case of special migration of the time section, aimed at identification of diffraction objects, under relatively weak reflection boundaries, zone of discontinuous fault can be detected with great precision (Fig.1, *d*) – in fact, edges of all inclined areas of the model are distinctly visible (compare Fig.1, *a* and 1, *d*).

Suggested way of migration can be used to detect various local objects in the geologic section and has been applied for the exploration of kimberlite pipes as zones of irregularity in flat sedimentary beds [8]. It can also be applied in processing of reflection seismology data to identify discontinuous faults in the sediments and in the basement.

Thus, according to reflection seismology materials, basement surface and its position are not normally defined, but instead reliable detection of discontinuous faults and zones of basement splits as irregularity objects is possible.

Application of refraction seismology. Before assessing possibilities of crystalline basement study using the method of refracted waves, specific features of their distribution in refracting beds should be described.

Physical foundation of refraction seismology is existence of geologic beds with increased rates of seismic wave distribution compared to overlying rocks. Method of refraction seismology differs from the method of reflection waves due to specific features of formation and distribution of refracted waves. In particular, in order to register refracted waves, the distance between source and receiver has to be 5-10 times bigger than the depth of reflection boundaries bedding, whereas for reflected waves registration the distance between source and receiver can approximate the depth of reflecting layer.

Due to specifics of formation and distribution of refracted waves, it is impossible to make refracted wave exit the bed at various angles, different from the critical one, in order to use repeated tests similarly to CPD method in reflection seismology, although repeated experiments in the method of refraction waves permit to get rid of various undesirable signals (e.g., overcritical reflections and interference of refracted waves from various refraction boundaries) [9, 10, 15]. Besides, to guarantee definitive processing of the materials, reversed records of refracted waves need to be obtained, which was not necessary for reflection seismography.

Refracted waves are always weaker than reflected ones, because their intensity is defined by the energy of the waves, falling on the refraction boundary in the plane of a solid critical angle, excluding the energy spent on formation of reflected waves in that plane. In actual geologic environment, due to specifics of elastic properties distribution and phenomenon of secondary refraction, relation of wave kinematics and dynamics to elastic properties of the media is getting very complex.

Due to physical distinctions of formation and distribution of refracted waves, their time and amplitude are related to elastic properties of geologic beds in a more complicated way compared to reflected waves. For instance, amplitude of the refracted wave depends on its distribution in the overburden and refraction bed, as well on refraction coefficient in the points where the wave enters and exits the bed. The issue of most interest is changing dynamics of refraction waves, caused by the bed entry and exit, i.e. the dependence of refracted wave amplitude on changing elastic properties on the refraction boundary.

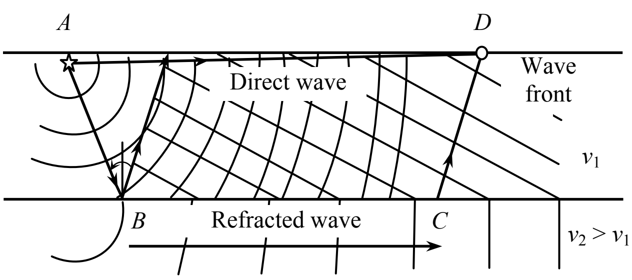

Fig.2. Map of refracted wave distribution in high-velocity bed

In Russian scientific literature refracted waves are regarded as «head ones» – i.e. as if their distribution occurs on the surface of refraction bed [2, 4]. It contradicts physical foundations of seismic wave distribution. The bed surface has zero thickness and zero energy distribution, whereas actual distribution of refracted waves occurs within refraction bed, and the energy exits through the top (Fig.2).

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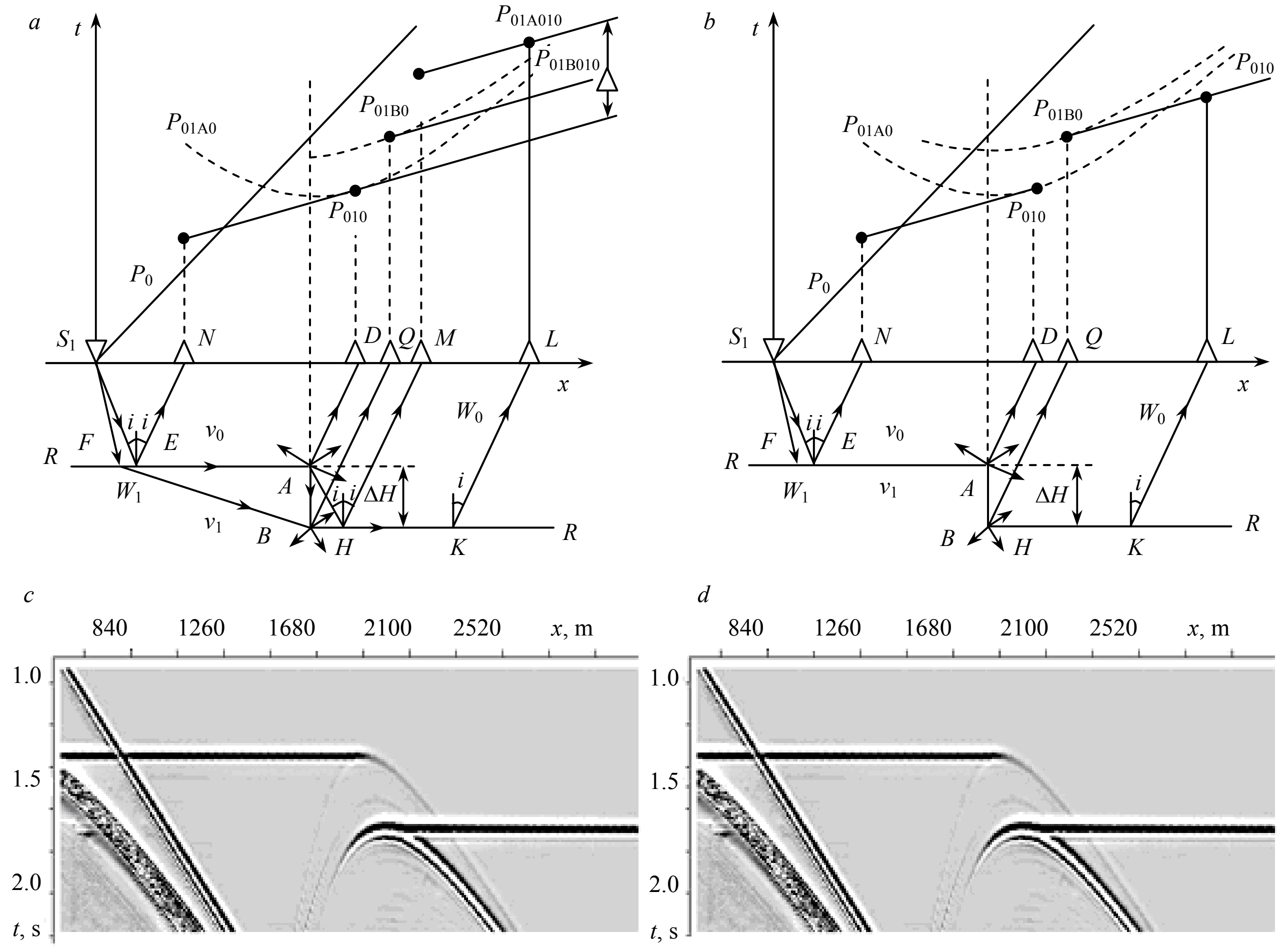

Fig.3. Kinematics and dynamics of refracted waves for a cliff (downthrow): *a* – kinematics represented by «head» waves, advancing along the top («head») of the bed [3, 5]; *b* – actual distribution of refracted wave in the bed; *c*, *d* – wave pattern for downthrow modeling (velocity reduction in the refraction bed). Dotted lines correspond to hodographs of refracto-diffracted waves

Assumption about distribution of «head» wave in the top bed is similar to the assumption about formation of a reflected wave from the boundary point, the energy equals zero in both cases. It is a well established fact that actual reflection occurs not from the boundary point, but rather from effective reflection area, the size of which depends on bedding depth and wavelet shape [1].

Specific features of refracted wave distribution are conformed by modeling a wave pattern over the cliff (downthrow) of the refraction boundary (Fig.3).

The wave pattern obtained as the result of modeling (Fig.3, *b*-*d*) contains no additional «head» wave 01*A*010, formed from a diffracted signal in the diffraction corner point *A*. Point *A* produces only a relatively weak diffraction signal, whereas a stronger wave comes from the *B* point. Difference in arrival time of refracted wave from the downthrow block, compared to the upthrown one, by the value Δt corresponds to primary transmission of boundary displacement ΔH by the refraction wave: $\Delta t = \Delta H / v_0$. This is a crucial point for definition of the nature of refracted wave distribution, i.e. in the downthrown block refracted wave is formed due to its distribution in the refraction bed (see Fig.2).

In the method of refracted waves, elastic properties of geologic media can be investigated by means of refracted and refracto-diffracted signals of various types: primary, secondary and converted ones, but the most frequently used are primary refracted and refracto-diffracted waves, while other regular and sporadic seismic vibrations are considered irrelevant.

Complex structure of the upper part of the basement defines specific recording of refracted wave, caused by the basement itself and characterized by changes in wave shape and amplitude (repeated in case of catching-up field geometry), drastic alteration of boundary velocity and existence of diffracted waves due to tectonic faults in the basement and its horizontal heterogeneity.

Optimal method of refractor seismology for investigation of changes in the basement elastic properties from the viewpoint of kinematic and dynamic properties of refracted waves is different from reflected wave method and should be selected individually for each area, basing on supposed depth range of refraction beds and velocity values. Main parameters of refraction wave method, providing continuous event tracking, are the following: maximum distance between source and receiver, interconnected reversed geometry fields for refracted waves and fold optimal of horizon tracking. It should also be taken into account that in reflection seismology optimal fold of tracking is selected for reflection horizon on the maximum depth of investigation, and actual fold of reflection boundaries decreases from the depth to the surface. In refraction seismology, on the contrary, for the chosen optimal fold at the maximum depth of refraction horizon, actual fold of tracking increases with decreasing depth. In the basement study, actual fold of its tracking varies with respect to the calculated value depending on depth alteration: decreases when depth increases and increases with depth decreasing.

Currently it is mostly kinematic processing of seismic records of refracted waves that is being carried out, i.e. the processing utilizes their arrival time; amplitude – wave dynamics, is required only for wave correlation and time estimation. All further processing is carried out only for registration time of refracted waves [1, 4, 13]. Detailed investigation of basement structure, however, requires dynamic processing of refracted waves and obtaining dynamic sections, similar to the ones built for reflected waves.

Lately, dynamic options of processing seismic records of refracted waves have been tested, but their practical application is still limited. We have proposed and developed an approach to dynamic processing of refracted signal records basing on migration of refracted waves, it is similar to dynamic processing of reflected wave records [8-11].

In order to obtain dynamic seismic sections from records of refracted waves it is necessary to perform certain operation.

1. To estimate distribution rates of elastic waves in the refraction bed by dynamic means using reversed records of refracted waves. Dynamic way of rate estimation for refractory bed is based on matching incline angles of refraction boundaries while enumerating migration rates of reversed records of refracted waves. This approach is similar to kinematic option of rate estimation in refraction bed by way of constructing time fields for different distances between source and receiver [1, 13].

2. In the course of seismic record processing to take into account changes in their dynamics for distribution in overlying media and in refraction bed. Accounting for attenuation (geometric divergence) of seismic waves advancing in overlying media happens due to the shape of diffracted wave hodograph, which is utilized to do the summing up in case of migration. Accounting for attenuation of refracted waves advancing in refraction bed is based on the conventional dependence of amplitude on the distance covered [11, 13].

3. To complete migration of seismic records of refracted waves basing on Kirchhoff integral. This is done taking into account attenuation of refracted waves with alteration of refraction horizon depth. Sections of migration records of refracted waves from reversed geometry fields are summed over common verticals – over conjugate points (common points on the boundary). Their amplitudes result from coefficients, characterizing exit of the wave from the refraction bed, and full amplitude of reversed records. For walkaway geometry fields, wave amplitudes are defined by coefficients, characterizing entry of the wave into the refraction bed.

4. To reduce undesirable signals and interference of refracted waves from refraction boundaries at different depths by repeated application of geometry field, similarly to summing over common reflection points in reflection seismology.

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Sections of migration records of refracted waves are summed over common verticals – over conjugate points (common points on the boundary). Their amplitudes result from coefficients, characterizing exit of the wave from the refraction bed, and full amplitude of reversed records. For walkaway geometry fields, wave amplitudes are defined by coefficients, characterizing entry of the wave into the refraction bed. Dynamic sections of refraction seismology are similar to the reflection ones, obtained as a result of migration of initial records in the method of reflection waves.

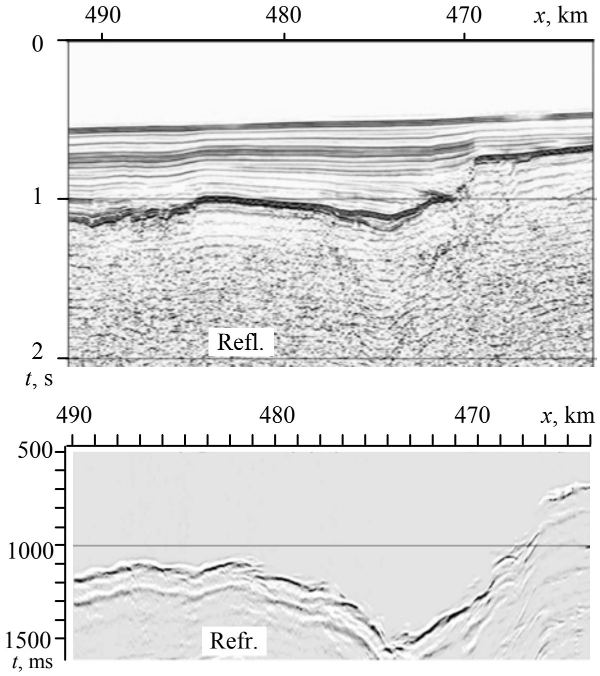

Fig.4. Fragments of seismic sections: reflection seismology with conventional processing and refraction seismology on the profile 2-DV in the northern part of Okhotsk Sea

Derived dynamic sections of refracted waves can be applied in any refraction-related operations for the solution of various geologic problems: from small-depth studies to investigation of the Earth crust on supporting profiles. Dynamic sections of refracted waves have a special significance for basement studies, particularly its surface and discontinuous faults.

As a result of processing, amplitudes of dynamic sections of refracted waves have to correspond to the coefficient of refracted wave exiting the refraction bed (or entering it, in case of walkaway geometry field) and characterize alteration of elastic properties in the exit point (on the effective refraction area), provided that the entry point of the refraction wave into the bed is constant. This conditions permit to use kinematic and dynamic properties of refracted waves in estimating alterations of basement elastic properties.

Modern application of reflected and refracted wave dynamics creates new opportunities for estimating alterations of elastic properties. Dynamic sections of reflected waves can be used to define alterations of elastic properties of reflection boundaries in sedimentary rocks, their configuration and rates of wave distribution. Dynamic sections of refracted waves record alterations of elastic properties of refraction boundaries, special importance is attributed to basement surface studies and, apart from that, estimation of distribution rates in the refraction bed. Combined results of reflection and refraction seismology allow more reliable forecasting of the depth, surface landscape and structure of the basement (Fig.4).

Using seismic materials of reflected waves, conventional processing has been carried out without specific emphasis on diffraction objects, therefore identification of split zones in the basement, judging by the reflection section, is ambiguous. Reflection horizons in the sediment section are well defined.

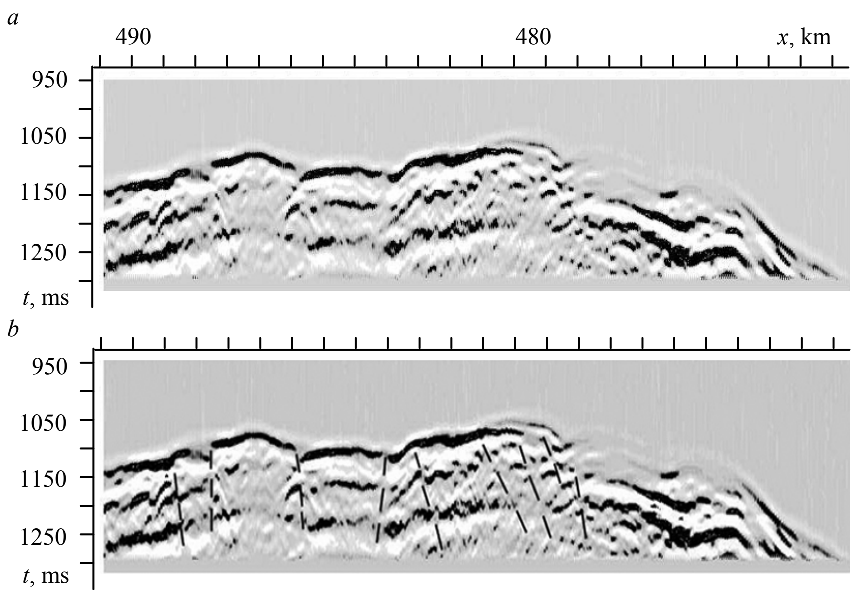

Fig.5. Fragment of dynamic seismic section of refraction seismology on the profile 2-DV in the northern part of Okhotsk Sea (*a*) and its application for identification of possible discontinuous faults in the basement (*b*)

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Dynamic sections of refracted waves play a special role in basement studies, particularly its surface and discontinuous faults. On the dynamic seismic section the following elements are clearly visible: crystalline basement surface, its block structure and discontinuous faults. As a matter of fact, the basement is divided into separate blocks of 1.2-2.0 km. Left part of seismic refraction section on a larger scale is presented in Fig.5.

Results. Practical application of suggested complex of oil and gas basement exploration demands preliminary seismic tests of refraction seismology to be carried out on the drilled and well investigated area with the basement depth of 2.0-2.5 km with completed reflection seismology works. Combined consideration of reflection and refraction seismology results will permit to assess efficiency of reflection seismology results in identification of basement split zones, as well as to select an optimal method of refraction seismology to investigate landscape of the surface basement.

Conclusion. The main geophysical method of oil and gas exploration is reflection seismology. To estimate oil and gas content of the basement, results obtained by this single method are not enough. Combining seismic methods of reflected and refracted waves in basement study increases reliability of forecasting its geological structure: in particular, its surface can be well defined by means of refraction seismology, and zones of discontinuous faults are identified from diffraction objects using both reflection and refraction methods.

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