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Geological Structures of the Norilsk Copper–Nickel Deposit: A New Interpretation of the Seismic Refraction Data

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Abstract—Regional seismic works in the area of the Norilsk copper–nickel deposit were made using the seismic refraction method in the 1980s. These data were used to derive new information about the studied area. The data of eight profiles of about 2900 km total length were processed by the homogeneous functions method and reinterpreted.
Based on the seismic sections thus derived, horizontal slices were built to identify the spatial positions of structures and produce the volume image of the basement's ledge. Seismic sections of 10–20 km in depth and horizontal slices contain the information about the boundaries, reflect the volume internal structure of sedimentary strata and basement, and show the faults.

Keywords: Norilsk copper–nickel deposit, seismic refraction method, method of homogeneous functions
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INTRODUCTION

The process of making a geological survey is very costly and laborious, starting from prospecting for natural resources until the economic assessment of a deposit, hence many enterprises try to optimize their prospecting works. Processing and reinterpretation of the seismic data from earlier works is an economically reasonable decision that provides additional information about the geological structure of a region. With the new knowledge taken into consideration, one can manage future geophysical works.

This work was performed for the Norilsk mining-and-metallurgical integrated works by the researchers of the Faculty of Geology of Moscow State University. The data on eight seismic profiles that are located in the area of the Norilsk copper–nickel deposit were reinterpreted (Fig. 1). Processing of the refracted wave travel-time curves was made by the method of homogeneous functions.

THE GEOLOGICAL STRUCTURE OF THE STUDY AREA

The sedimentary section in the area of Norilsk and in the adjacent territories includes the following complexes, with their respective geological evolution stages (Golodkovskaya, Demidyuk, and Shaumyan, 1977; Geologo-geokhimicheskie ..., 1989; Mishin, Panfilov, and Stepina, 2003): (1) terrigenous cover of young overlain plates and troughs (J–K; up to 7 km thick); (2) volcanic–terrigenous units in depressions or the feet of young plates (P_2–T_{1-3}; up to 7 km thick); (3) tuff–basaltic units of the trappean depressions (P_2–T_{1-2}; up to 3 km thick); (4) terrigenous-carboniferous rocks in the foot of the trappean depressions (C_2–P_2; up to 2 km thick).

The lower half of the sedimentary cover is presented by two rock complexes: a) carbonate (halogenic)-terrigenous rocks of the internal field and marginal troughs, which belong to the matured craton stage (PZ_{1-2}), up to 6 km thick; b) carbonate (volcanic?)-terrigenous rocks of the pericraton troughs and internal field of plates, which belong to the young craton stage (Rf–V), up to 8 km thick. The crystalline basement has a block relief.

In the sedimentary cover, the amplitude of interblock displacements gradually decreases and rarely reaches hundreds of meters on the surface. The lower half of the sedimentary cover (Riphean layers) smooths the relief of the crystalline basement and the upperlying Paleozoic beds have a gentle cratonic structure. The most distinctive peculiarity in the structure of the consolidated crust in the central part of Norilsk ore district (across the strike of its near-surface dislocations) is its keyboard-like structure.

If we compare the system of plicative dislocations of the sedimentary cover with the relief of the roof and foot of the consolidated crust, their conform (complementary) bedding can be identified. The generalized schematic geological section, which is typical for the discussed territory (Fig. 2), is taken from (Geologo-geokhimicheskie ..., 1989).

The area of the Norilsk ore district is covered with a dense network of point sounding (PS, which was

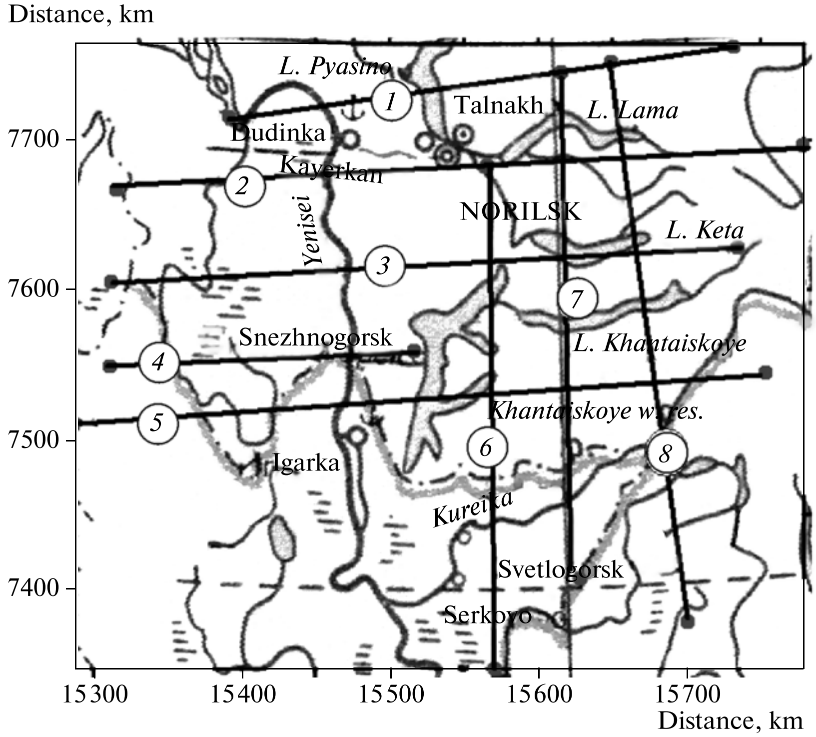

Fig. 1. The positions of point sounding profiles made with the seismic refraction method in the 1980s: *1*, Solyonaya–Ayan; *2*, Varngeyakha-Ayan; *3*, Mal. Kheta–Keta; *4*, Bol. Kheta–Khantaiskoye water res.; *5*, Russkaya–Ende; *6*, Rybnaya–Severnaya; *7*, Mikchangda–Degen; *8*, Erachimo–Mikchangda.

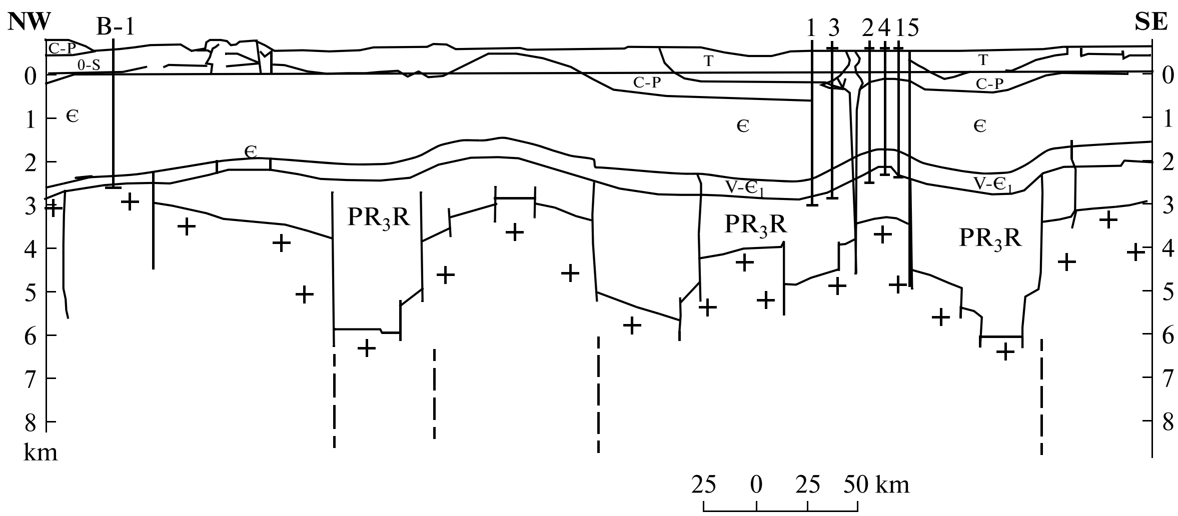

Fig. 2. The schematic geologic section of the study area, after (Geologo-geokhimicheskie ..., 1989) with modifications.

suggested in the 1960s by N.N. Puzyrev) profiles that were made by the seismic refraction method (SRM). This method is a low-detailed seismic study method and is applicable only in the case where all complex structures should be identified in a medium with a inhomogeneous velocity field. The positions of the studied PS-refrected wave profiles in the discussed area are shown in Fig. 1.

THE METHOD OF THE STUDY

The observations here are point ones, because there were no profile studies. The distance between shot points is 20 km on average, with 2–10 km between receivers. The interpretation was made in the past with N.N. Puzyrev's method (Puzyrev, Krylov, and Potap'ev, 1965). The principal peculiarity of this inter-

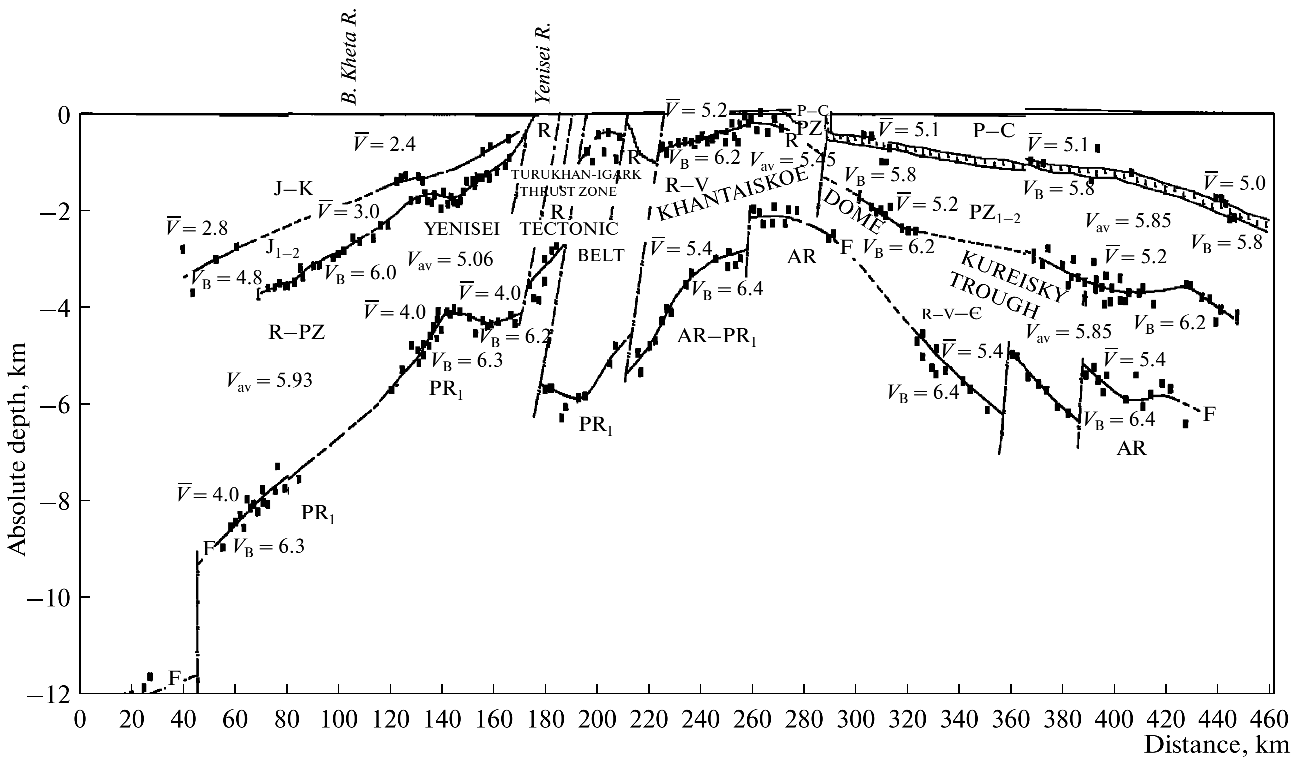

Fig. 3. The seismogeologic section along the Russkaya–Ende profile based on the results of seismic studies in the 1980s. The section contains the values of the boundary (V_B) and layer (V_{av}) velocities.

pretation is the building of special travel time fields, namely, travel time sections at equal distances. Such travel time fields are travel-time curves built in the special coordinate system, X and T, where X is the center of observation base (source–receiver) and T is the travel time measured at the given base. Graphically, such a field is seen as equal distance (offset) isolines. Use of these fields allowed researchers to distinguish the waves belonging to different boundaries, to interpolate travel-time curves and to calculate the values of boundary velocity. This is very important for low-resolution observations. Computation of boundaries' depths and average velocities in the 1980s was made with the t_0 method.

Figure 3 shows the section that was derived earlier along the Russkaya–Ende profile. The crystalline basement has an ledge in the central part of the profile; this ledge is covered with Riphean deposits. In the section the values of layer and boundary velocities are shown, along with the fault locations. The new techniques for section building, which we used, are automatic ones; therefore, a subjective interpretation is avoided. Nevertheless, it appeared that the sections we interpreted and those made in the past have common features.

The field observations were made with the use of Cherepakha-M and Taiga-2 hardware complexes. These stations are used for the recording of earthquake-produced waves. In the case of the present study, they recorded seismic waves from shots.

THE GODOGRAF SOFTWARE PACKET FOR INTERPRETING THE TRAVEL TIME CURVES OF REFRACTED WAVES

Refracted wave travel-time curves that were recorded during SRM works in 1980s were reinterpreted using the method of homogeneous functions (Piip, 1991, 2001). The GODOGRAF software is a universal program for interpreting all systems of refracted wave travel-time curves in complex media using the method of homogeneous functions. The interpretation process is completely automated. Either small-depth seismic survey information or travel-time curves from deep investigation methods can be used as the initial data. It does not require marking the segments that are related to different refraction boundaries in the refracted wave travel-time curves, since it is made automatically.

The program is applicable for any system of travel-time curves: from two reversed ones to the case when sources and receivers are located at random in the profile. This allows one to derive velocity sections, horizontal slices, curved surfaces (for example, the relief of boundaries), and sections that represent the distribution of physical parameters. In the velocity sections, the boundaries of the first (step-wise change of velocity)

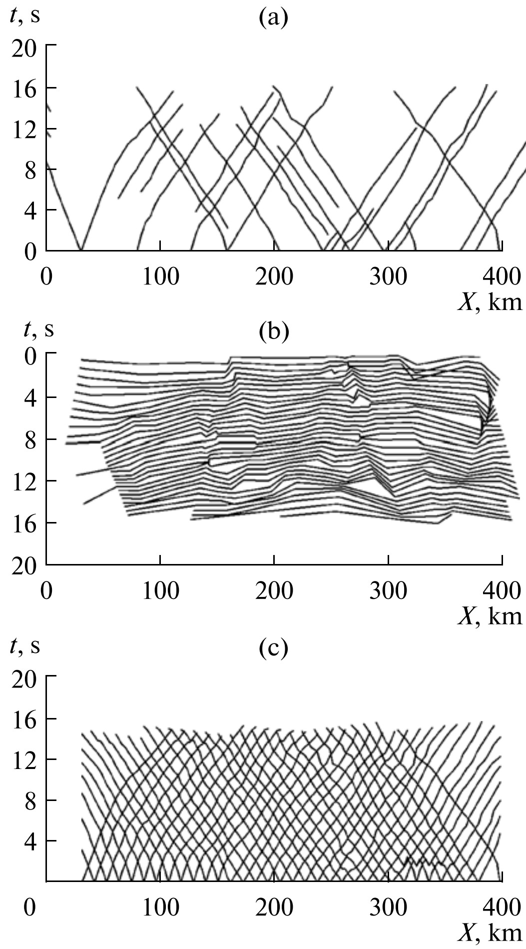

Fig. 4. The system of observed (a) and interpolated (c) refracted wave travel-time curves along the Russkaya–Ende profile; section (b) demonstrates the observed time section of the offsets.

or the second (change of velocity gradient) type boundaries are identified automatically. The depth to the roof of the waveguide is computed automatically as well, if the number of observations is sufficient.

The geological interpretation of the completed velocity sections and deep slices is made directly by an interpreter. The seismic section is seen as a velocity field in the form of isolines, with values of velocity determined in the points of a rectangular mesh.

The program allows one to interpolate the observation system by the addition of travel-time curves between the sources (shot points) and to derive the sections for profiles with poorly observation system.

The algorithm of the GODOGRAF program is based on the method of two-dimensional inversion of refracted wave travel-time curves, with the use of homogeneous functions. This method is based on local approximation of real velocity fields by homogeneous functions of two coordinates. The velocity sections are rendered as a mesh-based model; this allows modern computation methods to be applied for the visualization and interpretation of such sections.

The method of homogeneous functions is a method for the automatic interpretation of the highest-complexity data in the studies of two-dimensionally inhomogeneous media; applying this method does not require an initial model.

Note that the approximation of sections by homogeneous functions is useful for real geological media. Such functions are a broad type of multi-dimensional functions, where velocity can have significant vertical and horizontal gradients. A seismic model that is described by a homogeneous function can also include straight seismic boundaries (function jump lines or function's gradient lines). The complete section is built from numerous homogeneous functions, where every function corresponding to a pair of reversed travel-time curves.

THE NEW INTERPRETATION OF SEISMIC DATA

Based on the automated technique described above, we processed the travel-time curves for eight profiles. The positions of the profiles are shown in Fig. 1. The profiles compose a nearly evenly distributed rectangular network with 50–70 km steps between them.

The seismic wave travel-time curves (time section of equal distances) that were derived based on the data of M.V. Dmitriev and Yu.G. Zaitsev (1988) were digitized and used for building the new sections. An example of refracted wave travel-time curves that were observed along the Russkaya–Ende profile (5) is shown in Fig. 4, at the top. The travel time section of equal distances is shown in Fig. 4, in the center. This section was used for interpolation between the travel-time curves (Piip, 2001).

The interpolated travel-time curves for this profile are presented in Fig. 4 at the bottom. They were used for computation of the travel time section. As to the shot points, the travel-time curves were evenly interpolated with a step of 12.5 km.

In the new automatically computed seismic sections (Fig. 5), the following strata were identified, from bottom to top:

(1) In the crystalline basement (AR–PR) the velocity was 5.8 to 7.2 km/s and the gradient was relatively small;

(2) In the Riphean deposits (hatched in Fig. 5 and denoted as Rf) the velocity was 5.8 to 7.2 km/s and the gradient was average;

(3) In the Paleozoic deposits (PZ) the velocity was 4.8 to 6.6 km/s and the gradient was higher than average;

(4) In the Upper Paleozoic–Mesozoic deposits (PZ_3–MZ) the velocity was 2 to 5 km/s and the gradient was high.

The age of the layers in our interpretation is approximate and arbitrary. The velocity of the respec-

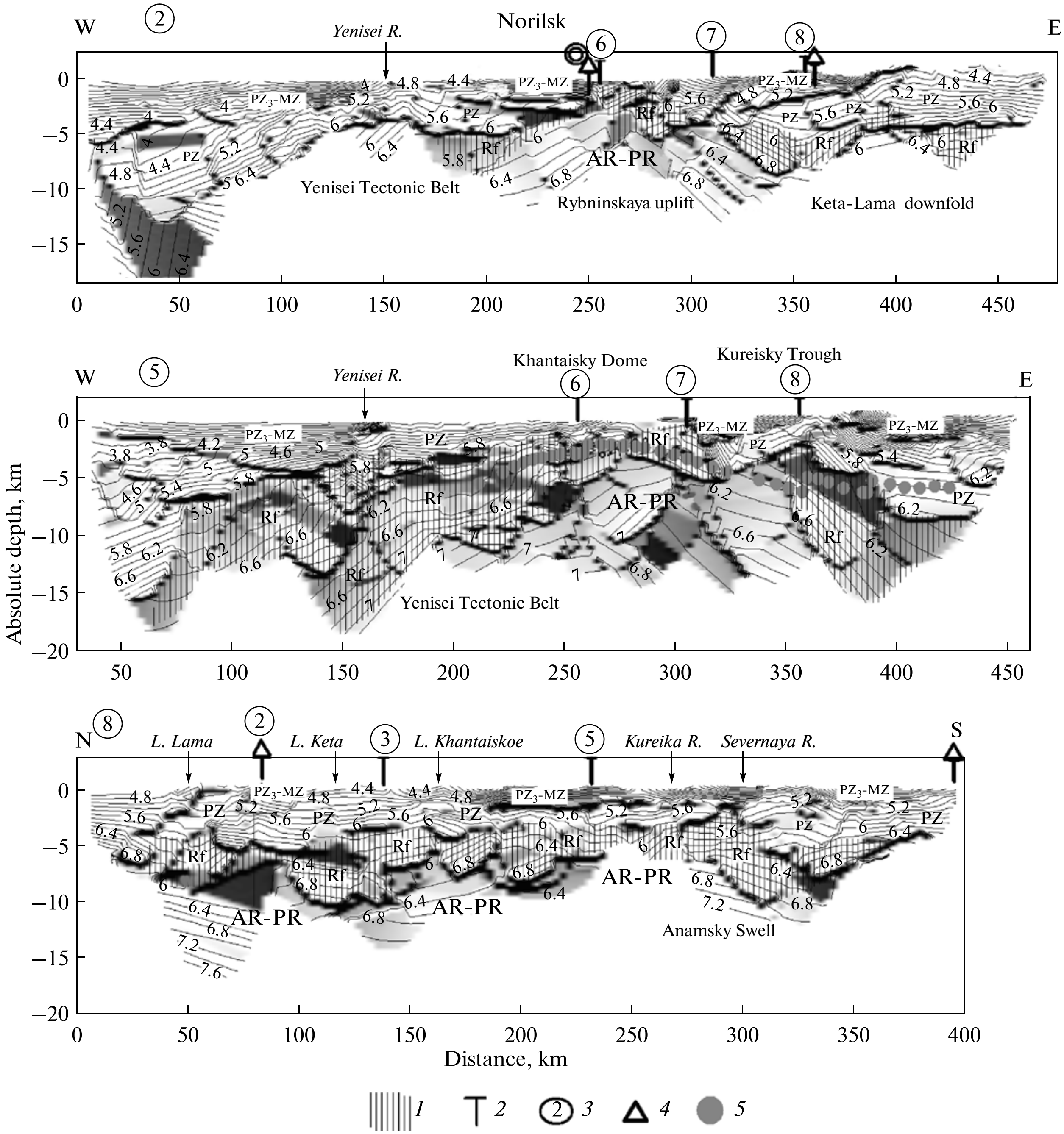

Fig. 5. The new seismogeological sections along several profiles in the study area: Varngeyakha-Ayan (2), Russkaya–Ende (5), Erachimo–Mikchangda (8). The step between velocity isolines is 0.2 km/s. *1*, Riphean deposits; *2*, crossing with the profile; *3*, profile number in Fig. 1; *4*, drillhole; *5*, the roof of the basement based on the previous interpretation along the Russkaya–Ende profile.

tive strata can vary in different sections within an insignificant range. All the mentioned strata are clearly divided by seismic inversion boundaries (the velocity is higher above the boundary than in the roof of the underlying layer). These strata differ in the values of velocity gradient (predominant distances between the velocity isolines).

The new sections are continuous in the sense that the values of velocity are calculated for every point of the section. The identified layers have internal structures that are characterized by the field of velocity isolines. The least recognizable layer is that denoted as PZ_3–MZ, since the wave recording started at a certain distance from the shot points.

The similarity of the sections along the sublatitudinal profiles. The deepest layer in all the sections is the *crystalline basement*. In the profiles it is seen as an offset in the central lower part of the section at absolute

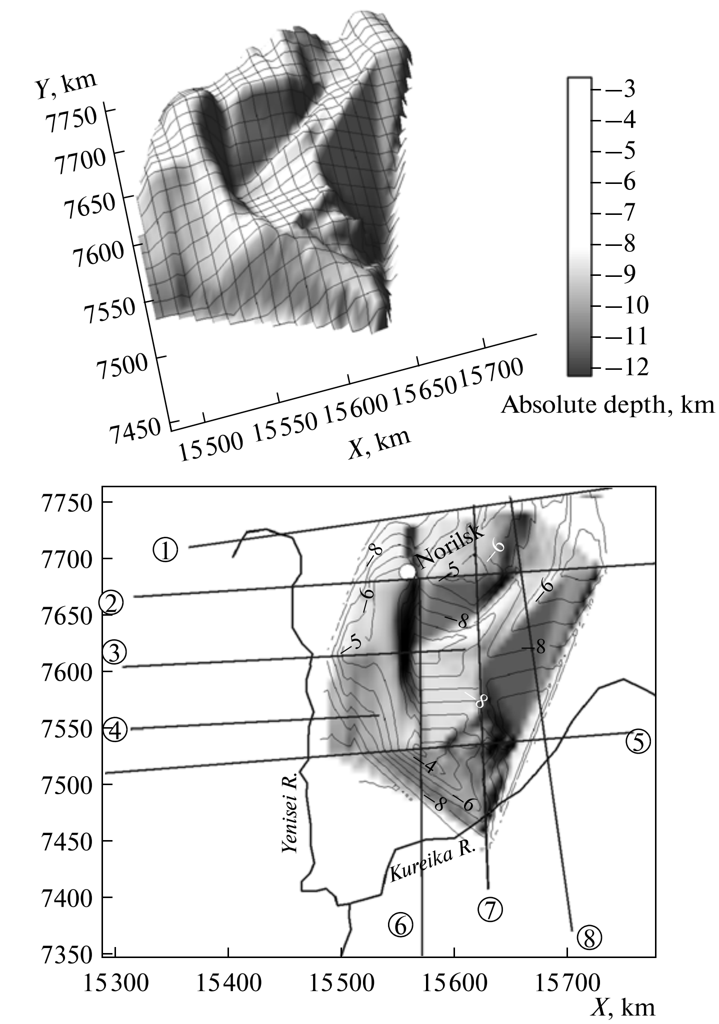

Fig. 6. The volume image of the crystalline basement's ledge in the study area (upper part). Isolines of the absolute depths of the basement's roof are drawn with 1-km steps. The digits in circles denote the numbers of the profiles.

depths from 13 to 3 km (Fig. 5, the Varngeyakha-Ayan (2) and Russkaya–Ende (5) profiles, at the top).

In the sections, the basement structure is a complex block one; the basement is characterized by the presence of faults and by a relatively low velocity gradient (5.8 to 7.2 km/s). The upper boundary of the basement in the sublatitudinal profiles is M-shaped with faults in the center (Fig. 5, top and middle parts). The Norilsk deposit, which is located near the Varngeyakha-Ayan profile (2), coincides with the deep fault in the basement and this fault is traced up to the surface (Piip et al., 2009).

The layer of *Riphean deposits* occurs above the basement. It has a smoothed surface east of Yenisei River approximately at the level of –4 km and an eroded foot. The values of velocity were from 5.8 to 7.2 km/s and the velocity gradient was average. West of Yenisei River the roof of the Riphean deposits goes down to the point of –15 km, beneath the Paleozoic deposits. The Riphean deposits in the sublatitudinal profiles along the Noril'sko-Kharaelakhsky Fault (250–280 and 280–300 km) rise up to the level of –0.6 km. The layers of *Paleozoic and Upper Paleozoic–Mesozoic deposits* occur relatively gently.

The section along the Russkaya–Ende profile (Fig. 5, middle part) contains the points for the previously interpreted depth of the basement surface. The points are located slightly higher than the new automatically computed surface of the basement; as well, this is the lower boundary in the old data (Fig. 3). The internal structure of the basement could not be derived by the earlier interpretation methods.

The sections along the submeridional profiles. Let us consider such sections based on the example of the Erachimo–Mikchangda profile (Fig. 5, at the bottom). The basement (AR–PR) is traced here in the lower part of the section. Its roof has a step-like relief at an absolute depth from 10–12 to 5 km. In the upper part, to the level of –3...–5 km, Riphean deposits are identified. They have a clear block structure: eight

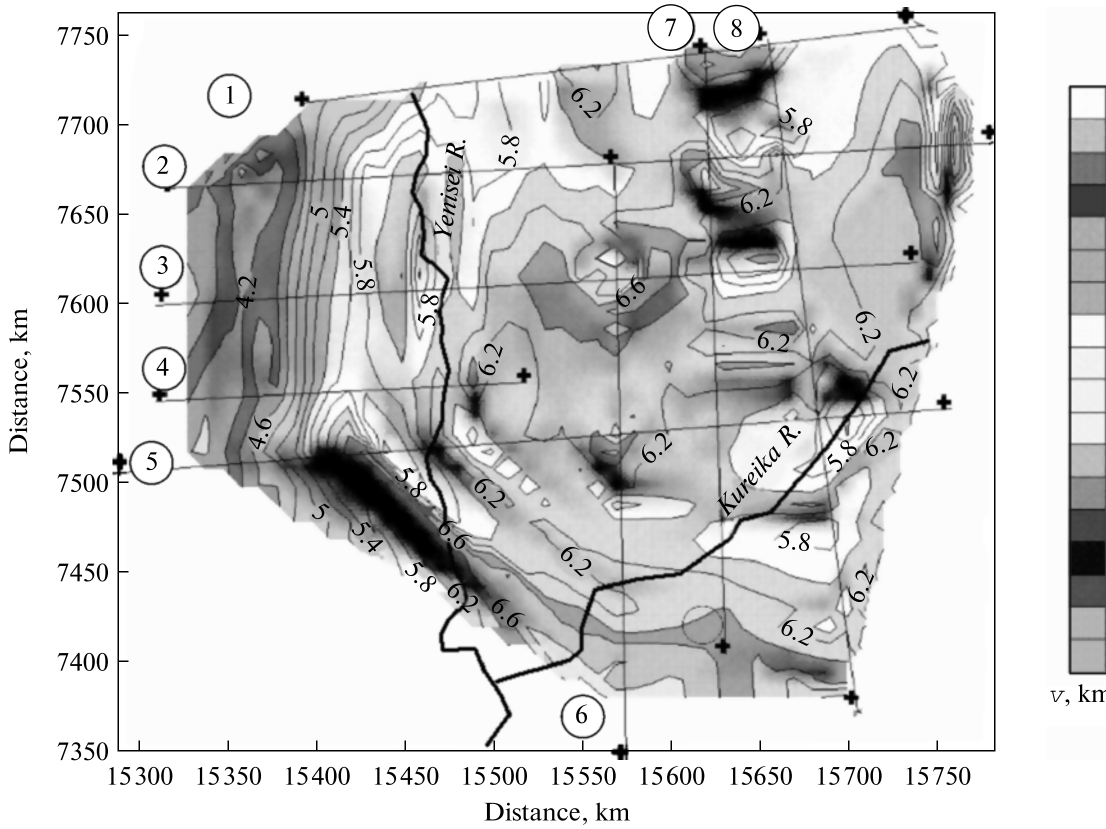

Fig. 7. The horizontal velocity slice at the level of –4 km. The step between velocity isolines is 0.2 km/s. The digits in circles denote the numbers of the profiles.

blocks are identified in the profile. The surface of the Riphean deposits is relatively smooth. Above this, the layer of Paleozoic deposits is distinguished; its values of velocity gradient are average and the structure is relatively undisturbed. In the northern part of the section, the uppermost layer is composed of Upper Paleozoic–Mesozoic deposits that have high values of the velocity gradient.

The volume image the *basement surface* that was derived on the basis of all 8 profiles sections is given in Fig. 6. As was derived from gravimetry data (Geologo-geokhimicheskie ..., 1989), the structure of the basement is keyboard-like. In the center of the study area, at the levels of –3 to –5 km, the basement surface with a branching fault in the center is identified. This is the fault to which the Norilsk copper–nickel deposit is associated (near the Varneyakha–Ayan profile (2)). The basement surface is lowered step-wise eastwards down to a depth of 10 km, and down to 9–10 km northwards and westwards. As is seen from Fig. 6, the ledge of the basement at the studied depth is traced only in the central zone, in the Yenisei–Kureika interfluve (Piip and Melikhov, 2009).

The structure of this territory is clearly seen in the *horizontal slice, which shows the velocity distribution* at the absolute depth of –4 km, near the roof of Riphean deposits (Fig. 7). The central part of the section is rounded, 300 × 300 km in size, and has nearly constant values of velocity (6.2 km/s) that are typical for the surface of Riphean deposits; this verifies the subhorizontal location of the roof of Riphean deposits here. The horizontal surface of these deposits is located in the Yenisei–Kureika interfluve.

However, there are places on this slice where the roof of Riphean deposits is not subhorizontal, for example, a rounded object at the crossing of the Mal Kheta–Keta (3) and Rybnaya–Severnaya (6) profiles. The values of velocity that were measured here were up to 6.8 km/s; the velocity of the layer grows monotonously with respect to depth; this fact indicates the uplift of Riphean deposits towards the surface (Fig. 5). Additionally, four rounded isometric zones ("subsidenses") with decreased velocities of 6.2 to 5.6–5.4 km/s and about 50 × 50 km in size were found in the relatively smooth surface of the section in the eastern part of the profile. The positions of these zones nearly coincide with the locations of large lakes: Lama, Keta, Dyupkun, and Agata. This may indicate the existence of these lakes here as early as the pre-Riphean time. Note that the subhorizontal segment of the surface of Riphean deposits generally coincides with the ledge of the crystalline basement (Fig. 6).

East of the Yenisei River and south of the Kureika River, the roof of Riphean deposits sinks and the sec-

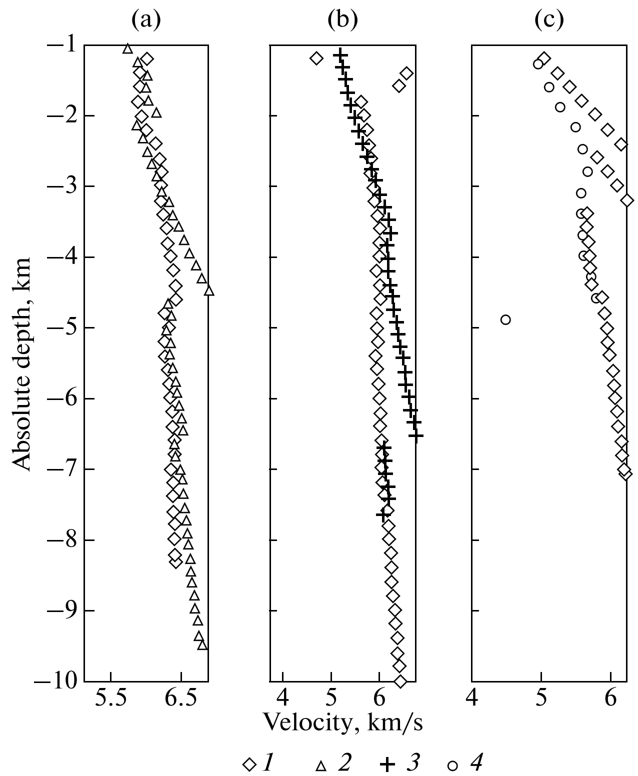

Fig. 8. Comparison of the velocity curves (a, b, c) in the points of profile crossings. The curves for the profiles are reflected in the respectively designated graphs: *1*, Russkaya–Ende; *2*, Rybnaya–Severnaya; *3*, Mikchangda–Degen; *4*, Erachimo–Mikchangda.

tions cross the zone of Paleozoic and Mesozoic deposits, which is indicated by the values of the velocity in the range from 5.8 to 4.5 km/s.

The validity of the sections. The degree of coincidence between the vertical velocity graphs in the crossing points of the profiles verifies the validity of the automatically computed sections; e.g., it is seen in Fig. 8 that the derived sections conform well and that the most precise sections are those, which are calculated for the depth range of 3 to 10 km.

CONCLUSIONS

As a result of the reinterpretation of observations that were made earlier, the volume image of the basement's ledge in the Yenisei–Kureika interfluve at depths from −11 to −2.5 km was obtained. The ledge of the crystalline basement is characterized by the presence of faults and a block structure. The Norilsk copper–nickel deposit coincides with a deep fault that cuts the crystalline basement's ledge.

The Riphean deposits cover the ledge of the basement. The horizontal velocity slice indicates the subhorizontal shape of the roof of Riphean deposits at the level of −4 km; the positions of four isometric low-velocity zones that coincide with large lakes in the region are seen from the slice as well.

The new interpretation method allows one to automatically derive and study the internal inhomogeneous structure of layers, the positions of faults, the facial variability of sedimentary layers, and the internal structure of the basement, as well as to build three-dimensional images of geological objects.

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