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6 NOVEMBER 1979 SEISMIC RESEARCH IN INACCESSIBLE AREAS AND THEIR USE IN SIBERIA 1 OF 3

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200020008-9

JPRS L/8751

6 November 1979

Translation

TECHNIQUES AND APPARATUS FOR REGIONAL SEISMIC RESEARCH IN INACCESSIBLE AREAS AND THEIR USE IN SIBERIA

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TECHNIQUES AND APPARATUS FOR REGIONAL SEISMIC RESEARCH IN INACCESSIBLE AREAS AND THEIR USE IN SIBERIA

Novosibirsk METODIKA I APPARATURA DLYA REGIONAL'NYKH SEYSMICHESKIKH ISSLEDOVANIY V TRUDNODOSTUPNOY MESTNOSTI I IKH PRIMENENIYE V SIBIRI in Russian 1978 signed to press 21 Apr 78 pp 1-208

[Book edited by V. V. Fedynskiy, "Nauka" Publishers, 1,500 copies]

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PUBLICATION DATA

English title	: TECHNIQUES AND APPARATUS FOR REGIONAL SEISMIC RESEARCH IN INACCESSIBLE AREAS AND THEIR USE IN SIBERIA
Russian title	: METODIKA I APPARATURA DLYA REGIONAL'NYKH SEYSMICHESKIKH ISSLEDOVANIY V TRUDNODOSTUPNOY MESTNOSTI I IKH PRIMENENIYE V SIBIRI
Author (s)	:
Editor (s)	: V. V. Fedynskiy
Publishing House	: Nauka
Place of Publication	: Novosibirsk
Date of Publication	: 1978
Signed to press	: 21 Apr 78
Copies	: 1,500
COPYRIGHT	: Izdatel'stvo "Nauka," 1978

UDC 551.1+550.83(571)

PROCEDURES AND EQUIPMENT FOR REGIONAL SEISMIC STUDIES OF INACCESSIBLE AREAS AND THEIR APPLICATION IN SIBERIA

Novosibirsk METODIKA I APPARATURA DLYA REGIONAL'NYKH SEYSMICHESKIKH ISSLEDOVANIY V TRUDNODOSTUPNOY MESTNOSTI (TRUDY INSTITUTE GEOLOGII I GEOFIZIKA, No 389 [Works of the Geology and Geophysics Institute, No 389]) in Russian 1978 signed to press 21 Apr 78 pp 1-208

[Book by N. N. Puzyrev, G. D. Babayan, A.I. Bochanov, G. V. Yegorov, S. V. Krylov, V. L. Kuznetsov, M. M. Mandel'baum, B. P. Mishen'kin, V. K. Monastyrev, A. L. Rudnitskiy, V. D. Suvorov, I. S. Chichinin, edited by Corresponding Member of the USSR Academy of Sciences V. V. Fedynskiy and Doctor of Physical and Mathematical Sciences I. P. Kosminskaya, Nauka Publishing House, 1500 copies]

[Text] The results of research performed by a collective of Siberian geophysicists in an attempt to create a theory, procedures and equipment for regional seismic studies in inaccessible parts of Siberia are discussed in this monograph. New data on the structure of the folded basement, deep zones of the earth's crust and upper mantle have been obtained by using the developed method of spot (differential) seismic soundings with the "Tayga" equipment in a number of areas of Siberia (the western Siberian platform, the Siberian platform, the Altaye-Sayanskaya Oblast, the Baykal rift zone).

This paper will be of interest to specialists in the field of developing seismic research methods and a broad group of geologists and geophysicists studying the deep structure of Siberia.

INTRODUCTION

The basic prospects for increasing the reserves of the most important types of mineral raw materials are connected with studying the deep structure of the little-developed and to a significant degree inaccessible eastern parts of our country -- Siberia and the Far East. Therefore the role of regional geophysical research aimed at quickly gathering information about the large-scale structural features of the upper part of the consolidated earth's crust, its deeper zones and the tops of the mantle over the entire territory is especially important. This information is needed for comparative evaluation of the prospects of the individual areas and the scientifically substantiated organization of exploration and prospecting for mineral deposits.

The necessity for expanding the studies of the earth's crust and upper mantle in order to understand the processes of the formation of the mineral deposits and their distribution laws has been emphasized in the "Basic Areas of Development of the National Economy of the USSR in 1976-1980," adopted at the 25th Congress of the CPSU.

Seismic studies are acquiring greater and greater significance among the methods of subsurface geophysics. The primary work is being done by the method of deep seismic sounding (DSS), that is, with the application of powerful artificial oscillation sources. The upper part of the consolidated crust (primarily the surface of the platform basement) has been studied for the most part by the correlation method of refracted waves (CMRW). The seismic techniques insure the highest accuracy and reliability of the determinations of the deep structure; the data gathered using seismic techniques are basic to the interpretation of the materials from other cheaper and simpler geophysical methods which, as a rule, are characterized by a significant degree of ambiguity in the solution of inverse problems.

The problems of subsurface seismic research can be provisionally divided into two groups. The first group includes the problems of studying the large-scale subsurface structural features over broad territories, including geologically inhomogeneous provinces. The second group of problems reduces to a detailed study of the relatively small and most interesting sections. In deep seismic research efforts are often made to combine relatively high detail with the study of large areas, which leads to high cost, slow accomplishment of work and insufficient effectiveness of the detailed and regional studies. At the same time examples of highly successful deep seismic studies have been known under the condition of concentration of them on problems of only a regional or only a detailed nature. Thus, new important information about the structure of the earth's crust and the upper part of the mantle over large territories has been obtained in relatively short time as a result of low-detail work in the vicinity of the transition from the Asian Continent to the Pacific Ocean [111] and at the transcontinental intersections of the North American Continent [128]. Detailed operations are most effective if they are not combined with the solution of regional problems, examples of which include the studies of parts of the Baltic Shield [23, 71], in the Ukraine [107, 108] and in other areas.

The reconnaissance (low-detail) operations must precede the studies of a detailed nature; they must be performed quickly over broad, sometimes inaccessible areas -- hence, as is known, we come to the efficient strategy of geological-geophysical research [123].

Seismic studies of the reconnaissance type have long not been actually performed in the eastern parts of our country, for the existing procedures and equipment in practice have not been suitable for effective use under the conditions of accessible terrain covered with taiga, swamps and mountains and almost devoid of roads. Therefore by the beginning of the 1960's a contradictory situation had developed: in the Siberian regions with their colossal potential with regard to still undiscovered mineral resources, such essential work had not been broadly developed primarily as a result of the absence of a procedural and equipment base. The application of the well-known seismic procedures (CMRW, DSS in the traditional continuous-profiling version) turned out to have low efficiency. It was only possible to investigate the surface of the basement of the platform regions on individual routes and in localized areas, but this did not provide any representative information about the regional structure. Over all of Siberia there was only one 300-kilometer DSS profile in the southern, steppe region of the Western Siberian plain (the Barabinskiy profile, the work of the NTGU [Novosibirsk Territorial Geological Administration], and the SNIIGGiMS [Siberian Scientific Research Institute of Geology, Geophysics and Mineral Raw Materials], 1958).

In recent times, the improvement of the seismic method of reconnaissance has been aimed predominantly at increasing its detail and accuracy [1, 12, 31]. The same trend is also characteristic of the development of a procedure for deep seismic sounding [43, 71, 81, 85, 126]. The purpose of this paper is the use of the preceding seismic reconnaissance experience to create a procedure for relatively low-detailed subsurface seismic studies over broad, sometimes inaccessible, areas.

The problem of the necessity for developing a special deep seismic exploration procedure for Siberian conditions, primarily as applied to the study of the basement, was stated for the first time by V. K. Monastyrev in the Western Siberian Geophysical Trust. In 1956, by his initiative a successful testing of the simplified systems of observations by the method of refracted waves calculated for use of the local elements of the hodographs of these waves instead of the difficult to realize continuous operation systems, was started. Later, this area was further developed procedurally and equipment-wise as well as in practice in the Tyumen' Oblast. The mass application and development of simplified refracted wave observations systems took place during the regional work in Central Asia and certain parts of the European territory of our country [24].

In 1961 N. N. Puzyrev, et al. began the development of a procedure making use of arbitrary systems of spot (differential) seismic soundings with waves of various types (reflected, head waves, refracted waves, and composite waves) at the Institute of Geology and Geophysics of the Siberian Department of the USSR Academy of Sciences. By the middle of the 1960's, the main components of this procedure had been developed and tested in practice: the discrete correlation of seismic waves; special two and three-dimensional time fields, which are a generalization of the concept of the seismic photograph to the case of an arbitrary system of sources and receivers of oscillations; the methods of determining the parameters of a medium by time fields; schemes for traverse and area seismic observations in inaccessible areas.

Simultaneously, a number of Novosibirsk, academic and branch organizations (IGiG SO AN SSSR [Institute of Geology and Geophysics of the Siberian Department of the USSR Academy of Sciences], IAiE SO AN SSSR [Institute of Anthropology and Ethnology of the Siberian Department of the USSR Academy of Sciences], SNIIGGiMS MG SSSR [Siberian Seismic Research Institute of Geology, Geophysics and Mineral Raw Materials of the USSR Ministry of Geology], the Siberian Special Design Office of the USSR Ministry of Geology) designed and tested lightweight, radio-controlled Tayga equipment for recording seismic oscillations during regional studies (see Chapter I-IV) and converted this equipment to series production.

The basis for the developed procedure is a new approach to the identification of waves recorded on short, separated sections (discrete correlation). A joint study was made of various types of waves from the most stable, extended boundaries in the earth's crust. The waves are identified with respect to a number of attributes based on using kinematic, dynamic characteristics of the oscillations and the general laws of the structure of the medium and the velocity distribution.

Observations are being performed on the simplest possible, to a significant degree arbitrary sounding systems (along the traverses or along the area network) made up of the source and a short (0.5-1 km) recording device, the spacing between which is selected in the region of greatest isolation of the investigated wave or group of waves considering local conditions. The arbitrariness of the observation systems and the use of the developed remote controlled equipment made it possible to obtain the required density of the points for determining the parameters of the medium (the reference point).

Along with the hodographs, another form of representation of the kinematic wave characteristics was used -- special two-dimensional and three-dimensional time fields. The geometric parameters of the seismic boundary and the velocity distribution of the medium are found by the time fields with sufficient accuracy for the reconnaissance phase.

In Chapter V, a new procedure is compared with the traditional types of regional seismic research.

The broad production introduction of the performed scientific-design developments has made it possible to proceed with the planned, deep seismic studies which are continuing at the present time in the Western Siberian platform with its mountain framework, the Siberian platform and the Baykal rift zone (see Chapter VI).

The performance of this complex scientific-production work on the creation of a new procedure and new equipment, their introduction and broad production use has turned out to be possible as a result of the close cooperation of a number of scientific and production organizations: IGiG SO AN SSSR, IAiE SO AN SSSR, IG YaF SO AN SSSR [Geology Institute of the Yakut Branch of the Siberian Department of the USSR Academy of Sciences], SNIIGGiMS MG SSSR, the ZapSibNIGNI Institute, the subdivisions of the Tyumen' Main Geology Administration, the Novosibirsk, Tomsk and Yakut Territorial Main Administration, the Eastern Geophysics Trust, the Krasnoyarskneftegazrazpedka Trust, the Siberian Special Design Office of the Scientific-Production Society of the Soyuzgeofizika of the Ministry of Geology of the USSR.

The successful improvement of the equipment and procedural developments, broad testing and introduction of the new methods into industry have been promoted by the new scientists and specialists. First of all the authors are grateful to Academician A. A. Trofimuk for his constant attention to the developments on all levels and also A. I. Bogdanov, V. V. Ansimov, N. P. Chunarev, Yu. G. Erv'ye, L. G. Tsibulin, N. N. Grachev, N. G. Rozhek, V. V. Tkachenko, V. A. Kondrashov, V. G. Sibgatullin, M. N. Ptitsyna and many other comrades.

V. V. Fedynskiy, Yu. Ye. Nesterikhin, E. E. Fotiadi, M. K. Polshkov, V. S. Surkov, N. V. Arkhipov, L. I. Orlov, I. D. Panin actively supported the development of the "Tayga" equipment.

Large collectives of the above-indicated organizations participated in the substantiation of the new methods, the design of the equipment, and the field experiments. Many of the specialists made a noteworthy contribution to the development and the procurement of the geological results:
E. S. Agadzhanov, V. V. Alekseyeva, G. P. Anistratov, Yu. F. Barinov, G. F. Bratova, A. A. Degryarev, V. I. Belov, I. I. Bobrovnik, D. D. and I. D. Bondar', Z. A. Bridzinskaya, I. I. Vayman, V. P. Vasil'yev, L. Sh. Girshgorn, A. N. Gretskiy, D. L. Dryga, L. V. Dubovik, A. I. Dyzhin, A. V. Yemel'yanov, Yu. G. Zaytsev, V. M. Zamskov, V. Ye. Zakharov,

A. M. Isaykin, V. A. Kalashnikov, V. N. Kartsenko, O. N. Klimov, A. L. Kogan, A. G. Komlyagin, A. F. Kolmakov, Yu. G. Konovalov, A. B. Kreynin, V. V. Krepets, A. L. Krylova, G. V. Krupskaya, N. M. Levina, V. G. Leont'yev, G. G. Maslennikova, V. M. Megerya, Z. R. Mishen'kina, V. F. Niknshina, V. M. Nosov, M. V. Pavlov, P. M. Prusova, G. V. Petrik, V. P. Ileskachev, I. V. Podnarkova, S. V. Potap'yev, R. A. Rakitin, V. G. Rodikov, A. G. Kyasik, A. S. Sal'nikov, A. S. Samoylovich, V. S. Seleznev, M. D. Sergeyev, T. G. Smirnova, M. Z. Sniper, S. K. Sulkovskiy, R. K. Taipov, L. L. Trusov, F. M. Trusova, V. F. Uarov, T. N. Kholodnyakova, M. F. Chernykh, Ye. S. Shlyakhter, A. S. Shtifanov, Yu. A. Shcherbakov, A. M. Yakimov, A. I. Yaniye, T. A. Yanushevich.

The authors of the individual chapters of this paper are as follows: Chapter I -- N. N. Puzyrev, S. V. Krylov, B. N. Mishen'kin, V. D. Suvorov, A. I. Bochanov, G. V. Yegorov, I. S. Chichinin; Chapter II -- N. N. Puzyrev, S. V. Krylov, B. P. Mishen'kin, V. D. Suvorov, V. K. Monastyrev; Chapter III -- A. I. Bochanov, G. V. Yegorov, I. S. Chichinin; Chapter IV -- N. N. Puzyrev, S. V. Krylov, V. L. Kuznetsov, B. P. Mishen'kin, V. K. Monastyrev, A. L. Rudnitskiy, V. D. Suvorov; Chapter V -- N. N. Puzyrev, S. V. Krylov, B. P. Mishen'kin, V. K. Monastyrev, A. L. Rudnitskiy, V. D. Suvorov; Chapter VI -- N. N. Puzyrev, G. D. Babayan, S. V. Krylov, V. L. Kuznetsov, M. M. Mandel'baum, B. P. Mishen'kin, V. K. Monastyrev, A. L. Rudnitskiy, V. D. Suvorov.

CHAPTER I. REQUIREMENTS ON REGIONAL SEISMIC RESEARCH

§1. Subject, Goals and Characteristic Features of the Regional Seismic Research Method

The most important goal of research is discovery of the regional structure and density of the depths to establish the relations of the surface geological features controlling the mineral deposits accessible for extraction to the structure of the subsurface zones of the earth's crust and the tops of the mantle.

The regional seismic studies constitute part of a complex of subsurface geophysics techniques. The seismic method must provide reference data for interpretation of the gravitational, magnetic and other natural physical field anomalies. By these anomalies the discovered subsurface structural features can be supplemented and extended to territories which are adjacent to the seismic operation zones.

At the present time there are numerous geological-geophysical facts and ideas about the model of the earth's crust which must serve as the basis for determining the characteristic features of the subsurface structure accessible to express investigation by the seismic method.

It is obvous that in the prospecting work the seismic method must isolate sufficiently large-scale structural features of the earth's crust and the tops of the mantle important to the understanding of the deep nature of the regional geological structures and the large-scale anomalies of the natural geophysical fields. The specific problems and objects of investigation are varied. Indisputably, it is necessary to consider that these include a comparative subsurface study of the platforms (young and old), the folded regions of various ages and the regions of tectonic activity (the rift zones, the regions of modern vulcanism). However, we must not limit ourselves to the study of these very large features as a whole containing internal inhomogeneities of different order. In order to estimate the possibility for the discovery of these inhomogeneities on the prospecting level, let us consider the geological data on the denuded regions and some of the results of deep seismic studies.

Let us use the materials from the tectonic regionalization of Siberia and the Far East by structural and formational attributes [22], limiting ourselves to the data pertaining to folded complexes, that is, the geological bodies which form the consolidated crust. The basic (largest) structures of the folded complexes are the geosynclinal troughs, the geoanticlinal uplifts, the orogenic type troughs and many others. These structures are distinguished with respect to internal structures and rock composition, and as a rule, they are bounded by large fractures. Statistical data are presented in Fig 1 on the horizontal dimensions of more than 60 such structures. The extended structures with a ratio of the axial lengths of 3 to 5 predominate. The dimensions along the long axis reach 800 km or more; the predominant values do not exceed 600 km. The width of the structures reaches 300 km with predominance of values near 100 km.

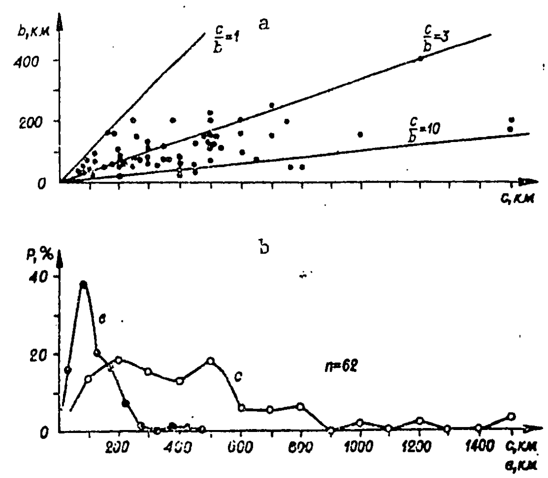

Figure 1. Characteristics of the horizontal dimensions of regional geological structures of the folded complexes of Siberia and the Far East.
a -- ratio of the width (b) and length (c) of the structures;
b -- histograms of the width and length of the structures

With respect to size, the investigated geological structures are similar to the outlines of the regional anomalies of the magnetic and gravitational fields [5]. Therefore the orientation of the prospecting seismic research for the discovery of the subsurface features on this scale is important not only for regional geology, but also for other geophysical methods of studying the earth's crust.

By the results of the detailed subsurface seismic studies, the actual distribution of the elastic properties of the earth's crust and upper parts of the mantle at the present time is approximated by a nonuniform layered-block model [43]. The layering is exhibited in the existence of almost horizontal, slightly wavy boundaries separating the medium into a number of layers with different elastic wave velocities. The blocking is expressed in the fact that over extended (up to several hundreds of kilometers) sections of the profiles of the depths of occurrence of the seismic boundaries, the thickness of the earth's crust, its fractured dismemberment vertically, the thickness of the individual layers and the elastic wave velocities vary little. The articulation of the sections with respect to the sustained structure usually take place along narrow steeply dipping zones where all or the majority of the mentioned parameters change sharply. These anomalous zones frequently are exhibited to the tops of the mantle, and they are considered as abyssal fractures delimiting the crust-mantle blocks. The discussed peculiarities characterize the macro-inhomogeneity of the deep interior. Sufficiently detailed seismic studies have established more broken blocking out of the earth's crust, discontinuity of the gently sloping seismic divisions, complex structure of them in the vertical cross section, the existence of short, sharply inclined boundaries and diffracting features.

Gently sloping seismic boundaries in many cases do not agree with the geological concepts of the structure of the crystalline crust, especially its upper part [14, 45]. However, the tracing of these boundaries, with procurement of the data on the velocity distribution of the elastic waves, permits sufficiently reliable isolation of the large blocks of the earth's crusts and the abyssal fracture zones. The blocking out of the crust according to the seismic data, as a rule, is in good agreement with the geological data on the structure of the upper part of the section. Examples of this agreement are known in practice in all exposed areas. The large geological structures frequently appear in the entire thickness of the earth's crust in the form of individualized blocks established by deep seismic studies.

The local peculiarities of the medium (frequent discontinuity of the boundaries, small inclined surfaces, diffracting features) obviously cannot be studied during reconnaissance prospecting. The deep boundaries must be investigated under the assumption of their being sustained over large territories, but even in a rough approximation this is not valid for all seismic divisions. The most stable reference boundaries are the surface of the mantle (the Mohorovicic discontinuity -- M) and the upper boundary of the consolidated crust corresponding to the surface of the crystalline (folded) basement in the platforms. These two boundaries must be studied in the reconnaissance prospecting phase. The intermediate intracrustal seismic discontinuities can be reliably investigated only under favorable conditions, for even when using the continuous profiling procedure, they have discontinuities and cannot always be identified in the near sections [43]. Nevertheless, during the reconnaissance operations the possibility of studying the sharpest boundaries inside the crystalline crust must be provided for.

It is extremely important to emphasize the insufficiency of studying only the morphology of the reference seismic boundaries. This arises, in particular, from the already-mentioned correspondence of the gently sloping seismic stratification of the earth's crust to the geological data from which it follows that the configuration of the extended boundaries far from exhausts all of the characteristics of the complex structure of the investigated medium. In addition, there are a number of examples where the gravitational anomalies which are sufficiently large with respect to horizontal dimensions and intensity cannot be explained by the slightly wavy stratification of the material of the earth's crust alone. Accordingly, in the reconnaissance prospecting phase, along with the morphology of the boundaries it is necessary to study the large-scale velocity distribution features (mean, boundary, stratal) along the traverses and with respect to area.

The information about the variation of the elastic wave velocities is no less important than the geometric characteristics. It is inadmissible to use constant values of the velocity carried over from other regions. The information about the velocity distribution of the elastic oscillations in the regions of modern tectonic activity with inhomogeneities of the elastic properties of the rock of the earth's crust and the top of the mantle important to subsequent analysis and, along with the electrometric and geothermal data indicating the possible anomalous state of the subsurface material is especially valuable. The information about the limiting velocity distribution when studying the basement surface of the platforms and the boundaries in the upper part of the consolidated crust is also important.

Consequently, the reconnaissance prospecting seismic studies of the earth's crust must be distinguished from the detailed studies not by the nature (composition) of the information obtained, but only the scale of the investigated inhomogeneities and the accuracy of determining the parameters respectively.

The importance of the information about the velocity distribution of the elastic waves will be illustrated in two characteristic examples of reconnaissance prospecting seismic operations in the Siberian areas.

The first example pertains to the study of the basement in the southern part of the Western Siberian platform. In the upper part of the crust two refracting boundaries are isolated (Fig 2, b): the F boundary corresponding approximately to the basement surface of the platform cover, and the lower-lying I boundary which is discontinuous. The boundary velocity over the F surface (Fig 2, a) changes sharply in the 5.3-6.2 km/sec range. The reduced values of the velocity (5.3-5.7 km/sec) are coordinated with the sections of existence of the I boundary. Wherever the latter boundary does not exist, the velocity on the F surface increases sharply to 6.1-6.2 km/sec. The joint investigation of the data on the velocities and the configuration of the seismic boundaries leads to the conclusion of the block-fractured structure of the basement and the probable geological meaning of the seismic boundaries and layers. The blocks with high velocity at the F boundary obviously correspond to the folded (geosynclinal) complex of basement rock. In the blocks with reduced velocity the tops of the basement (the layer between the F and I boundaries) probably are made up of an intermediate complex of rock with a relatively low degree of metamorphism; The geosynclinal formations run under the I boundary. This geological-geophysical analysis of the seismic data obviously would be impossible without information about the elastic wave velocity distribution.

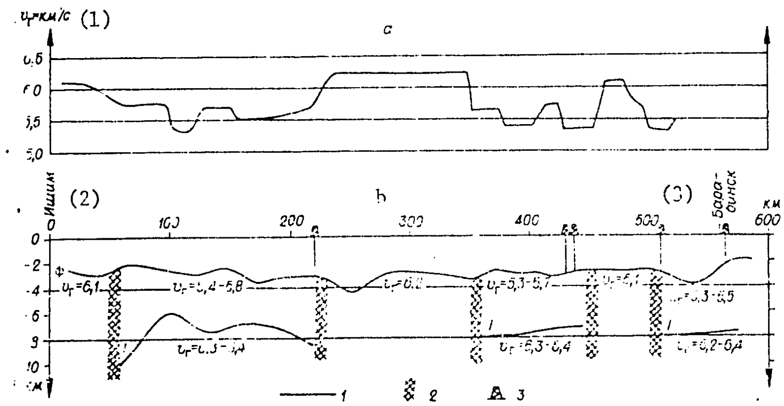

Figure 2. Seismic traverse of the cities of Ishim to Barabinsk (Western Siberia) [114]
a -- graph of the boundary velocity over the basement surface (F); b -- seismic section; 1 -- seismic boundaries; 2 -- fracture zones; 3 -- deep wells

Key:
1. $v_{boundary}$=km/sec
2. Ishim
3. Barabinsk

As another example let us consider the results of studying the surface of the mantle in the vicinity of Lake Baykal by two procedures: spot seismic sounding [55] and the seismological method of transmitted composite waves [106, 133]. The second procedure does not give information on the elastic wave velocities. In the sections obtained by closely arranged traverses, the transition from the Siberian platform to the highly active Baykal rift zone, according to the data of both procedures, is not accompanied by contrast changes in the morphology of the M boundary. Actually only the data on the reduction in the boundary velocity on the M surface to 7.7-7.8 km/sec indicates the anomalous properties of the tops of the mantle in the riftogenesis zone. This highly valuable information was lost during the seismological studies oriented in the given case only to the study of the configuration of the medium.

Let us discuss some general requirements on the procedure for deep seismic studies of the reconnaissance prospecting phase.

It was demonstrated above that obtaining full-valued information about the deep structure containing data not only on the morphology of the reference seismic boundaries, but also the velocity distribution in the medium, it is possible in the majority of cases only for the joint use of the waves of various types. The orientation of the seismic studies to recording waves of any one type (for example, composite waves in the first arrival), although it creates defined conveniences when performing the operations, usually leads to insufficiently complete information and even low reliability of the information about the medium period.

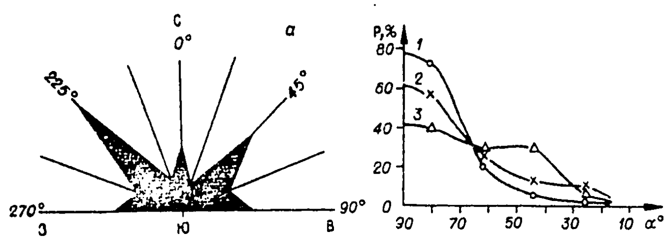

Figure 3. Substantiation of the seismic studies of the block structure of the earth's crust
a -- strike rose of the large faults of the Altaye-Sayanskaya Oblast and Kazakhstan; b -- histograms of the angles between the fractures and the rectilinear traverses of different length (curves 1-3 correspond to traverses 300, 600 and 1200 km long)

The joint use of waves of different types must be one of the basic principles of the method of reconnaissance prospecting seismic research. The presence of data on a number of waves even in the case of relatively low-detail observations permits reliable identification of the waves, more correct selection of the model of the medium and control of the results of determining its parameters. All this will promote an increase in the completeness and reliability of the information obtained without significant complication of the seismic observations themselves.

The problem of how to perform the reconnaissance prospecting study of the deep continuation of the regional near-surface geological structures -- with respect to the extended rectilinear profiles or by the area-wide observation network -- is important. It is known that the fractures and, consequently, the geological structures bounded by them, are grouped with

with respect to the strike directions into four orthogonal and diagonal systems. This phenomenon is illustrated by the strike rose of the large fractures of the Altaye-Sayanskaya Oblast and Kazakhstan (Fig 3, a) compiled by the tectonic map of Eurasia (editor A. L. Yanshin, 1966). Accordingly, the extended rectilinear traverses, even with optimal orientation of them, in many cases cannot run across the strike of the majority of intersecting structures. Thus, under the conditions of the Altaye-Sayanskaya Oblast and Kazakhstan, it is possible to intersect the regional structures almost at a right angle to the strike only by limiting the extent of the seismic profiles to the first hundreds of kilometers (Fig 3, b). The traverses about 1000 km long intersect the boundaries of the structures at predominant angles from 40 to 90°. All of the values of the angles in this range are almost equiprobable.

Consequently, the profile observations are not always advantageous: a significant part of the investigated structures will intersect almost along the strike, which decreases the information obtained per unit length of the profile and can cause difficulties when interpreting the wave field as a result of different types of side effects. It is expedient to combine the profile studies with the area studies.

The solution of the problem of the density of the network of seismic observations during the reconnaissance prospecting work depends to a great extent on the peculiarities of the specific seismic procedure -- the method of identification and type of waves used, the methods and accuracy of determining the parameters of the medium, and so on. These peculiarities will be investigated in Chapter IV, and here we shall consider that each single determination of the parameters of the medium (velocities, depths) is absolutely accurate, and the distortions of the shape of the relief of the seismic boundaries $h(x)$ and the graphs of the velocities along the profile $v(x)$ are caused by the discrete nature of the location at the points of determination of the parameters of the medium (the reference points). Under these conditions, it is possible to obtain an estimate of the maximum distance Δx_0 between the reference points, which must not be exceeded in order to avoid undesirable distortions of the results.

From information theory (the Kotel'nikov theorem or the reference theorem [127, 129]) it is known that the function $y(x)$ (in our case the function of the variation in depths or velocities along the mixed profile) with respect to its discrete values following through the Δx_0 interval, cannot be exactly recreated, for its spectral components are lost at frequencies above $\omega_0=\pi/\Delta x_0$. The least value of the relative mean square error in the recreation of the function $y(x)$ is:

$$\frac{\min \gamma}{\rho} = \left[\frac{\int_{-\infty}^{-\omega_0} |S(\omega)|^2 d\omega + \int_{\omega_0}^{\infty} |S(\omega)|^2 d\omega}{2\pi \int_{-\infty}^{\infty} y^2(x)\, dx} \right], \qquad (I.1)$$

where γ is the mean square error in recreation of the function $y(x)$; ρ is the mean square value of this function, $S(\omega)$ is its spectrum.

In order to use the presented relation, it is necessary to be given the form as a function $y(x)$, that is, $h(x)$ and $v(x)$. From the seismic operations experience (characteristic examples with respect to the Siberian areas are presented in Chapter V) it follows that the relief of the deep seismic boundaries obviously is primarily caused by the fracture-block structure of the earth's crust. The function $h(x)$ usually has a step form; smooth variations of the depths are noted. Statistical data are presented in Fig 4 for Western Siberia about the horizontal dimensions of the step and amplitudes of the discontinuities and their boundaries for the Mohorovicic surface and the higher-lying I boundary. The actual velocity distribution along the seismic boundaries $v_{boundary}(x)$ also can be approximated by step functions. This type of graph $v_{boundary}(x)$ is apparently connected with the block structure of the crust, and in the case of the basement surface (Fig 5) also with the erosion of the complex folded rock penetrated by intrusions. The horizontal distribution of the mean (effective) and mean interval velocities, which are the integral parameters of the medium, must be approximated not by step function, but by smooth functions containing anomalies with approximately the same horizontal dimensions as the corresponding blocks of the earth's crust.

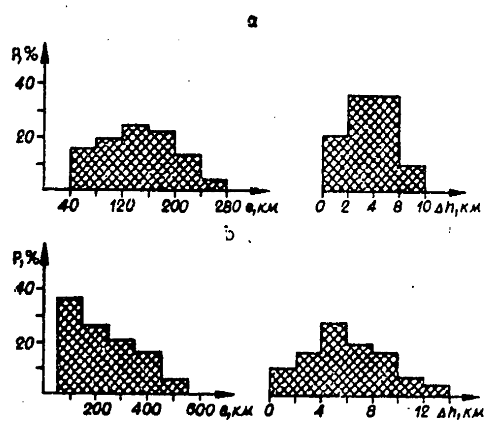

Figure 4. Histograms of the horizontal effect b and the amplitudes Δh of the steps in the relief of the seismic boundaries I (a) and M (b) by the results of the deep seismic soundings in Western Siberia

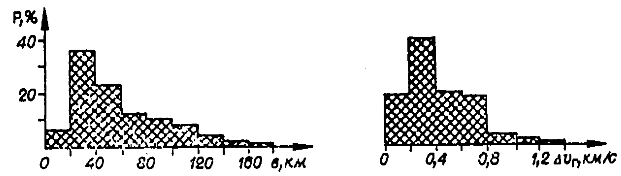

Figure 5. Histograms of the horizontal dimensions b and amplitudes $\Delta v_{boundary}$ of the step anomalies in the distribution of the boundary velocity over the basement surface of the Western Siberian platform (by the spot seismic sounding data)

For approximation of single anomalies of the depths and the velocities, let us take the following simple functions:

$$y_1(x) = \begin{cases} a \text{ for } \frac{b}{2} > x > -\frac{b}{2}, \\ 0 \text{ for } -\frac{b}{2} > x > \frac{b}{2} \end{cases} \qquad \text{(I.2)}$$

and

$$y_2(x) = ae^{-\frac{4\ln 100}{b^2}x^2}. \qquad \text{(I.3)}$$

The first function (square pulse, Fig 6) simulates the depth variation of the parameters reflecting the block structure of the medium. The second function, called a bell function, permits investigation of the continuous distribution of the parameters. Its width (b) is provisionally taken at the 0.01a level (Fig 6, b)

As a result of the substitution of the functions y_1 and y_2 in the expression for min γ/ρ and the mathematical transformations[1] we obtain the desired expression. For a square pulse

$$\frac{\min\gamma}{\rho} = \left[1 + 2\,\frac{1-\cos\pi\frac{b}{\Delta x_0}}{\pi^2\frac{b}{\Delta x_0}} - \frac{2}{\pi}\,\mathrm{Si}\left(\pi\frac{b}{\Delta x_0}\right)\right]^{-\frac{1}{2}}. \qquad \text{(I.4)}$$

[1]For the bell function these transformations are presented in Chapter IV, §1.

For the bell function

$$\frac{\min\gamma}{\rho}=\left[1-\Phi\left(\frac{\pi}{2\sqrt{2\ln 100}}\cdot\frac{b}{\Delta x_0}\right)\right]-\frac{1}{2}. \quad (I.5)$$

Here $\mathrm{Si}(u)=\int_0^u \frac{\sin^2 t}{t}dt,\ \Phi(u)=\frac{2}{\pi}\int_0^u e^{-t^2}dt$ is the integral sign and the Laplace function.

During reconnaissance prospecting in the majority of cases it is possible to consider it admissible to have relative distortions of the structural forms and velocity anomalies up to 25%. By the graphs of $\frac{\min\gamma}{\rho}\left(\frac{b}{\Delta x_0}\right)$ in Fig 7 we find that this condition will be satisfied if the distance Δx_0 between the reference points does not exceed one quarter (for the step anomalies) and one third (for the smooth forms) of the width b of the investigated objects. Assuming, in accordance with the results of the preceding analysis, for the deep parts of the earth's crust that $b\simeq 100$ km, we obtain $\Delta x_0 \leq 25$-30 km. When studying the upper part of the earth's crust where a great deal of detail in the results is necessary, clustering of the points of determination of the parameters of the medium can be used. In this case taking the width of the discovered anomalies at $b\simeq 30$ km (see Fig 5), we obtain $\Delta x_0 \leq 7.5$-10 km.

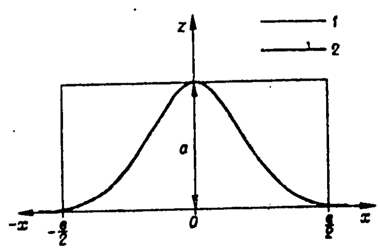

Figure 6. Rectangular (1) and bell (2) pulses

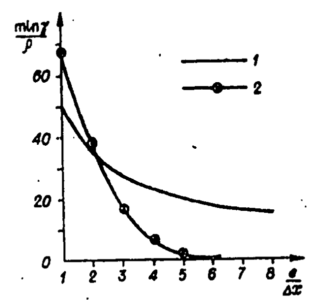

Figure 7. Minimum relative errors in the recreation of the square (1) and bell (2) pulses by discrete measurements

Thus, it is possible to formulate the subject and the problems of the deep seismic studies of the reconnaissance prospecting phase in the following way: the discovery of the large (about 100 km or more across) blocks of the earth's crust and the fracture zones separating them in order to discover the deep nature of the regional geological structures and the corresponding anomalies of the natural geophysical fields; the mandatory study of the foot, the roof of the consolidated crust and the basic peculiarities of the velocity distribution of the elastic waves in the medium. The effective procedure for reconnaissance prospecting seismic research must be based on the joint use of waves of various types during area and traverse observations with determination of the parameters of the medium no more rarely than every 25-30 km, and when studying the upper part of the crust, every 7.5 to 10 km.

Let us more specifically define these general requirements as applied to the study of the basement of the platform regions where recently new goals have been set for the regional seismic studies connected with estimation of the prospects of the oil-bearing nature of weakly metamorphic sedimentary rock belonging to the upper level of the basement. When solving these problems obviously it is impossible to limit ourselves to studying the surface of the basement. The deepness of the studies must not be less than the depths to the foot of the upper structural phase of the basement, the thickness of which can be 5 to 10 km. As a result of the three-dimensional nature of the investigated layered-block structure of the basement the work must be of predominantly an area nature with tracing in the plan view of the fractures separating the large (several tens of kilometers across) blocks of various types. Along with the data on the configuration of the boundaries, the information about the spatial distribution of the velocity in the medium bearing information about the actual composition of the rock has primary significance.

§2. Existing Deep Seismic Research Method

The corresponding procedural problems have been discussed in detail in references [43, 148, and so on]. Let us briefly consider the state of the art with respect to the problem, primarily in connection with the problem of reconnaissance research.

Predominantly profile observations are being used which are divided into continuous, piecewise continuous (the dashed lines) and spot (the dotted lines) observations. This separation does not apply to the observation systems alone. The working models of the medium, the procedures for wave identification, the interpretation procedures, the completeness and detail of the results obtained are also distinguished.

Continuous profiling (Fig 8, a) has become the most widespread in the USSR; no less than 90% of all of the DSS profiles on the dry land were investigated by this procedure. The observation systems are calculated for simultaneous recording basically on the z-component of the reflected (usually critical and transcritical), refracted (head waves, refracted waves) and other types of waves for a sufficiently detailed study of a section of the entire consolidated crust, and in individual cases, the upper part of the mantle itself. As a rule, a longitudinal profile is used with a spacing between the groups of seismographs of 100 to 200 meters and several identical multichannel seismic stations. The lengths of the hodographs reached

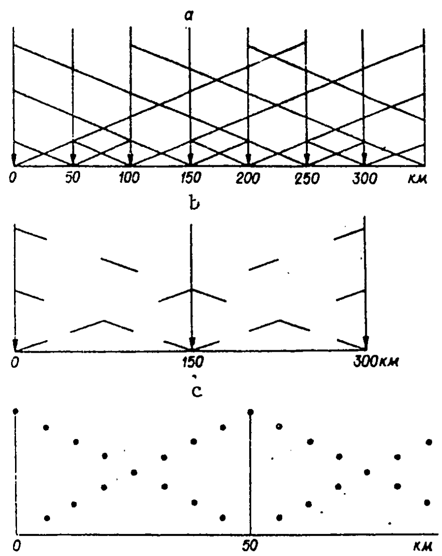

Figure 8. Diagrams of seismic observations
Profiling: a -- continuous; b -- piecewise continuous;
c -- spot

250-350 km (500-600 km when studying the boundaries inside the mantle). The spacing between the explosion points when studying the deep boundaries will on the average be 50 to 70 km, and sometimes to 100 km. In order to investigate the upper part of the section, a denser network of oscillation sources is given. The systems of overlapping and counter hodographs will permit continuous correlation of the waves over extended sections of the profile, the application of quite strict interpretation methods for determination of the configuration of the boundaries and the velocity distribution in the medium. The continuous profiling (longitudinal and nonlongitudinal) with detailed breakdown of the section of the earth's crust with respect to elastic properties is especially effective for detection and tracing of the faults and other irregularities. Detailed continuous observations are also needed to discover the nature of the recorded deep waves. The deep seismic bounding operations by the method of continuous profiling frequently are combined with seismic exploration of the sedimentary series which essentially increases the reliability and value of the data obtained. The operations by the reflected wave method with recording by the common depths point method for investigation of intracrustal boundaries have great theoretical significance.

As a result of the deep seismic research with respect to dense continuous observations sytems in the USSR, broad information has been obtained on the peculiarities of the recorded wave fields, the layered-block structure of the earth's crust under various geological conditions, the velocity distribution laws, the fine structure of the crust, the seismic anomalies in the abyssal fracture zones and other peculiarities. These results, in addition to their general scientific significance, constitute a basis for further improvement of the deep seismic sounding method, including in connection with the problems of operations in the reconnaissance prospecting phase. It must be noted that the operations with respect to the continuous profiling with the blast points separated from each other (by more than 250 to 300 km with approximately the same lengths of the hodographs) must be considered in the category of reconnaissance prospecting procedures by the nature of the information obtained on the deep structure and the reliability of determining the parameters of the medium.

Piecewise-continuous profiling (Fig 8, b) differs from continuous profiling by the presence of omissions in the seismograph installations with respect to profile and significantly less dense arrangement of the sources. In the USSR this type of observation was used in the initial phase of development of the deep seismic sounding method. Now it is used to a small extent in the inaccessible parts of Siberia for the so-called parametric sounding for preliminary study of the basic characteristics of the wave picture.

Piecewise profiling is the basic type of observation on the dry land when studying abroad. The short (no more than a few kilometers) seismograph installations are placed with significant (10 km or more) breaks along rectilinear profiles, beginning with the source of the observations to distances of about 300 km. Sometimes the extent of the hodographs obtained reaches 600 km. Often several dozen recording stations are used simultaneously. As a rule, the blast points are located no closer than 100 to 200 km to each other. Systems of single or counter hodographs are used, the extent of which is selected counting on obtaining recordings of the refracted wave from the M boundary in the first arrival.

The area systems of rectilinear profiles radiating from one common oscillation source have found application in the United States and Western Europe.

As a result of incompleteness of the investigated observation systems usually it is possible reliably to trace only the refracted waves recorded in the first arrivals over extended intervals of the profile. The use of the following waves, especially if they do not form sufficiently extensive hodographs, is complicated. When interpreting the data frequently studies are made of single hodographs without relating them, which forces simplification of the model of the medium, reducing it to a layered model with plane horizontal boundaries and constant velocities. As a result, in spite of the relatively high density of the seismic observations, the distances between the reference points of determination of the parameters of the medium turned out to be appreciably larger than the limiting values which were substantiated above beginning with the conditions of reliable discovery of the investigated objects. The horizontal nonuniformities, the block nature of the crust, and the deep fracture zones, as a rule, do not find reflection in the resultant constructions. Usually highly reliable data are obtained on the thickness of the crust and the boundary velocities at its foot. The intracrustal boundaries are determined with less reliability and they are not obtained everywhere.

It was possible to achieve a reliable separation of individual deep waves in the subsequent arrivals during piece profiling by recording them in specially selected intervals from the source. As an example, we can use the work of the Hungarian geophysicists for studying the M boundary by reflected waves recorded near the initial point [140]. In the Federal Republic of Germany, piecewise profiling systems are used which have been designed for tracing the waves reflected from the same part of the boundary for various blast-reception distances [142].

Spot profiling (see Fig 8, c) is used predominantly for marine investigations in the mobile blast version [32, 111]: stationary seismic stations on ships, buoys, bottom seismographs recording waves from the blasts moving along the profile line are used. The spot observations on dry land conducted abroad differ from the piece profiling by the application of one or several seismographs (frequently multicomponent seismograph) located at one point or in a very small space instead of the quite extensive recording devices. Seismological receiving equipment is often used in this case. At the present time such systems have become quite widespread for the recording of waves at great distances from the source (~1000 km or more).

The continuous profiling procedure permitting us to obtain more exact and reliable data on the deep structure obviously cannot be used in the reconnaissance prospecting phase of the operations as a result of its complexity, its great consumption and impossibility of performing continuous observations in inaccessible areas in large volume. The low-detail operations are performed on the continents (actually only abroad) using piecewise and spot profiling. The simplicity and the relatively small amount of labor involved in the observation systems characteristic of these procedures have been obtained within the framework of the traditional approach based on usirg the hodographs. The rarefaction of the observation network complicates identification of the waves, causing significant schematization of the models of the medium. As a result, the above-formulated problems of reconnaissance prospecting deep seismic studies during piecewise-continuous and spot observations are not always solved with sufficient completeness and reliability. In addition, in these methods it is necessary to perform operations with respect to sufficiently extended rectilinear profiles, which is far from always possible under conditions of inaccessible terrain and also in densely populated areas.

In the method of seismic sounding proposed below which is intended for the performance of the operations of the reconnaissance prospecting phase, an effort was made to surmount the indicated difficulties based on broad information about the wave field and the structure of the medium obtained as a result of detailed operations by the continuous profiling method.

§3. Requirements on the Equipment for Reconnaissance Prospecting Seismic Research

When performing reconnaissance prospecting studies by the deep seismic sounding method, the seismic waves are excited by blasting with powerful charges of from 2 to 4 tons, for the seismic waves are recorded at a distance of 200 meters or more from the blast point. As a rule, the charges are distributed in wells 20 to 40 meters deep with 100 to 200 kg of the explosive in each well.

The organization of the blast point, especially in inaccessible areas, is highly labor-consuming. It is possible to reduce the expenditures on the operations involved with the deep seismic sounding method primarily by increasing the points of simultaneous recording of the seismic waves excited by each blast, that is, increasing the use coefficient of each blast. Consequently, the problem reduces to recording the oscillations excited by the blast at the largest possible number of distributed observation points. Accordingly, the problem of transporting the recording equipment to the observation points arises which can basically be solved in inaccessible areas by using air transportation (helicopters). This determined the first basic requirements on the recording equipment -- the high transportability, small size and weight, for the equipment of all of the recording points is expediently transported by helicopter with successive landing at the largest possible number of observation points. The mass of the recorder which is adapted for being carried by one man together with the power supply must not exceed 30 kg, and as a rule the recorder is installed at some distance from the landing site of the helicopter.

The use of small-sized equipment not requiring the presence of service personnel at the recording points greatly facilitates the insurance of the necessary living conditions, especially in inaccessible areas and delivery of the personnel to the recording points. This also determines another requirement on the recording equipment -- autonomity, that is, the capacity to perform its functions during a defined time interval without service personnel.

The next requirement imposed on the recording equipment is insurance of reliable time coordination of the blast and the seismic information recorded by a large number of distributed recorders.

As a result of location of the recording points at different distances from the blast point, the intensity of the recorded oscillations will differ significantly; therefore the equipment must have a quite wide dynamic range. This requirement is best satisfied at the present time by using magnetic recording,

Since the placement of the large number of recording points and the organization of the blast point require comparatively identical expenditures, it is expedient at certain observation points to record seismic waves excited successively at several blast points. This gives rise to another requirement on the equipment and the basis of its autonomity -- the successive recording of information without any preparatory operations (for example, overloading the magnetic arrier), that is, the tape drive mechanism of the magnetic seismic recorder must be of the reel type.

The excitation of the oscillations in the deep seismic sounding method is a highly labor-consuming, expensive operation in connection with which it is necessary to use industrial blasts as the excitation sources insofar as possible. These sources are in some sense "uncontrollable"; therefore the equipment must be adapted to record induced or seismic oscillations.

Inasmuch as the equipment specially designed for the deep seismic sounding method is produced in the USSR, when performing the studies in Siberia in the first phase of the operations the information was recorded at a total of 2 to 4 points by the SS-24P standard seismic exploration equipment with the APMZ-ChM magnetic recording attachment, the characteristics of which were especially adapted for this purpose [26, 76]. The frequency band of the entire seismic channel was 4 to 20 hertz, and the dynamic range was about 40 decibels. The minimum recorded signal was 0.5-0.6 microvolts. The number of recording points was limited by the large size of the equipment and impossibility of operating it without service personnel.

When using the continuous profiling deep seismic sounding method in the USSR, as a rule, several identical multichannel seismic stations were used. The spacing between centers of the groups of seismographs was 100 to 200 meters.

The improvement of the deep seismic sounding method revealed the optimal length of one installation, especially in an inaccessible area, to be 0.5 to 1 km. Increasing the length did not lead to a significant decrease in the scattering of the defined values of the apparent velocities of the recorded waves.

This also determined another requirement on the equipment -- it must have about six recording channels. The number of channels is felt noticeably in the size and weight of the equipment installed at the observation point; therefore this parameter of the seismic recorders must be especially carefully determined.

Beginning with the indicated basic requirements on the seismic recording equipment, let us consider the characteristics of the Soviet and foreign equipment for the corresponding purpose.

Table 1

Parameter	"Zemlya"	"Cherepakha"	"Mars-66"
No of seismic channels	4	3 (on two levels each)	3
No of auxiliary channels	2	2	2
Dynamic range, decibels	40	70	60
Frequency band, hertz	0.5-10	1-20	0.3-100
Magnetic tape width, mm	25.4	25.4	6.25
Recording procedure on the magnetic tape	Direct with magnetization	Direct with magnetization	Frequency modulation
Magnetic tape drive speed	1 mm/sec	0.5 mm/sec	9.5 and 19.05 cm/sec
Type of tape drive mechanism	Reel	Reel	Reel
Time marking procedure	Quartz clock, by the radio channel	Quartz clock, by the radio channel	By radio channel
Autonomous operation time	10 days	10 days	1 hour
Intake power, watts	12	12	3
Weight of the recorder without a power supply, kg	20	20	30 with power supply

In recent years two types of autonomous seismic recording equipment have been produced in the USSR: the "Cherepakha" equipment developed by the "Kazgeofizpribor" plant and the "Zemlya" equipment developed at the "VNIIGeofizika" Institute. Both types are primarily designed for continuous (within the reserve limits) recording of earthquake waves at distributed observation points. Each set of equipment includes some number of autonomous seismic recorders with continuous driving of the magnetic tape and basic reproduction unit. The basic characteristics of the "Zemlya" and the "Cherepakha" recorders and also the "Mars-66" West German equipment especially designed for the deep seismic sounding method [138] are presented in Table 1.

From the table it follows that with a 12-volt intake the autonomous operating reserve of the "Zemlya" and "Cherepakha" recorders of 10 days is insured by 12-volt power packs with a capacity of 300 amp-hours (under the condition that 80% of the initial storage capacity will be used). This type of power pack can be arranged by using six NKN-100 batteries with a total weight of 300 kg. AS a result, taking into account the remaining equipment of the observation station (the seismographs, seismic cradle, and so on) which is widely used in the geological service, can transport the equipment for only two observation stations at a time. Already with respect to this parameter alone, the indicated equipment cannot satisfy the requirements placed on the deep seismic sounding operations in inaccessible areas, for the time required to equip 10 observation stations runs into several days during which the recorders will operate at idle.

The recoder of the "Mars-66" equipment which best satisfies the basic requirements, has two deficiencies: it only has three seismic recording channels and a short autonomous operating reserve (about 1 hour) requiring the presence of a duty operator at the observation station to switch on the recorder directly before the blast and switch it off after making the recording. It must be noted that it includes a radio receiver which receives the time mark signals over a long wave or short wave radio channel. The time marks have the following structure at the receiver output: second marks are represented by single pulses of 0.1 second duration and an amplitude of 8 volts; minute marks are made by double pulses of the same type and the hour marks, by triple pulses. For the longer time marks the recorder has a quartz-stabilized oscillator, the signal from which is recorded by one of the service channels. The second service channel is used to record the time marks received by radio.

In the USSR an effort has been made to use radio telemetric equipment to build equipment for the deep seismic sounding method [34, 35]. This equipment was created at the Earth Physics Institute of the USSR Academy of Sciences. One set of it includes seven portable field units, each of which transmit information from three seismic channels, and the central recording station with a 21-channel recorder. However, this equipment has not found broad application in the deep seismic sounding method as a result of limited range (20 km) using the ultrashort wave radio channel. The other radio wave bands do not insure the required carrying capacity of the radio telemetric channel; therefore the application of radio telemetry and the equipment for deep seismic sounding is not prospective.

An American patent is known [143], proposing a procedure and a device for recording the seismic signals by radio-controlled distributed single-channel magnetic recorders. The system includes a radio transmitter which transmits commands to the blast point and to the recorders. The radio receiver at the blast point starts the reel-to-reel magnetic recorder, which records the time signals transmitter on one channel, and on the other, the signal from the seismic receiver installed at the blast point.

The radio receivers with which each recorder is equipped, switch the recorders on. Then signals from the seismic receiver are recorded on one channel, and the time signals on the other. The successive blasts are recorded one after the other along the length of the magnetic tape. The field recordings on the base device are copied alternately on another magnetic carrier on a drum insuring matching with respect to the blast times or other marks, correction of the speed of the field tapes and suppression of the noise caused by nonuniformity of movement of the magnetic tapes.

All of this is primarily designed for the construction of a seismic exploration station without seismic cradle, that is, each seismic channel must be autonomous, it must have a radio receiver, decoder and tape drive mechanism. From the point of view of the requirements on the deep seismic sounding equipment, this solution is inefficient, for the cost of the equipment and the total mass calculated for one seismic recording channel are increased.

It must also be noted that the autonomity of each seismic channel leads to the highly labor-consuming subsequent operation of reproduction.

In addition, the proposed remote control system will have insufficient noiseproofness inasmuch as it is proposed that one attribute -- the presence of a signal of defined frequency at the output of the radio receiver -- be used to switch on the recorder. The further experience in the development, operation and maintenance of radio remote controlled equipment has shown that such simple measures are inadequate to insure the required noiseproofness.

Thus, the analysis of Soviet and foreign equipment for similar purposes indicates that the enumerated requirements will be most completely met by radio remotely controlled autonomous seismic recording equipment with magnetic recording (see the description in Chapter III).

CHAPTER II. THEORY OF SEISMIC SOUNDING

As has already been noted, seismic soundings to study inaccessible parts of Siberia have been developed in two versions. In the first of them, which initially arose as a simplification of observations by the refracted wave method (MPV), a study is made of the refracted waves in linear and spot soundings. This version [79, 80] has found application in studying the basement of the Western Siberian platform in the Tyumen' Oblast. Another version called the method of arbitrary spot (differential) sounding systems [98] is based on reflected and refracted waves using special time fields for interpretation. It is used both when studying the basement of the platform regions and the entire earth's crust and tops of the mantle.

§1. Properties of the Spot (Differential) Sounding Systems

In reconnaissance prospecting seismic research relatively simple observation systems are used. A study is made below of the general properties of the spot seismic observation systems. The problems of their practical realization are discussed in Chapter IV.

Sounding

The simplest seismic observation system is sounding made up of the source (O) and the receiver (S) of elastic oscillations (Fig 9, a). The source and the receiver are separated from each other by some (optimal for recording the investigated waves) spacing ℓ called the sounding base. The information about the kinematics of the wave field obtained by one sounding is exhausted by the wave propagation time (t).[1]

The sounding for monotypic waves does not have polarity; therefore the source and the receiver can change places. The propagation time of the monotypic waves does not change from this conversion.

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[1]In practice it is expedient to have a linear or area type installation of seismographs at the reception point. This makes it possible to determine the regularity of the waves and their apprent velocities, which is important for wave correlation. The sounding with a distributed receiver is called differential sounding.

The sounding position in the observation plane is determined by the coordinates of the central point of the base m and the angle θ formed by the sounding base with some fixed direction. For observations along the profile with which the x-axis is usually matched, it is sufficient to indicate the x-axis of the point m.

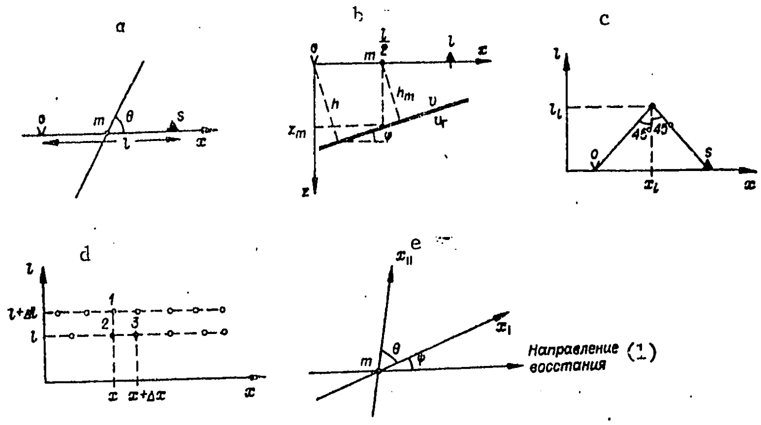

Figure 9. Spot observation diagrams

Key:
1. ascending direction

Any seismic observation system (continuous or discrete) can be made up of the soundings, just as the simplest elementary systems. Let us first consider the properties of a single sounding, limiting ourselves to the most widespread cases of recording reflected and refracted (head) waves.

It is impossible to study the seismic observation systems separately from a model of the medium approximating the actual geological section. As the model let us take a two-layer medium with plane boundary at a depth z_m under the sounding center, with an angle of inclination ϕ (Fig 9, b). The elastic wave propagation velocity in the upper layer (v) and along the boundary ($v_{boundary}$) are constant. The condition of constancy of the parameters v, $v_{boundary}$ and ϕ is introduced only for the local section occupied by one sounding. Therefore in the majority of cases this approximation is suitable for studying media with curvilinear interfaces and variable wave propagation rates.

G. A. Gamburtsev [20] introduced the concepts of complete and incomplete seismic observation systems. The system is considered complete, by the data of which a unique determination of all of the unknown parameters of the model of the medium is possible. If the observation system is inadequate for the unique solution of the problem, it is incomplete.

Only one value of the arrival time of the investigated wave is measured by a single sounding. Consequently, the sounding can be considered a complete system only in cases where the number of unknown parameters in the approximating model is no greater than one. For the adopted two-layer model the sounding is an incomplete system, for the number of unknown parameters reaches three in the case of observations of reflected waves (z_m, ϕ and v) and four when recording refracted waves (z_m, ϕ, v, $v_{boundary}$). Let us investigate the problem of ambiguity[1] of the determination of the depth of occurrence of the seismic boundary by the data of one sounding when the values of the velocities and the slope angle are given with some error. As the measure of the ambiguity we shall consider the magnitude of the error at depth occurring as a result of inexact assignment of the remaining parameters of the medium.

Let m_ϕ, m_V and $m_{v_{boundary}}$ be the errors of the parameters ϕ, v and $v_{boundary}$. Then the error in depth as a result of inexact assignment of each of these parameters will be equal to the following respectively:

$$\left.\begin{aligned} (m_z)_\varphi &= \frac{dz}{d\varphi} m_\varphi, \\ (m_z)_v &= \frac{dz}{dv} m_v, \\ (m_z)_{v_{\Gamma}} &= \frac{dz}{dv_{\Gamma}} m_{v_{\Gamma}}, \end{aligned}\right\} \qquad \text{(II.1)}$$

Key: 1. boundary

where z is the depth along the vertical at an arbitrary point of the sounding base, that is, $z=z(x)$, $0 \leq x \leq \ell$.

In order to find the derivatives it is necessary to have the function z(x) of the parameters of the medium. In the known hodograph equations for the two-layer model let us express the depth h with respect to the normal to the boundary under the oscillation source in terms of z(x), considering the angle ϕ positive in the direction of dropping of the boundary;

$$h = z(x)\cos\varphi - x\sin\varphi. \qquad \text{(II.2)}$$

For the cases of reflected (t_{refl}) and refracted (t_{refr}) we obtain, respectively:

$$t_{\text{отр}} = \frac{1}{v}\sqrt{4\left[z(x)\cos\varphi + \left(\frac{l}{2} - x\right)\sin\varphi\right]^2 + l^2\cos^2\varphi}, \qquad \text{(II.3)}$$

$$t_{\text{пр}} = \frac{2\cos i}{v}\left[z(x)\cos\varphi + \left(\frac{l}{2} - x\right)\sin\varphi\right] + \frac{l}{v_{\Gamma}}\cos\varphi, \qquad \text{(II.4)}$$

Key: 1. refl; 2. refr

[1]The velocity (v, $v_{boundary}$) and the angle of inclination of the boundary are differential parameters; therefore the problem of determining them is naturally solved not by the data from a single sounding, but by a system of soundings when measurement of the time gradients is possible.

where $i = \arc\sin v/v_{boundary}$.

From equations (II.3) and (II.4) we find the necessary functions:

$$z(x) = \left(x - \frac{l}{2}\right) \operatorname{tg} \varphi + \frac{1}{2} \sqrt{\frac{v^2 t^2_{\text{отр}}}{\cos^2 \varphi} - l^2}, \qquad \text{(II.5)}$$

$$z(x) = \left(x - \frac{l}{2}\right) \operatorname{tg} \varphi + \frac{v t_{\text{пр}}}{2 \cos i \cos \varphi} - \frac{l}{2} \operatorname{tg} i. \qquad \text{(II.6)}$$

After differentiation of equations (II.5) and (II.6) and simple transformations we obtain the following expression for the relative errors in determining the depth at an arbitrary point of the sounding base.

In the case of reflected waves:

$$\left.\begin{aligned} \frac{(m_z)_\varphi}{z_m} &= \left[\left(\frac{x}{z_m} - \frac{l}{2z_m}\right) \sec^2 \varphi + \left(1 + \frac{l^2}{4z_m^2}\right) \operatorname{tg} \varphi\right] m_\varphi, \\ \frac{(m_z)_v}{z_m} &= \left(1 + \frac{l^2}{4z_m^2}\right) \frac{m_v}{v}. \end{aligned}\right\} \qquad \text{(II.7)}$$

In the case of refracted waves:

$$\left.\begin{aligned} \frac{(m_z)_\varphi}{z_m} &= \left[\left(\frac{x}{z_m} - \frac{l}{2z_m}\right) \sec^2 \varphi + \left(1 + \frac{l}{2z_m} \operatorname{tg} i\right) \operatorname{tg} \varphi\right] m_\varphi, \\ \frac{(m_z)_v}{z_m} &= \frac{m_v}{v} \sec^2 i, \\ \frac{(m_z)_{v_\text{г}}}{z_m} &= \left(\frac{l}{2z_m} - \operatorname{tg} i\right) \frac{m_{v_\text{г}}}{v_\text{г}} \operatorname{tg} i. \end{aligned}\right\} \qquad \text{(II.8)}$$

From the formulas obtained for $(m_z)_\phi$ it follows that the effect of the error in the slope angle depends on the position of the point x at which the depth is calculated. The form of this function is determined to a great extent by the initial information about the slope of the boundary. Two cases are possible. In the first of them the sign of ϕ (the direction of drop of the boundary) is known in advance. In the second case which is more widespread in practice, the direction of the drop is unknown. The slope of the boundary usually is a sign-variable function; its most probable value can be assumed to be zero. This assumption leads to an error in giving the slope angle equal with respect to magnitude to the first slope ($m_\phi = \phi$).

Let us consider the first case. Let us orient the x-axis in the drop direction; then the angle ϕ will always be positive. From the first equations of the system (II.7) and (II.8) it follows that on the profile a point x_{opt} exists, at which $(m_z)_\phi = 0$, that is, the depth $z(x_{opt})$ is found uniquely. For reflected waves

$$\underset{(1)}{x_{\text{опт}}} = \frac{l}{2}\left[1 - \frac{z_m}{l}\left(1 + \frac{l^2}{4z_m^2}\right) \sin 2\varphi\right], \qquad \text{(II.9)}$$

Key: 1. opt

for refracted waves

$$x_{\text{опт}_{(1)}} = \frac{l}{2}\left[1 - \frac{z_m}{l}\left(1 + \frac{l}{2z_m}\operatorname{tg} i\right)\sin 2\varphi\right]. \qquad \text{(II.10)}$$

Key: 1. opt

The point x_{opt} is always shifted from the center of the sounding base in the ascending direction of the boundary. The magnitude of the shift increases with an increase in slope and with sufficiently large angles the point x_{opt} can go beyond the limits of the sounding base (see Fig 10).

In the second case where the direction of ascent (the sign ϕ) is unknown, the error $(m_z)_\phi$ cannot be indicated uniquely. Therefore it is expedient to consider the maximum value of the modulus of this error in each point of the sounding base to be $\max|(m_z)_\phi|$. For the reflected and refracted waves considering the fact that $m_\phi=\phi$, we shall have the following respectively:

$$\frac{\max|(m_z)_\varphi|}{z_m} = \left[\left|\frac{x}{z_m} - \frac{l}{2z_m}\right|\sec^2\varphi + \left(1 + \frac{l}{4z_m^2}\right)\operatorname{tg}|\varphi|\right]|\varphi|, \qquad \text{(II.11)}$$

$$\frac{\max|(m_z)_\varphi|}{z_m} = \left[\left|\frac{x}{z_m} - \frac{l}{2z_m}\right|\sec^2\varphi + \left(1 + \frac{l}{2z_m}\operatorname{tg} i\right)\operatorname{tg}|\varphi|\right]|\varphi|. \qquad \text{(II.12)}$$

At the center of the sounding base ($x=\ell/2$), the investigated functions have a minimum value which increases with an increase in the slope angle of the boundary (Fig 10, b). Consequently, in the given case the central point of the base is characterized by the least ambiguity in determining the depth. This characteristic has important significance in sounding theory.

As a result of investigation of both cases it is possible to formulate the following sounding property. The ambiguity of the determination of the depth caused by inexact assignment of the slope angle of the boundary is different at different points of the sounding base. In the general case where the ascending direction of the boundary is unknown, the center of the base is characterized by minimum ambiguity. If the ascending direction is given, then there is a point on the profile at which the depth will be found uniquely.

The second property of the sounding following from equations (II.7) and (II.8) consists in the fact that the ambiguity in determining the depth at any point of the source-receiver interval increases with an increase in the sounding base. The errors $(m_z)_\phi$ and $(m_z)_v$ in the case of reflected waves are proportional to the square of the base. For the refracted waves the values of $(m_z)_\phi$ and $(m_z)_{v_{boundary}}$ are proportional to the base.

Consequently, it is necessary to strive to use soundings with the least possible distances between the source and the receiver of the oscillations.

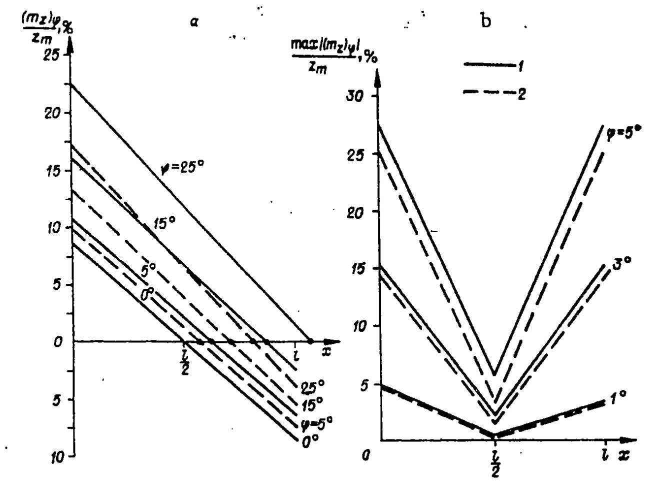

Figure 10. Indeterminacy in the depth of occurrence of the reflected (1) and refracting (2) boundaries caused by the effect of the slope angle $\ell/2z_m=5$, $i=50°$. The ascending direction ($m_\phi=2°$) is known (a), unknown ($m_\phi=\phi$) (b).

The practical importance of the last condition can be illustrated by the following example. Let us compare the errors in determining the depths of occurrence of the foot of the earth's crust under the conditions of platform regions ($z=40$ km, $\phi=0$) according to the sounding data using reflected waves with bases of $\ell_1=200$ km (transcritical reflections) and $\ell_2=100$ km (reflections near the critical angle) with fixed error at a calculated velocity v. Using the second equation of systems (II.7), we find the magnitude of the error ratio for $x=\ell/2$:

$$\frac{(m_z)_{v_1}}{(m_z)_{v_2}} = \frac{4z_m^2 + l_1^2}{4z_m^2 + l_2^2} \approx 2{,}8.$$

Consequently in the given example, decreasing the base from 200 to 100 km leads to almost triple decrease in ambiguity.

The depth error as a result of inexact assignment of the velocity in the covering medium in the case of refracted waves (see the second formula in system (II.8)) does not depend on the size of the sounding waves and is identical in the entire source-receiver range.

In practice by the sounding data it is expedient to determine not the vertical depth z, but the depth h along the normal to the boundary, for the value of h is more resistant to the effect of the slope angle of the boundary, especially for relatively small bases. It is possible to be convinced of this, in particular, by comparing the corresponding errors in the values of z and h at the central point of the sounding base. In the case of reflected waves:

$$(m_{z_m})_\varphi = z_m\left(1+\frac{l^2}{4z_m^2}\right)\ \mathrm{tg}\,\varphi m_\varphi,$$

$$(m_{h_m})_\varphi = z_m\frac{l^2}{4z_m^2}\sin\varphi m_\varphi,$$

$$\left(\frac{m_{z_m}}{m_{h_m}}\right)_\varphi = \frac{4\frac{z_m^2}{l^2}+1}{\cos\varphi} > 1.$$

For the head wave:

$$(m_{z_m})_\varphi = \left(z_m+\frac{l}{2}\,\mathrm{tg}\,i\right)\mathrm{tg}\,\varphi m_\varphi,$$

$$(m_{h_m})_\varphi = \frac{l}{2}\,\mathrm{tg}\,i\sin\varphi m_\varphi,$$

$$\left(\frac{m_{z_m}}{m_{h_m}}\right)_\varphi = \frac{2\frac{z_m}{l}\,\mathrm{tg}\,i+1}{\cos\varphi} > 1.$$

Sounding Systems

The sounding systems can be profile and area systems. In the first case the sources and the receivers of the oscillations are on one straight line; the position of the interfaces and the velocities in the plane of the seismic beam are determined by the data obtained. In the latter case the differently oriented soundings are in the observation plane; the spatial distribution of the depths and velodities is determined.

The profile systems are conveniently connected in the coordinate plane x, ℓ, directing the x-axis along the profile line. The scale of the distances along the vertical axis is taken half that of the horizontal axis. The sounding with the base ℓ_j and the x-axis of the center of the base x_j in the x, ℓ plane correspondings to a point (see Fig 9, c); the sounding system corresponds to the set of points. The sounding edges at which the source and receivers are located on the intersections with the x-axis of the straight lines drawn from the point x_j, ℓ at an angle of 45° to the coordinate axes.[1]

Let us proceed to the problem of the complete sounding systems. Let us find the systems, by the data of which all of the unknown parameters of the two-layer model of the medium with a plane inclined boundary and with constant values of the propagation rates of elastic waves in the section of the investigated system can be determined. First let us consider the profile systems.

Let us stipulate that the arrival time of the wave pertains to the center of the corresponding sounding base. Let the sounding center with the base ℓ be located at an arbitrary point of the profile x with a depth of occurrence of the seismic boundary z_m. Using formula (II.3) for the reflected wave, let us determine the derivatives dt/dx and dt/dℓ. For calculation of the derivatives dt/dx, we consider that dz/dx=tg ϕ. As a result, we have three independent equations for the given profile point:

$$\left.\begin{aligned} t &= \frac{1}{v}\sqrt{4z_m^2 + l^2\cos\varphi}, \\ \zeta &= \frac{dt}{dx} = \frac{4z_m}{v^2 t}\sin\varphi\cos\varphi, \\ \eta &= \frac{dt}{dl} = \frac{l}{v^2 t}\cos^2\varphi. \end{aligned}\right\} \quad \text{(II.13)}$$

From this system we find all three parameters of the model of the medium:

$$\left.\begin{aligned} z_m &= \frac{l}{2}\sqrt{\frac{t}{l\eta} - 1}, \\ \varphi &= \operatorname{arc\,tg}\frac{\zeta}{2}\sqrt{\frac{l}{\eta(t - l\eta)}}, \\ v &= \sqrt{\frac{l}{t}\cdot\frac{t - l\eta}{\eta(t - l\eta) + \frac{1}{4}\zeta^2 l}}. \end{aligned}\right\} \quad \text{(II.14)}$$

Here $h_m = z_m \cos\phi$.

Consequently, for the reflected wave the complete sounding system must provide for the measurement of three values at the given profile points: the time t and its gradients dt/dx and dt/dℓ.

The simplest system satisfying these requirements is made up of three soundings. Two of them must have different bases and a common center, and the

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[1]The discussed method of depicting sounding systems is similar to the "expanded profile" procedure used in seismic explorations [109], which is a version of the generalized observation plane introduced by G. A. Gamburtsev [19].

third, with the same base as any of the first two, must be shifted along the x-axis (see Fig 9, d, soundings 1, 2 and 3). Making the transition from differentials to finite increments, the data of this sounding system can be used to determine the necessary time gradients.

$$\left.\begin{aligned}\zeta &= \frac{t(x+\Delta x, l) - tg(x, l)}{\Delta x},\\ \eta &= \frac{t(x, l+\Delta l) - t(x, l)}{\Delta l}.\end{aligned}\right\} \quad \text{(II.15)}$$

In the general case where it is necessary to investigate a profile of some extent, the system made up of the number of soundings with two bases ℓ and $\ell+\Delta\ell$ located with defined density along the profile, will be complete.

For refracted waves under the same conditions for an arbitrary point of the profile we obtain the following system of equations:

$$\left.\begin{aligned}t &= \left(2z_m\sqrt{\frac{1}{v^2} - \frac{1}{v_r^2}} + \frac{l}{v_r}\right)\cos\varphi,\\ \zeta &= \frac{dt}{dx} = 2\sqrt{\frac{1}{v^2} - \frac{1}{v_r^2}}\sin\varphi,\\ \eta &= \frac{dt}{dl} = \frac{\cos\varphi}{v_r}.\end{aligned}\right\} \quad \text{(II.16)}$$

It is impossible to obtain a larger number of independent equations, for the derivatives of the second and higher orders for the investigated model are equal to zero. The number of unknown parameters in the case of refracted waves is equal to four (the value of $v_{boundary}$ is added). Therefore the complete profile of the sounding system using refracted waves sufficient for finding all of the unknown parameters is impossible to compile. The problem becomes resolvable if one of the parameters is given. Usually the velocity in the covering layer v is considered known. Then from the equations (II.16) the remaining three unknown parameters are determined, that is, the system becomes complete. In this case the solution has the form:

$$\left.\begin{aligned}z_m &= \frac{v}{2\cos i}(t - l\eta)(A^2 - v^2\eta^2)^{-\frac{1}{2}},\\ \varphi &= \arccos A,\\ v_r &= \frac{A}{\eta},\end{aligned}\right\} \quad \text{(II.17)}$$

where

$$A^2 = \frac{1}{2}\left[1 + v^2\eta^2 - \frac{1}{4}v^2\zeta^2 + \sqrt{\left(1 + v^2\eta^2 - \frac{1}{4}v^2\zeta^2\right)^2 - 4v^2\eta^2}\,\right].$$

Here, just as in the case of reflected waves,

$$h_m = z_m\cos\varphi.$$

The requirements on the complete profile system of refracted wave soundings and its practical realization are the same as in the case of reflected waves. The difference is that for refracted wave soundings one of the parameters of the medium must be known.

Let us proceed to the area sounding systems and a three-dimensional model of the medium. In this case for refracted waves the two-layer model is characterized by five parameters: the depth of occurrence (z_m), the true slope angle (ϕ), the dip azimuth (Ψ) of the boundary and the velocities v and $v_{boundary}$. For reflected waves the number of parameters is reduced to four (z_m, ϕ, Ψv).

Let us find the complete sounding systems by which all of the parameters of the medium are determined at some point m. Let us consider the system made up of soundings, the bases of which are located along two straight lines $\vec{x}_I$ and $\vec{x}_{II}$ passing through the point m at some angle θ to each other (see Fig 9, e). Let the $\vec{x}_I$ axis be oriented at an angle ϕ to the direction of drop of the boundary.

The apparent slope angles of the boundary ϕ_{kI} and ϕ_{kII} in the planes of the seismic beams corresponding to the directions x_I and x_{II} are related to the true slope angle ϕ by the known [88] expressions

$$\begin{aligned} \sin\varphi_{kI} &= \sin\varphi\cos\psi, \\ \sin\varphi_{kII} &= \sin\varphi\cos(\Psi+\theta). \end{aligned} \qquad \text{(II.18)}$$

We shall express the depth of occurrence of the boundary at the point m in terms of the depth (z_I and z_{II}) in the planes of the seismic beams:

$$z_m = \frac{z_I\cos\varphi_{kI}}{\cos\varphi} = \frac{z_{II}\cos\varphi_{kII}}{\cos\varphi}, \qquad \text{(II.19)}$$

hence

$$\left.\begin{aligned} \frac{dz_m}{dx_I} &= \frac{\sin\varphi_{kI}}{\cos\varphi}, \\ \frac{dz_m}{dx_{II}} &= \frac{\sin\varphi_{kII}}{\cos\varphi}. \end{aligned}\right\} \qquad \text{(II.20)}$$

Let the sounding centers oriented in the direction $\vec{x}_I$ and $\vec{x}_{II}$ be located at the point m. Considering expressions (II.19) and (II.20) let us write the expressions for the time of arrival of the reflected wave and its gradients. For the direction $\vec{x}_I$ we have:

$$\left.\begin{aligned} t_I &= \frac{1}{v}\sqrt{4z_m^2\cos^2\varphi + l^2\cos^2\varphi_{kI}},\\ \zeta_I &= \frac{dt_I}{dx_I} = \frac{4z_m\sin\varphi_{kI}}{v^2 t_I}\cos\varphi,\\ \eta_I &= \frac{dt_I}{dl} = \frac{l}{v^2 t_I}\cos^2\varphi_{kI}. \end{aligned}\right\} \quad \text{(II.21)}$$

For the direction $\vec{x}_{II}$:

$$\left.\begin{aligned} t_{II} &= \frac{1}{v}\sqrt{4z_m^2\cos^2\varphi + l^2\cos^2\varphi_{kII}},\\ \zeta_{II} &= \frac{dt_{II}}{dx_{II}} = \frac{4z_m\sin\varphi_{kII}}{v^2 t_{II}}\cos\varphi,\\ \eta_{II} &= \frac{dt_{II}}{dl} = \frac{l}{v^2 t_{II}}\cos^2\varphi_{kII}. \end{aligned}\right\} \quad \text{(II.22)}$$

The angles ϕ_{kI} and ϕ_{kII} are given by expressions (II.18).

From the six equations (II.21) and (II.22) for determining the parameters of the medium it is sufficient to take any four. Correspondingly, the area sounding system using reflected waves permitting us to find any four of the six values (t_I, η_I, ζ_I, t_{II}, ζ_{II}, η_{II}) in the lefthand side of these equations will be complete. It is possible to compile several versions of the complete systems. For example, by using the expressions for t_I, ζ_I, η_I, t_{II}, ζ_{II}, η_{II}, we obtain:

$$\left.\begin{aligned} z_m &= C\sqrt{\frac{l}{C - \zeta_I^2 l\,(B-\cos\theta)^2\operatorname{cosec}^2\theta}},\\ \varphi &= \arcsin\sqrt{\zeta_I^2 l\,\frac{(B-\cos\theta)^2\operatorname{cosec}^2\theta + 1}{\zeta_I^2 l + C}},\\ \psi &= \operatorname{arctg}(B\operatorname{cosec}\theta - \operatorname{ctg}\theta),\\ v &= \sqrt{\frac{lC}{t_I\eta_I\,(C+\zeta_I^2 l)}}, \end{aligned}\right\} \quad \text{(II.23)}$$

where

$$B = \frac{\zeta_{II}t_{II}}{\zeta_I t_I}, \quad C = 4\eta_I\,(t_I - l\eta_I).$$

In the case of recording refracted waves for the area sounding system it is possible to write the following six equations:

$$\left.\begin{aligned} t_{\rm I} &= 2z_m \sqrt{\frac{1}{v^2} - \frac{1}{v_{\rm r}^2}} \cos\varphi + \frac{l}{v_{\rm r}} \cos\varphi_{\rm \kappa I}, \\ \zeta_{\rm I} &= \frac{dt_{\rm I}}{dx_{\rm I}} = 2\sqrt{\frac{1}{v^2} - \frac{1}{v_{\rm r}^2}} \sin\varphi_{\rm \kappa I}, \\ \eta_{\rm I} &= \frac{dt_{\rm I}}{dl} = \frac{\cos\varphi_{\rm \kappa I}}{v_{\rm r}}. \end{aligned}\right\} \quad (II.24)$$

$$\left.\begin{aligned} t_{\rm II} &= 2z_m \sqrt{\frac{1}{v^2} - \frac{1}{v_{\rm r}^2}} \cos\varphi - \frac{l}{v_{\rm r}} \cos\varphi_{\rm \kappa II}, \\ \zeta_{\rm II} &= \frac{dt_{\rm II}}{dx_{\rm II}} = 2\sqrt{\frac{1}{v^2} - \frac{1}{v_{\rm r}^2}} \sin\varphi_{\rm \kappa II}, \\ \eta_{\rm II} &= \frac{dt_{\rm II}}{dl} = \frac{\cos\varphi_{\rm \kappa II}}{v_{\rm r}}. \end{aligned}\right\} \quad (II.25)$$

For the complete solution of the inverse problem of interpretation in the investigated case of the refracted waves it is sufficient to have five out of the six existing equations. Consequently, in this case it is possible to compile several versions of the complete area sounding systems. In particular, for the sounding system which permits us to find values of $t_{\rm I}$, $\zeta_{\rm I}$, $\eta_{\rm I}$, $\zeta_{\rm II}$, $\eta_{\rm II}$, the parameters of the medium can be calculated by the formulas:

$$\left.\begin{aligned} z_m &= \frac{(t_{\rm I} - l\eta_{\rm I})}{2\cos i} \sqrt{\frac{DE}{F\sin^2\theta - E\left(\zeta_{\rm I}^2 + \zeta_{\rm II}^2 - 2\zeta_{\rm I}\zeta_{\rm II}\cos\theta\right)}}, \\ \varphi &= \arcsin\sqrt{\frac{E\left(\zeta_{\rm I}^2 + \zeta_{\rm II}^2 - 2\zeta_{\rm I}\zeta_{\rm II}\cos\theta\right)}{F\sin^2\theta}}, \\ \psi &= \operatorname{arctg}\left(\frac{\zeta_{\rm II}}{\zeta_{\rm I}}\operatorname{cosec}\theta - \operatorname{ctg}\theta\right), \\ v &= \sqrt{\frac{DE}{F\left(E + \frac{1}{4}D\right)}}, \\ v_{\rm r} &= \sqrt{\frac{D}{F}}, \end{aligned}\right\} \quad (II.26)$$

where the following notation is introduced for short:

$$D = \zeta_{\rm II}^2 - \zeta_{\rm I}^2,\ E = \eta_{\rm I}^2 - \eta_{\rm II}^2,\ F = \zeta_{\rm II}^2\eta_{\rm I}^2 - \zeta_{\rm I}^2\eta_{\rm II}^2.$$

The velocity in the covering medium (v) by the data from the area sounding system using refracted waves can be determined if the slope angle of the boundary is not equal to zero and the lines $x_{\rm I}$ and $x_{\rm II}$ are arranged asymmetrically with respect to the direction of drop. The problem of observation systems obtaining hodographs providing for determination of the velocity in the covering medium by the refracted wave data was investigated by Yu. V. Riznichenko [103]. He obtained the solution for the special case of two mutually perpendicular profiles oriented along the strike and across the strike of the plane boundary.

Sounding Systems with Joint Use of Reflected and Refracted Waves

By the profile sounding systems using only one type of wave it is impossible to obtain complete information about the medium: the value of $v_{boundary}$ is not determined by the reflected wave data, when recording the refracted waves along, the value of v remains unknown. Complete information about the medium can be obtained as a result of the joint use of reflected and refracted waves from one boundary. Let us show that the corresponding sounding systems can be quite simple.

Let the reflected wave (t_{refl}) be recorded on the soundings 1, 2 and 3 (see Fig 9, d). The parameters z, ϕ and v are found by the formulas (II.14). In order to determine the missing parameter $v_{boundary}$ it is sufficient to supplement this system by one sounding with the center at the point x and with the recording of the refracted wave (t_{refr}). We find the value of $v_{boundary}$ from the first equation of system (II.16) considering the formula (II.14):

$$v_{\text{г}}^{(2)} = \frac{v\left(4z_m^2 + l_{\text{пр}}^2\right)\cos\varphi}{t_{\text{пр}}^{(1)} l_{\text{пр}} v + 2z_m\sqrt{\left(4z_m^2 + l_{\text{пр}}^2\right)\cos^2\varphi - t_{\text{пр}}^2 v^2}}. \qquad \text{(II.27)}$$

Key: 1. refracted; 2. boundary

In a number of cases the sounding bases using reflected and refracted waves can be selected identical ($\ell_{refr}=\ell_{refl}=\ell$). Then in order to obtain all five parameters of the two-layer medium, the same system of three soundings which is used when recording only reflected or refracted waves is sufficient. The calculation formula for $v_{boundary}$ is simplified:

$$v_{\text{г}}^{(3)} = \frac{\left(4z_m^2 + l^2\right)\cos\varphi}{t_{\text{пр}}^{(1)} l + 2z_m\sqrt{t_{\text{отр}}^{2\,(2)} - t_{\text{пр}}^2}}. \qquad \text{(II.27')}$$

Key: 1. refracted; 2. reflected; 3. boundary

The performed investigation of the simplest spot seismic observations systems indicates that they offer sufficiently broad possibilities for determining the elements of occurrence of reflecting and refracting boundaries and also elastic wave velocities.

§2. Spot Observation Time Fields

In the spot (differential) sounding procedure during interpretation it is not the hodographs that are used, but special two-dimensional and three-dimensional time fields [91], which are generalizations of the concept of the seismic hodograph to the case of an arbitrary set of sources and receivers of oscillations. Let us consider the basic characteristics of these fields, beginning with the two-dimensional case where the observations are performed along the profile.

With respect to the data from the set of soundings with bases which vary in some range, the field is constructed as follows: on the x, t plane the time t of arrival of the given wave with respect to each sounding pertains to the center of the base (the midpoint of the corresponding source-receiver interval). In interpolating between the individual values, a family of time lines is constructed for a number of fixed values of the bases ℓ_j. The family of lines obtained ℓ_j=const, and the time field $t(x, \ell_j)$ exist.[1]

In the case of reflected waves, the linear interpolation is more correct for values of t^2 and ℓ^2; therefore it is convenient to consider the field $t^2(x, \ell_j^2)$ constructed in semiquadratic coordinates t^2, x.

The time field and the hodographs are different types of representation of the kinematic characteristics of the seismic waves. There is a one to one corresponding between them: having the time field it is possible to construct the hodographs. The inverse transition is possible if a representative set of hodographs exists.

An example of the time field for four bases is presented in Fig 11, a. Two counter hodographs (I and II) with excitation point O_1 and O_2 are indicated there. The corresponding field and hodograph points are noted. In the time field the points are shifted along the x axis in the direction of the source by an amount equal to half the blast-reception distance. Matching of the mutual points of hodographs takes place. If we take the times along a number of isolines at a fixed point of the profile from the field $t(x, \ell_j)$ of the reflected wave and construct the graph $t(\ell)$ we obtain the "hodograph" corresponding to the results of the observations by the known common depth point method.

Time Fields of Basic Monotypic Waves

Reflected Waves. Let us consider the two-layer medium with constant velocity in the upper layer. The reflecting boundary is given in the form of a continuous curve having the equation $z=z(x)$ in the selected arbitrary system

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[1]In addition to the investigated field $t(x, \ell)$ other versions of the generalized representation of the seismic wave kinematics are proposed [87].

of rectangular coordinates. On the curves z(x) let us select some reflecting point $M(x_m, z_m)$, the length of the normal at which (Fig 11, b) is defined by the expression

$$N = z(x)\sqrt{1+\left(\frac{dz}{dx}\right)^2},$$

where

$$\frac{dz}{dx} = \mathrm{tg}\,\varphi;$$

ϕ is the slope angle of the boundary at the point $M(x_m, z_m)$; ℓ is the distance from the source to the receiver (base length). The time t of propagation of the reflected wave pertains to the point C' -- the center of the base.

The equation for the time field in general form in parametric form (the parameter x_m) is written as follows:

$$\left.\begin{aligned} x &= x_m + z\,\mathrm{tg}\,\varphi + \frac{1}{2\sin\varphi}\left(\sqrt{N^2 + l^2\sin^2\varphi} - N\right), \\ v^2t^2 &= l^2 + 2N\left(\sqrt{N^2 + l^2\sin^2\varphi} + N\right), \end{aligned}\right\} \qquad \text{(II.28)}$$

where N and ϕ are expressed in terms of z(x) and dz/dx according to the above-presented expressions, if we set $x=x_m$. In the special case of a plane interface: $z=z_0+x\,\mathrm{tg}\,\phi$, the parameter x_m is easy to exclude, and the field equation is represented in simple form:

$$t = \frac{1}{v}\sqrt{l_j^2\cos^2\varphi + 4(x\sin\varphi + z_0\cos\varphi)^2}, \qquad \text{(II.28')}$$

where z_0 is the depth at the beginning of the profile (x=0). Or presenting it differently,

$$t(x, l_j) = \frac{1}{v}\sqrt{4h^2(x) + l_j^2\cos^2\varphi}, \qquad \text{(II.29)}$$

where h(x) is the depth along the perpendicular to the boundary drawn from the point x.

Equations (II.28') and (II.29) are approximately valid for the curvilinear boundary if it is admissible to consider it locally plane in a small interval between the perpendicular to the boundary drawn from the sounding center x and the corresponding reflection point. An estimate of the extent of this interval for the specific conditions is presented in reference [99].

In the majority of practical cases the indicated assumption provides a high degree of approximation. The slope angle ϕ pertains to the vicinity of the reflection point.

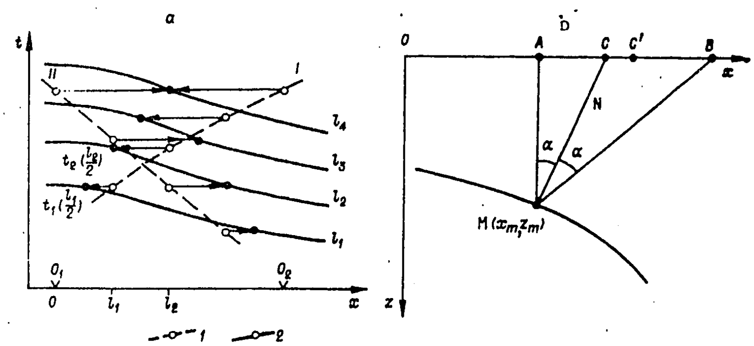

Figure 11. Relation of the time field and the hodographs (a). 1 -- hodograph; 2 -- lines ℓ=const. For derivation of the reflected wave time field equation (b).

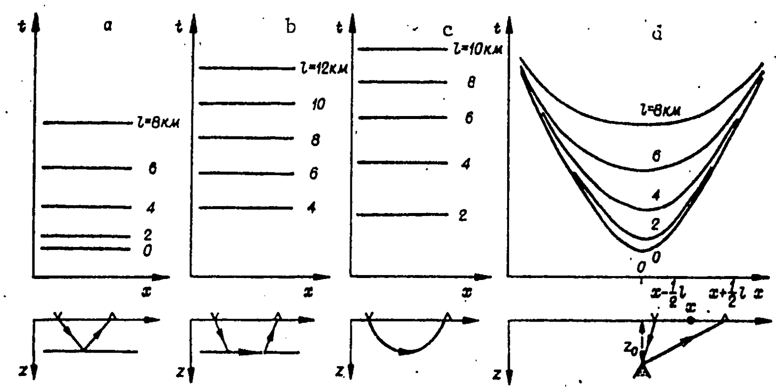

Figure 12. Time fields.
a -- reflected wave from the horizontal boundary (v=const);
b -- refracted wave from the horizontal boundary (v=const, $v_{boundary}$=const); c -- refracted waves at v=v(z);
d -- diffracted wave

The form of the time field of the reflected wave from a horizontal boundary is illustrated in Fig 12. The lines ℓ_j=const are straight lines parallel to the x-axis. The time intervals between adjacent isolines with equal spacing of the parameter ℓ_j increase with an increase in the base. The corresponding intervals between the field lines t^2 (x, ℓ_j^2) are constant.

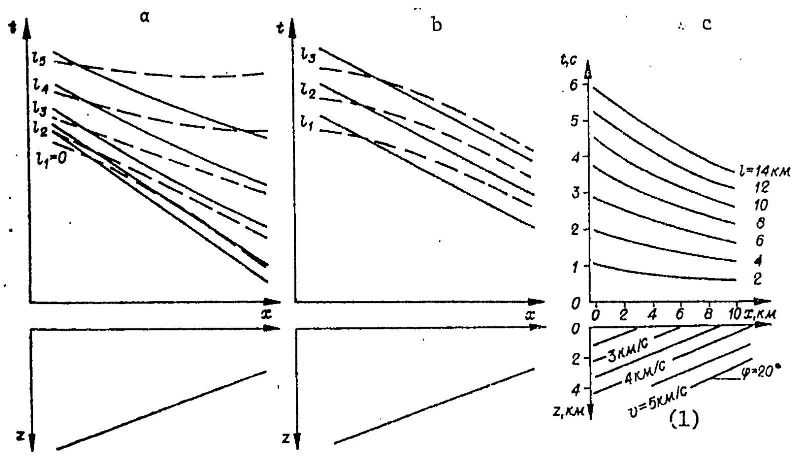

Figure 13. Wave time fields:
reflected (a), refracted for $v_{boundary}$=const (b) and refracted for $v=v_0+\beta$ (x sin ϕ+z cos ϕ) (c). Solid lines v=const, dashed lines -- $v=v_0(1+\beta z)$.

Key:
1. km/sec

In the case of sloped occurrence of a plane reflecting boundary (Fig 13, a) the field isolines (in addition to the lines ℓ=0) are distorted (hyperbolic) and are inclined in the ascending direction. The amount of slope decreases with an increase in the base, that is, the soundings with small bases are characterized by the greatest sensitivity to variation in depth.

The characteristics of the time field in the case of a curvilinear boundary are characterized by an example for an anticlinal structure (see Fig 14). The field isolines are in the first approximation a mirror reflection of the relief of the reflecting surface. The anomaly in time corresponding to the deep structure decreases with an increase in the parameter ℓ_j. For boundaries of concave shape with great curvature of the line ℓ_j=const form closed loops (see Fig 15).

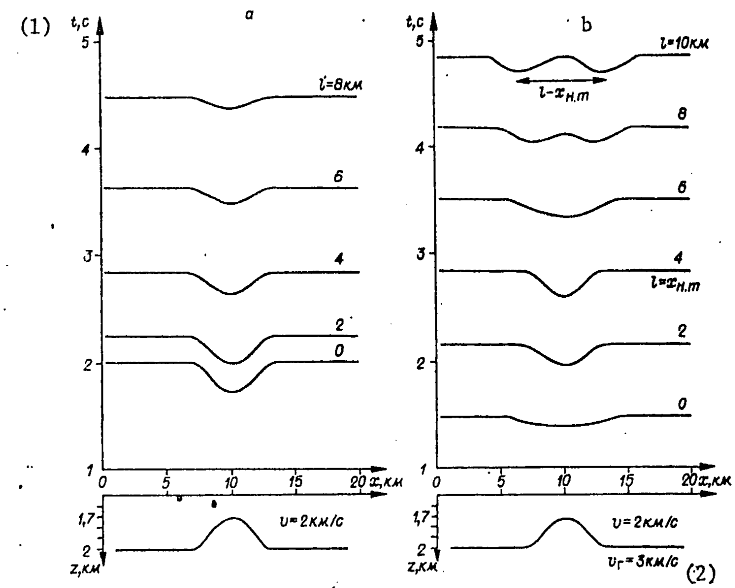

Figure 14. Time fields of the reflected (a) and refracted (b) waves for a model with curvilinear boundary

Key:
1. t, sec
2. km/sec

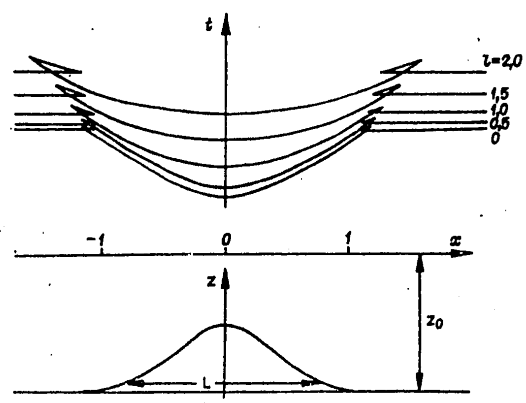

Figure 15. Time fields of the reflected waves (the case of loops on lines ℓ=const above the concave sections of the boundary)

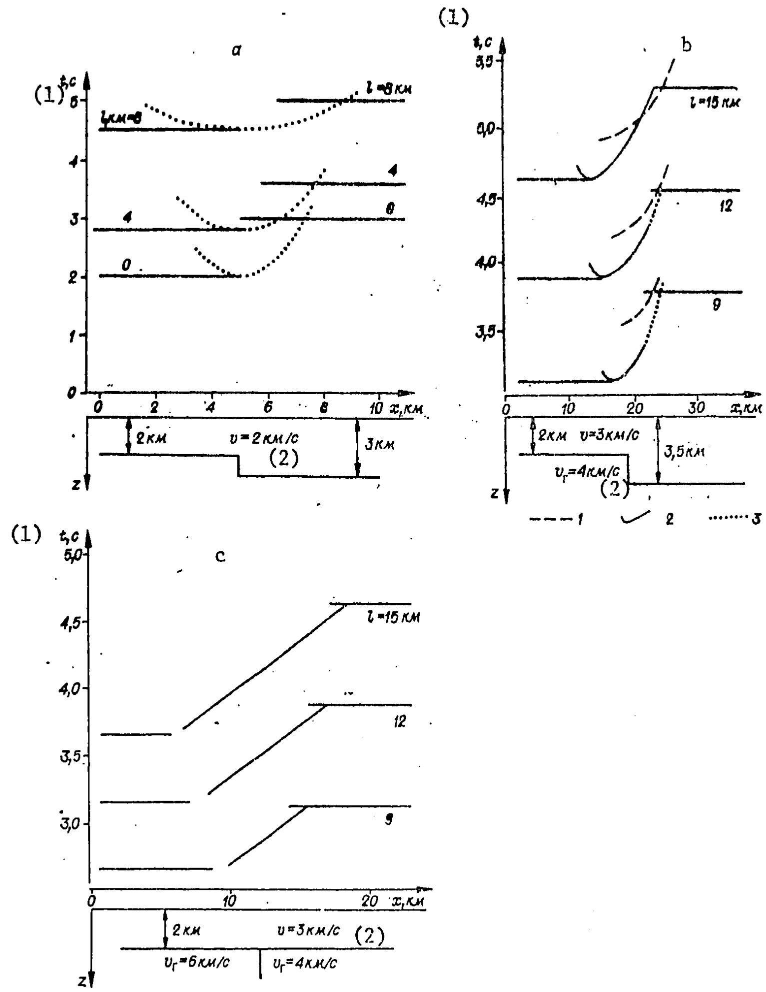

Figure 16. Time fields for the models of a scarp (a -- reflected wave, b -- refracted wave) and vertical contact (c -- refracted wave). 1 -- refracted transmitted wave, 2 -- refracted-diffracted; 3 -- diffracted.

Key:

1. t, sec
2. km/sec

In the case of a scarp or fault (Fig 16, a) the lines ℓ_j=const lose the discontinuity, the amplitude of which is maximum at ℓ=0. The extent of the transition zone in the discontinuity region where diffracted waves are recorded increases with an increase in the base (the diffracted waves are illustrated in Fig 16, a only from the upper edge of the scarp).

The horizontal velocity gradient in the covering medium with horizontal reflecting surface leads to inclination and approach of the time field isolines in the direction of increasing velocity (Fig 17, a). In contrast to the above-investigated case of an inclined boundary and constant velocity, the time intervals between the isolines decrease with a decrease in time for ℓ_j=const. The effect of the positive vertical velocity gradient is opposite to the effect caused by the boundary relief (see Fig 14, a).

Head Waves. Let us make the assumption that the refracted wave slides along the interface having the equation $z=z(x)$. Let $M_1(x_1,z_1)$ and $M_2(x_2,z_2)$ be the points of arrival and departure of the wave at a critical line $i=\arcsin v/v_{boundary}$. The values of x_1 and x_2 will be considered as parameters. Then in accordance with Figures 18-19, it is possible to write the following system of equations:

$$\left.\begin{aligned} l &= z_1\,\mathrm{tg}\,(i-\varphi_1)+z_2\,\mathrm{tg}\,(i+\varphi_2)+x_2-x_1,\\ x &= \frac{1}{2}\,[x_1+x_2+z\,\mathrm{tg}\,(i+\varphi_2)-z_1\,\mathrm{tg}\,(i-\varphi_1)],\\ vt &= z_1\sec(i-\varphi_1)+z_2\sec(i+\varphi_2)+\sin i\int\limits_{x_1}^{x_2}\sqrt{1+\left(\frac{dz}{dx}\right)^2}\,dx, \end{aligned}\right\}\quad \text{(II.30)}$$

where the integral term of the last equation is the length of the arc M_1M_2.

$$\mathrm{tg}\,\varphi_1=\left(\frac{dz}{dx}\right)_{x_1},\ \mathrm{tg}\,\varphi_2=\left(\frac{dz}{dx}\right)_{x_2}.$$

For a plane interface ($z=z_0+x\ \mathrm{tg}\ \phi$) the field equation has the form

$$t(x,\,l_j)=\frac{1}{v}\,(2z_0\cos i\cos\varphi+l_j\sin i\cos\varphi+2x\cos i\sin\varphi).\quad \text{(II.31)}$$

or, in more compact form

$$t(x,\,l_j)=\frac{2h(x)\cos i}{v}+\frac{l_j}{v_r}\cos\varphi,\qquad \text{(II.31')}$$

where

$$h(x)=x\sin\varphi+z_0\cos\varphi.$$

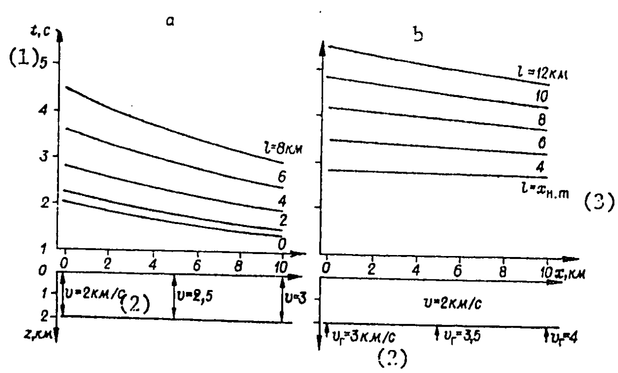

Figure 17. Time fields of the reflected wave for a model with constant horizontal velocity gradient (a) and a refracted wave with linear horizontal variation of the boundary velocity (v=const) (b)

Key:
1. t, sec
2. km/sec
3. x initial point

In the special case of a circular boundary for the head wave the expression can be proved which we shall present without awkward elementary calculations [59]:

$$t(x, l_j) = \frac{1}{kv_r}\left[2\operatorname{ctg} i + 2i - A - B + \operatorname{arctg}\frac{l_j z_0}{z_0^2 + (x_0 - x)^2 - \frac{l_j^2}{4}} - \operatorname{arctg}\frac{A+B}{AB-1}\right], \quad \text{(II.32)}$$

where

$$A^2 = \frac{k^2}{\sin^2 i}\left[\left(x_0 - x + \frac{l_j}{2}\right)^2 + z_0^2\right] - 1,$$

$$B^2 = \frac{k^2}{\sin^2 i}\left[\left(x - x_0 + \frac{l_j}{2}\right)^2 + z_0^2\right] - 1,$$

x_0 and z_0 are the coordinates of the center of the circle (the origin of the coordinates on the profile line), k is the curvature (a value which is the inverse of the radius of the circle). The sign of the curvature is considered positive for a concave boundary and negative for a convex boundary.

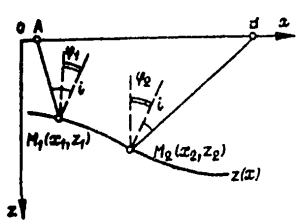

Figure 18. Derivation of the equation for the head wave time field

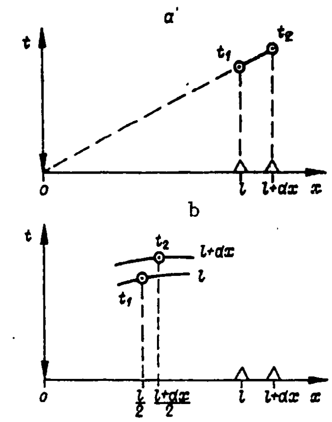

Figure 19. Determination of the apparent velocity by the time field. a -- hodograph element; b -- time field element

In the simplest case of a horizontal boundary and constant velocities (see Fig 12, b) the field isolines $t(x, \ell_j)$ are horizontal straight lines with equal interval between adjacent lines (with a fixed increment of parameter ℓ_j). For an inclined boundary (see Fig 13, b) the rectilinearity of the isolines and constancy of the time intervals between them are maintained, but all of the isolines are inclined in the ascending direction of the refracting surface. The rectilinearity of the isolines in the case of sloping occurrence is disturbed in the case of the vertical velocity gradient in the covering medium.

The effect of the curvilinearity of the boundary on the time field of the head wave depends on the magnitude of the base. Let us consider this relation in the example where the refracting surface forms an anticlinal structure (see Fig 14, b). The isoline with the base which is closest to the x-axis of the initial point ($x_{\text{initial point}}$) coincides with respect to shape in practice with the mirror reflection of the boundary relief. On making the transition to isolines with parameter ℓ_j distinguished from $x_{\text{initial point}}$ to the higher or lower side, the structure (its time effect) initially is laid out and extended along the horizontal, and then it decays into two fictitious "structures" similar with respect to shape to the one which occurs for $\ell \simeq x_{\text{initial point}}$, but with half the amplitude. The fictitious structures are arranged symmetrically with respect to the true structure. The distance between them increases with an increase in the value of $\ell_j - x_{\text{initial point}}$. The time field characteristics investigated for the given example have a quite general form in their qualitative form, and they are caused by the fact that the basic appearance of the underground relief in the form of the lines ℓ_j=const is caused by superposition of the effects of the variation of the boundary depths at the refraction points of the seismic beam. If the horizontal dimensions of the structural forms are small by comparison with the sounding base, then each of them is fixed twice: at the points of incidence and withdrawal of the beam. With a decrease in the base, these points come nearer together; the fictitious "structures" become nearer correspondingly, and they become superimposed. For $\ell \approx x_{\text{initial point}}$ the investigated points in practice coincide, and the corresponding field isoline approaches mirror similarity to the refracting boundary, just as in the case of reflected waves.

The appearance of a fault in the refracted wave time field is investigated in detail in reference [33]. On intersection of the fault across the strike (see Fig 16, b) a shift of the field isolines takes place, the amplitude of which is identical for all isolines and is equal to $(\Delta z/v)\cos i$, where Δz is the depth gradient. In the transition zone, the extent of which increases with an increase in the base, there are refracted-transmitted and diffracted waves. They correspond to the curvilinear lines ℓ_j=const which depend on the mutual arrangement of the source into the receiver.

The characteristics of the time field of the head wave in the case of vertical contact with the boundary velocity discontinuity are illustrated in Fig 16, c. Above the section with reduced boundary velocity the times for all the isolines and intervals between increase by identical amounts. On location of the soundings near the contact between the refraction points of the seismic wave, the lines ℓ_j=const are straight lines inclined in the direction of the medium with higher velocity. Near the contact there are discontinuities and overlaps of the isolines. The isolines of the diffracted waves not shown in the drawing depend on the mutual arrangement of the source and the receiver.

For continuous linear variation of the boundary velocity (see Fig 13, b) the lines ℓ_j=const become curvilinear and rise smoothly in the direction of a decrease in velocity with a simultaneous increase in the intervals between the isolines. The isoline with the parameter closest to the mean value of the x-axis of the initial point has the minimum reaction to variation of the boundary velocity.

Refracted Waves. With an increase in velocity with depth by the law v(z), using the known [20] expressions for a refracted wave, it is possible to write the function $t(x, \ell_j)$ in parametric form

$$\left.\begin{aligned} l &= 2\int_0^{z_{\max}} \frac{pv(z)\,dz}{\sqrt{1-p^2v^2(z)}},\\ t &= 2\int_0^{z_{\max}} \frac{dz}{v(z)\sqrt{1-p^2v^2(z)}}, \end{aligned}\right\} \qquad \text{(II.33)}$$

where z_{max} is the depth of maximum penetration of the seismic beam; $p=1/v(z_{max})$ is the beam parameter.

The exclusion of the parameter from equations (II.33) is possible for the specific laws v(z). In particular, for a linear increase in velocity $v=v_0(1+\beta z)$, the following expression is obtained [20]:

$$t(x, l_j) = \frac{2}{v_0\beta}\operatorname{arsh}\frac{l_j\beta}{2}. \qquad \text{(II.34)}$$

Here v_0 is the velocity on the observation surface, β is the vertical density gradient.

For any law of increase in velocity with depths the isolines of the time field of the refracted wave approach with an increase in the base (see Fig 12, c). The isolines are horizontal straight lines; there is no dependence on the x-coordinate, for the velocity varies only vertically. The equation of the time field isolines for the refracted wave in a medium with linear dependence of the velocity on the x and z coordinates, that is, for the law

$$v(x, z) = v_0 + k(x \sin\varphi + z\cos\varphi),$$

where ϕ is the slope of the velocity isoline; k is the velocity gradient with respect to the normal to these isolins; v_0 is the velocity at the origin of the coordinates on the observation surface, can be written in the form [72, 90]:

$$t(x, l_j) = \frac{2}{k}\operatorname{arsh}\frac{kl_j}{2\sqrt{(v_0 + kx\sin\varphi)^2 - \frac{k^2 l_j^2}{4}\sin^2\varphi}}. \qquad \text{(II.35)}$$

An example of the time field of a refracted wave is presented in Fig 13, c for the case of linear variation of the velocity with respect to the x and z directions. The field is represented by a family of concave curves ℓ_j=const inclined in the increasing direction of the velocity isolines.

Diffracted waves can occur at sharp inhomogeneities usually coordinated with the fracture zones. In the case of diffraction on a horizontal ridge for a profile directed across the strike of the ridge, the function $t(x, \ell_j)$ can be obtained on the basis of simple geometric arguments (see Fig 12, d):

$$t(x, l_j) = \frac{1}{v}\left[\sqrt{z_0^2 + \left(x - x_0 - \frac{l_j}{2}\right)^2} + \sqrt{z_0^2 + \left(x + x_0 + \frac{l_j}{2}\right)^2}\right]. \qquad \text{(II.36)}$$

The origin of the coordinates is placed at an arbitrary point of the profile, x_0 and z_0 are the coordinates of the diffracting object.

The lines ℓ_j=const are symmetric, they have a minimum above the diffracting object. Each of them is the sum of two hyperbolas shifted with respect to the diffracting ridge by the amount $\pm\ell_j/2$.

It is necessary to keep in mind that in a number of cases the form of the isolines of the time field of diffracted waves can depend on the mutual arrangement of the source and the receiver of the oscillations.

A further study of the properties of two-dimensional time fields t(x, ℓ) of reflected-diffracted waves was made in reference [39].

Time Field Gradients

The time field gradients are important characteristics of the time field related to the parameters of the medium. Let us find these relations for reflected and refracted waves in the case of the two-layer medium with locally plane boundary separating uniform media and also for refracted waves.

The vertical gradient of the time field will be determined as a result of differentiation with respect to ℓ of the equations (II.29) and (II.31'), (II.33) or with respect to the equations (II.13) and (II.16). In the case of reflected waves

$$\left[\frac{d(t^2)}{d(l^2)}\right]_{x=\text{const}} = \frac{1}{v}\cos^2\varphi, \qquad \text{(II.37)}$$

$$\left(\frac{dt}{dl}\right)_{x=\text{const}} = \frac{\cos\varphi}{v\sqrt{\left(\frac{2h_m}{l\cos\varphi}\right)^2+1}}. \qquad \text{(II.37')}$$

For refracted (head) waves

$$\left(\frac{dt}{dl}\right)_{x=\text{const}} = \frac{1}{v_r}\cos\varphi. \qquad \text{(II.38)}$$

In the case of refracted waves

$$\left(\frac{dt}{dl}\right)_{x=\text{const}} = \frac{1}{v(z_{\max})}. \qquad \text{(II.39)}$$

From the formulas obtained it follows that the magnitude of the vertical gradient depends on the values of the velocities v, $v_{boundary}$, $v(z_{max})$ of propagation of the elastic waves inthe medium. The dependence on the slope angle of the boundaries is weak, for the value of cos ϕ in the formulas (II.37) and (II.38) differs little from one for the usually encountered values of ϕ.

In the case of reflected and refracted waves we obtain the horizontal gradient by differentiation with respect to x of the expressions (II.29) and (II.31') taking into account that $dh/dx=\sin\phi$ (considering the slope of the boundary positive in the drop direction).

For reflected wave:

$$\left[\frac{d(t^2)}{dx}\right]_{l^2=\text{const}} = \frac{8h}{v^2}\sin\varphi, \qquad \text{(II.40)}$$

$$\left(\frac{dt}{dx}\right)_{l=\text{const}} = \frac{1}{v\sqrt{1+\left(\frac{l}{2h}\cos\varphi\right)^2}}\sin\varphi. \qquad \text{(II.40')}$$

In the case of refracted waves

$$\left(\frac{dt}{dx}\right)_{l=\text{const}} = \frac{2\cos i}{v}\sin\varphi. \qquad \text{(II.41)}$$

From the formulas obtained it follows that the horizontal field gradient depends primarily on the slope angle of the seismic boundaries. This property is approximately valid also for refracted waves in the presence of a horizontal velocity gradient where the equal velocity lines are inclined at some angle (Fig 13, c, [72]).

The apparent velocity is expressed in terms of vertical and horizontal gradients of the time field. Let us consider the element of the hodograph obtained in the section [ℓ, ℓ+dx]. The source of the oscillations is at the origin of the coordinates, the x-axis is directed from the source to the receiver (see Fig 19, a). In this case

$$\frac{1}{\vec{v}_k} = \frac{t_2 - t_1}{dx}.$$

The location of the corresponding points in the time field is also illustrated in Fig 19, a. It is obvious that

$$t_2' = t_1 + \left(\frac{dt}{dl}\right)_{x=\text{const}} \cdot dx + \left(\frac{dt}{dx}\right)_{l=\text{const}} \cdot \frac{1}{2}\,dx.$$

Substituting this expression in the preceding formula, we obtain the desired relation for the apparent velocity:

$$\frac{1}{\vec{v}_k} = \left(\frac{dt}{dl}\right)_{x=\text{const}} + \frac{1}{2}\left(\frac{dt}{dx}\right)_{l=\text{const}}. \qquad \text{(II.42)}$$

For the apparent velocity in the opposite direction we have

$$\frac{1}{\overleftarrow{v}_k} = \left(\frac{dt}{dl}\right)_{x=\text{const}} - \frac{1}{2}\left(\frac{dt}{dx}\right)_{l=\text{const}}. \qquad \text{(II.42')}$$

If the gradients are defined at the point x_j, ℓ_j in the time field, the obtained apparent velocities pertain to the elements of the hodographs respectively at the points $x_j \pm \ell_j/2$ with sources at the points $x_j \pm \ell_j/2$.

In practice, considering the time field in a bounded region uniform, it is possible to convert from differentials to finite time increments and distances from field points corresponding to one hodograph. For simplicity, matching the origin of the x-axis to the investigated oscillation source (O_1 in Fig 11, b), we have the following formula for determining the apparent velocity in the distance range $[\ell_1, \ell_2]$ from this source:

$$v_k = \frac{l_2 - l_1}{t_2\left(\frac{l_2}{2}\right) - t_1\left(\frac{l_1}{2}\right)}. \qquad \text{(II.42'')}$$

Transformation of the Time Field with Variation of the Bases

This transformation, which is important in various steps of the interpretation, can be substantiated for refracted and reflected waves, and it is based on the fact that under certain conditions the time field of these waves is determined by giving only two lines ℓ_j=const.

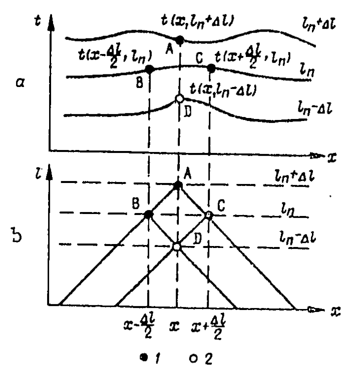

Figure 20. Substantiation of the transformation of the time field of a head wave with variation of the bases.
a -- time field; b -- observation system in the plane x, ℓ.
1 -- initial point; 2 -- points subject to determination.

In the case of refracted waves we consider that the seismic beam slides over the boundary without penetrating into the depths of the refracting layer (the overlapping hodographs for are parallel). The observation surface relief and the velocity distribution in the covering and refracting media can be arbitrary. Let us demonstrate that under these conditions the assignment of two arbitrary isolines of the field permit us to find isolines with other bases with the interval $\Delta\ell$ equal to the difference of the initial bases.

Let ℓ_n and $\ell_{n+1}=\ell_n+\Delta\ell$ be the parameters of the given field isolines. Let us prove that for an arbitrary point of the profile x at the time t $(x, \ell_n-\Delta\ell)$ corresponding to the isoline $\ell_{n-1}=\ell_n-\Delta\ell$ is determined by the values of the initial time at the points $x-(1/2)\Delta\ell$, x and $x+(1/2)\Delta\ell$ (Fig 20). Returning to the observation plane x, ℓ, where the lines ℓ_j=const have the shape of straight lines parallel to the x-axis, let us write the obvious equality expressing the property of parallelness of the overlapping hodographs of the head wave:

$$t(x, l_n+\Delta l) - t\left(x-\frac{\Delta l}{2},\ l_n\right) = t\left(x+\frac{\Delta l}{2},\ l_n\right) - t(x,\ l_n-\Delta l),$$

from which we obtain the desired function

$$t(x,\ l_n-\Delta l) = t\left(x-\frac{\Delta l}{2},\ l_n\right) + t\left(x+\frac{\Delta l}{2},\ l_n\right) - t(x,\ l_n+\Delta l). \qquad \text{(II.43)}$$

Applying the relation found for a number of points of the profile, it is possible to construct the line $\ell_n-\Delta\ell$. Then, considering the lines ℓ_n and $\ell_n-\Delta\ell$ as the initial lines, we find the times for $\ell_n-2\Delta\ell$. Continuing this process successively, it is possible to reproduce the entire field in some region in the direction of increase or decrease of the bases.

Designating for brevity the values of the times obtained when recalculating the initial values of t_{n+1} and t_n for lower levels ℓ_{n-1}, ℓ_{n-2}, $\ell_{n-3}, \ldots$ ℓ_n-k by t_{n-1}, t_{n-2}, t_{n-3}, ..., $t_{n-}k$, as a result of the successive application of formula (II.43) we find:

$$t_{n-1}(x) = t_n\left(x-\frac{\Delta l}{2}\right) + t_n\left(x+\frac{\Delta l}{2}\right) - t_{n+1}(x),$$

$$t_{n-2}(x) = t_n\left(x-\frac{\Delta l}{2}\right) + t_n(x) + t_n\left(x+2\frac{\Delta l}{2}\right) - \\ - t_{n+1}\left(x-\frac{\Delta l}{2}\right) - t_{n+1}\left(x+\frac{\Delta l}{2}\right),$$

$$t_{n-3}(x) = t_n\left(x-3\frac{\Delta l}{2}\right) + t_n\left(x-\frac{\Delta l}{2}\right) + t_n\left(x+\frac{\Delta l}{2}\right) + \\ + t_n\left(x+3\frac{\Delta l}{2}\right) - t_{n+1}\left(x-2\frac{\Delta l}{2}\right) - t_{n+1}(x) - t_{n+1}\left(x+2\frac{\Delta l}{2}\right),$$

$$t_{n+k}(x) = \sum_{j=0}^{k} t_n\left[x-(k-2j)\frac{\Delta l}{2}\right] - \sum_{j=0}^{k-1} t_{n+1}\left[x-(k-2j-1)\frac{\Delta l}{2}\right]. \qquad \text{(II.44)}$$

It is possible analogously to obtain the corresponding expression for recalculating the times t_{n-1} and t_n in the direction of increases bases:

$$t_{n+k}(x)=\sum_{j=0}^{k} t_n\left[x-(k-2j)\frac{\Delta l}{2}\right]-\sum_{j=0}^{k-1} t_{n-1}\left[x-(k-2j-1)\frac{\Delta l}{2}\right]. \quad \text{(II.44')}$$

For each act of recalculating the time field of the head wave the extent of the isolines obtained is reduced from both edges by the amount $\Delta \ell/2$.

The recalculation of the time field of reflected waves is possible under more rigid restrictions: in the case of a plane observation surface, locally plane boundary and constant velocity in the covering series. Under these conditions the time $t_3(x)$ corresponding to the arbitrary base ℓ_3 is found by the two given lines $t_1(x)$ and $t_2(x)$ with the bases ℓ_1 and ℓ_2 [90]:

$$t_3^2(x)=t_1^2(x)+\frac{l_3^2-l_1^2}{l_2^2-l_1^2}\left[t_2^2(x)-t_1^2(x)\right]. \quad \text{(II.45)}$$

In the special case where $\ell_3=0$ and $t_3=t_0$, we obtain the formula for the recalculation to the line $t_0(x)$:

$$t_0^2(x)=\frac{l_2^2 t_1^2(x)-l_1^2 t_2^2(x)}{l_2^2-l_1^2}. \quad \text{(II.45')}$$

Reduction of the Time Field to a New Observation Line

The investigated reduction can be carried out for waves of any type if the structure of the medium between the initial and the new levels is known. The essence of recalculating the time field to the new observation level consists in the fact that the angles formed by the seismic beam with the day surface and the source and receiver points are located with respect to the initial field. Then by the laws of geometric seismics, the beam trajectory before intersection with the selected reduction level is restored. The source and the receiver are converted to the found intersection point.

Let us consider the sufficiently general case where the medium between the observation line and the reduction level consists of an arbitrary number of layers with curvilinear boundaries and a velocity which is variable along the vertical. Using the known [20] expressions for the medium with vertical velocity gradient, we find the horizontal shift Δx and the time Δt of the path of the beam in each layer (Fig 21). For the n-th layer we have:

$$\left.\begin{aligned}\Delta x_0 &= \int_0^{h_n}\frac{p_n v_n(z)\,dz}{\sqrt{1-p_n^2 v_n^2(z)}},\\ \Delta t_n &= \int_0^{h_n}\frac{dz}{v_n(z)\sqrt{1-p_n^2 v_n^2(z)}}.\end{aligned}\right\} \quad \text{(II.46)}$$

The origin of the coordinates in each layer refers to the point of entry of the seismic beam into it. The parameter p_n is equal to $\sin i_{0n}/v_{0n}$. The angle i_{0n} for all layers, except the first, is determined from the refraction law:

$$i_{0n} = \arcsin \frac{v_{0n} \sin (i_{n-1} + \varphi_n)}{v_{n-1}(h_{n-1})} - \varphi_n. \qquad \text{(II.47)}$$

In the presented expressions h_n is the vertical projection of the beam trajectory in the given layer, $v_{n-1}(h_{n-1})$ and v_{0n} are the velocities at the foot and in the cover of the layers respectively with the indexes n-1 and n. The remaining notation is clear from Fig 21.

The angle i_{01} of approach of the beam to the observation line is found by the formula

$$i_{01} = \arcsin \frac{v_{01}}{v_k} - \varphi_1. \qquad \text{(II.48)}$$

The value of the apparent velocity v_k is defined in terms of the vertical and horizontal time field gradients (see II.42).

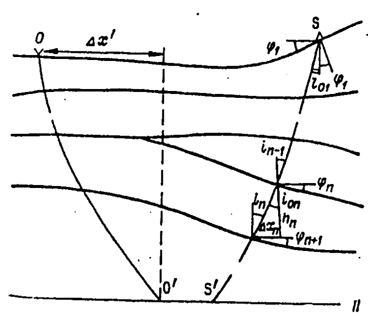

Figure 21. Substantiation of the transition to the new observation level.
I -- observation line; II -- reduction level.

Applying formulas (II.48), (II.47) and (II.46) successively, let us calculate the values of Δx and Δt in all layers (beginning with the first) for the beam reaching the point S. The values of Δx^1 and Δt^1 are found analogously for the beam emerging from the source 0. For reduction of the sounding OS to the new observation line (0^1S^1) the time must be changed by the amount

$$\Delta T = -\left(\sum \Delta t_n + \sum \Delta t_n^1\right),$$

the sounding center is shifted along the x-axis by

$$\Delta x = \frac{1}{2}\left(\sum \Delta x_n^1 - \sum \Delta x_n\right),$$

and the sounding base is altered by the amount

$$\Delta L = -\left(\sum \Delta x_n + \sum \Delta x_n^1\right).$$

The summation is carried out with respect to all layers between the initial and the new observation lines. The values of Δx and Δt are positive on recalculation downward, and as they are negative on transition to the observation line above the initial level. The corrections ΔT, Δx and ΔL are calculated for the required number of points of the initial time field; the new field is constructed by the corrected values.

Instead of the calculations by formulas (II.46) it is possible to use the radiation patterns for the given laws $v_n(z)$. In the special case where the velocities in each layer are constant and the boundaries are curvilinear, equations (II.46) acquire the form:

$$\left.\begin{aligned} \Delta x_n &= h_n \operatorname{tg} i_n, \\ \Delta t_n &= \frac{h_n}{v_n \cos i_n}. \end{aligned}\right\} \qquad (II.46')$$

Still greater simplifications are obtained in the case of the horizontally stratified medium:

$$\left.\begin{aligned} \Delta x_n &= \frac{h_n v_n}{\sqrt{v_k^2 - v_n^2}}, \\ \Delta t_n &= \frac{h_n v_k}{v_n \sqrt{v_k^2 - v_n^2}}. \end{aligned}\right\} \qquad (II.46'')$$

Here v_k is the value of the apparent velocity at the intersection point of the day surface by the seismic beam.

Appearance of Surface Inhomogeneities in the Time Field

We shall consider the travel time difference of the wave in the presence of a surface inhomogeneity and without it with unknown position of the source in the receiver as the surface distortion. In the latter case the upper inhomogeneous part of the section is replaced by a homogeneous medium with the same velocity as in the underlying rock. On the different field isolines the influence of the surface distortions turns out to be distributed differently.

Actually, we have two field isolines $t_1(x)$ and $t_2(x)$ which correspond to the bases ℓ_1 and ℓ_2. At an arbitrary point of the profile x the time $t_1(x)$ will contain the effect of the inhomogeneities at the points $x-\ell_1/2$ and $x+\ell_1/2$ where the corresponding source and receiver of the oscillations are located. The value of $t_2(x)$ will be distorted by the inhomogeneities at the points $x-\ell_2/2$ and $x+\ell_2/2$. Consequently, the time distortions $t_1(x)$ and $t_2(x)$ can turn out to be different with respect to magnitude.

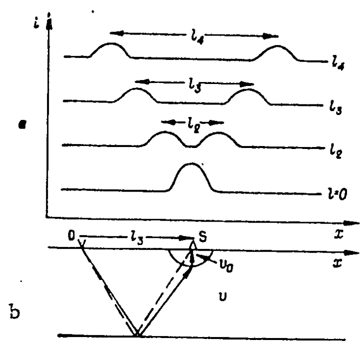

Figure 22. Appearance of the surface inhomogeneities in the time field
a -- time field; b -- section and beam diagram

A characteristic example of the appearance of the surface inhomogeneities in the time field is illustrated in Fig 22 for the case of relatively simple structure of the medium and reflected wave soundings. For $\ell \neq 0$ the section with low velocity v_0 is intersected by the seismic beam twice for different positions of the sounding center. On the lines ℓ_j=const two anomalies in time are recorded which are separated from each other by a distance close to the corresponding value of ℓ_j.

In practice the values of the velocities in the upper nonuniform layer (in the low velocity zone and for operations by the deep seismic sounding method, in the series of loosely compacted sediments) are usually significantly less than in the lower medium; therefore it is possible to neglect the dependence of the surface distortions on the angle of approach (exit) of the seismic beam at the foot of the nonuniform layer. Then each point of the profile in which the source or the receiver of the oscillations is located can be assigned some magnitude of the distortion $\delta(x)$ which does not depend on the sounding base. Under this condition the equation of the field isolines with the paramter ℓ_j is written as follows:

$$t_j(x) = t'_j(x) + \delta\left(x - \frac{l_j}{2}\right) + \delta\left(x + \frac{l_j}{2}\right). \qquad \text{(II.49)}$$

where $t'_j(x)$ is the undistorted time.

In the special case where the function $\delta(x)$ is linear, the distribution of the time field distortions does not depend on the magnitude of the sounding bases. All of the isolines will be distorted identically.

Peculiarities of the Time Field with Area Observations

If the set of soundings with the bases which vary in some interval is placed in an area (in the observation point x, y), then, just as before, referring the times to the centers of the corresponding soundings, it is possible to construct a number of isochron maps for fixed values of the bases ℓ_j. As a result, we obtain the surface field $t(x, y, \ell_j)$. Let us consider its peculiarities for the reflected and the refracted waves.

The surface time field is nonuniform, for the time of arrival of the wave depends on the azimuth ψ which will be reckoned from the direction of drop of the boundary (see Fig 9, d) for soundings with fixed base and invariant position of the center.

In the case of reflected waves

$$t_\psi = \frac{1}{v}\sqrt{4h^2 + l_j^2(1 - \sin^2\varphi\cos^2\psi)}, \qquad \text{(II.50)}$$

where ϕ is the total slope angle of the boundary; h is the depth along the normal to the boundary at the center of the base.

The minimum time will be obtained with orientation of the sounding base across the strike of the reflecting surface

$$t_\perp = \frac{1}{v}\sqrt{4h^2 + l_j^2\cos^2\varphi}, \qquad \text{(II.50')}$$

the maximum time will be obtained for the strike direction

$$t_\parallel = \frac{1}{v}\sqrt{4h^2 + l_j^2}. \qquad \text{(II.50'')}$$

From the preceding three equations it is possible to derive the following expression:

$$t_\psi^2 = t_\parallel^2\cos^2\psi + t_\perp^2\sin^2\psi, \qquad \text{(II.50''')}$$

permitting the required calculation of the fields. This expression can also be interpreted in the sense that the spatial time field of the reflected wave is characterized by two functions: $t_\parallel(x, y, \ell_j)$ and $t_\perp(x, y, \ell_j)$. Knowing these functions when solving the direct problem, it is possible to construct the field $t_{\psi_j}(x, y, \ell_j)$ for the given arbitrary orientation of the individual soundings in accordance with the transformation (II.50''').

The ambiguity of the field $t(x, y, \ell_j)$ at each point of the observation surface can be characterized by the difference between the maximum time and the time for orientation of the sounding at the arbitrary azimuth ψ:

$$\Delta t_\psi = t_n - t_\psi = t_\parallel \left(1 - \sqrt{1 - \frac{1}{1+\frac{4h^2}{l_j^2}} \sin^2 \varphi \cos^2 \psi} < \right.$$
$$\left. < t_\parallel \left(1 - \sqrt{1 - \sin^2 \varphi \cos^2 \psi}\right). \quad \text{(II.51)}$$

The time difference is maximal for soundings which are located along the strike and across the strike:

$$\Delta t_{max} = t_\parallel - t_\perp = t_\parallel \left(1 - \sqrt{1 - \frac{1}{1+\frac{4h^2}{l_j^2}} \sin^2 \varphi}\right) < t_\parallel (1 - \cos \varphi). \quad \text{(II.51')}$$

Analogous relations for the head waves have the form:

$$t_\psi = \frac{2h \cos i}{v} + \frac{l_j}{v_r} \sqrt{1 - \sin^2 \varphi \cos^2 \psi}, \quad \text{(II.52)}$$

$$t_\perp = \frac{2h \cos i}{v} + \frac{l_j}{v_r} \cos \varphi, \quad \text{(II.52')}$$

$$t_\parallel = \frac{2h \cos i}{v} + \frac{l_j}{v_r}. \quad \text{(II.52'')}$$

The corresponding relation between the times is expressed by the relation

$$t_\psi = t_\parallel - \frac{l_j}{v_r} + \sqrt{\left(\frac{l_j}{v_r}\right)^2 \sin^2 \psi + \left(t_\parallel - t_\perp + \frac{l_j}{v}\right)^2 \cos^2 \psi}. \quad \text{(II.52''')}$$

In the given case the value of $\ell_j/v_{boundary}$ enters into the time conversion formula.

For the time difference Δt_ψ and Δt_{max} we have:

$$\Delta t_\psi = t_\parallel - t_\psi = \frac{l_j}{v_r} \left(1 - \sqrt{1 - \sin^2 \varphi \cos^2 \psi}\right), \quad \text{(II.53)}$$

$$\Delta t_{max} = t_\parallel - t_\perp = \frac{l_j}{v_r} (1 - \cos \varphi). \quad \text{(II.53')}$$

The ambiguity of the surface time field increases with an increase in the slope angle of the reflecting and refracting boundaries. For $\phi=0$ the field is unique. By formulas (II.51') and (II.53'), it is possible to estimate the degree of ambiguity for specific conditions. The extended seismic boundaries in the earth's crust usually have small slope angles measurable by the first degrees. Therefore for deep seismic studies in the majority of cases it is possible to neglect the dependence of the time on the sounding azimuth. If the slope angles are large, the effect of the ambiguity of the time field can be excluded by reducing the time to some defined direction, for example, the strike direction. In this case the corrections to the observed values of the times are calculated by the formulas (II.51) and (II.53). The azimuths ψ required to calculate the corrections are determined by the isochron maps or by the structural maps constructed in the first approximation without considering ambiguity of the field.

For a complex structure of the medium, the necessity for considering the ambiguity of the field $t(x, y, \ell)$ caused by an anisotropy of the velocities can occur. The effects caused by the dependence of the boundary velocity on the azimuth when studying the surface of the platform basin by refracted waves can be especially significant.

As is noted above, the field $t(x, y, \ell)$ in the observation plane has ambiguity even for the simplest models with a plane interface and uniform medium.

In reference [94], which is a further development of the theory of spatial reflected wave soundings, the possibility of the construction of a unique field of some magnitude M determined by the measurements on the orthogonal cross soundings with orthogonal orientation in the observation plane is demonstrated. Here the uniqueness of the field is maintained with great accuracy for a quite large set of standard models. This has offered the possibility of strict solution of the inverse problem [96].

In conclusion, let us point out that the theory of time fields developed above in recent times has begun to be used in structural seismic prospecting both in the solution of the problem of isolating signals against an interference background and for more proper solution of the inverse problems.

§3. Peculiarities of the Identification of Waves and Use of Their Dynamic Characteristics

When working with the sounding procedure, we are dealing with waves excited at various points and recorded on short installations not connected to each other. Under these conditions, for wave identification it is impossible to use the known rules of positional and transpositional correlations which presuppose the presence of continuous observations and placement of observation sources fixed in a defined way. In the spot sounding procedure, use is made of the so-called discrete wave correlation in which, along with analyzing the wave field, broad use is made of the a priori data on the general laws of the geometry of the investigated medium and its physical properties.

The dynamic characteristics of the oscillations which play an important role in wave identification carry valuable information about the properties of the medium, including those which cannot be reliably investigated only by the data on the travel times of the elastic waves recorded for low-detail observations. Therefore the attraction of the dynamics of the observations to obtain additional information about the deep structure even in the reconnaissance research phase is natural. Existing methods of solving this problem basically have been calculated for the use of seismic recordings in a wide range of distances from the source with careful monitoring of the conditions that the excitation points and recording of the oscillations; therefore they cannot be used in the spot sounding procedure without considering its specific nature.

Peculiarities of Wave Correlation During Reconnaissance Prospecting Research

The discrete correlation, in addition to the sounding procedure, is used in one form or another in the works designed to obtain hodographs, above all, dotted and piecewise continuous. The wave identification conditions in these cases are not identical as a result of the peculiarities of the observation systems used: and these conditions reduce to the following.

If we depart from the instability of the conditions at the points of excitation and reception of the oscillations, then the basic causes of variation of the characteristics of the tracked wave along the profile can be considered to be the variation in structure of the investigated medium and inconstancy of the distances from the source to the receiver. As a result of inconstancy of the distance, significant alterations of the wave picture are possible: the reflection-refraction conditions of the waves vary, at certain distances these interfere with other oscillations. When working on obtaining extended hodographs, the two mentioned factors have an effect. The conditions of discrete correlation in the spot sounding procedure are more favorable, for the observations are made with low-variable sounding bases selected in a relatively narrow region of the most reliable generation of the tracked wave. Accordingly, the recorded wave field is more stable, its variation along the profile (or with respect to area) is primarily caused only by the structural peculiarities of the medium.

The basis for the investigated discrete correlation procedures is the proposition of the existence of sustained seismic boundaries commensurate with respect to extent with the dimensions of the investigated section which correspond to stable reference waves. With thickening of the observation network, the possibility appears for tracing waves from less extended boundaries and waves with more variable characteristics.

The requirements on the reference waves are different for different observation systems. For the spot sounding operations, stability of the wave characteristics in a relatively narrow range of distances from the source is sufficient. The recording of reflected waves in the vicinity of the angles close to critical where the reflections often predominate with respect to intensity although it is not always possible to construct sufficiently elongated hodographs by them can be a situation which is characteristic and frequently used in the sounding procedure. When obtaining the hodographs the stability of the characteristics must be observed over significantly longer intervals and distances from the source.

The discrete correlation is based on joint use of three groups of attributes: wave, physical and geological.

The group of wave attributes includes kinematic and dynamic parameters of the waves taken from the seismograms: the travel times, apparent velocity, relative intensities, apparent periods and other characteristics of the oscillations. A study is made of the relationsof these parameters for different waves considering the laws of variation on removal from the source. For reliable determination of the wave parameters, as a rule, it is sufficient to have a recording of the oscillations at one point. Distributed installation of the seismographs no less than 0.5 to 1 km long is needed. As a result, the possibility appears of not investigating the waves with short cophasalness axes and estimating the apparent velocities and their relations for different waves. It is desirable to make a three-component recording of the oscillations to monitor the regularity of the waves with respect to their polarization characteristics and involve other types of waves, in particular, composite waves, in the deciphering of the structure.

The physical attributes are based primarily on the data obtained as a result of the interpretation of the effective, boundary and stratal velocities of elastic waves. With proper identification of the waves, the velocities found, their distribution with respect to depth and along the profile (over the area) must not contradict the laws existing or presupposed for the investigated area. This requirement is not absolute. The presence of contradictions serves only as grounds for repeated critical analysis of the correlation. The matching of the independent determinations of the velocity with respect to waves of various types, tying to the data with respect to other physical properties (density, electrical activity) in accordance with the existing correlations has great significance.

The geological attributes (section attributes) encompass the morphological characteristics of the surfaces with which the seismic boundaries are identified. We have in mind the depths of occurrence of the boundaries, the slope angles in them, curvatures, thickness of the layers, matching of the structural plans on different section levels characteristic of the given area of the peculiarities of the structural forms, and so on. The basis for this group of attributes is knowledge of the geology of the area and analogies with similar territories.

The relations of the different attributes have a large role in discrete correlation. Regional and local relations are used for the distribution of the physical properties of the rock with the peculiarities of geological structures, the dependence of the wave parameters on the model of the medium characterized by geological and physical attributes.

The source of information for substantiation of the discrete correlation attributes is the results of detailed seismic operations pertaining both to the study of the wave field and to the structural laws and properties of the earth's crust and tops of the mantle. In addition to the laws of a general nature, as a rule, it is necessary to consider the peculiarities of the specific areas. Therefore, along with analysis of the materials with respect to other territories with a similar geological situation, usually before beginning work in the new area special parametric observations are made by the method of piecewise continuous profiling to discover the local peculiarities of the wave field.

In connection with broad use, along with the wave attributes of the data on the properties of the medium, the process of discrete correlation cannot be considered as an isolated, initial step of the interpretation. This process continues in the steps of determining the elastic properties of the medium and construction of the sections and structural maps. The noncorrespondences in the results obtained provide a basis for investigation of other versions of the wave correlation.

Let us discuss two peculiarities in the method of reconnaissance prospecting research important to the discrete wave correlation.

The first peculiarity is joint application of waves of different types (reflected, head, refracted). When using individual correlation attributes and their interrelations, it is necessary to consider the corresponding peculiarities for the different waves. In addition, further possibilities appear for control of the correlation with respect to the criterion of non-contradictoriness of the results obtained by waves of different types.

The second peculiarity is the great extent of the investigated seismic profiles and regions encompassing nonuniform blocks of the earth's crust with distinguished seismological conditions and wave picture. Therefore the basic assumption regarding the maintenance of the seismic boundaries and the waves corresponding to them often is made not for the entire territory as a whole, but only within the limits of one or several comparatively uniform blocks, the transverse dimensions of which usually do not exceed several hundreds of kilometers. On making the transition from one block to another, sharp variations in depths of occurrence of the seismic sections, wedging out of the individual layers, curtailment of the tracing of certain boundaries, and variation in the propagation rates of the elastic oscillations are possible. All of this can lead to differences in the discrete correlation attributes and their interrelations for individual blocks of the earth's crust. Consequently, a careful analysis of the seismic recordings made is needed directly during the course of the field operations for introduction of the corresponding corrections to the observation technique.

Peculiarities of Using Dynamic Wave Characteristics

These characteristics, which are highly sensitive to the properties of the medium can be used to obtain information about the deep structure. The information about the peculiarities of the medium whish are weakly manifested in the kinematic parameters of the elastic waves recorded in a sparse low-detail observation is especially valuable.

The usual methods of utilizing the dynamic characteristics, as a rule, cannot be used without alterations in the method of spot sounding as a result of the specific nature of the work. A characteristic feature of the operations is frequent changing of the oscillation excitation and recording points, separateness of the receivers, which complicates the monitoring of the variation of the excitation and reception conditions of the elastic waves. Therefore it is impossible to obtain comparable data on the absolute values of the dynamic characteristics of the oscillations in a series of soundings. The sounding bases calculated for tracking a defined wave are kept almost invariant over significant territory; consequently, the required materials are not available for investigation of the dynamic characteristics of the individual waves as a function of distance to the source.

Under such conditions in order to exclude the effect of the distorting factors not taken into account at the source and receiver stations it is expedient to use not the absolute values of the dynamic parameters (amplitudes, frequencies), but the ratio of like parameters of two waves recorded on one seismogram. The distribution of the magnitude of this ratio over the investigated territory is obtained for a number of soundings, the bases of which vary little or are fixed. Here it is possible jointly to consider the waves corresponding to the different boundaries or the waves of different types from one boundary.

It is expedient to use the following approach to estimating the properties of the medium by dynamic characteristics of the oscillation. Initially, a model of the medium is constructed by the data on the travel times of the waves. As a rule, some of its parameters (the magnitude of the velocity gradient in individual layers, the fine structure of the seismic boundaries) can vary within certain limits without significant changes of the kinematics of the corresponding wave field. The direction dynamic problem is solved for the model obtained with variation of the indicated parameters. By comparing the calculated and experimental dynamic characteristics, the values of the additional parameters of the medium are estimated, and the reliability of the results obtained by the kinematic wave characteristics is monitored. In order to increase the stability of the results it is necessary to average the experimental data ove.: a set of soundings considering the block structure of the earth's crust.

The methods of determining the properties of the medium with respect to dynamic characteristics of the oscillations and practical procedures for discrete correlation of the waves are investigated in Chapter IV.

§4. Sounding by Refracted Waves Using Hodograph Elements

A study is made below of the basic characteristics of the version of soundings by refracted waves developed in reference [79, 80] and used to study the surface of the basement in the territory of the Tyumen' Oblast.

The version is broken down into two groups: linear (LZ MPV) and spot (TZ MPV) sounding. By LZ MPV we mean the soundings for which the observations are made using a linear installation of defined length, and the apparent velocity is used during the interpretation to calculate the values of t_0, the depths, the boundary velocities, and so on. By TZ MPV we mean the soundings, on interpretation of which only the times of arrival of the refracted wave are used, and the apparent velocities obtained on the defined base are used only for recognition are identification of the waves.

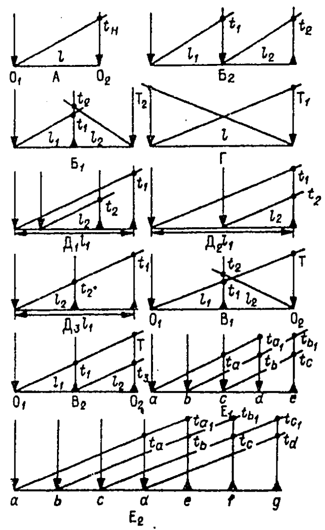

Figure 23. Linear and sounding diagrams using the refracted method

The linear and spot observations include (Fig 23): 1) elementary sounding (A); 2) systems of two elementary soundings (B_1, B_2, D_1, D_2, D_3); 3) sounding system with recording of time at a mutual point (B_1, B_2); 4) systems with calculated mutual time (E_1, E_2).

The interpretation of data with respect to systems A, B_1, B_2 and G in the final analysis reduces to tracing the hodographs to the blast points; the values obtained for t_0 depend on the correctness of the value of the boundary or apprent velocity selected for location. In addition, by system B_1 it is possible to find the boundary velocity by the element of the difference hodograph, and the defined value of the reciprocal time (T) obtained by continuation of the hodographs to the blast point offers the possibility of obtaining a segment of the line t_0 within the limits of the installation.

It is possible to consider the asymmetric system D_1 a generalization of symmetric sounding [39], and systems D_2 and D_3, extreme special cases of it.

The value of t_0 is determined by the systems B_1 and B_2 from the expression in the KMPV refracted wave method [20]:

$$t_0 = t_1 + t_2 - T, \qquad (II.54)$$

that is, the source-receiver distances and the values at the boundary and apprent velocities are not used in calculating t_0. The expression for t_0 by the systems E_1 and E_2 in the final analysis leads to an analogous form. The noted observation systems also permit us to find the mean value of the boundary velocity.

For the indicated observation systems, the time field theory (see §2 of this chapter) and the interpretation methods based on it are valid. Let us consider another approach to the solution of the inverse problem with respect to the sounding data by the refracted wave method for the model of a two-layer medium with plane inclined boundary.

Elementary Soundings. In the x and t coordinate system, we take the point O_1 as the origin of the coordinates (see Fig 23, A). The distance to the point O_2 will be denoted by ℓ, the arrival time of the wave at this point t_H; t_0 at the point O_1, t_{01}, at the point O_2, t_{02}. The expression for the time t_H is written in the form

$$t_H = t_{01} + \frac{l}{v}\sin(i \pm \varphi) \qquad (II.55)$$

or, beginning with the duality principle:

$$t_H = t_{02} + \frac{l}{v}\sin(i \pm \varphi). \qquad (II.55')$$

The top sign on the ϕ corresponds to the boundary drop. Let us write the coordinates of the point t_{01} and t_{02}:

$$t_{01}[o,\ t_H - \frac{l}{v}\sin(i \pm \varphi)],$$

$$t_{02}[l,\ t_H - \frac{l}{v}\sin(i \pm \varphi)].$$

The equation of the line t_0 passing through the points t_{01} and t_{02} will have the form

$$t_0 = \frac{x}{l}(t_{02} - t_{01}) + t_{01}.$$

Considering equation (II.55), we obtain

$$t_0 = t_H - \frac{l}{v}\sin(i \pm \varphi) \pm \frac{2x}{v}\cos i \cdot \sin\varphi. \qquad (II.56)$$

For the known value of the boundary velocity v_0 we find t_0 expressed as follows:

$$t'_0 = t_n - \frac{l}{v_r}. \qquad \text{(II.57)}$$

Solving the last two equations jointly, we find that t'_0 is equal to the value at the point having the x-axis:

$$x = \frac{l}{2}\left(1 \mp \operatorname{tg} i \cdot \operatorname{tg} \frac{\varphi}{2}\right).$$

Thus, at the point with the x-axis $\frac{l}{2}\left(1 \mp \operatorname{tg} i \cdot \operatorname{tg} \frac{\varphi}{2}\right)$ the value of t_0 is equal to $t_H/\ell/v_{boundary}$.

When using a single-point observation system (system A) for determination of t_0 it is necessary to know the value of the boundary velocity $v_{boundary}$ which can be obtained for soundings by the more complete systems of observations, by the KMPV refracted wave method profiles.

The expression for the relative error in t_0 as a result of the error in the boundary velocity has the form

$$\frac{m_{t_0}}{t_0} = \pm \frac{l_m v_r}{v_r (t_n v_r - l)}.$$

If it is known that the slope angle ϕ is small, then $\operatorname{tg} i \cdot \operatorname{tg} \frac{\varphi}{2} \simeq 0$ and for the x-axis of the depth reference point we obtain the approximate formula $x \simeq \ell/2$. The relative error assumed when using this formula is expressed by

$$\frac{m_x}{x} = -\frac{\operatorname{tg} i \cdot \operatorname{tg} \frac{\varphi}{2}}{1 - \operatorname{tg} \frac{\varphi}{2}}.$$

Spot Sounding Systems. Keeping the assumptions made, let us consider the observation system with two blast points O_1 and O_2 and two reception points A_1 and A_2 having observed times t_1 and t_2 respectively (Fig 24, a). According to the duality principle, the times t_1 and t_2 can be carried over to the point O_1 and O_2. Thus, if the origin of the coordinates is placed at the point O_1, then in the x, t coordinate system we have four points (K, L, G, H) with the coordinates:

$$K(S + l_2,\ t_2),\ G(0,\ t_1),$$
$$L(l_1,\ t_1),\ H(S,\ t_2).$$

The equation of the straight lines running through the points K and L has the form

$$\frac{x-(S+l_2)}{l_1-(x_1+l_2)}=\frac{t-t_2}{t_1-t_2}. \qquad \text{(II.58)}$$

The straight line running through the points G and H is described by the equation

$$\frac{x}{S}=\frac{t-t_1}{t_2-t_1}. \qquad \text{(II.59)}$$

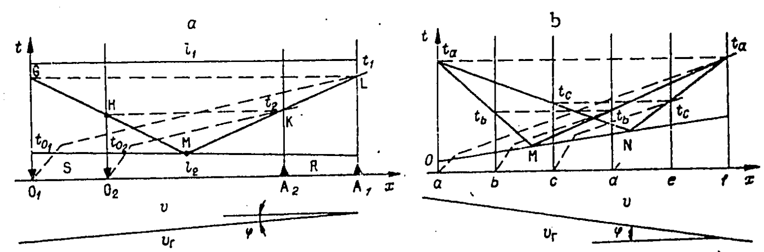

Figure 24. Derivation of the calculated formulas for soundings by the refracted wave method in the cases of: a -- two sources, b -- three sources

For the times t_1 and t_2 it is possible to compile the following equations:

$$\left.\begin{aligned} t_1 &= t_{01}+\frac{l_1}{v}\sin(i-\varphi),\\ t_2 &= t_{02}+\frac{l_2}{v}\sin(i-\varphi). \end{aligned}\right\} \qquad \text{(II.60)}$$

Here t_{01} and t_{02} are the values of t_0 at the blast points O_1 and O_2. The equation of the line t_0 running through t_{01} and t_{02} is written as follows:

$$\frac{x}{S}=\frac{t-t_{01}}{t_{02}-t_{01}}.$$

Considering equations (II.60), we have

$$\frac{x}{S}=\frac{t-t_1+\frac{l_1}{v}\sin(i-\varphi)}{t_2-\frac{l_2}{v}\sin(i-\varphi)-t_1+\frac{l_1}{v}\sin(i-\varphi)}. \qquad \text{(II.61)}$$

Solving equations (II.58),(II.59) and (II.61) jointly, we find that all three lines intersect at one point M, the coordinates of which

$$\left.\begin{aligned} x_M &= \frac{l_1}{1+\frac{R}{S}}, \\ t_M &= \frac{t_2 l_1 - t_1 l_2}{l_1 - l_2}. \end{aligned}\right\} \quad \text{(II.62)}$$

Thus, for observation systems of this type (D in Fig 23) it is possible to find the value of t_0 and the x-axis x_{t_0} to which this t_0 belongs. Let us note that in this case t_0 and x_{t_0} do not depend on the boundary velocity in the slope angle of the boundary ϕ. Now let us find the boundary velocity. Subtracting one equation of (II.60) from the other, as a result of simple algebraic transformations we obtain:

$$v_r = \frac{(t_1 - t_2)(R+S)\cos\varphi}{(t_1-t_2)^2 - \frac{(R-S)^2\sin^2\varphi}{v^2}} \times$$
$$\times \left\{1 \mp \sqrt{1 + \frac{[(R-S)^2\sin^2\varphi + (R+S)^2\cos^2\varphi]\left[\frac{(R-S)^2\sin^2\varphi}{v^2} - (t_1-t_2)^2\right]}{(t_1-t_2)^2(R+S)^2\cos^2\varphi}}\right\}. \quad \text{(II.63)}$$

Let us present the expressions for determining the values of t_0 and $V_{boundary}$ in the case of the system of elementary sounding made up of three blast points and three reception points (see Fig 24, b) without intermediate calculation.

Proceeding analogously to the previous case, we find the equation of line t_0 in the form

$$t_0 = t_a + \frac{x\left[(t_a - t_b) - (t_a - t_c)\frac{af-bd}{af-ce}\right] + \frac{af}{af-ce}[ab(t_a-t_c) - ac(t_a-t_b)]}{\frac{af-bd}{af-ce}ac - ab}. \quad \text{(II.64)}$$

The final formula for the boundary velocity has the form

$$v_r = \frac{(af-bd)\cos\varphi}{t_a - t_b - \frac{[(af-bd-2ab)t_a(bd-ce) - t_b(af-ce) + t_c(af-bd)]}{2ac(af-bd) - 2ab(af-ce)}}. \quad \text{(II.65)}$$

The investigated sounding system permits us to obtain other simpler systems of the type D_1, D_2, D_3, B_1, B_2, E_1, E_2, and so on(see Fig 23).

The three-point system with subsequent matching of the observation points with the blast points (see Fig 23, B_1), which is a special case of the above-investigated general three-point system, is of the greatest interest. In this case the time t_0 is determined by the formula (II.54), and the following expression is valid for the boundary velocity:

$$v_{\Gamma} = \frac{2l_1 l_2 \cos\varphi}{l_1 (T - t_0) + l_2 (T - t_2)}. \qquad \text{(II.65')}$$

For small boundary slopes, it is admissible to consider cos ϕ=1.

CHAPTER III. REMOTE-CONTROLLED TAYGA SEISMIC SYSTEM

§1. Functional Diagram of the Equipment

The structural diagram of the equipment is presented in Fig 25. One set of the equipment includes an arbitrary number of portable remotely controlled six-channel magnetic recorders with reel-to-reel tape drives, one dispatch station for generating the remote-control signals and time marks and also the base reproduction unit on which the magnetic recordings are reproduced, the seismic signals are filtered and the seismograms are recorded on a photographic carrier. During the seismic studies, these elements function as follows.

The dispatch station, which is made up of an instruction coder and a powerful radio transmitter, is installed at the blast point. A time loop is connected to the instruction coder.

Any form of transportation is used to install the seismic recorders at the planned observation points, the number of which is limited only by the number of recorders available to the seismic crew. At the observation point, two three-channel seismic cradles with groups of seismic receivers and a radio receiving antenna are connected to the recorder. Then the recorder is put in the ready mode where the electric power is supplied only to the radio receiver and a special remote-control instruction decoder, and it is left unattended at the observation point.

The recorder will stay in the ready mode until the radio transmitter from the dispatch station begins to transmit a special signal generated by the coder.

The dispatch station is switched to the transmission mode when all of the recorders have been installed and the charge is ready for detonation.

The remote control signal generated by the coder is simultaneously an encoded time mark signal.

The signal transmitted from the dispatch station is received by the radio receivers of all the recorders and goes to the decoder inputs. At one of the outputs of each decoder there is a servo relay, and its other output is connected to the input of the circuit for recording the time mark signals on magnetic tape. The servo relay switches on the power of the tape drive mechanism on the recorder, the seismic signal on amplifiers, modulators and time mark recording circuit, that is, it switches the recorder to the record mode. On completion of the transient processes after switching on the power supply, the recorders are ready to receive seismic signals.

Thirty to 40 seconds after switching on the dispatch station, the charge is detonated. This generates seismic waves and simultaneously breaks the time loop connected to the coder. The sudden breaking of the time loop changes the structure of the time mark signals, recording the blast time. Then, a calibrated interval after the blast time, the structure of the time mark signal returns to the initial structure and varies subsequently with a given period with high accuracy. This process will be investigated in detail below.

All of the processes occuring in the coder are transmitted over the radio channel to the recorders and by the time mark recording system they are recorded on magnetic tapes simultaneously with the seismic signals.

The decoders of the recorders are constructed in such a way that the servo relay remains connected during the entire time interval that the signals transmitted from the dispatch point are present at the output of the radio receiver, independently of the changes in their structure,

On expiration of the defined time after the blast, sufficient for the seismic wave to travel from the blast point to the most remote observation point, the dispatch station is switched off. As a result, all of the recorders automatically return to ready and remain so until it is necessary to record seismic signals from the next blast. After processing one segment of the profile or area, the recorders are gathered up and installed at new observation points, and the magnetic tapes with the recordings are reproduced on the base reproduction unit and processed.

For the case where it is not possible to record the blast time by a time loop, a special mode is provided in the coder. In this case the coder generates a cyclic code with an ambiguity period comparable to the maximum travel time of the seismic waves, and the blast time is determined by the recordings of a recorder installed in direct proximity to the blast point.

When developing the Tayga equipment it is necessary to solve two primary problems:

1) Develop a highly efficient channel for magnetic recording of the seismic signals on the magnetic tape corresponding to the requirements discussed in Chapter I, §3;

2) Develop a highly noise-resistant radio remote control system especially designed to control the operation of the distributed seismic recorders and simultaneously providing for time gridding of the received information and the blast time.

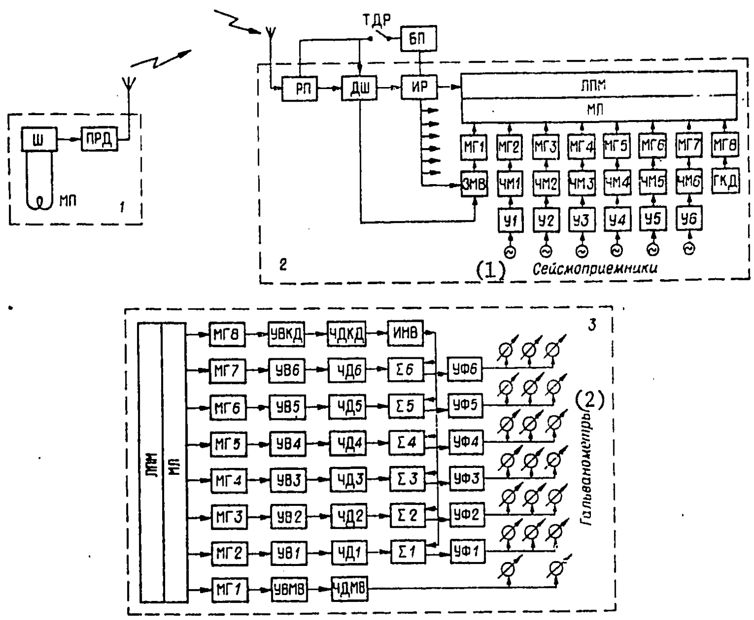

Figure 25. Structural diagram of the Tayga equipment
1 -- dispatch station: МП -- time loop; Ш -- coder; ПРД -- radio transmitter. 2 -- seismic recorder: РП -- radio receiver; ДШ -- decoder; ИР -- servo relay; БП -- recorder power supply; ТДР -- ready switch; ЛПМ -- tape drive; МЛ -- magnetic tape; МГ1 to МГ8 -- magnetic head unit; ЗМВ -- time mark recording circuit; ЧМ1 to ЧМ6 -- frequency modulators of the seismic channels; У1-У6 -- seismic signal amplifier; ГКД -- detonation compensation channel generator. 3 -- reproduction unit: ЛПМ -- tape drive; МЛ -- magnetic tape; МГ1 to МГ8 -- magnetic head unit; УВМВ, УВКД, УВ1 to УВ6 -- reproduction amplifiers and ЧДМВ, ЧДКД, ЧД1 -- ЧД6 -- frequency demodulators of the time mark channels; detonation compensation and seismic channels respectively; ИНВ -- detonation compensation channel inverter; Σ1 to Σ6 -- adders; УФ1 to УФ 6 -- low-frequency filter amplifiers.

Key:
1. seismic receivers
2. galvanometers

§2. Seismic Signal Magnetic Recording Channel

From the point of view of such characteristics of the recording channel as the dimensions, mass and energy consumption, the proper selection of the structure of the seismic signal magnetic recording channel has important significance. In the seismic equipment the most widespread is a direct recording with high-frequency magnetization; a recording with frequency and pulse-width modulation was used somewhat less broadly [122]. In recent years pulse-code or digital methods of recording have begun to be used more and more intensely in the foreign and Soviet seismic recording equipment. These recordings are superior to the analog recording with respect to accuracy of recording the signals on the magnetic tape, but they require significantly higher magnetic tape drive speeds and significantly more complex electronic systems to convert the analog signals to digial form. This leads to the fact that the digital recording systems are essentially inferior to analog systems and appreciably more complex than the latter from the point of view of economy. Therefore when developing autonomous, highly economical, small-size equipment the application of digital recording systems is inexpedient.

The analysis of the analog systems for recording seismic signals indicates that the direct recording with high-frequency magnetization is less wide band and requires minimum magnetic tape drive speed. Therefore, this type of recording is primarily used in the autonomous seismological equipment with continuous magnetic tape drive as occurs in the above-mentioned Cherepakha and Zemlya equipment. However, the dynamic range of the recording with this recording procedure does not exceed 40 decibels, which is its basic disadvantage. In addition, in order to insure this recording range it is necessary to use wide recording and reproducing magnetic heads which are shielded well from each other. Therefore in the Cherepakha equipment, for example, for parallel recording of information on 8 channels of which only 6 are used for recording seismic information, the width of the magnetic tape is 25.4 mm. This automatically complicates the tape drive mechanisms and increases its size and weight.

Frequency and pulse-width modulation are approximately equivalent from the point of view of wide-band nature and, consequently, the requirements on the magnetic tape drive speed [29].

The FM-recording is preferable primarily because it does not require the application of wide magnetic heads and good shielding between them in the module. In contrast to direct recording with magnetization in FM-recording it turns out to be possible to have 8 to 9 parallel recorded channels on a magnetic tape 12.7 mm wide using standard magnetic head units designed for pulsed methods of recording.

It is known that the basic source of interference limiting the dynamic range of the recorders with FM recording is inconstancy of the magnetic tape drive speed with respect to the recording and reproducing magnetic heads [3, 29].

Therefore, for recorders with FM-recording it is necessary either to construct the precision tape drive mechanisms with very low instability of the tape drive speed or to use effective methods of controlling this problem, usually called tape drive detonation. These procedures are well known and are described, in particular, in references [3, 29].

The first procedure is unacceptable for building portable, autonomous equipment, that is, it is impossible to make highly stable tape drives sufficiently economical and simple. Therefore it is expedient to consider the following problems: what level of detonation is admissible when recording seismic signals, how does the detonation influence the accuracy of the recording, what does the effectiveness of controlling it depend on, and what are the maximum admissible values of the dynamic range.

From the point of view of using FM-recordings of seismic signals when developing the Tayga equipment, a theoretical analysis is made in order to answer the questions. The results of the analysis were used in the process of constructing the equipment.

In references [2, 29] it was demonstrated that the detonation of the tape drives leads to the occurrence of two types of interference, one of which is multiplied times the useful signal (multiplicative component of the interference), and the other issummed with the signal (additive component of the interference). The first type of interference leads to spurious modulation of the useful signal, that is, to its nonlinear distortions; the second type of interference limits the dynamic range of the recording for this interference exists at the output of the reproduction channel even in the absence of the useful signal.

The depth of spurious amplitude modulation of the useful signal is determined by the sum of the detonation coefficients of the recording and reproducing tape drives.[1]

If we permit, as provided for by the standard for analog seismic equipment, 3-percent nonlinear distortions of the useful signal, then in the equipment it is possible to use recording tape drives with a detonation coefficient of 2-2.5%, and reproduction units with 0.5-1% detonation coefficient, inasmuch as it is semistationary and the only one for a large group of recorders.

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[1]The detonation coefficient is the ratio of the maximum deviation of the instantaneous tape drive speed to its average speed $m=\Delta v/v_{average}$.

Thus, from the point of view of the admissible level of multiplicative noise in the seismic equipment recorders, it turns out to be possible to use very simple tape drives. However, in this case if the total detonation coefficient of the recording and reproducing tape drive is 3%, with a frequency modulation coefficient of 0.6-0.7 the level of additive detonation noise will be about -30 decibels from the maximum signal, that is, the dynamic range of the recording channel will not exceed 30 decibels, which is clearly inadequate.

The analysis of the known method of suppressing the additive component of the detonation interference by recording the reference frequency signal on the magnetic tape simultaneously with the frequency-modulated signal demonstrated that the additive noise can be completely suppressed under defined conditions and, consequently, the dynamic range of the recorder will in this case become infinite with respect to this type of interference. Of course, in a real system it will be limited by the interference of some other nature. We shall discuss this problem below.

When developing the Tayga equipment, it was demonstrated theoretically and experimentally that the degree of suppression of the additive detonation noise essentially depends on the structure of the device suppressing this noise and the stability of the carrier frequencies of the frequency modulators used.

The adoption of special measures with respect to stabilization of the parameter of the electronic circuits of the equipment and the development of the corresponding schematic for the device to suppress additive detonation interference have made it possible to expand the dyanmic range of seismic recorders to 60 decibels or more (see Fig 26).

The structural diagram of the device for suppressing the additive detonation interference used in the Tayga equipment differs from those known from the literature [2, 29 or more] by the fact that the subtraction of the detonation interference from the signal reproducible in seismic channels is done before the filtration operation, that is, before generation of the low-frequency component. At the same time the effect of instability of the phase characteristics of the filters on the quality of the noise suppression is excluded.

In the ЧД1 to ЧД6 and ЧДКД frequency demodulators (see Fig 25, 3) univibrators are used which generate a train of square pulses of constant amplitude and duration. In the seismic channels the repretition frequency of these pulses at the ЧД1—ЧД6 output is modulated by the seismic signal and noise, and in the detonation compensation channel at the ЧДКД output the square pulse repetition frequency is modulated only by the detonation noise, for in each seismic recording the МГ8 magnetic head records the reference frequency signals from the ГКД stabilized oscillators on magnetic tape (see Fig 25, 2). The inclusion of the ИНВ inverter at the ЧДКД output in the reproduction unit permits 180° shifting of the detonation interference phase in the compensation channel with respect to the detonation interference in the seismic channel.

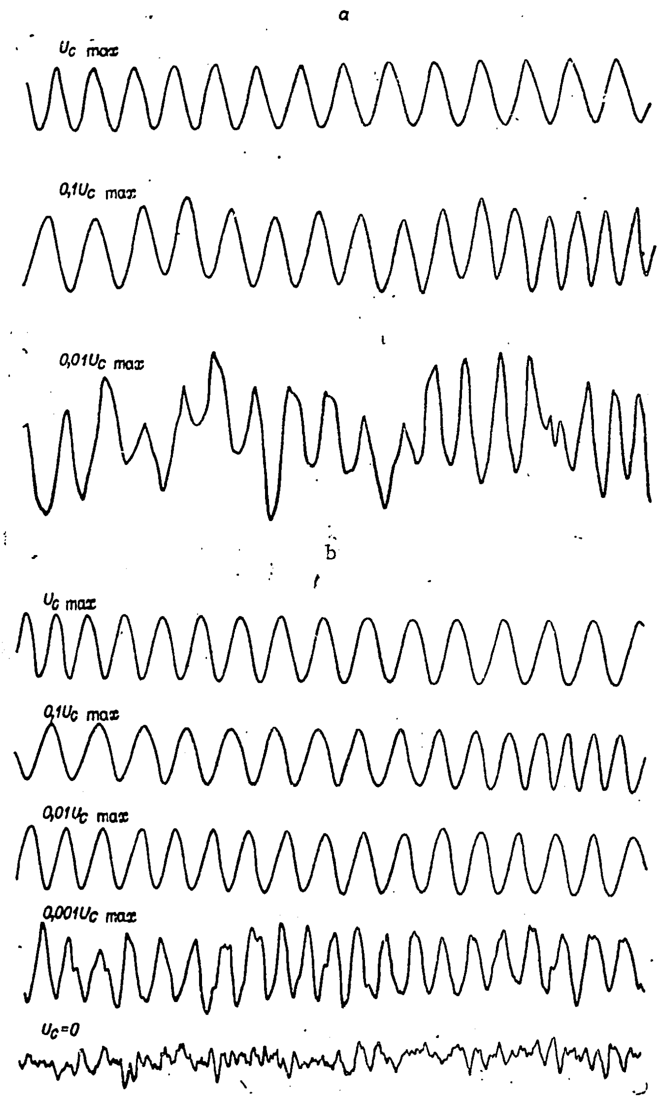

Figure 26. Oscillograms characterizing the operating quality of the magnetic recording and reproduction channel

Frequency of the described signal 20 hertz. $U_{c\ max}$ is the maximum signal recorded by the recorder with amplification coefficient of 0.75. The oscillograms of the signals reproduced without detonation compensation (a) and with detonation compensation (b).

The suppression of the additive detonation interference is realized by successive summation of two trains of square pulses from the outputs of the corresponding frequency demodulators and from the output of the ИНВ inverter in the Σ1 to Σ6 adders. As a result, the instability of the phase characteristics of the low-frequency УФ1 to УФ6 filter amplifiers, which generates seismic signals in the corresponding channels, has no influence on the quality of the detonation noise suppression.

Oscillograms are presented in Fig 26 which demonstrate the quality of the seismic signal magnetic recording channel of the Tayga equipment.

The seismic recording unit with dynamic recording range of 60 decibels using simple and highly economical tape drives was built for the first time in the USSR. In addition, it was demonstrated theoretically and experimentally that the dynamic range of somewhat more than 60 decibels is the maximum admissible range, for it is then limited to the effect of the spurious amplitude modulation of the pulse signals reproduced from the magnetic tape.

On the basis of the studies performed, reel-to-reel tape drives have been developed for the seismic recorders of the Tayga equipment with drive from the highly economical DC motors with a detonation coefficient no more than 2% permitting parallel recording of the information from six-channels and two auxiliary ones on the tape 12.7 mm wide. The magnetic tape stored on the reels driven at 9.5 cm/sec provides for successive recording of more than 10 blasts with 3 to 4 minute recordings of each blast.

§3. Radio Remote Control System

The radio remote control system of the Tayga system is designed for performing the following operations: 1) switching the recorders to the record mode; 2) shaping and recording the large and small-scale time mark signals; 3) transmission of the blast mark signal to all recorders; 4) disconnection of the recorder from the record mode and transfer of it to ready.

As follows from what has been discussed above, the remote control system of this equipment has been built so that the recorders are switched on by the time mark signals, and they are switched off automatically after cessation of the transmission of the coded time mark signals from the dispatch station. This has greatly simplified the remote control system as a whole and the recorder decoder in particular, which is extremely important, for its economicalness determines the electric power intake in the ready mode.

The coder of the remote control system shapes the time mark signals, the structure of which permits reliable time gridding of the information recorded by all of the seismic recorders. The reference point of the time mark scale coincides with the blast time. This offers the possibility of multiple transmission of the blast time mark signal after calibrated time intervals during one session. The block diagram of the coder and the structure of the time marks are presented in Figures 27, 28.

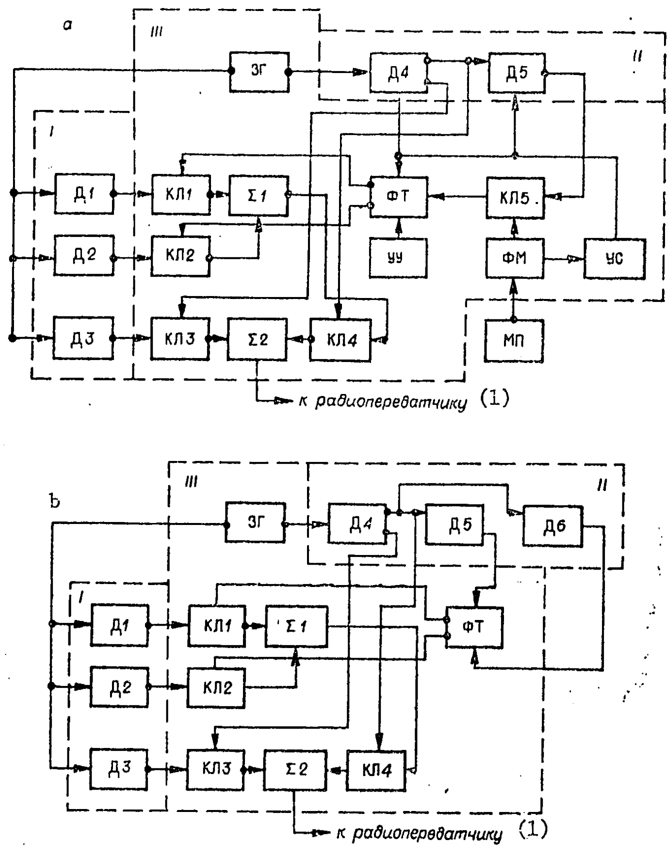

Figure 27. Block diagram of the coder: a -- when operating with the blast time mark; b -- when recording the "uncontrolled blasts." ЗГ -- master oscillator; Д1 -- Д6 -- frequency dividers; КЛ1--КЛ5-- switches; Σ1, Σ2 -- adders; ФТ -- shaping trigger; УУ -- preset unit; УС -- clear circuit; ФМ -- blast time pulse shaping circuit; МП -- time loop.

Key:

1. to the radio transmitter

The coder is made up of three basic modules: the module for shaping the subcarrier frequencies -- I, shaping the marking frequencies -- II, and shaping the time mark structure -- III.

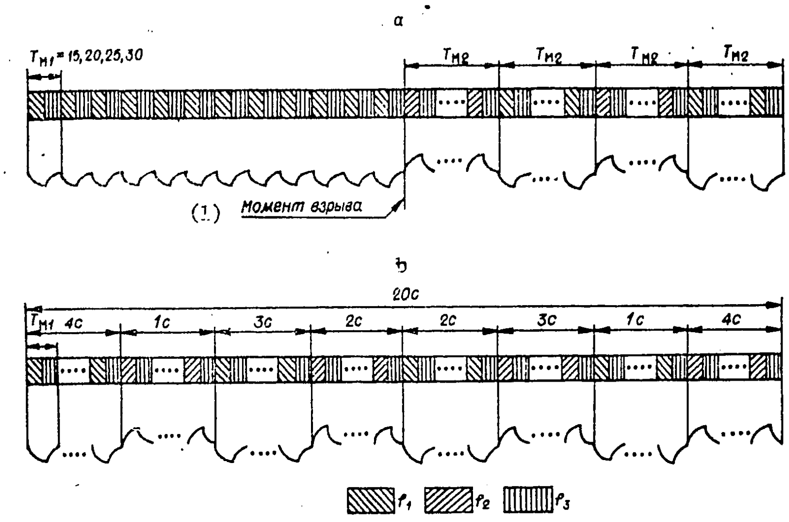

Figure 28. Structure of the time mark signals at the input of the radio transmitter and shape of the time mark recording on the seismogram
a -- when working with the blast time mark; b -- when recording "uncontrolled blasts."

Key:
1. blast time

The quartz-stabilized master oscillator of the coder generates a signal of sufficiently high frequency which is simultaneously fed to the D1, D2 and D3 dividers which generate the subcarrier frequency signals f_1, f_2, f_3 and the dividers D4, D5, which shape the marking frequency signals. The subcarrier frequencies f_1, f_2, and f_3 are located in the radio telephone channel band of 0.3 to 3.0 kilohertz. The oscillation periods of the marking frequencies T_{M1} and T_{M2} have values from the following series: T_{M1}=30 milliseconds, 25 milliseconds, 20 milliseconds, 15 milliseconds and T_{M2}=1.5 seconds, 1 second and 0.75 seconds. Every set of equipment has its own combination of values of subcarrier and marking frequencies. These values are established by replacing the division coefficients D1, D2, D3, D4, and D5.

The shaping of the time mark signals is realized by module III in the following way. At the time the coder is switched on by the preset unit (УУ) the shaping trigger (ФТ) is set to the position where the switch КЛ1 is closed, and the switch КЛ2 is open. For a closed time loop (МЛ) the blast time pulse shaping circuit (ФМ) keeps КЛ5 in the open position. The subcarrier frequency signal f_1 goes through КЛ1 and the adder Σ1 to the input of КЛ4, and the subcarrier frequency signal f_3 is fed to the input of the КЛ3 . The КЛ3 and КЛ4 switches are alternately closed by the signals which come from the opposite arms of the output trigger of the D4 frequency divider, at the same time manipulating the subcarrier frequencies f_1 and f_3 at the input of the adder Σ2, the output of which is connected to the input of the radio transmitter. Thus, the frequency manipulated signal is radiated into space before the blast time. The keying frequency of the subcarrier frequencies f_1 and f_3 is equal to the marking frequency f_{M1} which determines the scale divisions of the fine time mark scale. The recorders are switched to the record position by the shaped signal.

At the time of detonation of the charge, the time loop МП is broken, and the state of the ΦM circuit is switched, which through the YC initializes D4 and D5, changing the state of the shaping trigger ΦT so that КЛ1 opens and КЛ2 closes. Simultaneously, the ΦM circuit closes КЛ5. As a result, from the time of the blast the feed of the subcarrier frequency signal f_1 ceases, and the signal of the subcarrier frequency f_2 begins to go through the КЛ2 and the adder Σ1 to the input of the КЛ4. Now the marking frequency signal f_{M1} will manipulate the subcarrier frequency f_2 and f_3 at the input of Σ2 using КЛ3 and КЛ4. The state of the shaping trigger ΦT does not change until the first pulse goes to its counting input through КЛ5 from the D5 output, which shapes the signal of the second marking frequency f_{M2} giving the large time scale divisions. Then ΦT operates in the counting mode, manipulating the subcarrier frequency f_1 and f_2 at the input of Σ1 using КЛ1 and КЛ2 in accordance with the large divisions of the time scale. Clearing D4 and D5 at the blast time automatically ties the reference point of the time scale to the blast time. This not only creates defined convenience when processing the seismograms, but it also increases the noiseproofness of the transmission and the blast time mark, for it repeats after calibrated intervals in accordance with the large time scale divisions. The division coefficient D4 and D5 are selected so that an integral number of frequency periods f_{M1} will be laid out in one frequency period f_{M2}.

If it is impossible to record the blast time by using the time loop, the structure of the coder shown in Fig 27, b is used. In this case the large time scale divisions are given as before by manipulation of the subcarrier frequencies f_1 and f_2 using the shaping trigger ΦT, which operates here in the mode of separate starting of the outputs of the D5 and D6 dividers which give the frequencies f_{M2} and f_{M3}. If we select $f_{M2}=1/5$ hertz, and $f_{M3}=1/4$ hertz, then the shaping trigger ΦT will shape the code of the large time mark divisions with a repetition period of 20 seconds as shown in Fig 28, b. This code permits a unique time coordination of the seismograms for any types of regional seismic operations.

Thus, in the coder of the remote control system for the Tayga equipment it is possible to transmit the blast time mark signals, the signals of the large and small time mark scale divisions to the observation points and control the operation of the recorder by manipulating all three subcarrier frequencies.

The decoder of the remote control system of the Tayga system is designed for isolation of the signals emitted from the dispatch station against the background of various types of signal interference, switching the recorder to the record mode, reduction of the time mark signals to the initial form for recording on the magnetic tape together with the seismic signals. The block diagram of the decoder together with the time mark signal recording system are presented in Fig 29.

The signals emitted from the dispatch station are generated as follows. From the output of the radio receivers РП, the signal goes to the inputs of three parallel-included subcarrier frequency filters (Ф1, Ф2 and Ф3), which improve the signal-noise ratio, for the filter pass band (Ф1, Ф2 and Ф3) is a total of 300-400 hertz on the -3 decibel level. Then the signal is rigidly limited with respect to amplitude by the ОГР limiter, and it is fed simultaneously to the input of three such subcarrier frequency filters.

The outputs of Ф1 and Ф2 are connected to the detector D1, the output Ф3, to D2. The detector D1 passes a positive halfwave of the signal of the subcarrier frequencies f_1 and f_2, D2, the negative halfwave of the signal of the subcarrier frequency f_3, performing the function of an inverter. After summation of the detected signals in the Σ adder, the signal is fed to the input of the $ФМ_1$ filter which is tuned to isolate the marking frequency f_{M1}. The transmission band of the $ФМ_1$ filter is very small (1-2 hertz); therefore a sinusoidal signal of marking frequency is generated at its output, which is detected by the detector D3 and is fed to the input of the integrator. On appearance of the signal at the input of the integrator, the voltage at its output increases slowly, reaching the response threshold of the threshold circuit ПУ after 10-15 seconds, which includes the servo relay ИР, and, in turn, the latter switches the recorder to the record mode.

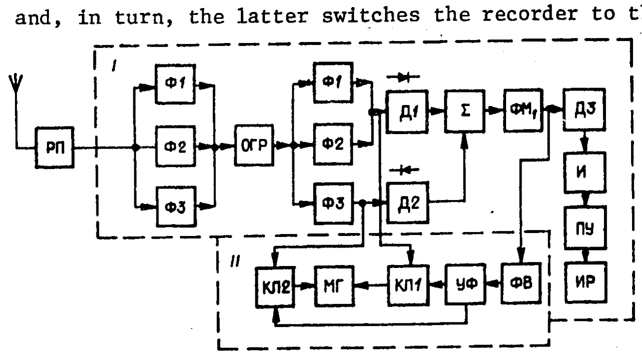

Figure 29. Block diagram of the decoder and the time mark recording circuit.
РП -- radio receiver; D1, D2, D3 -- amplitude detector; Ф1, Ф2, Ф3, $ФМ_1$ -- subcarrier and marking frequency filters; ОГР -- amplitude limiter; Σ -- adder; И -- integrator; ПУ -- threshold circuit; ИР -- servo relay; ФВ -- phase shifter; КЛ1 and КЛ2 -- switches; МГ -- magnetic head; УФ -- shaping circuit; I -- decoder; II -- time mark recording circuit.

The isolated marking frequency signal in the decoded channel turned out to be out of phase with respect to the input signal; therefore the phase shifter ΦB shifts the phase of the signal so that the pulse fronts of rectangular shape of the marking frequency formed by the YΦ shaper will coincide with the switching times of the marking frequencies at the decoder input. The switches KJI1 and KJI2 are alternately closed and opened, feeding the subcarrier frequency signals f_1, f_2 or f_3 from the output of the corresponding filters to the input of the magnetic head MΓ.

Thus, the shape of the current in the magnetic head corresponds exactly to the shape of the signal emitted by the dispatcher station. The sequence of described filters realizes the optimal algorithm for generation of signals of known shape against a background of random interference to the degree to which this can be done using the R, L and C-circuits without significant complication of the field equipment.

Fig 30 shows the experimental curve characterizing the noiseproofness of the decoder. The voltage amplitude of the output of the marking frequency filter $ΦM_1$ is plotted on the y-axis, the ratio of the effective signal voltage to the effective voltage of the fluctuating interference at the input of the decoder is plotted on the x-axis.

As is obvious, the signal amplitude at the output of the $ΦM_1$ depends slightly on the signal-noise ratio at the input of the decoder to values of U_c/U_{noise} =0.4, and it decreases to the level of 0.7 of its maximum value for U_{signal}/U_{noise}=0.33. The fine line on the 0.4 volt level denotes the defined experimental interference amplitude at the output of the $ΦM_1$ under the effect of fluctuation interference on the decoder input. The dash-dot line on the 0.5 volt level denotes the experimentally determined value of the interference amplitude at the output of $ΦM_1$ under the effect of the most dangerous pulse interference on the input of the decoder: namely, the pulse interference was simulated by a plane of pulsed signals with repetition frequency of the marking frequency of f_{M1}, off-duty factor of 2, where the pulse was made up of the sum of the signals of three subcarrier frequencies f_1, f_2 and f_3 of idential amplitude. The interference of the more dangerous type in practice is not encountered.

The theoretical estimate of the probability of false responses in the presence at the filter output $ΦM_1$ of an inertialless threshold device with response threshold of 2.1 volts gives a value of 10^{-13} [13], which is unconditionally entirely sufficient, for the reliability of the structural design of the recorder as a whole will be appreciably worse.

The integrator И between $ΦM_1$ and the threshold circuit ΠY is introduced for reduction of the probability of the suppression of the signal by the pulsed interference. From the operating conditions of the seismic recorder it follows that even brief disconnection of the tape drive is inadmissible during recording. If at the filter output $ΦM_1$ there is an inertialless threshold device any time at an interference pulse exceeds the effective signal voltage of the input of the decoder even for a short time so much

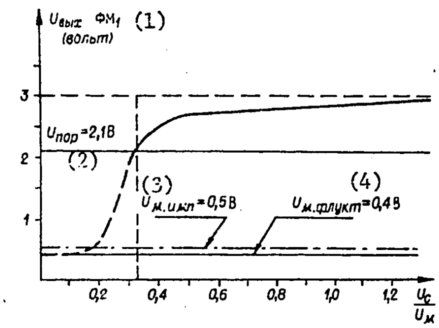

Figure 30. Voltage at the output of the marking frequency filter of the decoder as a function of the signal-noise ratio at its input

Key:

1. U_{output} (volts)
2. $U_{threshold}$=2.1 volts
3. U_{pulse}=0.5 volts
4. $U_{fluctuation}$=0.4 volts

that the voltage at the output of the filter ΦM_1 drops below the response threshold PY, the recorder will disconnect. The probability of such cases, which is very high as a result of the effect of atmospheric interference and signals from outside radio stations, will become insignificant when the integrator is included at the PY input. When the voltage at the output of ΦM_1 as a result of signal suppression by the interference drops below the value corresponding to the response threshold of ПY, the voltage at the output of the integrator begins to decrease slowly, gradually approaching the response threshold of ПY, that is, quick disconnection of the recorder does not take place. If the interference was brief, then the voltage of the output of the integrator will be restored.

The theoretical estimate of the probability of suppression of the signal by fluctuating noise indicates that if we admit the possibility of disconnecting the recorder when suppressing the signal for more than one second (this condition determines the time constant of the integrator), the probability of disconnecting the recorder will be quite low. However, the most real danger is presented by the pulse atmospheric interference; therefore the value of the time constant of the integrator И must be such that the recorder will disconnect no faster than 3 to 5 seconds after suppression of the signal. The introduction of the integrator decreases the probability pulse responses. When developing the radio remote control system for the Tayga equipment, the following results are achieved.

1. The problem of insuring autonomous operation of the seismic recorders after installation at the observation points is solved.

2. The coder of the dispatch station of the equipment has been developed which will insure reliable control of the operation of autonomous seismic

recorders, the certified time coordination of the recordings obtained by the distributed recorders, recording of the seismic oscillations excited by the "uncontrolled" sources (industrial explosions, air bombs), transmission of the blast time mark signals and the time marks by a highly reliable method.

3. A highly economical system has been developed for the receiving channel of the remote control system insuring high noiseproofness of it;

The decoder permits realization of a reliable remote control of the operation of the seismic recorders when the signal at the output of the radio receiver is hardly heard against the noise background, that is, when the operative telephone communications between the dispatch station and the observation point in practice is impossible;

The system for generating time mark signals insures reliable time marking of the seismograms obtained;

The tests of the remote control channel have demonstrated that for various noise levels at the input of its receiving channel spontaneous inclusion of the recorder does not take place (including under the effect of powerful atmospheric interference).

§4. Structural Design and Basic Technical Characteristics of the Tayga Equipment

As a result of the described studies in the field test of the model, the design documentation was developed for the Tayga equipment.

The seismic recorder, the power pack of the recorder and the dispatch station are made in the form of portable units (Fig 31). In the radio remote control channel of the seismic recorder the Nedra radio previously produced by Soviet industry is used which has also been installed at the dispatch station.

The reproduction unit is also made in the form of three portable units. In one there is a tape drive which was developed on the basis of the series-produced Kometa-201 tape recorder and the power pack of the reproduction unit; in the other are the reproduction amplifiers, and in the third, the low-frequency filter amplifiers.

The operation of a large lot of Tayga units (about 400 seismic recorders) has revealed certain deficiencies in the design of the equipment. The main one of them is the use of the first model of one type of coded signal in the remote control channel and all sets of the equipment; therefore the seismic crews working with the Tayga system of this model interfered with each other even at significant distances apart, causing the seismic recorders of a neighbor to be switched on by another's dispatch stations.

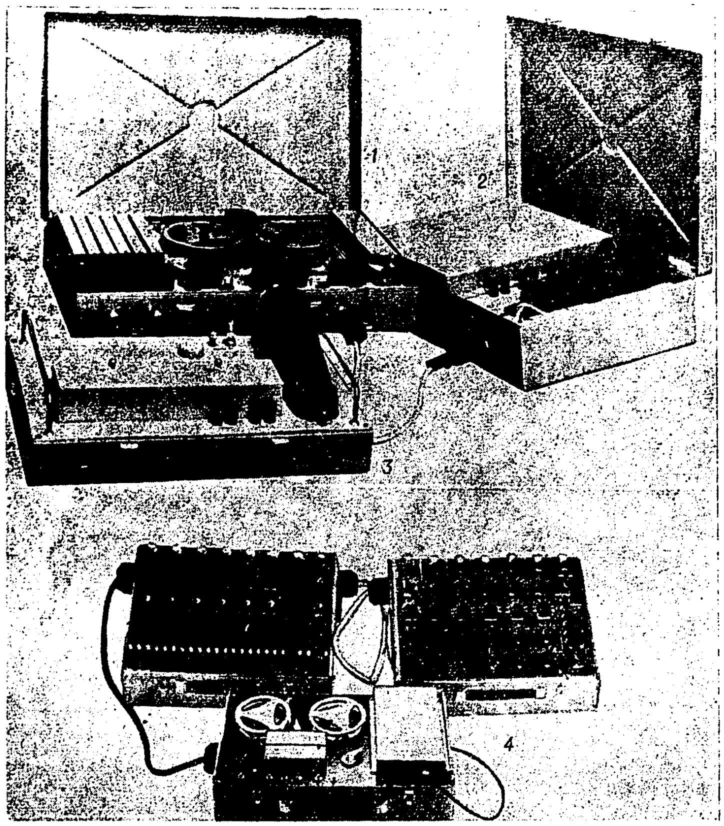

Figure 31. Tayga equipment.
1 -- seismic recorder; 2 -- power supply for the recorder;
3 -- dispatch station; 4 -- reproduction unit

However, the first model of the Tayga equipment is being used successfully by many geophysical organizations of the country at the present time.

In 1972-1974, a new model of Tayga-2 equipment was developed. The design of the Tayga-2 equipment (see Fig 32) basically was the same as for the first model except the field units of the equipment -- the seismic recorder and its power pack -- were placed in sealed, mechanically significantly stronger housings. In the seismic recorders instead of the Nedra radio, a more modern Karat radio is used which is placed in the recorder housing and not in the power pack. The coder of the dispatch station is made from integrated microcircuits, and its possibilities have been expanded. The coders of the Tayga-2 equipment can provide for independent operation of 12 sets of equipment on one radio frequency without interference between each other. The radio was taken out of the coder design. The coder output was made universal, matching with the single-band radio transmitters of different power.

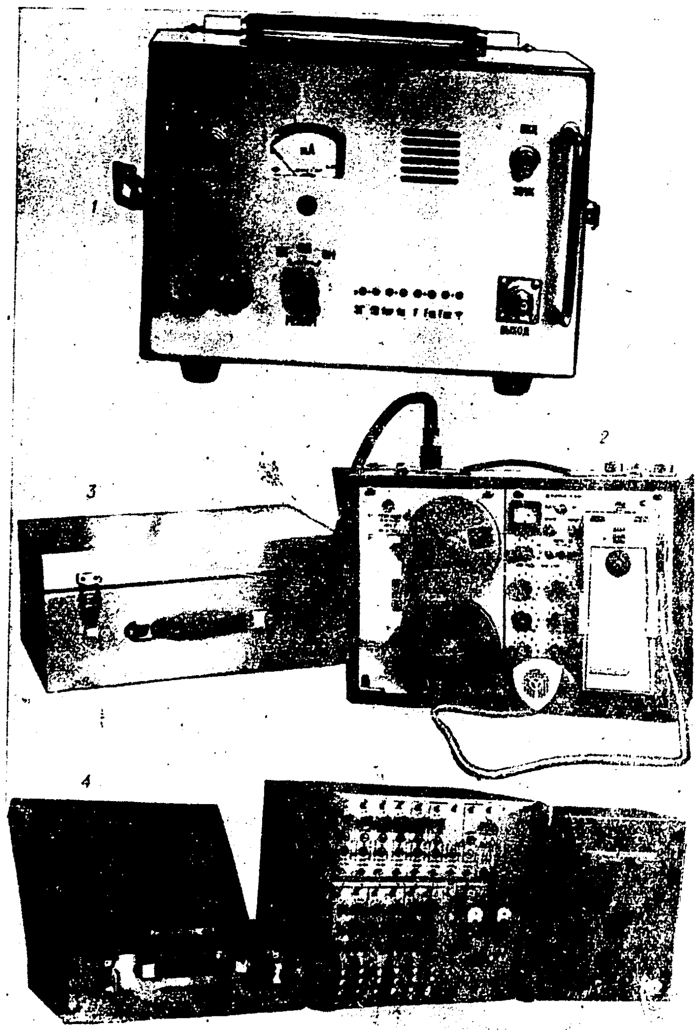

Figure 32. Tayga-2 equipment
1 -- coder; seismic recorder; 3 -- recorder power pack;
4 -- reproduction unit

The reproduction unit is made structurally in standardized housings, and it is equipped with a loop oscillograph. The seismograms reproduced from magnetic tape must record on photographic paper simultaneously on three filtrations.

The Tayga-2 equipment has the following basic technical characteristics:

Seismic Recorder

Seismic channel	6
Auxiliary channel	2
Magnetic tape recording system	PTM
Magnetic tape	
Type	6L
Width, mm	12.7
Total recording time for one cassette, minutes	45
Frequency band of the seismic channel, hertz	0.5 to 100
Noise level of the seismic channel, microvolts no more than	1.0
Dynamic band, decibels, no less than	50
Band for step adjustment of the amplification of the seismic channel, decibels, no less than	50
Operating temperature range, °C	-10 to 150
Power supply	NKGK-11D storage batteries or 165U type dry batteries
Intake power, watts, no more than	
in the ready position	1
in the operating position	15
Power reserve provides for the recorder to be left in the ready position	Up to 10 days
Overall dimensions, m	
The recorder	450x345x225
of the power pack	450x345x200
Weight, kg	
of the recorder	14
of the power pack	21
Stability of the master oscillator	10^{-5}
Scale divisions of the fine time mark scale depending on the code number, milliseconds	15, 20, 25 or 30
Time of division of the large time mark scale as a function of the code number, sec	0.75, 1.0 or 1.5
No of different combinations of coded signals	12
Radius of the reliable remote control when using the Rodnik radio transmitter, km, no less than	300

Reproduction Unit

Reproduction of seismic signals	Multichannel
Reproduction of the signals from each seismic channel	Simultaneous on three filtrations
Steepness of the tips of the frequency characteristics of the filters, decibels/octave	12 and 24
Power pack	
from the AC network	220/127 volts, 50 hertz
from the storage batteries (for the loop oscillograph)	24 volts
Intake power, watts	
from the AC network	100
from the storage batteries	90
Limiting frequencies of the filters on reproduction are determined by the type of operations and have five values each for the upper and lower frequency filters	

obtained from the recordings with ordinary excitation of the oscillations. Frequently the number of points of industrial explosions is small, and they are distributed nonuniformly over the terrain, which complicates their use in the operations attaining a system of hodographs. In the sounding procedure, this difficulty is overcome to a significant degree by using area systems of observations and the application of a large number of simultaneously operating recorders. In many cases during mining operations the directional blasts are used which excite shear stresses. Such blasts can be sources of intense transverse waves. The recording of the latter jointly with the longitudinal waves will permit us to obtain more complete data on the morphology of the deep boundaries and physical properties of the rock. In addition, as a result of the nonsimultaneous explosion of large groups of charges practiced in a number of cases, their use is accompanied by known difficulties. In particular, in the vicinity of Yakutia when recording waves from blasts in the Mir and Aykhal diamond pipes where 10 to 25 groups of charges were exploded with a deceleration interval of 0.035 to 0.050 seconds, complex, difficult to interpret seismic recordings were obtained.

The above-noted method of exciting the oscillations requiring the use of heavy drilling rigs, deep bodies of water, the presence of appropriate industrial blast points, far from always can be realized in areas which are accessible only to helicopter transportation, under the conditions of the development of permafrost and rock. Accordingly, for regional operations in Siberia, an important role is played by the surface seismic sources with area grouping of a very large number (many tens and hundreds) of small charges in shallow (1÷2 m) wells and bodies of water. Let us consider the available experience in using such sources.

By the results of the experimental studies [37, 6, 69], the dependence of the amplitude A of the seismic wave excited during simultaneous explosion of a group of n unit charge on the main factors can be approximately represented in the form

$$A = \kappa \cdot K_v \cdot K_m \cdot K_z \cdot K_x \cdot K_n \cdot Q,$$

where k is the proportionality factor; Q is the total mass of the charge. The remaining coefficients are considered: K_v is the type of explosive; K_m is the physical-mechanical properties of the medium and its flooding; K_z is the depth of placement of the charge; K_x is the distance between unit charges; K_n is the number of unit charges.

For comparison of the effectiveness of the explosions of two charges which are identical with respect to toal mass executed under different conditions, we shall have the ratio

$$\frac{A_1}{A_2} = \frac{K_{v_1}}{K_{v_2}} \cdot \frac{K_{m_1}}{K_{m_2}} \cdot \frac{K_{z_1}}{K_{z_2}} \cdot \frac{K_{x_1}}{K_{x_2}} \cdot \frac{K_{n_1}}{K_{n_2}}.$$

CHAPTER IV. FIELD OBSERVATIONS AND INTERPRETATION OF MATERIALS

§1. Characteristic Features of Field Operations

Let us consider the problems of the field operation procedures using the work experience in Siberia [50, 51, 56, 60, 79, 68, 10].

Excitation of Oscillations

The reconnaissance prospecting seismic studies must be carried out in the shortest possible time over large territories, often with difficult surface conditions; therefore the solution to the problems of excitation of the oscillations, one of the most labor-consuming operations, has great significance. When working in Siberia, along with the methods of exciting waves that are traditional in seismic exploration (explosions in wells, natural bodies of water), industrial explosions [50] and explosions of a large number of small charges in shallow (about 1 meter) wells [65, 66, 69, 114] were used. The observation systems in the sounding procedure are more arbitrary by comparison with the ordinary method of seismic profiling. Therefore usually there is significant freedom in selecting appropriate places for the oscillation sources. The sources can be placed at some distance from the basic route, not necessarily at strictly defined distances from each other or one source can be common to several soundings. As a rule, all this permits successful solution of the problem of exciting the oscillations by ordinary methods during operations even in inaccessible taiga, marshy and mountainous regions. Under the varied conditions of Siberia the blasts in bodies of water (lakes, meanders) 4 to 10 meters deep turn out to be quite effective for exciting waves at distances to 200-240 km from the recorders. The required magnitude of the explosive charge concentrated as much as possible with respect to area reaches 2 to 4 tons. In the areas where the use of drilling equipment is possible, the excitation of the waves by explosions in a group of wells 20 to 40 meters deep permits the weight of the charge to be reduced by two or three times under such conditions. No more than 100 to 200 kg of explosives was placed in each well, and the distance from adjacent wells in the area group usually was about 15 meters.

For large industrial explosions, intense waves are excited which can be used for studying the structure of the earth's crust and the tops of the mantle. The experience in recording the waves from the blasts in the coal mines of the Kuznetsk basin [50] indicates small difference of the seismograms

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Let us consider the probable ranges of variation of the coefficients for the actual conditions of the new-surface blasts in the Siberian regions.

The coefficients K_v are identical in practice for the explosives widely used in seismic operations (TNT, smokeless powder, ammonite) [37]. The properties of the soil at the blast point essentially influence its effectiveness: the magnitude of the coefficient K_m for water-saturated clays and water exceeds by more than 2 and 4 times respectively its value for drying loams under other equal conditions [37]. On variation of the depth of submersion of the charge from 1 to 10 meters the coefficient K_z increases by fourfold [6, 69]. It is possible to obtain an idea about the effect of the distribution of the near-surface blasts from the results of special experiments with small charges in low-velocity zones [69]. It is usually noted that the variation of the distance from 1 to 10 meters between charges of 0.4 kg almost doubles the coefficient K_x, and further disperseness does not have a noticeable effect. The value of K_n varies with an increase in number of charges in the group approximately as $n^{1/3}$, that is, if the number of charges is increased from 10 to 1000, then K_n increases by almost 5 times.

Taking the extreme values from the presented actual values of the coefficients, we find that the effectiveness of detonating a charge of one and the same total mass can differ by almost 100 times. From this comes the importance of correct selection of the parameters of the group surface sources. From an analysis of the presented multiparameter experimental relations it follows that it is possible to obtain a quite high seismic effect for various types of surface explosions if we select their parameters correspondingly. This permits sufficiently flexible use of one type of source or another considering the local conditions and production possibilities.

Group sources making use of lightweight charges in a large number of shallow holes have found very broad application primarily in the vicinity of the Tungusskaya syneclise. The choice of the efficient parameters for such sources is based on experimentally established relations for the amplitude and frequency composition of the excited oscillations as a function of the group charge parameters. As an example let us consider the relations (see Fig 33) established [69, 70] in the southeastern part of the Western Siberian platform for blasts in weathered arenaceous-argillaceous rock with a longitudinal wave velocity of 350 meters/sec. Reference reflected waves were recorded at distances about 200 meters from the source using standard seismic prospecting equipment with wide-band frequency filtration without a shifter and an automatic amplitude regulator with calibrated sensitivity.

It was demonstrated (see Fig 33, a) that the detonation of a concentrated charge in a well about 1 meter deep essentially is more effective than detonating the same charge on the surface and in prospecting holes 0.3-0.4 m deep. At a fixed depth (1 meter) a significant increase in oscillation amplitude is noted with an increase in the weight of the charge from 0.1 to 2 kg; with a further increase in mass of the charge the gain in amplitude is insignificant (see Fig 33, b). The increase in oscillation

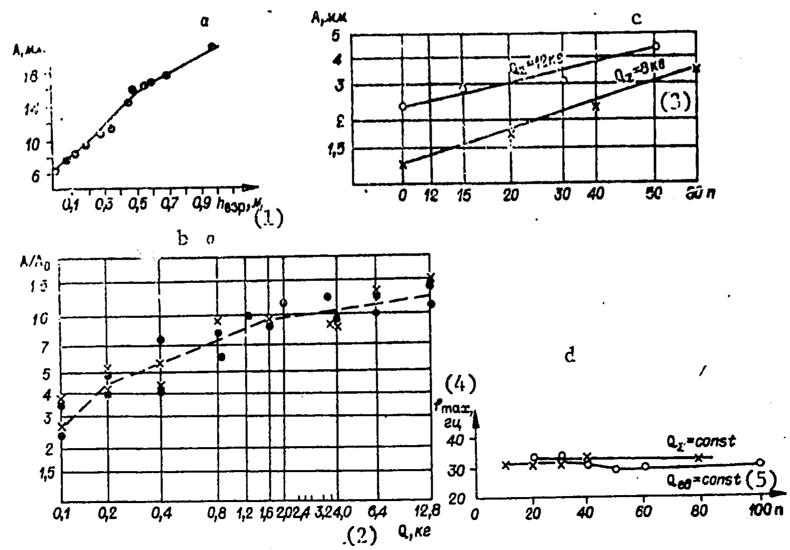

Figure 33. Some experimental relations for the elastic wave amplitude as a function of the group charge parameters
Dependence of the wave amplitude: a -- on the depth of the blast hole, b -- on the mass of a unit charge in wells 1 meter deep, c -- on the dispersion of a charge of constant mass, d -- dependence of the maximum amplitude spectrum of the wave on the number of unit charges in the group

Key:

1. h_{blast}, meters
2. Q, kg
3. kg
4. f_{max}, hertz
5. Q_{unit}=const

amplitude approximately proportional to the cube root of the number of unit charges has been established (see Fig 33, c) for a fixed total mass of the charges (8 and 12 kg) distributed in the area group of wells at a distance of 5 meters from each other.

The study of the frequency composition of the oscillations has demonstrated that the frequency has a maximum amplitude spectrum (f_{max}) in practice does not vary with an increase in the number of charges in the group from 10 to 100 (Fig 33, d). Here either the mass of a unit charge Q_{unit} or the total mass Q_{Σ} was recorded, and the depth of the blast holes and their location remained the same as in the preceding experiment.

On the basis of the discussed experiments, a method of exciting oscillations by blasts in large groups of holes 1 meter deep was created and introduced into practice. The holes were drilled by light portable drilling rigs which creates in practice unlimited possibities for use of air transportation in inaccessible areas for the operations. The method is suitable under permafrost conditions and in areas where rock has developed with thin surface layers of loose deposits where the application of the traditional methods of exciting oscillations is very difficult.

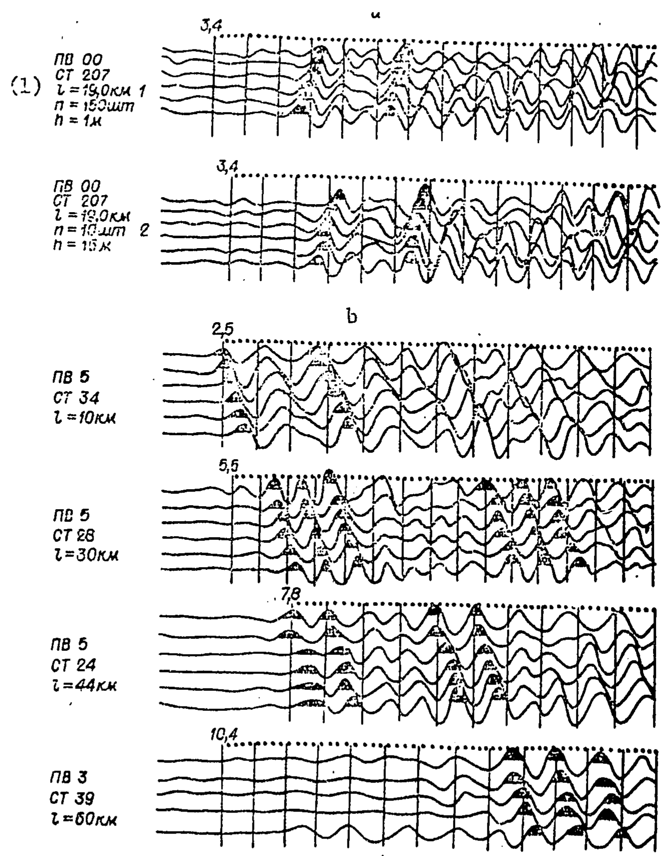

Figure 34. Seismograms characterizing the effectiveness of large groups of small charges in wells 1 meter deep.
a -- comparison of the seismograms recorded during traditional and distributed blasts; b -- nature of recording regular waves at different distances for detonation of 1000 charges of 2 kg each in holes 1 meter deep

Key: 1. PV 00; ST 207, r=19.0 km, n=150, h=1 meter.

[redacted]

The indicated procedure is basic for the regional study of the basement in the vicinity of the Tungusskaya syneclise, where along with very difficult surface conditions there is shielding of the deep waves by widely developed trap formations. Groups containing up to 1000 single charges weighing 1-2 kg in holes 1 meter deep are used. The single charges are distributed over an area in a rectangular grid with 3 meter spacing between them, exceeding twice the radius of the crater formed. The group occupies an area of up to 900 m^2. The charges are detonated by a fuse. The intensity of this group source is sufficient for recording waves at distances to 60-120 km. Seismic recordings from a group source and for more ordinary explosions in deep holes do not differ in practice (see Fig 34, a). The standard seismograms with recordings of refracted and reflected waves obtained in a section of the Nizhnyaya Tunguska River with large groups of new-surface blasts are shown in Fig 34, b.

When investigating the basement in the southern part of the Siberian platform (in the vicinity of the Nepskiy Arch) group charges have been successfully used in shallow (1.5-2 m) natural bodies of water. A charge weighing about 700 kg is distributed in 20 to 30 parts with spacing between the individual charges of 8 to 10 meters.

The method of exciting seismic waves by dropping bombs from aircraft [130] in Siberia has not found sufficiently broad application as a result of its organizational complexity and insufficient effectiveness at great (more than 150 km) distances from the source required for full-value studies by the deep seismic sounding method.

Equipment

In addition to the general requirements imposed on the seismic recording equipment, during regional operations in inaccessible areas it must be portable, it must have increased stability and a wide range of variation of the parameters in view of the variety of seismological conditions of the investigated areas.

The reproducible (magnetic) recording of the oscillations permitted in practice complete avoidance of repetition of the explosions and copying with optimal amplification parameters for each traced wave and frequency filtration considering the variation of the wave field characteristics. The broad dynamic range of the equipment with magnetic recording greatly facilitates the choice of the size of the explosive charges on extended traverses with variable surface and subsurface conditions.

These requirements are fully met by the Tayga equipment with magnetic memory and remote control, the application of which has significantly increased the effectiveness and the traverse and area operations in the inaccessible parts of Siberia. For remote control usually powerful RSO-300 type radio stations are used which insure reliable remote control of the recorders at distances of 300 km or more.

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200020008-9

In the initial phase of the operations, the rebuilt [130, 131] SS-24P seismic stations, the APMZ-ChM magnetic recording attachments and the low-channel recorders made from series assemblies were used.

Low-frequency (with a natural frequency of 4 to 5 hertz) receivers of the NS-3 and S-205 type are used as the seismic sensors. When recording waves at large (200 km) distances from the source, expecially under unfavorable conditions of excitation of the oscillations, it is important to insure high sensitivity of equipment for which grouping of a large number of seismographs is used (for the operations in Siberia -- up to 16 estimates per channel) with optimal electrical connection of them in the group.

During the operations in the Tyumen' Oblast, the submerged seismic receiver method was used [13] which with the help of a special container makes it possible to locate the seismic receivers at a depth to 8-10 meters under the loose deposits in the low-velocity zones. As a result, the microseism background is almost completely eliminated, which in a number of cases permits the amplification of the seismic recording channel to be increased by 20 to 30 times. In addition, this method decreases the resonance phenomenon in the seismic receiver and soil system, and it eliminates the most absorbing surface layer of low-velocity rock from the path of transmission of the waves.

Parameters of the Recording Device

The oscillations are recorded not at a point, but on a distributed (usually 6-channel) linear or area installation of seismographs. This makes it possible to isolate the regular cophasalness axes, exclude the irregular oscillations from the investigation and estimate the values of the apparent wave velocity, one of the basic discrete correlation wave attributes.

The length of the linear installation, especially for operations in inaccessible terrain obviously must be not very great (no more than 1 km). The experimental data (see Fig 35) on the ratio of the apparent velocities of a defined wave corresponding to the recording devices of different lengths with coinciding centers indicate that increasing the extent of the installation does not lead to a significant decrease in the scattering of the values of the apparent velocity.

Strict orientation of the installation with respect to the direction of the blast point is not mandatory. Deviations of up to 10 to 15° are entirely admissible, for this leads to insignificant (2-3%) distortions of the apparent velocity. In inaccessible terrain, especially when using the area sounding systems, it is not the linear but the X, Γ or T-type receivers that are convenient, which permits the determination of the apparent velocity independently of the direction of the blast point.

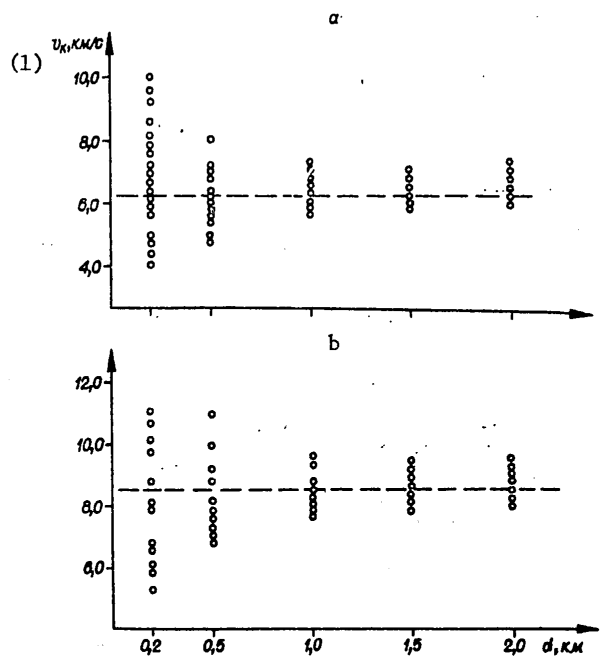

Figure 35. Accuracy of determining the apparent velocity as a function of length (d) of the recording device under the conditions of the Western Siberian lowland a -- refracted wave from the intracrustal boundary and b -- from the M boundary. The circles correspond to the individual determinations of the velocity for different lengths of installation; the dotted line is the velocity over the entire hodograph.

Key:

1. v_k, km/sec

The small number of seismic channels permits us to use a quite powerful area grouping of seismographs (to 16 instruments per channel) to increase the effective sensitivity and average the effect of the surface inhomogeneity. Under the conditions of sparsely-populated areas, the basic interference usually is the oscillations caused by the wind which are suppressed by selecting the spacing between the seismographs in a group (about 15 meters from each other).

Observation Systems

The field operations are conducted on the sounding network and on parametric profiles.

The parametric observations are usually made at the beginning of the studies in a new area. Their primary goal was to study the wave picture, discover the reference waves, the optimal regions for recording them and the discrete correlation attributes. The tuning of the equipment, the methods of exciting the oscillations and other problems are more precisely defined simultaneously. The observations are designed to obtain one or several counter and open hodographs under standard conditions for the given area. The profile line is so far as possible located under simple conditions not intersecting fracture zones. Usually piecewise-continuous observations are made on a short profile with several blast points. The results obtained are used to design the sounding network which can be traverse or area-type.

The sounding bases are selected in the region of most reliable recording of the traced waves. In order to insure the required completeness of investigation of the section, usually several sounding systems are needed with essentially different bases (Fig 36). In the Western Siberian lowland the basement surface is studied by soundings by refracted waves with bases of 8-16 km, refracted and reflected waves from the foot of the earth's crust are recorded on soundings with bases of 180 to 200 km. The sounding system for the intermediate refracting and reflecting boundaries has bases of 40-60 km. In the Siberian platform and in the exposed areas in the south of Siberia, only the last two of the indicated sounding systems are used, for the refracted wave from the basement surface is recorded here on soundings with bases of 30 to 60 km.

When using refracted waves, the sounding system must provide for construction of the $t(x, \ell)$ field along the investigated profile for the base range (ℓ) which permits characterization of the required depth interval. Thus, when studying the earth's crust in the Baykal rift zone (including with the goal of discovering the wave guide layers) the range of values without soundings was 10-200 km, and the variation step size of the bases was 15-20 km.

In order to determine the velocities in the medium, it is necessary to have no less than two field isolines $t(x, \ell)$. Consequently, each sounding system must include observations for two (not necessarily strictly fixed) bases ℓ_1 and ℓ_2 which correspond to the times t_1 and t_2. The magnitude of the difference of the bases is selected beginning with the required accuracy of determining the velocity for the given errors in the initial data.

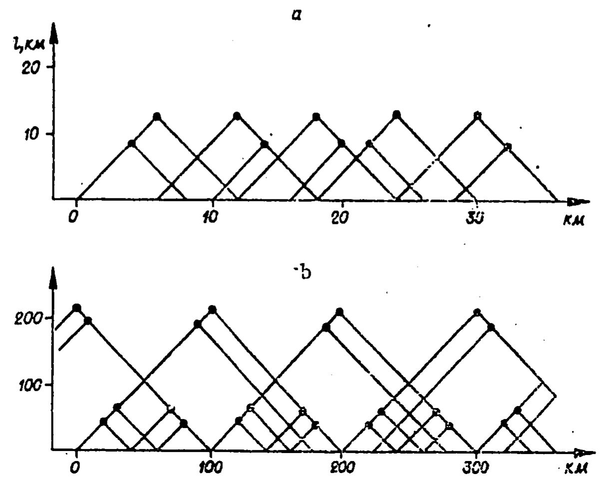

Figure 36. Sounding systems.
a -- for studying the surface of the basement by refracted waves under the conditions of the Western Siberian platform;
b -- for studying the intracrustal boundaries and the M surface

By the recordings of the refracted waves, the boundary velocity is calculated under the assumption that the slope angles of the boundary are small (≤10°)

$$v_{\Gamma(1)} \approx \frac{l_2 - l_1}{t_2 - t_1}.$$

Key: 1. boundary

Differentiating the last expression, we find the relative errors in the boundary velocity $m_{v_{boundary}}/v_{boundary}$ caused by the errors in measuring distances m_ℓ and the time m_t:

$$\left(\frac{m_{v_\Gamma}}{v_{\Gamma(1)}}\right)_l = \frac{\sqrt{2}}{l_2 - l_1} m_l, \quad \text{(IV.1)}$$

$$\left(\frac{m_{v_\Gamma}}{v_\Gamma}\right)_t = \frac{v_\Gamma \sqrt{2}}{l_2 - l_1} m_t. \quad \text{(IV.2)}$$

Key: 1. boundary

Considering the errors to be independent, let us determine the total error

$$\frac{m_{v_\Gamma}}{v_\Gamma} = \frac{1}{l_2 - l_1} \cdot \sqrt{2\left(v_\Gamma^2 m_t^2 + m_l^2\right)},$$

from which

$$l_2 - l_1 = \frac{\sqrt{2\left(v_r^2 m_t^2 + m_l^2\right)}}{m_{v_r}/v_r}. \qquad \text{(IV.3)}$$

Knowing under specific conditions the mean values of the errors in measuring the distances and times of arrival of the wave, it is possible to use this formula to find the difference in the bases insuring determination of the value of $v_{boundary}$ with an error not exceeding the given value of $m_{v_{boundary}}/v_{boundary}$.

Analogously, for soundings by refracted waves we have:

$$\left(\frac{m_v}{v}\right)_l = \frac{m_l}{(l_2 - l_1)\sqrt{2}}, \qquad \text{(IV.4)}$$

$$\left(\frac{m_v}{v}\right)_t \approx \frac{v^2 \bar{t} m_t}{\bar{l}(l_2 - l_1)\sqrt{2}}, \qquad \text{(IV.5)}$$

where v is the velocity in the covering medium, $\bar{l}$ and $\bar{t}$ are the mean values of the bases and times.

The final formula for calculating the required base difference has the form

$$l_2 - l_1 \approx \frac{\sqrt{v^4 \bar{t}^2 m_t^2 + \bar{l}^2 m_l^2}}{\frac{m_v}{v} \bar{l} \sqrt{2}}. \qquad \text{(IV.6)}$$

The formulas for the reflected waves are valid when the base difference is several times less than the base itself.

Taking the admissible error in determining the velocity equal to 3-4%, we find that when studying the basement surface of the Western Siberian platform a base difference of 4-5 km is needed. When investigating the deeper boundaries the soundings must have a base difference of 20 to 40 km. The error in measuring the distances is taken equal to 100 meters, and the time error, no more than one oscillation phase.

In the inaccessible terrain it is not always possible to have soundings strictly along a straight line. Let us estimate the admissible deviations of the sounding centers and the directions of their bases from the profile line. The shift of the sounding to the position parallel to this line leads to a change in time of the traced waves if the profile is deflected from the direction of dip (ascent) of the boundary. The case of orientation of the profile along the strike direction is the most unfavorable. Let us make estimates for this case. Shifting the sounding a distance Δy leads to a change in depth to the boundary by the amount $\Delta y \sin \phi$, where ϕ is the true slope angle of the boundary. The corresponding variation in time for the refracted wave is

$$\Delta t = 2\Delta y \sqrt{\frac{1}{v^2} - \frac{1}{v_r^2}} \cdot \sin \varphi. \qquad \text{(IV.7)}$$

In the case of a reflected wave

$$\Delta t = \frac{1}{v}\left[\sqrt{4(h + \Delta y \sin \varphi)^2 + l^2} - \sqrt{4h^2 + l^2}\right]. \qquad \text{(IV.8)}$$

Usually within the limits of each block of the earth's crust the deep seismic boundaries have small slopes (no more than 5°). The calculations by the presented formulas indicate that under these conditions with a shift of the soundings to 5-10 km the variations in time are small (less than one oscillation period). For large deviations the distortions can be considered after determination in the first approximation of the elements of the spatial occurrence of the boundaries.

The effect of the deviation of the sounding base from the profile line by some angle γ (the center of the base on the profile oriented with respect to the strike of the boundary) can be determined by using formulas (II.51) and (II.53) for a surface time field. The corresponding graphs for the reflected and refracted waves presented in Fig 37 can serve to estimate the distortions under specific conditions. For the usually encountered slope angle of the deep boundaries ($\phi<5°$) angular deviations to 45° or more are admissible, for the distortions that occur, as a rule, are appreciably less than 0.05 seconds.

The presented estimates pertained to the case of a plane boundary which is close to the actual conditions if the investigated sounding is within the limits of one block. On the boundaries of the blocks, as a rule, the deep structure is complicated. In such sections, which usually appear in the anomalies of natural geophysical fields, it is necessary to strive for minimum deviations of the soundings from profile line.

Let us consider the area sounding systems which are realized in several versions depending on the conditions of the terrain, the peculiarities of the deep structure and the requirements on the operating results.

1. The arbitrary location of the soundings with respect to each area is a set of arbitrarily oriented soundings arranged with the required average density. The sounding bases vary within some range, which permits construction of the field $t(x, y, \ell)$ in the form of two or more isochron maps for fixed bases. For economical field operations it is expedient to make

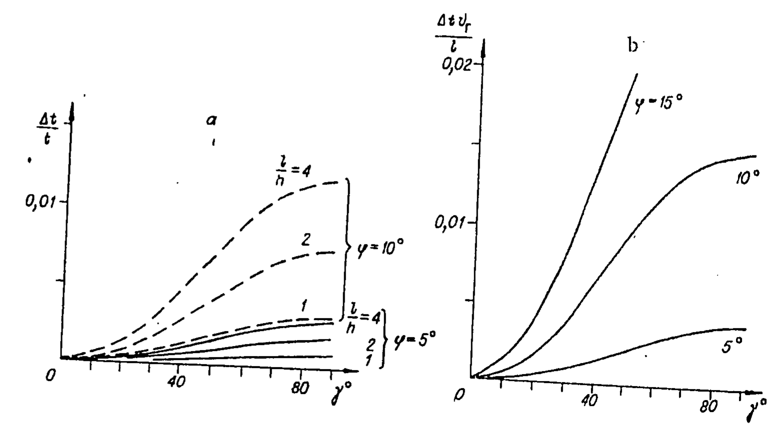

Figure 37. Estimation of the time distortions for angular deviation of the soundings from the profile line in the cases of reflected (a) and refracted (b) waves

each source and receiver common to several soundings. This system is preferable as a result of its opportunities for realization under very difficult surface conditions.

2. Area profile element systems. The profile element is made up of three soundings (Fig 38, a), by the data of which the time and both of its gradients are determined. Various combinations of profile elements are possible in the observation plane. It is convenient, but not economical to have arbitrary (with given average density of the centers) arrangement of the elements. It is more convenient to arrange the profile elements so that they will form a network of closed polyhedrons adjacent to each other in the terrain. Here the sources and part of the receivers are located at the corners of the polyhedrons, and they are used a multiple number of times in several soundings. As an example in Fig 38, b we have a segment of the area sounding network made up of rectangles. For uniformity of placement of the points at which the parameters of the medium are determined, a diagonal element is introduced. This sounding system is used for area study of the basement in the southern part of the Western Siberian platform. When studying the basement surface in the territory of the Tyumne' Oblast, the sounding systems B_1, B_2, E_1 and E_2 have found application as the profile elements (see Fig 23, Chapter II, §4).

An example of the set of profile elements used for the area studies of the surface of the mantle by reflected and refracted waves in the vicinity of Lake Baykal is presented in Fig 39. Five blast points are located on the southeast shore of the lake, and the receiving stations (controlled by the Tayga recorder radio) were located within the limits of the Irkut amphitheater and along the shores of the lake. Each profile element was made

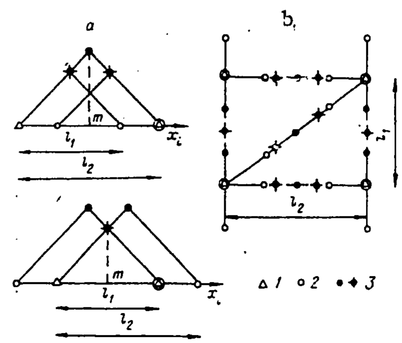

Figure 38. Diagrams of the area observations
a -- profile elements of the area sounding system; b -- fragment of the rectangular network of profile elements; 1 -- blast points, 2 -- receiving stations; 3-- sounding centers

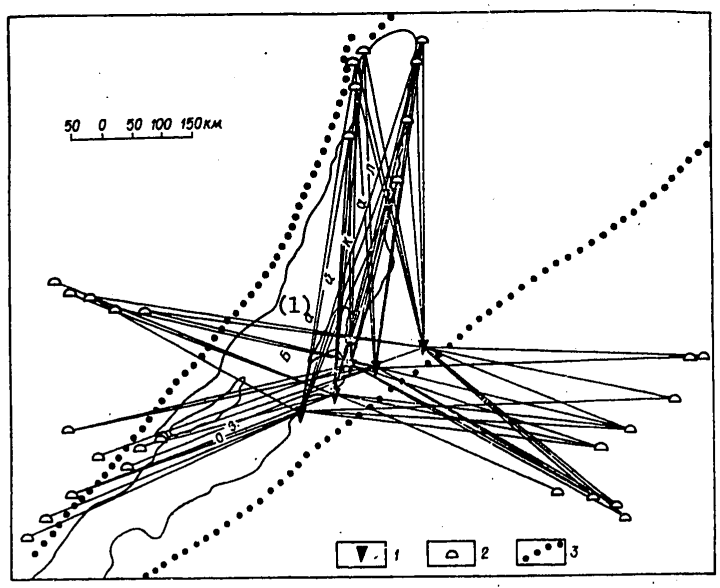

Figure 39. Area system of soundings used to study the surface of the mantle by reflected and refracted waves in the vicinity of Lake Baykal
1 -- blast point; 2 -- recording station; 3 -- boundaries of the Baykal rift zone according to V. P. Solonenko.

Key: 1. Lake Baykal

up of soundings with orientation of the bases located in a defined strip differing little from each other. The magnitudes of the bases were 170-240 km.

3. The area system of sounding profiles usually is used for operations with increased detail. The required sounding system is developed in each profile. The basement of the profiles in the terrain is determined by the problems of studying specific sections.

In practice the investigated versions of the area sounding systems are used in one combination or another.

Substantiation of the Density of the Sounding Network

When selecting the density of the soundings it is necessary to take a number of factors into account which can be reduced to the following three groups.

1. The peculiarities of the structure of the regions including the dimensions of the structures which are the objects of investigation.

2. Various types of errors occurring during observation and interpretation. Among them it is necessary to distinguish the errors of a random nature and systematic errors usually connected with idealization of the structure of the medium.

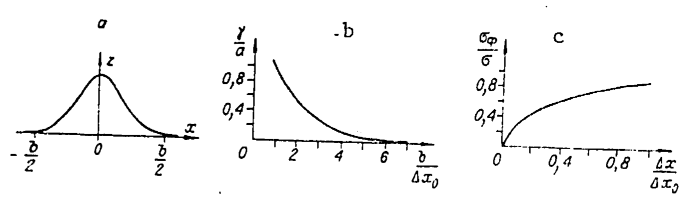

Figure 40. Determination of the density of the sounding network

3. The admissible level of distortions of the structural forms and velocity distribution. To a significant degree this level is determined by the goals set for the investigated studies.

We shall consider that the errors connected with idealization of the medium are reduced to a minimum by using the corresponding interpretation methods. First, for simplicity we assume that the errors of a random nature are small by comparison with the amplitudes of the explored structures (or the velocity distribution anomalies). The density of the network will be determined beginning with the admissible magnitude of the distortions in the relief of the seismic boundary (the velocity distribution with respect to the profile).

Let the series of soundings with the interval Δx_0 between their centers be located on the profile. By the soundings we find the values of the depths $z(j\Delta x_0)$. For determinacy we shall consider that the boundary relief is obtained by discrete values using the V. A. Kotel'nikov series [109]:

$$z(x)=\sum_{-\infty}^{+\infty} z(j\Delta x_0)\frac{\sin\frac{\pi}{\Delta x_0}(x-j\Delta x_0)}{\frac{\pi}{\Delta x_0}(x-j\Delta x_0)}.$$

The obtained relief lines z(x) will differ from the true one even if the values of $z(j\Delta x_0)$ are found exactly. The error, which depends on the observation step size, can be estimated by the inequality proved by I. T. Turbovich [106, 111] for functions with relatively quickly decreasing spectrum

$$\frac{\gamma^2}{\rho^2}\leqslant 4\frac{\int\limits_{-\infty}^{-\omega_0}|S(\omega)|^2d\omega+\int\limits_{\omega_0}^{+\infty}|S(\omega)|^2d\omega}{2\pi\int\limits_{-\infty}^{+\infty}z^2(x)\,dx}, \tag{IV.9}$$

where γ is the mean square value of the indicated error, ρ is the mean square value of the function z(x), $S(\omega)$ is the spectrum of the curve z(x), ω_0 is the boundary frequency equal to $\pi/\Delta x_0$.

As the function representing the outline of the vertical cross section of the geological structure let us consider the relation

$$z(x)=ae^{\frac{-4\ln 100}{b^2}x^2}, \tag{IV.10}$$

where a is the amplitude of the structure, b is the width on the 0.01 a level. This function, called a "bell" function permits approximation of the simplest geological structures (Fig 40, a). Depending on the sign of a, we have an uplift or a depression.

For the function (IV.10) let us find the expression which enters into the righthand side of the inequality (IV.9),

$$\int\limits_{-\infty}^{+\infty} z^2(x)\,dx=2a^2\int\limits_0^{\infty} e^{-\frac{8\ln 100}{b^2}x^2}dx=\frac{\sqrt{\pi}a^2b}{2\sqrt{2\ln 100}}. \tag{IV.11}$$

Let us determine the spectrum of the functions z(x);

$$S(\omega) = a\int_{-\infty}^{+\infty} e^{-\frac{4\ln 100}{b^2}x^2} e^{-j\omega x}\,dx = \frac{\sqrt{\pi}\,ab}{2\sqrt{\ln 100}}\,e^{-\frac{b^2\omega^2}{16\ln 100}}.$$

For the expression in the numerator of the righthand side of the inequality (IV.9) after transformations we obtain

$$\int_{-\infty}^{-\omega_0} |S(\omega)|^2 d\omega + \int_{\omega_0}^{+\infty} |S(\omega)|^2 d\omega = \frac{\pi\sqrt{\pi}a^2 b}{\sqrt{2\ln 100}}\left[1 - \Phi\left(\frac{\omega_0 b}{2\sqrt{2\ln 100}}\right)\right], \qquad \text{(IV.12)}$$

where

$$\Phi(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-t^2}dt$$

is the Laplace function for the probability integral.

As a result of substitution of expressions (IV.11) and (IV.12) in (IV.9) we find

$$\frac{\gamma^2}{\rho^2} \leqslant 4\left[1 - \Phi\left(\frac{\omega_0 b}{2\sqrt{2\ln 100}}\right)\right]. \qquad \text{(IV.13)}$$

The mean square value ρ of the function z(x) will be determined by the interval (-M, M), where this function differs significantly from zero. Requiring that

$$\frac{\int_0^\infty |e^{-t^2}|^2\,dt - \int_0^x |e^{-t^2}|^2\,dt}{\int_0^\infty |e^{-t^2}|^2\,dt} < 0{,}005,$$

by the tables of the probability integral we find: x=2. Accordingly for the function of interest to us (IV.10), we obtain

$$M = \frac{b}{\sqrt{2\ln 100}}.$$

Considering the equality (IV.11) we find

$$\rho^2 = \frac{\int_{-M}^{M} z^2(x)\,dx}{2M} \approx \frac{\int_{-\infty}^{\infty} z^2(x)\,dx}{2M} = \frac{\sqrt{\pi}}{4} a^2.$$

Substituting the expression obtained in the inequality (IV.13),we finally transform it:

$$\frac{\gamma^2}{a^2} \leqslant \sqrt{\pi}\left[1 - \Phi\left(\frac{\pi}{2\sqrt{2\ln 100}} \cdot \frac{b}{\Delta x_0}\right)\right]. \qquad \text{(IV.14)}$$

Expression (IV.14) gives the maximum estimate of the desired value of the distortions of the seismic section as a function of the density of the discrete operation network (Δx_0) and the parameters of the structures (a, b). The graphs (see Fig 40, b) calculated by the formula can be used to select the maximum step size of the observations under the specific conditions by the given magnitude of the admissible distortions. Let, for example, the object of investigation be an uplift of width (b) on the order of 10 km. Distortions of no more than 10% of the amplitude of the uplift ($\gamma/a=0.1$) are admissible. By the given value of γ/a we find: $b/\Delta x_0=3.8$. Consequently, the distances between the sounding centers must not exceed the value of Δx_0=10 km: 3.8≈2.6 km.

It was proposed above that the amplitudes of the structures significantly exceed the errors at depths with respect to magnitude. In practice this is not always satisfied. When investigating the structural forms, the amplitudes of which are commensurate with the errors of the unit determination, additional thickening of the sounding network can be required.

The error distribution in the determination of the depths by the soundings located along the profile at an interval Δx can be considered as a function in the form of adjacent rectangles of identical width (Δx), the height of which is equal to the error at the given point. For this case the following expression is obtained for the spectral density of the error of a random nature [38]:

$$\frac{\sigma^2 \Delta x}{\pi} \cdot \frac{\sin^2 \frac{\omega \Delta x}{2}}{\left(\frac{\omega \Delta x}{2}\right)^2},$$

where σ is the mean square error,

From the last expression it follows that decreasing Δx leads to lowering the spectral density of the random errors in the low-frequency region. This fact permits attenuation of the effect of the errors by introducing the filter which does not transmit the frequencies above some boundary value ω_0. For fixed magnitude of ω_0, the error filtration will be more effective, the smaller the step size of the observation network.

As a result of this filtration,[1] the expression for the error (σ_Φ) assumes the form

$$\sigma_\Phi^2 = \sigma \frac{\Delta x}{\pi} \int_0^{\omega_0} \frac{\sin^2 \frac{\omega \Delta x}{2}}{\left(\frac{\omega \Delta x}{2}\right)^2} d\omega.$$

After integration and substitution of $\omega_0 = \pi/\Delta x_0$, we finally obtain:

$$\frac{\sigma_\Phi^2}{\sigma^2} = \frac{2}{\pi} \left[\frac{\cos \pi \frac{\Delta x}{\Delta x_0} - 1}{\pi \frac{\Delta x}{\Delta x_0}} + \mathrm{Si}\left(\pi \frac{\Delta x}{\Delta x_0}\right) \right]. \qquad (IV.15)$$

In the graph (see Fig 40, c) calculated by formula (IV.15) it is obvious that in order to cut the effect of the random errors in half it is necessary to increase the density of the network by 3 times. Considering that the assumption used as the basis for the derivation regarding the mutual independence of the errors for various small values of Δx in practice usually is not satisfied, it is necessary to increase the density of the observation network to some limit which depends on the error correlation radius.

The value of Δx_0 determined by the graph in Fig 40, b is selected so that the above-investigated conditions of admissible distortions of the structural forms will not be violated.

The practical use of the relations obtained is illustrated in an example. Let it be required that the step size of the sounding network be found when prospecting structures with parameters a=150 meters, b=10 km. The accuracy of the single determination σ=120 meters. Let us require that the errors in the seismic section not exceed half the amplitude of the structures (σ_Φ=75 meters). Initially, let us determine the magnitude of Δx_0. By the graph in Fig 40, b, for γ/a=0.5 we find: $b/\Delta x_0$=2. Consequently, Δx_0=10 km x 0.5=5 km. Then by the graph in Fig 40, c, for σ_Φ/σ=75 km: 120 m =0.63 we determine: $\Delta x/\Delta x_0$=0.42 Hence, the desired distance between the sounding centers Δx=5 km x 0.42≈2.1 km.

Along with the other methods of [95], the discussed examples can also be used to calculate the density of the area observation network inasmuch as the latter can be represented as a series of mutually perpendicular profiles.

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[1] For practical realization of this filtration when processing geophysical data see [38].

During the reconnaissance prospecting studies, the sounding network density is determined in accordance with the general problem consisting primarily in discovering the blocks of the earth's crust 100 km or more across. When studying the upper part of the earth's crust (the basement surface of the platforms and boundaries close to it) the requirements of geological practice are taken into account (for example, the tectonic regionalization of the territory in connection with oil and gas prospecting). As an example let us present data on the average density of the soundings during traverse studies in Siberia. The spacing between the sounding centers to study the surface of the basement (in the Western Siberian lowland) was 3 to 5 km; when investigating the internal structure of the consolidated crust it was 10-20 km, the Mohorovicic discontinuity, 20-30 km. In the complex sections of greatest interest (the zones of articulation of the blocks of the earth's crust, in the Baykal rift zone, the region with anomalously low velocity on the surface of the mantle), the sounding network was made more dense.

§2. Discrete Correlation Methods

The discrete wave correlation during seismic sounding, the basic principles of which were investigated in §3 of Chapter II is always based to one degree or another on the a priori information about the structure of the wave fields and the nature of the investigated media. Therefore the possibility of performing a discrete correlation appears only in a defined phase of the study of one region or another or the type of objects where data are accumulated on the basic laws of the tectonic structure, the nature of the wave guide picture, or the peculiarities of the distribution of the elastic parameters in the medium.

At the present time, for continental areas there is a sufficiently large amount of information about the wave field and the seismic models pertaining primarily to the roof and the foot of the consolidated crust (the surface of the basement of the platforms and the Mohorovicic discontinuity). It was obtained as a result of detailed seismic studies during the KMPV refracted wave method and deep seismic sounding operations under various conditions and it was generalized and classified to a significant degree [17, 43, 81]. Obviously, these generalized concepts require refinement and more specific definition in each area. Therefore, before the beginning of work, an analysis is made of the materials of the preceding geological-geophysical studies in the given and adjacent territories, information is brought in on the other areas with similar geological situations. The purpose of the analysis is to select the basic attributes of the discrete correlation, establish the relations between them with construction of the corresponding histograms and correlations. An example of substantiation of the attributes pertaining to the problem of studying the Mohorovicic discontinuity is presented in reference [137]. Usually it is possible in this way to obtain sufficient information for regionally widespread boundaries (the surface of the basement of the platforms and the foot of the earth's crust).

A number of attributes, basically wave attributes, are sustained in limited areas. For substantiation of them it is admissible to have available primary materials from seismic studies in the given region. If there are no such materials, then the operations in the field begin with the so-called parametric soundings (piecewise-continuous profiles with a small number of blast points). As a result, the reference waves, the optimal regions of recording them, the wave attributes of the discrete correlation are planned. During the course of the field operations these data are more precisely defined.

Discrete Correlation Methods

Let us discover the basic features of the process of discrete correlation based on the experience of seismic studies in Siberia.

The actions of the interpreter can be divided into three basic phases: 1) isolation of the light waves on the seismograms; 2) analysis of the matching of the set of seismic recordings; 3) critical estimation of the seismic sections obtained, the velocity distribution in the medium and their correspondence to the other geological-geophysical data. The correlation is carried out during the entire interpretation process. Nonmatching discovered and subsequent steps makes it necessary to return to the seismograms and estimate the other versions of the wave identification.

First Step. A successive study is made of the individual seismograms. The traced wave (or group of waves) is isolated only by the wave attributes. The most typical of them are the following: the time of arrival of the wave (considering the magnitude of the sounding base), the mutual arrangement of the wave on the seismogram, the values of the apparent velocities and their relation for several cophasalness axes, the amplitudes of the oscillations with respect to the "background" and other waves. As a rule, primary significance is attached to one or two attributes. The remaining attributes are used in "unified" form, forming the concept of a generalized wave picture for the interpreter with which he compares each of the analyzed seismograms as a whole.

As an illustration let us consider the characteristic seismograms of soundings with wave recordings from the basic reference boundaries in the earth's crust in Siberia.

The refracted wave from the surface of the folded basement of the Western Siberian platform (Fig 41) is reliably isolated immediately after it becomes one of the first arrivals for bases equal to triple or quadruple the depths to the basement. The primary wave attributes are the following; the apparent velocities usually are within the range from 5,0 to 6,5 km/sec, the oscillation amplitude is smaller, and the apparent velocity is larger than for the subsequent wave refracted on the boundary in the sedimentary mantle. The presence of a "fan" of cophasalness axes located with removal from the source is characteristic for the seismograms as a whole.

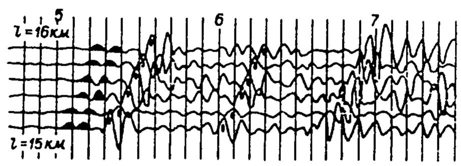

Figure 41. Sounding seismogram when studying the surface of the mantle of the Western Siberian platform. In the first arrivals, the refracted wave from the surface of the basement; in the subsequent part of the recording, waves from the boundaries in the sedimentary mantle.

The reflection from the boundary at a depth of 20 km with a sounding base of 40 to 60 km (Fig 42) is recognized primarily as the first wave with high (more than 7.5 km/sec) apparent velocity. The preceding cophasalness axes are characterized by smaller (usually no more than 6.5 km/sec) velocities. The attribute of the ratio of the apparent velocities is quite reliable also when the investigated wave is commensurate with respect to intensity with the adjacent oscillations. The time difference of arrival of the reflection in the wave in the first arrivals in the given seismograms within the limits of the uniform block is quite stable.

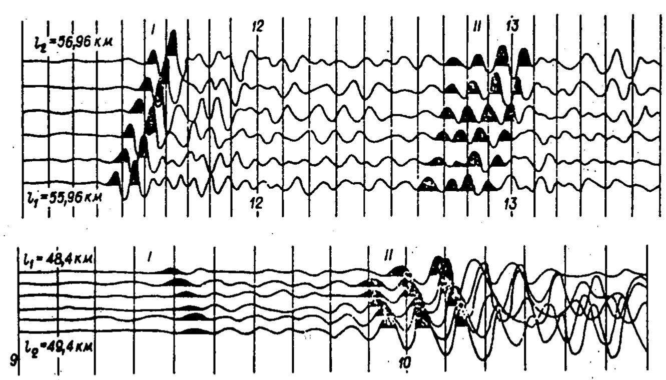

Figure 42. Seismograms of the soundings when studying the internal structure of the consolidated crust of the Western Siberian platform. In the first arrivals, the refracted wave from the boundary at a depth of about 10 km; in the subsequent part of the recording, reflection from the boundary at a depth of 15-20 km.

The isolation of the waves from the Mohorovicic discontinuity (see Fig 43) in the transcritical region (180-200 km from the source with a thickness of the crust of 35-40 km) is facilitated by the fact that on one seismogram it is possible jointly to investigate the refracted and reflected waves from this boundary. The number of stable attributes increases. Let us enumerate the basic attributes (the corresponding histograms are presented in reference [137]): the times of arrival of the waves and the magnitude of their difference for the reflected and refracted waves are sustained; the apparent velocity of the refracted wave in the first arrivals is close to 8 km/sec, and for the transcritical reflection, 7 km/sec; the ratios of the apparent velocities and the amplitudes of the refracted and reflected waves are stable; the magnitude of the first ratio is greater than one, and the second, less than one; the apparent oscillations periods for the reflected wave usually are somewhat larger. The mentioned attributes of the waves are characteristic for many continental regions.

As a result of the first correlation steps, the "groundwork" is created subject to checking and more precise definition during the subsequent analysis. Doubtful sections with several competing versions of the wave identification are especially isolated.

Second Step. The analysis of the matching of the set of seismic data is realized basically by the physical and geological attributes. It can be performed by two methods. In the first case after construction of the section and determination of the velocities, the parameters of the medium obtained are compared with the corresponding histograms and the correlations of the physical and geological attributes. This approach agrees with the previously introduced division of the attributes into groups.

The other method requires additional transformation of certain attributes, permitting all of the groups of attributes to be encompassed and the effective methods of controlling the correlation to be used. A study is made not of the values of the velocities and the sections, but the fields $(t(x, \ell_j)$ and the montage of seismograms. The essence of the analysis of the set of data lies in the following. The variability (gradients) of the kinematic and the dynamic wave characteristics is determined for variation of two parameters: the sounding base (ℓ) and the position of the sounding centers (x) on the profile. On variation of one of the mentioned parameters the second is fixed. When comparing the gradients obtained with the corresponding histograms, the degree of reliability of the investigated version of the correlation is estimated for the seismograms, by the data of which the gradient is determined.

The variability of the dynamic characteristics is determined by the montage of seismograms. It is not necessary to go to the gradients in the strict understanding. It is possible to consider the difference in values of the relative amplitudes, periods, the duration of the oscillations and other characteristics for closely located soundings with different bases and also for adjacent sounds with bases that differ little.

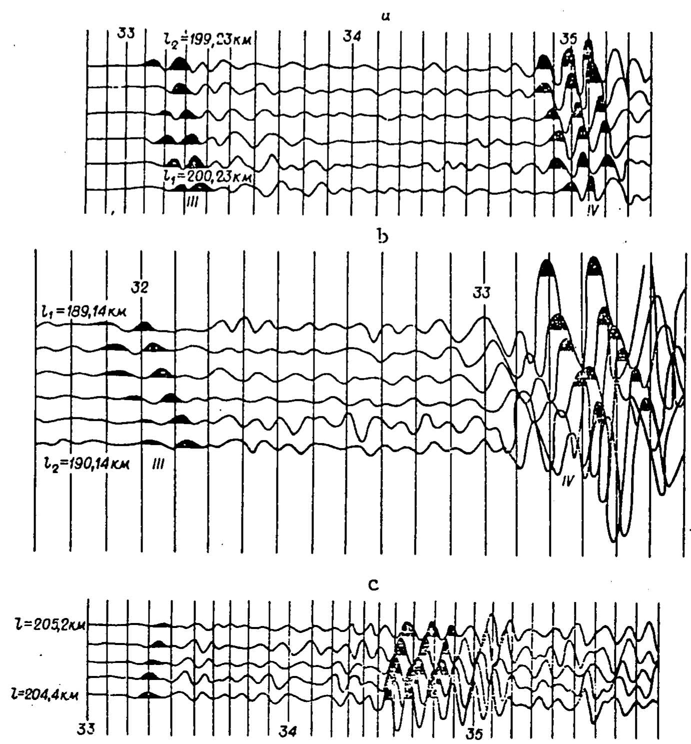

Figure 43. Sounding seismograms when studying the foot of the earth's crust in the southern part of Western Siberian platform (a, b) and in the Baykal rift zone (c). In the first arrivals, the refracted wave, in the subsequent part of the recording, the transcritical reflection.

For analysis of the time field the physical and geological attributes are recalculated to the time field parameters. For example, the velocity histograms of the elastic waves and the slope angles of the boundaries can be converted respectively to the histograms of the vertical and horizontal gradients of the time field by the formulas (II.37-II.41). It is possible approximately to determine the ratio of the relief of the different values by the ratio of the form of the lines ℓ_j=const for the corresponding waves.

Let us briefly consider the methods of monitoring the correlation by the time field which must be regular. The recoils of the individual points, the intersections of the isolines, as a rule, are caused by the wave identification errors.

For media that are not very complex, the time field is characterized by defined laws which must not be sharply violated in the case of proper correlation. The vertical gradient $(dt/d\ell)_{x=const}$ of the time field of the head wave remains constant for different ℓ if within the limits of the maximum sounding base the observation surface and the interface are flat, and the velocities in the medium do not vary. In the case of reflected waves, the value of $(dt/d\ell)_{x=const}$ increases with an increase in the bases. For the refracted waves, the vertical gradient of the field decreases with an increase in ℓ. It is obvious that it is possible to use the enumerated laws investigated in detail in Chapter II, §2, if the time field contains more than two isolines.

An effective method of control is comparison of the values of the apparent velocity determined by the seismogram and calculated by the time field. The formulas (II.42) correct for any monotypic waves are used for the calculation.

The time field of the reflected and refracted waves for certain restrictions imposed on the model of the medium is determined by assignment of only two lines ℓ=const. Therefore recalculation of the field with variation of the bases discussed in Chapter II, §2, is possible. Comparison of the recalculated values of the times will permit estimation of the matching of the set of data.

Third Step. The third step includes a comparison of the section of the earth's crust obtained with the data of the other geophysical methods and estimation of the geological reliability of the results.

Inasmuch as the structure of the earth's crust is depicted in a number of geophysical fields (gravitational, magnetic and so on), the matching is natural at least in general features, of the seismic results with these fields considering the known correlation between the corresponding physical properties of the rock. It is preferable to consider the physical fields themselves and not the results of the geological interpretation which frequently are ambiguous and depend strongly on the concept of the interpreter which is not always clearly stated.

The matching index of the seismic results with the gravitational field gives low intensity of the residual anomalies of this field. The residual anomalies are obtained as the difference between the observed values and the values calculated by the seismic section. Here use is made of the known, quite close correlations between the velocity of the longitudinal waves and the density. The admissible value of the residual anomalies is estimated beginning with accuracy of determination of the depths and the velocities achieved for regional seismic studies.

The discrete wave correlation in the contact zones of the inhomogeneous blocks of the earth's crust is the most complex. Here the velocities and depths of occurrence of the interfaces vary sharply as a result of which the smoothness of the form of the time field lines is disturbed, and the values of the series of correlation attributes can go beyond the fiducial limits. The coordination with these sections of the linear zones of intensive positive magnetic anomalies, gravitational "steps," sharp changes in structure of the natural fields is considered as an indirect confirmation of the possibility of anomalous values of the correlation attributes. Similar seismic "anomalies" not appearing in the magnetic and gravitational fields can be caused by correlation errors and require critical reexamination.

When estimating the geological reliability of the results, the interpreter and seismic explorer uses the method of analogies with other, well investigated regions, which is widespread in geology. The detected significant differences in the structure of the earth's crust cannot be wholly referenced to the correlation as a result of errors, but they are sufficient for checking the identification of the waves in the corresponding section.

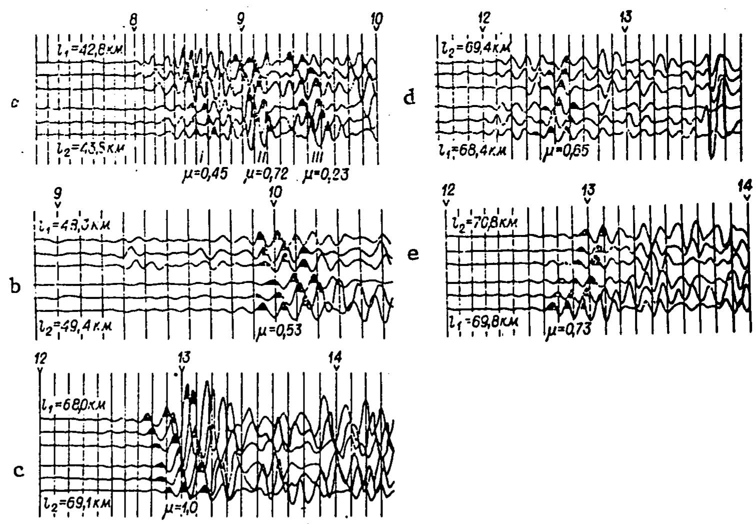

Figure 44. Sounding seismograms along the Angara traverse (the western part of the Siberian platform) with estimates (μ) of the reliability of the discrete correlation.

Let us consider an example of the indication of certain methods of discrete correlation in the sounding material with respect to the profile along the broad course of the Angara River (the western part of the Siberian platform) [60]. In this region parametric observations were first carried out for distances from the source from 35 to 70 km. On the recordings obtained (see Fig 44, a, b) a reference reflection was isolated, which is the first intense wave on the seismogram having increased apparent velocity of 7.5-9.0 km/sec. These peculiarities were taken as the basic wave attributes for tracing the reflected wave in the sounding system with bases of 40-70 km (Fig 45, b). By the above-mentioned wave attributes the reflection is isolated quite reliably in the majority of soundings (Fig 44, c, d, e) with the exception of sounding 4 where three versions of the correlation are possible (I, II, III).

By the results of the first step in the correlation the time field is constructed (see Fig 45, a). From these competing waves in sounding No 4 only case II corresponds to the regular field. The other versions of correlation apparently are erroneous, for they lead to disturbances of the similarity of the shape of the isolines, regular variation of the magnitude of the vertical gradient and the corresponding values of the effective velocities and depths.

The obtained results of the interpretation (Fig 15c) are entirely plausible. The uplift of the reflecting boundary in the easterly direction agrees with the shape of the isoline of the stratal velocity in the mantle obtained by the refracted wave data. The high value of the effective velocity (5.8 km/sec) does not contradict the magnitude of the stratal velocity and the known petrographic composition of the rock (the tight sediments, penetrated by trap intrusions).

The high effectiveness of the above-discussed methods of wave identification was confirmed by comparison with the results of the continuous correlation under various conditions. The comparison was made by the materials of the continuous deep seismic sounding profiles in Central Asia, in the southern part of Western Siberia, in the Urals and Ukraine (the Carpathians, the Donetsk depression). For the reference waves from the sustained boundaries (the basement surface,the Mohorovicic discontinuity and certain boundaries inside the consolidated crust) the divergences with the continuous correlation, as a rule, were no more than one or two oscillation phases.

Formation of the Discrete Correlation

The reliability of the discussed nonformalized approach to the wave correlation of the soundings depends to a great extent on the experience of the interpreter, who to some degree always is subjective in his estimates. A study is made below of the problems of obtaining objective, quantitative estimates of the reliability of the wave identification in the individual steps of the discrete correlation. Moreover, during reconnaissance prospecting deep seismic studies, the role of the interpreter must remain quite active inasmuch as at the present time there is still much unexplained in the problems even of the common features of a model of the earth's crust and the nature of the recorded wave field. It is also necessary to consider the significant variability of the conditions on the extended regional profiles.

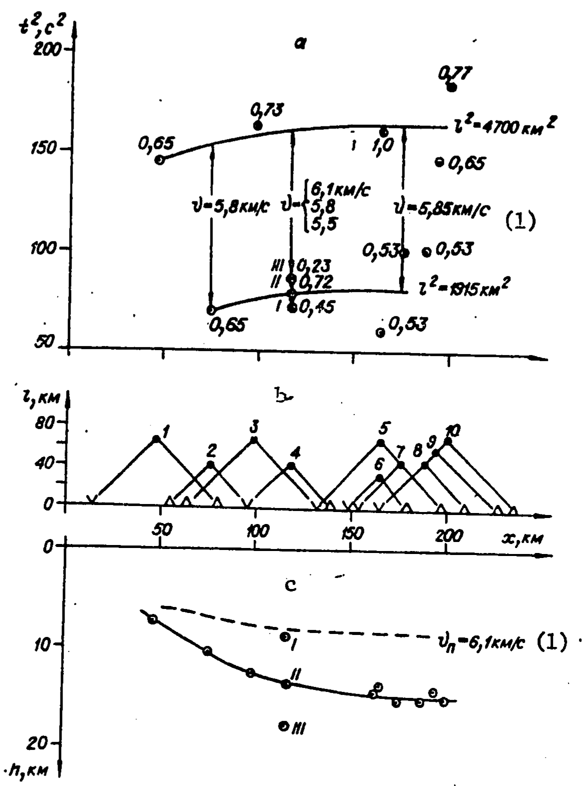

Figure 45. The Angara deep seismic sounding traverse.
a -- time field of the reflected wave with reliability estimate of the discrete correlation; b -- observation system; c -- seismic section.

Key:
1. km/sec

Formalization of the Attributes. Using the greatest amount of statistical material possible, the histograms are constructed for each attribute. For all of the attributes the grouping interval on the histograms is uniquely selected. It can be taken equal to a defined part of the standard deflection of each attribute. Obviously it is necessary to use all of the functionally connected attributes, for example, such as the apparent velocity and the difference in the time of arrival of the wave at the edges of the seismograph installation. It is sufficient to limit ourselves to one of these attributes.

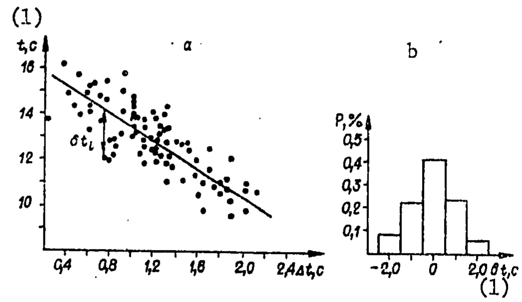

Figure 46. Example of the transition from the correlation of two attributes (a) to the histogram (b).
t -- reflected wave time; Δt -- difference in reflection time of the wave in the first arrivals on one seismogram.

Key:
1. sec

The correlations between the attributes are conveniently represented in the form of a histogram of the deviations from the regression line. The procedure for transition to the histogram is clear from Fig 46 where the relation is depicted between two attributes of the wave (the time of arrival and difference in times of the reflected and refracted waves correspondingly), as a function of the intracrustal boundary in the Western Siberian lowland. The same histograms must be used jointly with the corresponding regression lines.

The attributes are not equivalent with respect to their significance. Therefore the problem arises of determining their weight coefficients γ. An estimate is made below of the "weight" of the attribute by the results of their tests on materials with known proper version of the correlation (standard). As the standard it is better to take the results of the continuous correlation or the version of the discrete correlation obtained jointly by several experimental interpreters. The tests consist in identifying the wave only by one attribute. The ratio of the number of coincidences with the standard to the total number of tests is investigated as the weight coefficient of the given attribute. The weights of the jointly used attributes are normalized so that their sum will be equal to one.

As an example, let us present the weight coefficients for the wave attributes pertaining to the reflected and the refracted waves fron the Mohorovicic discontinuity in the transcritical region of distances from the source (170-200 km) in Western Siberia. When testing on 50 seismograms the following attributes received identical weights (γ=0.15): the times of arrival of the waves, the time difference, the magnitude of the apparent velocities and their ratio considering the distance from the source. The attribute of the amplitude ratio of the reflected and refracted waves has smaller weight (γ=0.10).

Let us consider the two systems for estimating the reliability of the wave generation. These systems include quite simple algorithms which are available for use under field conditions without the application of computers.

System I. The attributes of the correlated wave and their interrelations are given in the form of histograms. The characteristics of the competing waves are unknown. The reliability of the generation of the wave with respect to n attributes is estimated by the value of the "total probability" P:

$$P = \frac{1}{n} \sum_{j=1}^{n} \gamma_j P_j, \qquad \text{(IV.16)}$$

where γ_j and P_j are the wave coefficient and the probability (frequency) of the j-th attribute respectively. The value of P_j is picked up from the histograms for the given value of the attribute. The histograms are normalized so that the total of the products of the maximum probabilities of each attribute times its weight coefficient will be equal to one.

$$\sum_{j=1}^{n} \gamma_j P_{j\max} = 1. \qquad \text{(IV.17)}$$

With this normalization the values of P will be included in the interval from 0 to 1. The wave which maximizes the function P is taken as the desired wave on the given seismogram. The generation of the wave is considered to be more reliable the larger the value of P. The fiducial intervals for the function P are best determined by comparison with the continuous profiling results. The generation of the wave can be provisionally considered reliable for $0.6<P\leq 1$, satisfactory for $0.12\leq P\leq 0.6$ and unreliable for $P\leq 0.12$.

System II is based on using the "holotype" algorithm [18]. The essence of the operations consists in the following. From among the seismograms on which the investigated wave is reliably generated, the most typical recording of this wave called the "holotype" is selected. The reliability of the discrete correlation is estimated by the degree of closeness of the waves to the "holotype."

The seismograms used to select the "holotype" are compared with each other, and as a result, the coefficient of their similarity with respect to each attribute is defined:

$$\mu_j(\rho, q) = 1 - \frac{|\alpha_p^j - \alpha_q^j|}{m(j) - 1}. \qquad \text{(IV.18)}$$

Here ρ and q are the numbers of the compared seismograms, j is the number of the attribute, m(j) is the number of the intervals in the range of values within this attribute, α_ρ^j and α_q^j are the order numbers of the attribute intervals into which the seismograms ρ and q fall.

Then the similarity coefficients are calculated for each seismogram by the set of all n attributes considering their weight coefficients (γ_j).

$$\mu(\rho, q) = \frac{1}{n} \sum_{j=1}^{n} \gamma_j \mu(\rho, q). \qquad \text{(IV.19)}$$

The minimum $\mu^+(\rho)$, maximum $\mu^{++}(\rho)$ and arithmetic mean $\bar{\mu}(\rho)$ values of the similarity coefficient are found for each seismogram; the typicalness coefficient is calculated:

$$\eta(\rho) = \frac{\bar{\mu}(\rho)}{\mu^{++}(\rho) - \mu^+(\rho)}. \qquad \text{(IV.20)}$$

The seismogram with the largest typicalness coefficient is taken as the "holotype." Let us denote its order number by r.

The reliability of generation of the wave on each new seismogram (s) is estimated by the similarity coefficient $\mu(s,r)$ between the investigated wave and the "holotype." The value of $\mu(s,r)$ is calculated by formula (IV.19). If $\mu(s,r) \gtrsim \mu^+(r)$, the wave is considered identically reliable. For $\mu(s,r) < \mu^+(r)$ the identification is unreliable.

The above-presented description of the systems for quantitative estimation of the correlation was presented as applied to the first step -- generation of the waves on the seismograms. The same estimates can also be made in subsequent steps for the set of soundings, sections of the time field and seismic section. Examples of the quantitative estimates for the set of soundings are investigated in detail in reference [33].

Let us point out some differences in the investigated systems for estimating the correlation. In system I it is necessary to have mass preliminary data available to construct the histograms of the attributes. Therefore it can be used for sufficiently well studied areas where a defined quantity of data has been accumulated on the basic attributes.

System II is convenient for the fact that it can be used in the initial phase of operations in the new area. Of course, the danger of selection of an insufficiently standard object as the "holotype" by a small number of initial data is not excluded.

Both systems have been tested on the materials from deep seismic soundings in Western Siberia, and no significant differences in the results have been noted with respect to one procedure or another. In the overwhelming majority of cases the estimates correspond to the decisions of experienced interpreters, and they significantly facilitate the choice of the defined version of the correlation in complex sections.

Let us illustrate system II in the previously investigated example of correlation of the reflected wave with respect to the Angara profile. The conditions in this section were for the most part new, and sufficient statistical data were not available.

The "holotype" is determined by five seismograms on which the wave is generated quite reliably. The following wave attributes are used: the time of arrival of the reflection (considering the size of the base), its delay time with respect to the wave in the first arrivals, the magnitude of the apparent velocity of the preceding waves, the ratio of the oscillation amplitude of the reflected wave to the mean amplitude of the "fan" on the given seismogram. The seismogram (Fig 44, b) with the value $\mu^+(r)=0.53$ turned out to be the "holotype."

The correlation is made with respect to the maximum similarity coefficients $\mu(s, r)$ for competing waves on each seismogram. The values of this coefficient are written in the time field and on the seismograms (see Fig 44, 45). All of them exceed the value of $\mu^+(r)$. The three versions of wave generation (see Fig 44, e) have essentially different similarity coefficients: 0.45, 0.72 and 0.23. The second version is taken as the reliable one.

§3. Interpretation Procedures

The procedures for determining the velocities of the elastic waves and the depths of occurrence of the seismic boundaries by the materials from the traverse and area sounding systems are based on principles discussed in Chapter II. Let us consider these procedures for reflected and refracted waves and also for joint use of the waves of different types. For each of the mentioned waves first the calculation formulas are presented in the case of the simplest model of the medium, and then the methods of interpretation are discussed for the more complex model. A study is also made of some of the methods of using the dynamic characteristics of the waves as applied to the spot sounding material.

Traverse Observations

A two-dimensional field $t(x, \ell_j)$ or $t^2(x, \ell_j^2)$ is constructed by the results of the observations along the traverse, and by this field the velocity distribution in the medium is found and the position of the seismic boundary is determined.

Reflected Waves. The calculation formula for determining the velocity v in the covering medium is obtained from expression (II.37) by transition from the differentials to finite time and base increments. For any point of the profile x by which two isolines of the time field $t_1(x)$ and $t_2(x)$ with bases ℓ_1 and ℓ_2 are given, we have

$$v(x) = \sqrt{\frac{l_2^2 - l_1^2}{t_2^2(x) - t_1^2(x)}} \cos \varphi. \qquad \text{(IV.21)}$$

From equation (II.29) the calculation formula is obtained for depths of occurrence of the reflecting boundary along the normal to it

$$h_m(x) = \frac{1}{2} \sqrt{v^2(x)\, t^2(x) - l^2 \cos^2 \varphi}. \qquad \text{(IV.22)}$$

The value of cos ϕ in the case of small slope angles (to 10-15°) is admissibly set equal to one. When necessary the boundary slope can be expressed in terms of the vertical and horizontal gradients of the time field (see (II.14)). In practice, in order to calculate the effect of the slope of the boundary it is first convenient to construct the section under the assumption that ϕ=0, and the approximate values of the slope angle determined by them are introduced into (IV.21) and (IV.22). The approximation process can be repeated, but usually there is no necessity for this.

In the results of the calculations of v and h_m the curvature of the reflecting boundary under actual conditions, as a rule, turns out to be small.

The inverse problem of finding the integral parameters of the medium v,h,ϕ can be solved also in the more general case of arbitrary arrangement of the sounding centers (x_i, ℓ_i, t_i) on the observation line. For this purpose it is sufficient to have three soundings in theory. Let us compare for simplicity the origin of the coordinates with the first sounding, setting x_1=0, and let us refer the depth h to this point. Then, according to reference [86], using the time function $t^2(x, \ell^2)$, the velocity v is found from the equation:

$$Av^4 - 2Bv^2 + C = 0, \qquad \text{(IV.23)}$$

where

$$A = \left[(t_2^2 - t_1^2)(\alpha + \gamma) - \beta\delta\right]^2 + 16\, Bx_2^2\left[t_1^2(\alpha + \gamma) - \beta t_1^2\right];$$

$$B = \left[(l_2^2 - l_1^2)(\alpha + \gamma) - \alpha\delta\right]\left[(t_2^2 - t_1^2)(\alpha + \gamma) - \beta\delta\right] + 8x_2^2\left[\alpha(\alpha + \gamma)\, t_?^2 - \beta(\alpha - \gamma)\, l_1^2\right];$$

$$C = \left[(l_2^2 - l_1^2)(\alpha + \gamma) - \alpha\delta\right]^2 + 16\alpha\gamma l_1^2 x_2^2.$$

In these expressions α, β, γ, δ have the following values:

$$\alpha = x_3(l_2^2 - l_1^2) - x_2(l_3^2 - l_1^2),$$
$$\beta = x_3(t_2^2 - t_1^2) - x_2(t_3^2 - t_1^2),$$
$$\gamma = 4x_2x_3(x_3 - x_2),$$
$$\delta = l_2^2 - l_1^2 - 4x_2^2.$$

The depth h is found by the formula (IV.22), and the angle ϕ, from the expression

$$\sin^2\varphi = \frac{\alpha - \beta v^2}{\alpha + \gamma}. \qquad \text{(IV.24)}$$

If there are more than three soundings, then when solving the inverse problem it is necessary to use equalization by the least squares method.

In this case it is expedient to write the time function in the form

$$\theta = a\lambda - b^2\lambda + (2bx + c)^2, \qquad \text{(IV.25)}$$
$$\lambda = l^2;\ \theta = t^2;\ a = \frac{1}{v^2};\quad b = \frac{\sin\varphi}{v};\quad c = \frac{2H_0}{v},$$

H_0 is the depth of the origin of the coordinates.

The parameters b and c, as shown in reference [78], are found from the system of two nonlinear equations:

$$\left.\begin{aligned} P_{10}b + P_{30}b^3 + P_{12}bc^2 + P_{21}b^2c + P_{01}c + P_{03}c^3 = 0,\\ Q_{10}b + Q_{30}b + Q_{12}bc^2 + Q_{21}b^2c + Q_{01}c + Q_{03}c^3 = 0,\end{aligned}\right\} \qquad \text{(IV.26)}$$

where the coefficients P_{ij} and Q_{ij} have the values:

$$P_{10} = 2(\Sigma x^2\lambda \cdot \Sigma\lambda\theta - \Sigma x^2\theta \cdot \Sigma\lambda^2),$$
$$P_{30} = 8[\Sigma x^4 \cdot \Sigma\lambda^2 - (\Sigma x^2\lambda)^2],$$
$$P_{12} = 2[3\Sigma x^2 \cdot \Sigma\lambda - \Sigma x^2\lambda \cdot \Sigma\lambda - 2(\Sigma x\lambda)^2],$$
$$P_{21} = 12(\Sigma x^3 \cdot \Sigma\lambda^2 - \Sigma x\lambda \cdot \Sigma x^2\lambda),$$
$$P_{01} = \Sigma x\lambda\Sigma\lambda\theta - \Sigma x\theta \cdot \Sigma\lambda^2,$$
$$P_{03} = \Sigma x\Sigma\lambda^2 - \Sigma\lambda \cdot \Sigma x\lambda,$$
$$Q_{10} = 2P_{01};\ Q_{30} = \frac{2}{3}P_{21};\ Q_{12} = 6P_{03};\ Q_{21} = 2P_{12};$$
$$Q_{01} = \Sigma\lambda \cdot \Sigma\lambda\theta - \Sigma\lambda^2 \cdot \Sigma\theta,\ Q_{03} = n\Sigma\lambda^2 - (\Sigma\lambda)^2,$$

n is the number of soundings for the given reflected wave.

Summation is carried out in all cases over the entire set of observations. The system (IV.26) is solved by the iteration method by special programs on a computer. The parameter a is found from the equation:

$$a = \frac{1}{\Sigma\lambda^2}[\Sigma\lambda\theta - b^2\Sigma\lambda(4x^2 - \lambda) - c^2\Sigma\lambda - 4bc\Sigma x\lambda]. \qquad \text{(IV.27)}$$

In the case of the vertical velocity gradient in the covering layer, the effective velocity will be obtained. It is determined, in particular, by two lines ℓ_j=const, that is, at a fixed distance from the sources. Therefore in many cases its difference from the beam velocity will in practice be constant for different points of the profile. The effect of the velocity gradient in the upper medium will basically turn out to be at the depth of occurrence of the boundary, and it will have little influence on the shape inasmuch as the latter is determined by the nature of the curve ℓ_j=const. This is the essential advantage over calculation by hodographs where it is necessary to know the beam velocities for different distances between the source and the receiver.

Often the reflected waves (for example, the reflections from the Mohorovicic surface) are recorded at very large distances from the source, significantly exceeding the depth of occurrence of the boundary. In this case the effective velocity will differ significantly from the mean and beam velocities. Under such conditions it is expedient to determine, instead of the effective velocity, another parameter which characterizes the peculiarities of the gradient medium in the best way. This can be done if there are some data available on the dependence of the velocity on depth, for example, the initial velocity v and the general form of the function v(z). The problem can be solved analytically or graphically. For example, for the function $v(z)=v_0(1+\beta_n z)^{1/n}$, where n is the integer, the graphical solution consists in selection of the value of β_n by the corresponding mean diagrams [83] for the given v_0 and n so that the points with the coordinates $(\beta_n\ell_1, v_0\beta_n t_1)$ and $(\beta_n\ell_2, v_0\beta_n t_2)$ will be on the straight line parallel to the axis of the diagram. The value found for β_n must be considered effective if the effective form of the function v(z) differs significantly from the adopted function. However, whatever the difference, the effect of the curvature of the seismic beam will be taken into account, and the accuracy of the constructions will be higher than using the mean velocity method.

The difference in the effective depths from the true depths can be onsidered also using the given dependence of the effective velocity on the depths [112]. For this purpose, a model with some vertical distribution of the initial velocity will be placed in correspondence to this real medium, approximately considering that the values of the effective and mean velocity are equal. A correction is found for this model for reduction of the effective velocity to the beam velocity used then when calculating the depths. The calculations on standard models of the earth's crust indicate the accuracy of the approximate method.

For the multilayer covering medium (including with curvilinear boundaries) the interpretation problem can be reduced to the case of the two-layer model by recalculation of the time field in the investigated wave to a deeper level coinciding with the roofs of the layer under the corresponding reflecting boundary. The time field is recalculated by the method discussed in Chapter II, §2. The situation is most favorable where reflecting waves are recorded from the boundaries of all the layers. In this case the use of the recalculation procedure and formulas (IV.21) and (IV.22) will permit determination of the relief of the boundaries and the stratal velocities in the layers.

Refracted Waves. The following calculation formulas were obtained from expressions (II.16) and (II.31) for the distribution of the boundary velocity and the depths along the profile on which the two time field isolines are given:

$$v_{\underset{(1)}{\Gamma}}(x) = \frac{l_2 - l_1}{t_2(x) - t_1(x)} \cos\varphi, \qquad \text{(IV.28)}$$

$$h_m(x) = \frac{v}{2\cos i}\left(t(x) - \frac{l}{v_{\Gamma}(x)}\cos\varphi\right). \qquad \text{(IV.29)}$$

Key: 1. boundary

These formulas are valid for a plane refracting boundary with invariant value of $v_{boundary}$ in the section of length $\ell - 2h_m \mathrm{tg}\, i$ (ℓ is the maximum base of the sounding, h_m is the depth along the normal to the boundary in the center of the base). They are also used when processing data by the A, B, D systems (see Fig 23).

For the type D sounding systems (see Fig 23) the value of t_0 is calculated by the formula

$$t_0 = \frac{t_2 l_1 - t_1 l_2}{l_2 - l_1} \qquad \text{(IV.30)}$$

and it pertains to the point with the x-axis $x = \dfrac{l_1}{1 + \dfrac{R}{S}}$, where R is the distance between the blast points, S is the distance between the observation points, and the origin of the axis x is matched to the lefthand edge of the system.

Just as in the case of reflected waves, the effect of the slope of the boundaries for small angles ϕ (to 10–15°) can be neglected. The consideration of the effect of the slope of the boundary is possible by using the time field gradient (see (II.17)) or by successive approximations as was indicated above for reflected waves.

The inverse problem can also be solved for arbitrary distribution of the soundings on the observation line. Let us represent the time function in the form

$$t = t_0 + rx + Sl,$$

where

$$t_0 = 2h_0\sqrt{\frac{1}{v_1^2} - \frac{1}{v_r^2}},\ r = 2\sin\varphi\sqrt{\frac{1}{v_1^2} - \frac{1}{v_r^2}},\ S = \frac{1}{v_r} - \cos\varphi.$$

For an arbitrary number of soundings the indicated parameters are found from the system of linear equations:

$$\left.\begin{aligned} nt_0 + r\Sigma x + S\Sigma l &= \Sigma t, \\ t_0\Sigma x + r\Sigma x^2 + S\Sigma xl &= \Sigma xt \\ t_0\Sigma l + r\Sigma xl + S\Sigma l^2 &= \Sigma lt, \end{aligned}\right\},$$

the solution of which is found by the standard programs on a computer. The transition to the parameters h_0, $v_{boundary}$, ϕ is possible for the given velocity in the covering medium.

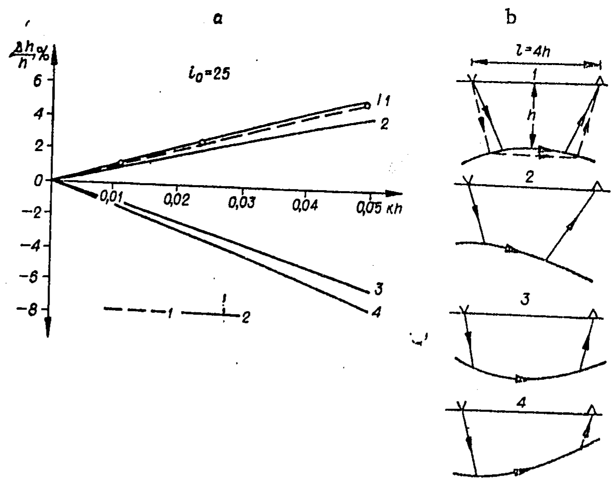

Figure 47. Depth errors as a function of the curvature of the refracting boundary for standard sections in the case of penetration (1) and sliding (2), waves (a); standard sections (b)

Let us estimate the effect of the curvilinearity of the refracting boundary on the results of calculating the depths and the boundary velocity.

We shall consider that the refracting boundary is approximated by the arc of a circle with the radius $R=1/k$. Using the corresponding equation (II.32) of the line ℓ=const, we find the depth error as the difference of the value of h determined by formula (IV.29) by substitution of the time t from (II.32) in it and the true value of the depth at the sounding center. The boundary velocity is considered exactly known. Meeting the intermediate calculations, let us present the formulas for the relative error in the characteristic cases. When the middle of the sounding base is located above the center of the circular boundary we have [59]

$$\frac{\bar{h}-h}{h}=\frac{\operatorname{tg} i}{kh}\left[\pm \operatorname{ctg} i \pm i \pm A \operatorname{arctg} \frac{k(lA+2h)+2}{k(2hA-l)+2A}-\frac{kl}{2}\right]-1. \quad \text{(IV.31)}$$

If the center of the circular boundary is on the vertical under the source or the receiver, then

$$\frac{\bar{h}-h}{h}=\frac{1}{2kh}\left[\left(\pm 2i \pm A \pm B+\operatorname{arctg} \frac{kl}{1+kh} \pm \operatorname{arctg} \frac{A+B}{AB-1}-\right.\right.$$
$$\left.\left.-kl\right)\operatorname{tg} i \pm 2\sqrt{1-\frac{k^2h^2}{4}} \pm 4\right]-1. \quad \text{(IV.32)}$$

In formulas (IV.31) and (IV.32) the signs at the top correspond to the concave boundary, and the bottom signs to the convex boundary. The origin of the coordinates refers to the lefthand sounding edge. The provisional notation is the same as in formula (II.32).

Fig 47 shows the graphs of the relative errors in the depths calculated by the formulas (IV.31) and (IV.32) for the conditions of investigating the basement surface of the Western Siberian platform ($i=25°$, $\ell/h=4$). The distortions increase with an increase in the sounding base, the curvature and the depth of occurrence of the boundary. For the concave form of the refracting surface the depths become lower, and in the convex sections, higher, that is, the structural forms are smoothed out. The penetration of the beams under the second medium on the convex sections (see Fig 47) does not essentially change the magnitude of the error. The values of kh usually do not exceed 0.01 to 0.02; the corresponding distortions do not exceed 1-2% of the total value of the depth.

Let us consider the effect of the curvilinearity of the refracting surface on the boundary velocity. Referring to Fig 48 where the system of two symmetrically arranged soundings, the elements of the hodographs and the corresponding beam systems are depicted, it is possible to show that the determination of the boundary velocity by formula (IV.28) is equivalent to calculation of this parameter by the known expression:

$$\frac{1}{v_{\Gamma(1)}}=\frac{1}{2}\left(\frac{1}{v_{k1}}+\frac{1}{v_{k2}}\right)\cdot\frac{1}{\cos\varphi}.$$

Key: 1. boundary

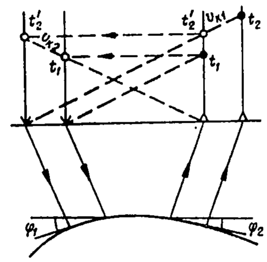

Figure 48. Estimation of the distortions of the boundary velocity in the case of a curvilinear refracting boundary

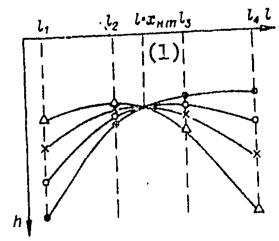

Figure 49. Determination of the x-axis of the initial point of the head wave by the time profile
Key:
1. initial point

The apparent velocities entering into this expression are the following;

$$v_{k1}=\frac{v}{\sin(i+\varphi_1)},\quad v_{k2}=\frac{v}{\sin(i+\varphi_2)}.$$

The errors in determining $v_{boundary}$ are caused by the difference in the slope angles ϕ_1 and ϕ_2 in the boundary sections which include the values of the apparent velocity.

Using the recorded expressions, after simple transformations we obtain the following formula for the relative error in the boundary velocity:

$$\frac{\bar{v}_r-v_r}{v_{r(1)}}=\left[\left(\cos\frac{\varphi_1+\varphi_2}{2}+\operatorname{ctg} i\cdot\sin\frac{\varphi_1+\varphi_2}{2}\right)\cos\frac{\varphi_1+\varphi_2}{2}\right]^{-1}-1,\quad \text{(IV.33)}$$

Key: 1. boundary

where $\bar{v}_{boundary}$ is the boundary velocity without considering the curvature, $v_{boundary}$ is its true value. The angles ϕ_1 and ϕ_2 are considered positive if the corresponding values of the apparent velocities are determined by the drop of the boundary and, negative in the direction of ascent.

For the angles ϕ_1 and ϕ_2 no more than 10 to 15°

$$\frac{\bar{v}_r-v_r}{v_{r(1)}}\approx-\left(1-\frac{\operatorname{tg} i}{\sin\frac{\varphi_1+\varphi_2}{2}}\right)^{-1}.\qquad \text{(IV.33')}$$

From expressions (IV.33) it follows that on the convex sections of the boundary the boundary velocity is found to be low (angles ϕ_1 and ϕ_2 are positive), and above the concave sections, the velocity rises. The distortions are more significant for small values of the critical angle i. Under standard conditions the perceptible distortions are obtained for a difference in the slope angles of several degrees.

If we construct the boundaries with the boundary velocities found without considering the curvature of the boundary, the errors in the depths are opposite with respect to sign to those which occur for the spot value of $v_{boundary}$. Accordingly, compensation for the depth distortions is possible, but it is not complete, and in order to obtain a proper representation of the form of the boundary it is possible to consider the distortions that occur.

There are several procedures for considering the effect of the curvilinearity of the refracting boundary when determining the depths and the boundary velocity [59, 79, 98]. The most correct is the method based on the recalculation of the time field discussed in Chapter II, §2 with a decrease in the bases. The field is recalculated so that one of the isolines will have the base close with respect to magnitude to the x-axis of the initial point ($x_{initial\ point}$) of the head wave. The value of $x_{initial\ point}$=2htgi can be estimated by preliminary data on $v_{boundary}$ and h or, more strictly, by the field $t(x, \ell_j)$. In the latter case at the fixed point of the profile the depths are calculated formula (IV.29) for a number of bases with different values, and graphs depicted in Fig 49 are constructed. The value of $x_{initial\ point}$ is determined by the intersection of the lines $v_{boundary}$=const, for when $\ell=x_{initial\ point}$ the depths do not depend on the value of $v_{boundary}$.

By the two recalculated isolines of the field, one of which corresponds to a base close to $x_{initial\ point}$, the boundary velocity is determined by the formula (IV.28). The result of the recalculation depends little on the curvature of the boundary and the inconstancy of $v_{boundary}$ for the rectilinearity of the boundary and the sustaining of the velocity in this case are assumed in a significantly smaller interval having an extent approximately equal to the difference of the bases used. For calculation of the depths, the isoline with $\ell \approx x_{initial\ point}$ is used. The assumptions regarding the structure of the medium in this case will be the least rigid, approximately the same as in the known method of conjugate points.

When interpreting systems of the B and E type depicted in Fig 23, the following assumptions are made which are similar to those on application of the method t_0 widely used in the KMPV refracted wave method. By the data from systems B_1 and B_2, the values of t_0 and $v_{boundary}$ are determined by the formulas (II.54) and (II.65'). If the values of t_0 are known at the points O_1 and O_2, then the value of $v_{boundary}$ can be obtained more exactly;

$$\left.\begin{aligned} v_{\Gamma} &= \frac{2l_1}{t_1 + T - t_2 + t_{01}}, \\ v_{\Gamma} &= \frac{2l_2}{t_2 + T - t_1 + t_{02}}, \end{aligned}\right\} \qquad \text{(IV.34)}$$

where t_{01} and t_{02} are the values of t_0 for the blast points 0_1 and 0_2.

For the observation systems of the type of E_1 and E_2, the value of t_0 can be determined by the formulas:

$$\left.\begin{aligned} t_{0E_1} &= t_a + t_b + t_c - t_{a_1} - t_{b_1}, \\ t_{0E_2} &= t_a + t_b + t_c + t_d - t_{a_1} - t_{b_1} - t_{c_1}. \end{aligned}\right\} \qquad \text{(IV.35)}$$

With a significant vertical velocity gradient in the refracting medium, it can be necessary to consider the effect of penetration of the seismic beams. For this purpose it is expedient to reduce the observed values of the times to the values corresponding to the uniform refracting medium.a In the special case of linear buildup of the velocity by the law

$$v_{\Gamma} = v_{\Gamma_0}(1 + \beta z),$$

where $v_{boundary_0}$ is the velocity on the refracting surface, β is the gradient, for horizontal occurrence of the boundary we have the expression [92]

$$t = \frac{2h \cos i_0}{v} + \frac{l}{v_{\Gamma_0}} - \frac{\beta^2}{24 v_{\Gamma_0}}(l - x_{\text{н.т}})^3,$$

Key: 1. initial point; 2. boundary

hence it follows that the desired correction is equal to the third term in the righthand side of the presented equation. The values of $x_{initial\ point}$ and $v_{boundary_0}$ are taken by the results of processing without considering the effect of the velocity gradient. This procedure can be used approximately also for the nonlinear dependence of the velocity on depth if we introduce the concept of the mean gradient [88]. The methods of estimating and considering the penetration phenomenon by the so-called convergence of the overlapping hodographs are investigated in reference [78].

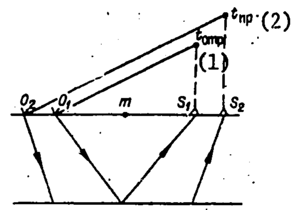

Figure 50. System of symmetric soundings by reflected and refracted waves

Key:
1. $t_{reflected}$
2. $t_{refracted}$

Joint Use of Reflected and Refracted Waves from One Boundary. Let us consider the system of two symmetrically arranged soundings with the bases ℓ_1 and ℓ_2 with matched centers (Fig 50. The reflected wave ($t_{reflected}$) is recorded on one of them, and the refracted wave ($t_{refracted}$) from the same boundary, on the other. When recording both waves on one seismogram ($\ell_1=\ell_2$) we have the simplest system from one source and receiver. The latter case usually arises when studying the Mohorovicic discontinuity. For the model depicted in Fig 50, we have:

$$\left.\begin{aligned} t^2_{\substack{отр\\(1)}} &= \frac{4h^2_m}{v^2} - \frac{L^2_1}{v^2},\\ t_{\substack{пр\\(2)}} &= \frac{2h_m}{v}\sqrt{1-\frac{v^2}{v^2_г}} + \frac{L_2}{v_г},\end{aligned}\right\} \qquad \text{(IV.36)}$$

Key: 1. reflected; 2. refracted

where $L_{1,2}=\ell_{1,2}\cos\phi$. The effect of the slope of the boundary, as was demonstrated above, can be considered by the set of observations when necessary.

Excluding the value of h from the last equation, we obtain

$$\left(t_{пр} - \frac{L_2}{v_г}\right)^2 = \left(t^2_{отр} - \frac{L^2_1}{v^2}\right)\left(1-\frac{v^2}{v^2_г}\right),$$

where two parameters are unknown; v and $v_{boundary}$. Either of them can be found if the other is known.

For the known value of the velocity of the covering medium, the boundary velocity is found

$$v_г = \frac{v}{C^2-1}\left(CD + \sqrt{D^2 - C^2 + 1}\right), \qquad \text{(IV.37)}$$

where

$$C^2 = \frac{v^2 \cdot t^2_{\text{пр}}}{v^2 \cdot t^2_{\text{отр}} - L_1^2}, \quad D^2 = \frac{L_2^2}{v^2 t^2_{\text{отр}} - L_1^2}.$$

For mass calculations it is expedient to use the nomogram in the coordinate system 1/C and $L_2/vt_{\text{refracted}}$ in which the lines with the parameter v_{boundary}/v will be straight lines.

If the boundary velocity is known, then the value of v is found by the formula

$$v^2 = \frac{v_\text{г}^2}{2}\left[F - E + 1 \pm \sqrt{(E - F - 1)^2 - 4F}\right], \qquad \text{(IV.38)}$$

where

$$E = \frac{\left(t_{\text{пр}} - \frac{L_2}{v_\text{г}}\right)^2}{t^2_{\text{отр}}}, \quad F = \frac{L_1^2}{v_\text{г}^2 \cdot t^2_{\text{отр}}}.$$

The plus sign is taken in front of the radical if subcritical reflections are used, and the minus sign, for reflections beyond the critical angle. For mass calculations it is possible to use the nomogram presented in reference [100].

For interpretation of the data by the series of soundings it is expedient to consider the combined time field of the reflected and refracted waves. For complete solution of the problem -- determination of the velocities v and v_{boundary} and construction of the section-- it is sufficient to have three lines ℓ_j=const: two for one of the waves and one for the other. One of the elastic parameters (v or v_{boundary}) will be found by the first two isolines. Then the above-discussed procedure can be used to determine the values of the second parameter. The depths are calculated by the usual procedures, preferably by the reflected wave data. The refracted waves are used for monitoring.

The combined procedure is especially effective when using transcritical reflections recorded on the same seismograms as the refracted wave from the given boundary. The sounding system includes only two bases. This procedure is widely used when investigating the foot of the earth's crust.

In addition to the reflected and refracted waves from one boundary, in the point sounding procedure longitudinal and exchanged (transmitted and refracted) waves are used, in particular for the construction of the basement surface of the platforms, usually characterized by significant elastic property gradient. The methods of determining the depths in this case are widely known [20, 90].

Refracted Waves. The field $t(x, \ell_j)$ is used to find the velocity distribution in the plane of the seismic section. The stratal velocities ($v_{stratal}$) and the corresponding depths of penetration of the seismic beam are determined, then the line field v_{π}=const is constructed by interpolation. In the case of relatively simple structure of the medium when the velocity depends basically only on the depth, it is possible to use strict or approximate methods of interpretation developed for the hodographs of the refracted waves. For a complex form of velocity isolines, special procedures are used.

Let us first consider the peculiarities of the first approach, considering within the limits of the maximum sounding base the lines of v_{π}=const to be straight with relatively small slope ϕ with respect to horizontal. By the time field it is expedient to construct not the ordinary hodographs, but the function $t(\ell)_{x=const}$ for a series of mixed profile points. The transition to this function permits to a significant degree the decrease in the distorting effect of the horizontal velocity gradient, for it is closer to the hodograph for the case of horizontal velocity isolines than the observed hodograph. Let us demonstrate this in the example of a linear variation of the velocity with respect to the x and c axes with gradients α and β by the law

$$v(x, z) = v_0(1 + \alpha x + \beta z)$$

Using the corresponding expressions from references [53, 54], after transformations we obtain

$$\Delta_1 = \frac{t_\varphi - t_{\varphi=0}}{t_{\varphi=0}} = \frac{\operatorname{arsh} \dfrac{\beta x}{2\sqrt{1 - \frac{1}{4}\beta^2 x^2 \operatorname{tg}^2 \varphi \cos \varphi}}}{\operatorname{arsh} \dfrac{\beta x}{2}} \cos \varphi - 1, \quad \text{(IV.39)}$$

$$\Delta_2 = \frac{t(l)_{x=\text{const}} - t_{\varphi=0}}{t_{\varphi=0}} = \frac{\operatorname{arsh} \dfrac{\beta x}{2\sqrt{1 - \frac{1}{4}\beta^2 x^2 \operatorname{tg}^2 \varphi \cdot \cos \varphi}}}{\operatorname{arsh} \dfrac{\beta x}{2}} \cdot \cos \varphi - 1. \quad \text{(IV.39')}$$

The first expression characterizes the relative divergence of the hodographs t_ϕ and $t_{\phi=0}$ for the cases $\alpha \neq 0$ and $\alpha=0$ (the remaining parameters are invariant), and the second expression characterizes the same divergence for the function $t(\ell)_{x=const}$. The point to which this function refers is matched to the oscillation source (x=0) for the investigated hodographs. In the given case $x=\ell$.

The graphs for the relative deviations are calculated by formulas (IV.39) (see Fig 51). The value of Δ_2 is appreciably less than Δ_1. Considering the value of β as the mean velocity gradient, by the graphs obtained it is possible to estimate the effect of the nonhorizontalness of the velocity

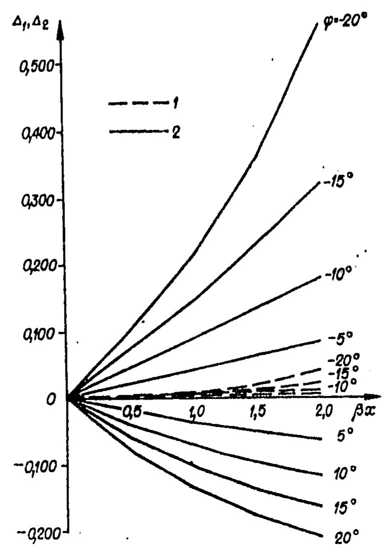

Figure 51. Graphs of the relative deviations of the times of the refracted wave:
1 -- for the function $t(\ell)_{x=const}$; 2 -- for the observed hodographs

isolines for the times $t(\ell)_{x=const}$ under specific conditions. Usually this effect is negligibly small for $\phi \leq 10°$. Thus, for the deep seismic sounding condition it is possible to set $\beta=0.01$ km^{-1}, $\phi=10°$, x=100 km. The corresponding value of Δ_2 is a total of only 0.002, which corresponds to the absolute divergence of about 0.03 sec. Consequently, by the function $t(\ell)_{x=const}$, just as by the hodograph, it is possible in many cases to determine the function v(z) without considering the horizontal velocity gradient.

For interpretation, the known strict Vikhert-Gerglotets-Chibisov procedure or the approximate procedures [42, 101, and so on] can be used. The application of the strict method is justified only in the case of sufficiently complete initial data. In the remaining, more widespread cases, the simpler approximate methods are more preferable, which under defined assumptions regarding the type of hodograph or the law of variation of the velocity will permit interpretation of incomplete hodographs and their elements.

If the slope of the velocity isolines exceeds 10°, consideration of the horizontal velocity gradient is needed. The strict solution of the problem of interpreting the time field of the refracted waves in this case was obtained only for the linear dependence of the velocity on the coordinates x and z [72]. On the basis of this solution, in the indicated paper an approximate procedure has been constructed for the successive approximation for the nonlinear velocity variation. The time field gradients are used for the calculations.

In a number of cases the velocity distribution in the medium within the limits of the maximum sounding base cannot be approximated with the required accuracy by the family of straight lines v_{π}=const. The vertical-block model is the frequently encountered form of this complex medium.[1] Under such conditions the distortions of the results obtained by the above-indicated methods of interpreting refracted waves will be less, the less the sounding base. It is possible to decrease the magnitude of the bases without loss of deepness of the reconnaissance artificially by successive recalculation of the observed time field for deeper levels, using the procedure substantiated in Chapter II, §2 for reducing the field to the new observation line for this purpose. The velocity distribution in the upper part of the section will be found by the soundings with small bases. The remaining lines ℓ_j=const are recalculated to the level above which the structure of the medium has been investigated. The process is repeated to achievement of the depths of penetration of the seismic lines corresponding to the maximum bases. It is inexpedient to make a large number of recalculations, for this can lead to an inadmissible accumulation of errors.

Consideration of the Effect of the Surface Nonuniformities. The surface nonuniformities, the effect of which must be considered during reconnaissance prospecting deep seismic studies, as a rule, are caused by failure to sustain the thickness and elastic properties of the sedimentary mantle, especially if it is complicated by terrigenic rock. The usual method of consideration consists in reduction of the arrival time of the deep waves to the level near the foot of the sedimentary layer (the surface of the folded or crystalline basement). The recalculation of the field $t(x, \ell_j)$ to this level is realized by the previously discussed method (Chapter II, §2).

Let us consider the procedures for considering the effect of the surface inhomogeneities and the possibility of their discovery when the structure of the upper part of the section is unknown, and only two isolines of the deep wave time field are given.

Above (Chapter II, §2) it was demonstrated that the surface inhomogeneities distort the isolines of the field $t(x, \ell_j)$ of the deep wave differently, which leads to distortions in the values obtained for the velocities (mean, boundary, stratal). The distortions of the velocities will be eliminated if the initial field is transformed so that the surface

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[1]The statement and the algorithms for the solution of the problem by the refracted wave hodograph system for a continuous-nonuniform medium were investigated in reference [11].

inhomogeneities will appear identically on both lines ℓ_j=const.

We shall consider that the following two conditions are satisfied: 1) the nondistorted isolines of the time field in the profile interval not exceeding with respect to extent the largest of the sounding bases can be approximated by straight lines. For constant velocities in the medium this condition corresponds to the local-plane refracting boundary and the reflecting boundary in the form of a segment of a hyperbola; 2) the propagation rate of the elastic properties in the upper nonuniform thickness are appreciably less than in the underlying rock. The satisfaction of the indicated conditions in practice is discussed in detail in reference [62]. If they are observed, then the equation of any isoline of the field with the base ℓ_j is written as follows:

$$t_j(x) = a_j + k_j x + \delta\left(x - \frac{l_j}{2}\right) + \delta\left(x + \frac{l_j}{2}\right), \qquad \text{(IV.40)}$$

where $t_j(x)$ is the observed value of the time, $t'_j(x)=a_j+k_jx$ is the undistorted time, $\delta(x)$ is the surface distortion.

Let us solve the problem: having two isolines of the observed field $t_1(x)$ and $t_2(x)$ let us transform the second isolines so that the effect of the inhomogeneities on it will be distributed just as the first isoline, that is, let us find

$$\tilde{t}_2(x) = t'_2(x) + \delta\left(x - \frac{l_1}{2}\right) + \delta\left(x + \frac{l_1}{2}\right).$$

For the sounding system in Fig 52, a, we shall have (the origin of the coordinates at the center of the system)

$$t_1\left(-\frac{l_2}{2}\right) = a_1 - k_1\frac{l_2}{2} + \delta\left(-\frac{l_2+l_1}{2}\right) + \delta\left(-\frac{l_2-l_1}{2}\right),$$

$$t_1(0) = a_1 + \delta\left(-\frac{l_1}{2}\right) + \delta\left(\frac{l_1}{2}\right),$$

$$t_1\left(\frac{l_2}{2}\right) = a_1 + k_1\frac{l_2}{2} + \delta\left(\frac{l_2-l_1}{2}\right) + \delta\left(\frac{l_2-l_1}{2}\right),$$

$$t_2\left(-\frac{l_1}{2}\right) = a_2 - k_2\frac{l_1}{2} + \delta\left(-\frac{l_2-l_1}{2}\right) + \delta\left(\frac{l_2-l_1}{2}\right),$$

$$t_2\left(\frac{l_1}{2}\right) = a_2 + k_2\frac{l_1}{2} + \delta\left(-\frac{l_2-l_1}{2}\right) + \delta\left(\frac{l_2+l_1}{2}\right).$$

Using these equations, we write the expression

$$t_2\left(-\frac{l_1}{2}\right)+t_2\left(\frac{l_1}{2}\right)-t_1\left(-\frac{l_2}{2}\right)+2t_1(O)-t_1\left(\frac{l_2}{2}\right)=$$
$$=a_2-k_2\left(\frac{l_1}{2}\right)+\delta\left(-\frac{l_2-l_1}{2}\right)+\delta\left(\frac{l_2-l_1}{2}\right)+a_2+k_2\frac{l_1}{2}+$$
$$+\delta\left(-\frac{l_2-l_1}{2}\right)+\delta\left(\frac{l_2+l_1}{2}\right)-a_1+k_1\frac{l_2}{2}-\delta\left(-\frac{l_2+l_1}{2}\right)-$$
$$-\delta\left(-\frac{l_2-l_1}{2}\right)+2a_1+2\delta\left(-\frac{l_1}{2}\right)+2\delta\left(\frac{l_1}{2}\right)-a_1-k_1\frac{l_2}{2}-$$
$$-\delta\left(\frac{l_2-l_1}{2}\right)-\delta\left(\frac{l_2-l_1}{2}\right)=2\left[a_2+\delta\left(-\frac{l_1}{2}\right)+\delta\left(\frac{l_1}{2}\right)\right].$$

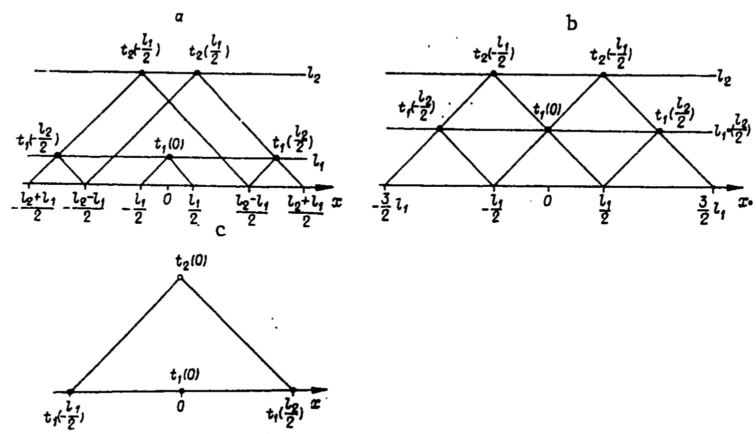

Figure 52. Sounding systems used for conversion of the time field in order to consider the surface distortions.

The expression in brackets is equal to the desired time $\tilde{t}_2(o)$. Inasmuch as the origin of the coordinates is selected arbitrarily, for any point of the profile we shall have

$$\tilde{t}_2(x)=\frac{1}{2}\left[t_2\left(x-\frac{l_1}{2}\right)+t_2\left(x+\frac{l_1}{2}\right)-t_1\left(x-\frac{l_2}{2}\right)+2t_1(x)-t_1\left(x+\frac{l_2}{2}\right)\right]. \quad \text{(IV.41)}$$

The transformation found is valid for any monotypic waves and can be realized both with respect to the time field constructed with the required detail and by the specially obtained time values corresponding to the sounding system in Fig 52.

The boundary and stratal velocities calculated by the transformed time fields of the refracted waves will not be distorted, for the time difference in the corresponding calculated formulas will not contain the surface distortions. In the case of reflected waves when calculating the velocity in the covering medium, the difference in squares of the times is used; therefore the effect of the nonuniformities is not completely excluded. If we represent the nonuniform part of the section as a bed of variable thickness, then by the transformed time field of the reflected wave, the effective velocity will be found for the two-layer medium in which the parameters of the upper layer are equal to the arithmetic mean of the values at the point $x-\ell/2$ and $x+\ell_1/2$.

The isolation of the surface distortions δx from the observed function field, which characterizes the "delay" time of the deep wave on passage through the upper nonuniform part of the section with reduced velocity is highly interesting.

Let us form the difference of the observed and the transformed times for the same base:

$$t-\tilde{t}=\delta\left(x-\frac{l_1}{2}\right)+\delta\left(x+\frac{l_1}{2}\right)-\delta\left(x-\frac{l_2}{2}\right)-\delta\left(x+\frac{l_2}{2}\right). \tag{IV.42}$$

The function $\delta(x)$ will be represented in the form of a power series

$$\delta(x)=c_0+c_1x+c_2x^2+c_3x^3+\ldots=c_0+c_1x+\Delta(x), \tag{IV.43}$$

where $\Delta(x)$ is the nonlinear part of the function.

After substitution of (IV.43) in (IV.42), we obtain

$$t-\tilde{t}=\Delta\left(x-\frac{l_1}{2}\right)+\Delta\left(x+\frac{l_1}{2}\right)-\Delta\left(x-\frac{l_2}{2}\right)-\Delta\left(x+\frac{l_2}{2}\right). \tag{IV.42'}$$

Consequently, the difference of the observed and transformed times will be determined only by the nonlinear part of the surface distortion function. Therefore the distribution of the surface distortions can be determined incompletely and with accuracy to its linear component.

Let us proceed to the spectral representation of the expression (IV.42')

$$S_{t-\tilde{t}}(\omega)=S_\Delta(\omega)\left(e^{-i\omega\frac{l_1}{2}}+e^{i\omega\frac{l_1}{2}}-e^{-i\omega\frac{l_2}{2}}-e^{i\omega\frac{l_2}{2}}\right)=$$
$$=2\left(\cos\omega\frac{l_1}{2}-\cos\omega\frac{l_2}{2}\right)\cdot S_\Delta(\omega),$$

where $S_{t-\tilde{t}}(\omega)$ and $S_\Delta(\omega)$ are the complex spectra of the functions $t-\tilde{t}$ and $\Delta(x)$. Let us find the spectrum of the nonlinear part of the surface distortions:

$$S_\Delta(\omega) = \frac{S_{t-\tilde{t}}(\omega)}{2\left(\cos\omega\frac{l_1}{2} - \cos\omega\frac{l_2}{2}\right)}.$$

By the inverse Fourier transformation, we obtain the desired distribution function of the nonlinear part of the surface distortions:

$$\Delta(x) = \frac{1}{4\pi}\int_{-\infty}^{+\infty} \frac{S_{t-\tilde{t}}(\omega)}{\cos\omega\frac{l_1}{2} - \cos\omega\frac{l_2}{2}} \cdot e^{i\omega x} d\omega. \qquad \text{(IV.44)}$$

This result can be considered as an indication of theoretical possibilities of obtaining the function Δx using the recordings of the waves from the deep boundaries. For the realization of this possibility it is necessary to develop convenient noiseproof calculation procedures. For the calculations by formula (IV.44), it is necessary to have the time difference function in the entire section where it is essentially different from zero. This means that the surface inhomogeneities available for discovery (their linear component) must have limited extent along the horizontal axis.

The investigated procedure for isolating the surface distortions can find application for discovery of the large peculiarities in the structure of the sedimentary layer by the recordings of the waves passing through it. The possibility of the solution of this problem is illustrated by the theoretical example (Fig 53) simulating the conditions of investigation of the Mohorovicic section by soundings of the refracted waves in the presence in the top of the graben section made up of rock with reduced velocity. By by the two "observed" lines ℓ=const the transformation of the line ℓ=200 km by the formula (IV.41) was carried out. Then the values of the surface distort-ions were found by the formula (IV.44). The obtained function $\delta(x)$ (see Fig 53, b) not containing a linear component in the given example is a mirror representation of the relief line of the lower surface of the graven and for known velocities in the medium can be recalculated to the seismic section.

Let us present the method of solving the problem of isolating the time distortions caused by the surface inhomogeneities for the case where there are more than two lines ℓ=const. Let us consider the case of three bases ℓ_1, ℓ_2 ℓ_3 (Fig 54). At the points with the numbers i+2, i+3, i+4 (the coordinates x_{i+2}, x_{i+3}, x_{i+4}) the nonuniformities on the base $\ell 2$ are recalculated to ℓ_1. At the point x_{i+3} the base ℓ_3 is recalculated to ℓ_2 and ℓ_1. Then we can write the system of equations of time differences $t-\tilde{t}$ at the indicated point and for the corresponding bases:

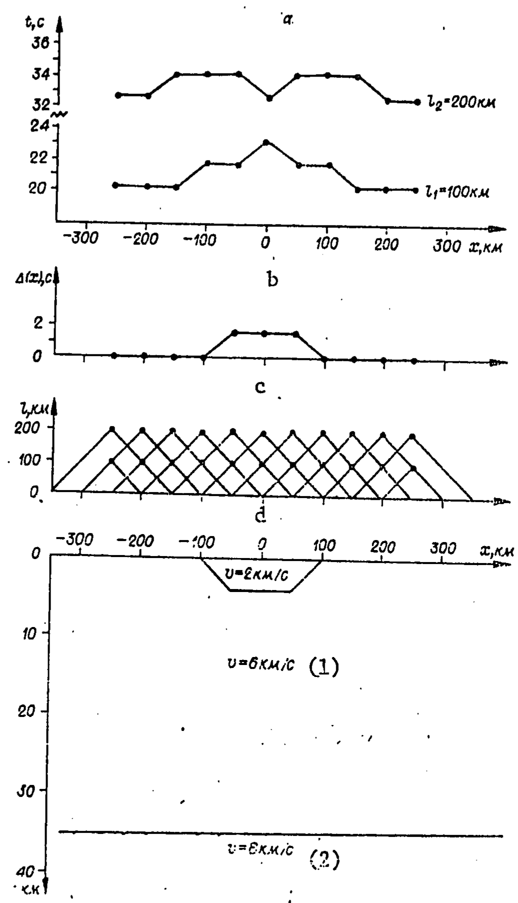

Figure 53. Theoretical example of determining the surface distortions for the soundings by refracted waves: a -- observed time field; b -- graph of the calculated values of the surface distortions; c -- observation system; d -- section

Key:
1. v=6 km/sec
2. v=8 km/sec

$$\delta(x_i) + \delta(x_{i+4}) - \delta(x_{i+1}) - \delta(x_{i+3}) = \Delta^{2,1}_{i+2},$$
$$\delta(x_{i+1}) + \delta(x_{i+5}) - \delta(x_{i+2}) - \delta(x_{i+4}) = \Delta^{2,1}_{i+3},$$
$$\delta(x_{i+2}) + \delta(x_{i+6}) - \delta(x_{i+3}) - \delta(x_{i+5}) = \Delta^{2,1}_{i+4},$$
$$\delta(x_i) + \delta(x_{i+6}) - \delta(x_{i+1}) - \delta(x_{i+5}) = \Delta^{3,2}_{i+3},$$
$$\delta(x_i) + \delta(x_{i+8}) - \delta(x_{i+2}) - \delta(x_{i+4}) = \Delta^{3,1}_{i+3}.$$

Here the double superscript indicates the number of the initial base (the first number), the nonuniformities on which are recalculated to the base with the corresponding number (the second number). In the given system only the first three equations having seven unknowns are linearly independent. For its solution, it is necessary to give the distortions at four points of the profile. Adding the corresponding equations for the points with the coordinates x_{i+5}, x_{i+6}, and so on to this system successively, we can find the distortions along the extended profile. In the special cases of the ratio of the sounding bases, the solution of the problem can be obtained also with a smaller number of points at which it is necessary to give the magnitudes of the distortion. In the case of $\ell_1=0$, it is necessary to give the distortions at two points, for $\ell_n=3\ell_1$, at three points.

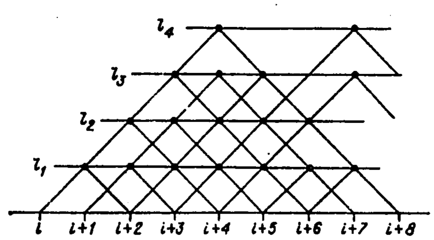

Figure 54. Isolation of the time distortions caused by the surface inhomogeneities. The case $\ell_n=n(\ell_1)$ (n is an integer) and $\ell_1\neq 0$

Area Observations

As has already been noted above (§1 of the given chapter), the area observation systems have several versions. Let us consider the peculiarities of the interpretation of the data in these cases.

Arbitrary Location of the Differently Oriented Soundings in the Area. A three-dimensional time field $t(x, y, \ell)$ is constructed by the set of data obtained, which is represented in the form of two isochron maps for the attached values of the bases. Here x and y are the x-axes of the sounding centers to which the times t are referred; ℓ is the sounding base. Neglecting the dependence of the time on the base orientation, by the above-presented formulas for the two-dimensional case the area distributions of depths and the velocities are found (boundary, in the case of refracting waves, effective, for reflected waves), which are considered the first approximation subject to more precise definition. If the ambiguity of the time field (dependence on the azimuths without soundings) is caused primarily by the effect of the configuration of the reflecting or the refracting boundary, the required more precise definitions can be obtained as a result of the successive correction of the initial field by introduction of corrections taking into account the noncoincidence of the sounding bases with some defined correction, for example, the decrease or extension of the boundary (Chapter II, §2, formulas (IV.51) and (IV.53)). If (in the case of the refracted waves) the effect of the variability of the boundary velocity predominates, then by using the results of the first approximation, the source and the receiver of each sounding are carried over to the refracting surface. By the values obtained for the times of sliding wave, the boundary velocities are calculated in the corresponding azimuths, and the depth distribution is more precisely defined. This process is repeated until the converging values are obtained.

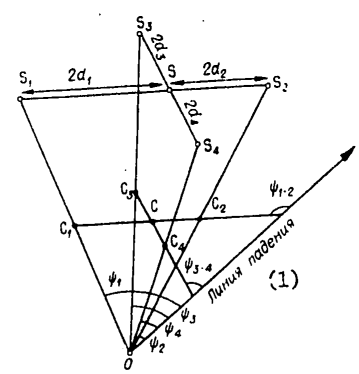

Figure 55. Spatial system of four soundings with one source

Key:

1. Incidence line

Area Systems of Profile Elements. The area systems of profile elements permit more correct interpretation of the data not neglecting the azimuthal relations of the time field, which is especially important when using refracted waves under the conditions of sharply variable boundary velocity. Using the time values and the time gradients, which are determined by each profile element (see §1 of this chapter), by the formulas for the two-dimensional model the depth, velocity (boundary or average) and slope of the boundary in the plane of the seismic beam for the given element are calculated. Then the area constructions are realized by the set of data for all the elements.

Area System of Sounding Profiles. The two-dimensional time fields obtained by each profile are interpreted by ordinary methods. Inasmuch as these observations frequently are given for investigations of increased detail, quite dense sounding systems are developed in them which permit application of the strictest method of interpretation. Thus, when using the refracted waves, it is preferable to recalculate the observed field to the bases which are close with respect to magnitude to the x-axis of the initial point of the head wave or to $\ell=0$, offering the possibility of finding the two-dimensional distribution of the depths and the boundary velocities with high detail.

The area system with one source is convenient for operations with industrial blasts than inaccessible terrain.

The simplest system made up of one source 0 and four receivers S_1, S_2, S_3 and S_4 with the times of arrival of the wave t_1, t_2, t_3 and t_4 is depicted in Fig 55. Rigid conditions are not imposed on the location of the oscillation receivers. They are located in the region of certain tracing of the given waves so that the point S of intersection of the straight lines S_1S_2 and S_3S_4 is within the interval S_1, S_2, possibly closer to its center. The recordings of the reflected and refracted waves are interpreted under the assumption of a plane boundary and constant velocities (v and $v_{boundary}$) in the upper and lower media. The values of the velocities and the elements of occurrence of the boundary are found. Let us note the derivation of the calculated formulas (a detailed substantiation of them is presented in reference [48]).

In the case of reflected waves, the relations (II.18) and (II.21) were used, and we write the expressions for the times of arrival at the points S_1, S_2, S_3 and S_4

$$\left.\begin{aligned}
v^2t_1^2 &= 4(h - d_1\cos\psi_{1-2}\sin\varphi)^2 + l_1^2(1 - \cos^2\psi_1\sin^2\varphi),\\
v^2t_2^2 &= 4(h + d_2\cos\psi_{1-2}\sin\varphi)^2 + l_2^2(1 - \cos^2\psi_2\sin^2\varphi),\\
v^2t_3^2 &= 4(h - d_3\cos\psi_{3-4}\sin\varphi)^2 + l_3^2(1 - \cos^2\psi_3\sin^2\varphi),\\
v^2t_4^2 &= 4(h + d_4\cos\psi_{3-4}\sin\varphi)^2 + l_4^2(1 - \cos^2\psi_4\sin^2\varphi),
\end{aligned}\right\} \quad \text{(IV.45)}$$

where h is the depth with respect to the normal to the boundary under the point C, ϕ is the true angle of incidence, ψ is the azimuth of the individual soundings. The remaining notation is illustrated in Fig 55.

By the values of t_1^2, t_2^2 and t_3^2, t_4^2, by linear interpolation we find the squares of the times $\tilde{t}_1^2$ and $\tilde{t}_2^2$ for the point S.

$$\left.\begin{aligned}\tilde{t}_1^2 &= \frac{t_1^2 d_2 + t_2^2 d_1}{d_1 + d_2},\\ \tilde{t}_2^2 &= \frac{t_3^2 d_4 + t_4^2 d_3}{d_3 + d_4}.\end{aligned}\right\} \qquad \text{(IV.46)}$$

The corresponding interpolated squares of the bases will be:

$$\left.\begin{aligned}\tilde{l}_1^2 &= \frac{l_1^2 d_2 + l_2^2 d_1}{d_1 + d_2},\\ \tilde{l}_2^2 &= \frac{l_3^2 d_4 + l_4^2 d_3}{d_3 + d_4}.\end{aligned}\right\} \qquad \text{(IV.46')}$$

On the basis of the recorded relation, the expression is found for the velocity in the covering medium.

$$v^2 = \frac{\tilde{l}_1^2 - \tilde{l}_2^2}{\tilde{t}_1^2 - \tilde{t}_2^2} - \frac{\sin^2\varphi}{\tilde{t}_1^2 - \tilde{t}_2^2}\left(\frac{l_1^2 d_2 \cos^2\psi_1 + l_2^2 d_1 \cos^2\varphi_2}{d_1 + d_2} - \frac{l_3^2 d_4 \cos^2\psi_3 + l_4^2 d_3 \cos^2\psi_4}{d_3 + d_4} + d_1 d_2 \sin^2\psi_{1-2} - d_3 d_4 \sin^2\psi_{3-4}\right). \qquad \text{(IV.47)}$$

In this formula the first term can be considered as the main part of the solution, and the second term, as the correction which can be found after determination of the first approximation of the value of v and the elements of occurrence of the boundary. The correction contains the factor $\sin^2\phi$, for small slope angles close to zero. Therefore under the conditions of gently sloping structures, it is admissible to neglect the correction term and perform the calculations by the simple formula

$$v \approx \sqrt{\frac{\tilde{l}_1^2 - \tilde{l}_2^2}{\tilde{t}_1^2 - \tilde{t}_2^2}}. \qquad \text{(IV.47')}$$

The depths h_1, h_2, h_3 and h_4 under the sounding centers C_1, C_2 and C_3, C_4 will be found by the ordinary procedure by formula (IV.22). The determination of the remaining elements of occurrence is conveniently made graphically by the depth gradients G_1 and G_2 in the directions C_1, C_2 and C_3, C_4.

$$G_1 = \frac{h_2 - h_1}{d_1 + d_2}, \quad G_2 = \frac{h_4 - h_3}{d_3 + d_4}.$$

The direction of the complete vector G will determine the azimuth of incidence, and its value, the true slope angle of the boundary $\phi = \arcsin G$. When necessary ($\phi > 10°$) the following approximations are made also for the elements of occurrence.

For refracted waves the times of arrival will be represented in the form:

$$t_1 \simeq \frac{2}{v}(h - d_1 \cos\psi_{1-2} \sin\varphi)\cos i + \frac{l_1}{v_r} - \frac{l_1}{2v_r}\cos^2\psi_1 \sin^2\varphi,$$

$$t_2 \simeq \frac{2}{v}(h + d_2 \cos\psi_{1-2} \sin\varphi)\cos i + \frac{l_2}{v_r} - \frac{l_2}{2v_r}\cos^2\psi_2 \sin^2\varphi,$$

$$t_3 \simeq \frac{2}{v}(h - d_3 \cos\psi_{3-4} \sin\varphi)\cos i + \frac{l_3}{v_r} - \frac{l_3}{2v_r}\cos^2\psi_3 \sin^2\varphi,$$

$$t_4 \simeq \frac{2}{v}(h + d_4 \cos\psi_{3-4} \sin\varphi)\cos i + \frac{l_4}{v_r} - \frac{l_4}{2v_r}\cos^2\psi_4 \sin^2\varphi.$$

In these expressions the terms with sin ψ to the fourth or higher powers are omitted.

Let us determine the interpolated time and bases at the point S.

$$\tilde{t}_1 = \frac{t_1 d_2 + t_2 d_1}{d_1 + d_2}, \quad \tilde{t}_2 = \frac{t_3 d_4 + t_4 d_3}{d_3 + d_4}, \quad \tilde{l}_1 = \frac{l_1 d_2 + l_2 d_1}{d_1 + d_2}, \quad \tilde{l}_2 = \frac{l_3 d_4 + l_4 d_3}{d_3 + d_4}.$$

Executing the same operations in the case of reflected waves, we obtain the formula for the boundary velocity

$$v_r \simeq \frac{\tilde{l}_1 - \tilde{l}_2}{\tilde{t}_1 - \tilde{t}_2} - \frac{\sin^2\varphi}{2(\tilde{t}_1 - \tilde{t}_2)}\left(\frac{l_1 d_2 \cos^2\psi_1 + l_2 d_1 \cos^2\psi_2}{d_1 + d_2} - \frac{l_3 d_4 \cos^2\psi_3 + l_4 d_3 \cos^2\psi_4}{d_3 + d_4}\right). \quad \text{(IV.48)}$$

The boundary velocity is calculated initially by the firat approximation formula

$$v_r \approx \frac{\tilde{l}_1 - \tilde{l}_2}{\tilde{t}_1 - \tilde{t}_2}, \quad \text{(IV.48')}$$

and the elements of occurrence are calculated. Then, just as for the reflected waves, the correction is introduced to the velocity equal to the second term in the righthand side of equation (IV.48).

Use of the Dynamic Characteristics of the Oscillations

In Chapter II, §3, a discussion is presented of the general peculiarities of using the wave dynamics in the method of spot soundings for determination of the parameters of the medium, and the expediency of investigating the magnitude of the ratio of the like dynamic characteristics of two reference waves for the set of soundings with fixed bases is substantiated.

Let us consider the standard case corresponding to the conditions of investigation of the Mohorovicic discontinuity on the continent. The refracted waves and the waves reflected at a critical angle are recorded simultaneously from this discontinuity on the soundings with bases of about 200 km. For the indicated conditions let us investigate the dependence of the magnitude of the amplitude ratio of the oscillations of the reflected and refracted waves ($A_{reflected}/A_{refracted}$) on the properties of the medium. Without resorting to significant complication of the model of the medium, let us estimate the effect of the absorption, the amount of discontinuity of the elastic parameters in the boundary, the layering of the covering series and the vertical velocity gradient under the Mohorovicic discontinuity.

The calculations of $(A_{refracted}/A_{reflected})_{t=200\ km}$, carried out by the beam method for a model of a one-layered or multilayered earth crust (see Fig 56), lead to the following estimates. The transition from the single-layer to the multilayer (in the given example four-layer) model is accompanied by an insignificant decrease in the magnitude of the investigated ratio (curves I and II in Fig 56). The absorption has a somewhat bigger influence: the variation of the absorption coefficient from zero t9 $1.7\cdot10^{-2}$ km^{-1} for series of the earth's crust and to $8\cdot10^{-3}$ km^{-1} for the tops of the mantle, decreases the ratio of the amplitudes by approximately 2-3 times. The variation of the velocity under the Mohorovicic discontinuity from 7.5 to 8.5 km/sec with the corresponding change in the other elastic parameters changes the investigated value by no more than 2 times. The introduction of the vertical velocity gradient (β) in the tops of the mantle offers an unjustifiably high effect. With an increase in β from 0 to 0.002 km^{-1}, the amplitude ratio of the reflected and the refracted waves decreases by approximately 100 times. Consequently, out of all of the investigated factors the predominant one is the velocity gradient in the mantle.

On the basis of the results obtained, it is possible to propose the following procedure for using the amplitude ratio of the reflected and refracted waves from the Mohorovicic discontinuity. The model of the medium is determined by the kinematic characteristics of the waves. For this model, the direct dynamic problem is solved with variation of the vertical velocity gradient at the tops of the mantle. By comparing the average experimental values $(A_{reflected}/A_{refracted})_{\ell=const}$ with the theoretically calculated values, the magnitude of the gradient is estimated.

Let us illustrate this procedure in the example of the Western Siberian lowland, where mass data were obtained on the amplitudes of the reflected and refracted waves from the Mohorovicic discontinuity for soundings with bases of about 200 km. Over the greater part of the investigated territories the amplitude ratio usually is from 1.5 to 10 and is on the average equal to 4. The anomalous, sharply increased values of $(A_{reflected}/A_{refracted})_{\ell=200\ k}$ with a mean value of 26 and a range of variation of 10-50 parts of the Western Siberian lowland, in the vicinity of the cities of Omsk, Ishim, Tobol'sk (see Fig 43, a, b). With respect to their appearance the anomalous recordings are not connected with the service conditions and variations of the internal structure of the earth's crust, for a single amplitude ratio

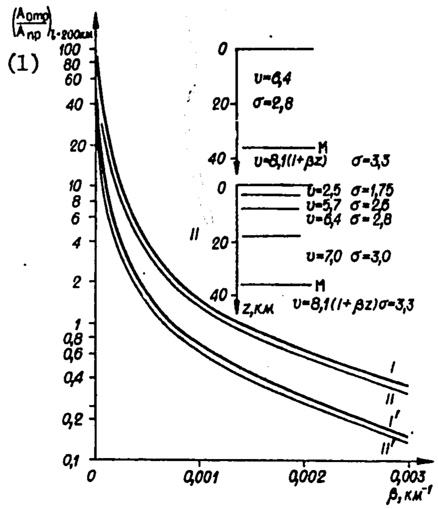

Figure 56. Models of the medium and the dependence of the amplitude ratio of the reflected and refracted waves for the Mohorovicic discontinuity (ℓ=200 km) as a function of the vertical velocity gradient in the tops of the mantle. I and II -- curves for models without absorption, I' and II' -- with absorption (the absorption coefficient in the earth's crust is $1.7 \cdot 10^{-2}$ km^{-1}, and in the mantle, $8 \cdot 10^{-3}$ km^{-1}), v is the velocity of the longitudinal waves, km/sec; $v_p/v_s=\sqrt{3}$; ρ is the density, g/cm^3.

Key:

1. $A_{reflected}/A_{refracted}$

of the investigated waves was obtained in sections with different structure of the crust. A comparison of the experimental values with the theoretical calculated graphs of the amplitude ratio (see Fig 56) leads to the following estimates of the velocity gradient in the mantle. The "normal" values $(A_{reflected}/A_{refracted})_{\ell=200\ km}$ corresponds to the gradient β=0.00025-0.0005 km^{-1}, which indicates an increase in the velocity by 2-4 m/sec per km of depth. In sections with anomalously high amplitude ratio the velocity in the first mantles increases with depths very slowly or remains invariant ($\beta<0.0001$ km^{-1}). The presented values pertain to the most uppermost layer of the mantle 1-2 km thick. The above-obtained values of the velocity gradients and their differences are very small. In practice they cannot be discovered by the kinematic characteristics of the waves, but they appear noticeably in their dynamic peculiarities.

In the case of low-detail investigations under the conditions of media with weak differentiation of the elastic properties often difficulties arise in determining the type of longitudinal waves recorded in the first arrivals.

By the field $t(x, \ell_j)$ or by the dotted hodographs, it is not always possible to solve the problem reliably as to whether these waves are refracted in the medium with continuous increasing velocity. In this case it is expedient jointly to consider the longitudinal wave and the corresponding exchanged (transverse at the output) wave from the same boundary. The fact of existence of the exchanged wave (refracted, transmitted) indicates the presence in the section of a relatively sharp boundary. An example of the use of this phenomenon can be the work in the vicinity of the Kuznetsk depression [52, 74]. Here quite intensive exchanged waves indicating the probable existence of a sharp seismic boundary (the surfaces of crystalline basement of the trough) at a depth of about 10 km were recorded on the horizontally oriented seismographs.

The development of the methods of direct dynamic problems, by all appearances, will permit expansion of the possibilities of using the dynamic characteristics of the longitudinal and the exchanged waves recorded on one seismogram, obtaining the additional quantitative data on the fine structure of the deep seismic discontinuities; distinguishing of the boundaries with discontinuity of the elastic parameters, the transition waves, bunches of thin layers and other information about the medium.

§4. Construction of the Seismic Sections by a Set of Data

Based on the experience in applying the method of spot soundings during reconnaissance prospecting studies in Siberia, let us consider the peculiarities of the interpretation of the entire set of seismic materials (the waves of different types from different boundaries) calling on the data of other geophysical methods. For convenience of the discussion let us divide the interpretation process into individual elements. It is necessary to consider that in the sounding procedures the individual interpretation elements (discrete wave correlation, determination of the depths and velocities, compilation of the sections with respect to the set of all data) are not isolated steps, but they are closely interconnected.

Construction of Seismic Boundaries

Initially the uppermost of the investigated boundaries -- the basement surface (Φ), separating the upper, as a rule, most nonuniform part of the section (the sedimentary layer) from the consolidated earth's crust, is constructed. In addition to the large independent value, the exact knowledge of the position of this boundary is needed when analyzing deep waves and determination of the parameters of the under-lying part of the medium.

The basement surface in the majority of cases is studied by soundings of refracted (quasihead) waves recorded in the first arrivals. Here, in order to decrease the effect of the averaging of the parameters of the media on the sounding base characteristic of head waves, in the complex sections recalculation of the time field to the bases close to the x-axis of the initial point of the head wave is used.

The basement, especially its upper part, about 10 km thick, is highly complex and not uniform with respect to elastic properties in the medium with which quite complex and variable wave fields are quite often connected. Therefore usually it is insufficient to interpret the seismic materials pertaining to the surface of the basement in an isolated fashion, separate from the study of its internal structure. It is expedient jointly to investigate the time fields for the waves connected both to the surface Φ and penetrating the basement. In Fig 57, a, the time field of the first waves is presented for the Irtysh traverse in the Western Siberian lowland. On the soundings with bases of 16 and 23 km the refracted wave from the Φ boundary is recorded everywhere. For large bases, the first waves have a different nature in the different sections. This is established when comparing the barriers of the velocity determined at the fixed points of the profile by different isolines of the field. On the edges of the traverse, the velocity in practice does not vary with an increase in the bases, and it is 6.0-6.1 km/sec. In the midpart of the traverse, an increase in the values of the velocity is noted from 5.4-5.6 to 6.1-6.2 km/sec, which indicates the appearance of the refracted wave from the deeper boundary I in the first arrival. On the constructed seismic section (see Fig 57, b), the block structure of the medium is discovered with the presence in the midsection of the traverse in the composition of the basement of thick (to 5 km) series with relatively low (5.4-5.7 km/sec) velocity.

In order to study the surface of the basement, along with the refracted waves, reflected and exchanged waves are used. The reflections from the Φ boundary and the boundaries close to it will permit us to obtain important information about the velocity and the covering medium and about the parts of the structural relief, especially in the complicatedly constructed sections. Using the exchanged waves (the PPS type refracted and transmitted waves) gives additional information about the depths of occurrence of the D boundary. The observations of the exchanged waves at the points with known depth to the exchange boundary and the average velocity of the longitudinal waves are used for more precise determination of the velocity of the transverse waves in the covering medium. In addition, the fact of recording the intense exchanged waves under defined conditions can be considered as an indication of a sharp, and not a smooth variation of the elastic properties on transition through the exchange boundary.

When constructing the boundaries in the consolidated crust and on the M surface it is necessary, even in the reconnaissance prospecting phase, to consider the influence of the horizontal nonhomogeneity of the medium. The calculation is made in two procedures. Initially, as has already been noted, the times of the deep waves are reduced to the foot of the sedimentary layer, which is usually the most nonuniform. Then by the corrected times, the velocities in the consolidated part of the section are found. The horizontal variations of these velocities to a significant degree are controlled by the block structure of the medium. Therefore the averaging of the velocity values used to calculate the depths is expediently carried out within the limits of the large uniform blocks.

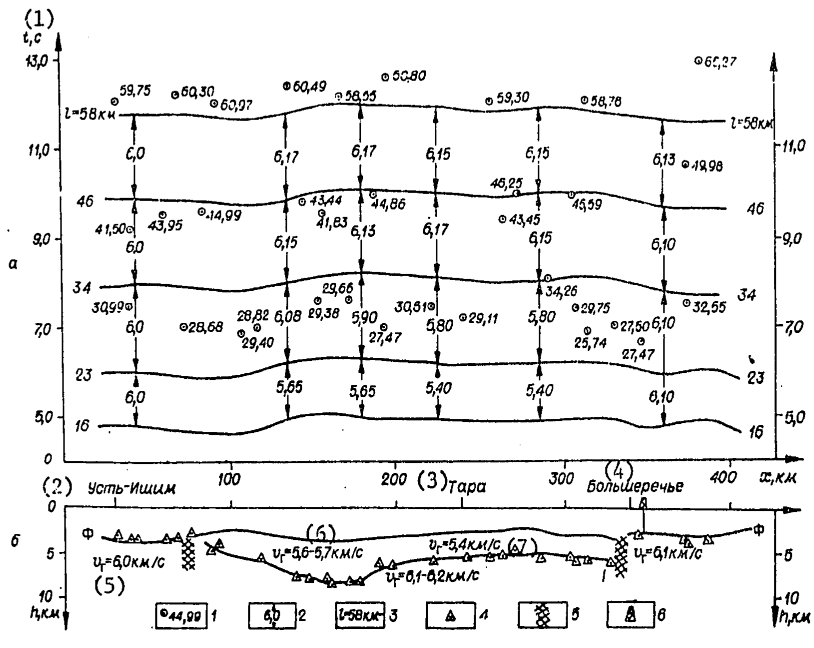

Figure 57. Example of the interpretation of the time field in the first arrivals along the Irtysh traverse (Western Siberia):

a -- time field; b -- section. 1 -- values of the times with indication of the sounding base (in km); 2 -- vertical gradient of the time field; 3 -- isolines of the time field; 4 -- depths according to the refracted wave data; 5 -- fracture zones; 6 -- boreholes

Key:

1. t, sec
2. Ust'-Ishim
3. Tara
4. Vol'sherech'ye
5. $v_{boundary}$=6.0 km/sec
6. $v_{boundary}$=5.6-5.7 km/sec
7. $v_{boundary}$=5.4 km/sec

The construction of the M boundary usually is carried out both by the reflected and by the refracted waves. Here preference, especially in the sections of sharp variation of depths, is given to the reflected waves. The data for the refracted waves are used as control data. In order to decrease the effect of the curvilinearity of the refracting boundary the calculation of the depths by the data for the refracted waves is expediently realized by the lines ℓ=const recalculated for the values close to the x-axis of the initial point.

Peculiarities from the Discovery of Velocity Distribution Anomalies

The information about the velocity distribution in the earth's crust in the tops of the mantle, as has already been noted, is no less important than the information about the configuration of the seismic boundaries. In order to insure the required accuracy of determining the velocities it is necessary to have sufficient magnitude of the difference of the sounding bases, the methods of evaluation of which are discussed above. The detail of the study of the velocity distribution along the traverses, especially when using head waves, depends on the sounding bases used. Therefore in order to discover the relatively nondrawn out anomalies of the boundary velocity it is necessary to use the data on soundings with the smallest possible bases or to decrease them artificially by the corresponding recalculation of the refracted wave time field.

In individual cases, there can be no direct data on the nonuniformities of the upper part of the section. In such situations consideration of their effect when determining the velocities can be given by preliminary transformation of the field $t(x, \ell_j)$ with redistribution of the effect of the surface inhomogeneities (Chapter II, §2).

The block structure of the earth's crust can lead to nonobservation of the assumptions of the model of the medium used as the basis for the methods of determining the velocities. Therefore the most reliable are the results obtained by the soundings within the limits of one block. For small dimensions of the blocks it is expedient to determine the velocities by the soundings specially oriented with respect to the strike of the block.

The effective criterion when estimating the reliability of the data on the velocities is convergence of the results obtained by the waves of different types. Thus, when studying the Mohorovicic discontinuity by the reflected or refracted waves the boundary velocity on the surface of the mantle can be found both by the time field of the refracted waves and with the joint use of refracted and reflected waves from this boundary. As an example of such determinations with sufficiently high convergence of the results we have the data on the Baykal region (Chapter V), by which the region was discovered reliably with anomalously low (7.7-7.8 km/sec) velocity on the surface of the mantle within the limits of the Baykal rift zone and on the adjacent territory.

Isolation of the Blocks of the Earth's Crust and Deep Fractures

The fracture-block structure of the earth's crust is caused by the following peculiarities, sufficiently reliably established during the reconnaissance prospecting operations by the procedure of spot seismic soundings. In the extended (about 100 km) or more) sections of the profiles of the depth of occurrence of the seismic boundaries, the thickness of the earth's crust, the broken nature of its fracturing into individual layers, the thickness of these layers and the velocities of the elastic waves vary little.

In the narrow articulation zones of such sections, as a rule, manifested with respect to the entire thickness of the consolidated crust the mentioned parameters vary sharply. Frequently these zones are used as the tracing boundaries of certain seismic surfaces inside the earth's crust. The amplitudes of the sharp variations of the relief of the seismic boundaries (in the form of flexures or discontinuities) usually are 3-7 km. The thickness of the layers can vary still more. The discontinuities of the boundary velocity at the basement surface reach 0.5-1 km/sec. In certain cases the values of the mean and the stratal velocities vary noticeably.

The sections with sustained structure of the depths are considered as blocks of the earth's crust. In the articulation zones of the blocks, in all probability the large deep fractures have been developed, many of which penetrate the entire body of the crust and, possibly, the tops of the earth's mantle. The majority of deep fractures were manifested in the gravitational and magnetic fields in the form of extended zones of intensive positive magnetic anomalies, gravitational "steps" and shifting of the structure of the anomalous fields. This permits more certain isolation of the zones of probable deep fractures and routing of them to a significant distance from the seismic traverses. The study of the discovered zones of deep fractures must become one of the main problems of subsequent detailed studies.

CHAPTER V. SPOT SOUNDINGS AND OTHER TYPES OF DEEP SEISMIC STUDIES

The procedure of spot soundings and the traditional forms of deep seismic studies (continuous, dashed and dotted profiles) do not contradict each other. They must be efficiently combined with consideration of the specific problems and the conditions of performing the operations. This combination will be natural if we assume the above-investigated principle of the staged nature of the studies. In addition, in the reconnaissance prospecting phase of the operations it can turn out to be expedient to complete various types of deep seismic studies.

A comparison of the spot seismic soundings with other types of seismic studies has been undertaken to estimate the possibilities of a new procedure, the accuracy of the results obtained and also to discover the economic expediency of its application during operations of varying detail.

§1. Testing the Sounding Procedure Using Continuous Profiling Data and Comparison with the Drilling Data

The test discussed below was undertaken in order to estimate the possibilities of a new procedure and accuracy of the results obtained regarding the structure of the basement surface and deeper sections. The testing was carried out in a number of regions characterized by various surface and deep conditions: sections of the ancient Russian platform, the Ukrainian shield, the young platforms (Turanskaya and Western Siberian), exposed regions of the Hercinian (Central Urals) and alpine (Carpathians) folding. In these areas the KMPV refracted wave method and deep seismic sounding profiles which have been investigated in detail were selected. The observation systems were compiled by these materials to simulate the operations by the procedure of spot seismic soundings.

The testing of the sounding procedure began with investigation of the materials (the hodographs, the seismogram montages) for one and two blast points characterizing the standard conditions. These materials replace the results of the parametric observations required to familiarize with the conditions of the new area. Then sounding systems were compiled which were calculated primarily to study the roof and the foot of the consolidated crust. The data from each sounding were simulated by one seismogram at the required distance from the source. In all cases no more than 10% of the total number of continuous profiling seismograms were used. In spite of the relatively high detailing of the initial observation systems, in the majority of cases it was not possible to achieve complete simulation of the operations by the sounding procedure. The sounding systems obtained did not have sufficient uniformity and density of the work, which led in a number of cases to the data on the structure of the medium schematically obtained by them.

A comparison with the drilling results over a quite large volume was made for the basement surface of the Western Siberian platform.

Western Siberian Platform

Here the results of the studies of the basement surface were estimated in a number of sections, and the data on the structure of the entire thickness of the earth's crust by the deep seismic sounding profiles south of the city of Barabinsk were evaluated.

A comparison of the depths with respect to the basement surface with the drilling data was made both for the sounding systems used during the operations in the Tyumen' Oblast providing for recalculation of the observed refracted wave times to the time t_0 (the systems E and B in Fig 23) and for the arbitrary systems of spot soundings by the refracted wave.

The mass comparison (with respect to 47 wells) of the data by the E and B systems was made in the Shaimskiy Rayon and on the traverse along the Konda and Irtysh Rivers. In the Shaimskiy Rayon, in the vicinities of the Tolumskoye and Severo-Teterevskoye uplift, the drilling of the wells was carried out after completion of the sounding operations. Very high convergence of the results was obtained (see Table 2): the mean square error is ± 40 m, that is, about 2% of the depth of occurrence of the basement.

In the broad Ob' region of Priob'ye where the basement occurs deeper (2.5-3.1 km), the mean square divergence of the depths with ten wells for the same sounding systems was ± 72 m or 2.6% [119].

A comparison of the depths with respect to the data from arbitrary sounding systems using refracted waves and drilling made at several dozen points in the areas with an average thickness of the platform mantle of about 3 km gave a mean square error of ± 110 meters or 3.5%. Some increase in errors, apparently, is caused by the effect of the errors in determining the distances and thus complete (by comparison with the operations in the Tyumen' Oblast) consideration of the distortions introduced by the surface and deep nonuniformities.

Table 2

Comparison of the depths to the basement surface by the data from spot sounding using the refracted wave method with the drilling results in the Tyumen' Oblast

Скважина (1)	Глубина фундамента по бурению $h_б$, м (2)	Глубина фундамента по ТЗ-МПВ $h_з$, м (3)	Различие глубин $\|h_з - h_б\|$, м (4)	Относит. погрешность $\frac{h_б - h_з}{h_б}$, % (5)
(6) Маршрут по рекам Конда и Иртыш				
Р-13	1603	1605	2	0,1
(7) Р-4	1496	1480	16	1,07
Р-11	1437	1436	1	0,0
Р-3	1389	1405	16	0,15
Р-2	1355	1359	4	0,3
Р-5	1383	1417	34	2,46
Р-36	1421	1435	14	1,0
Р-33	1493	1471	22	1,5
Р-102	1781	1764	17	1,0
(8) Р-1 (Леуши)	1907	1980	73	3,88
(9) Р-1 (Нахрачи)	2619	2513	106	4,04
(10) Р-1 (Фролы)	3157	3210	53	1,7
(11) Шаимский район				
(12) *Толумское поднятие*				
1	1725	1720	5	0,3
3	1659	1720	61	3,5
4	1672	1746	74	4,2
5	1710	1759	49	2,8
6	1718	1670	48	2,7
7	1666	1632	34	1,9
11	1700	1676	24	1,4
12	1720	1650	70	3,9
13	1646	1700	54	3,1
14	1757	1742	15	0,8
15	1780	1770	10	0,5
16	1753	1795	42	2,3
17	1746	1763	17	0,9
18	1668	1690	22	1,3
19	1668	1740	72	4,1
20	1742	1720	22	1,2
24	1740	1640	100	5,6
25	1738	1735	3	0,2
(13) *Северо-Тетеревское поднятие*				
371	1671	1670	1	0
368	1654	1600	54	3,1
168	1627	1600	27	1,6
161	1622	1625	3	0
367	1584	1540	44	2,7
386	1599	1590	9	0,5
377	1575	1580	5	0,3
362	1608	1600	8	0,5
267	1567	1580	13	0,8
268	1595	1600	5	0,4
351	1575	1580	5	0,4
352	1650	1610	40	2,3
146	1605	1600	5	0,3
147	1580	1590	10	0,6
366	1650	1690	60	3,5
(14) *Семивидовское поднятие*				
3	1707	1670	37	2,0
8	1757	1715	42	2,3

Key:

1. Well
2. Depth of basement by drilling h_b, meters
3. Depth of basement by the TZ-MPV refracted wave method h_3, m
4. Difference in depths $|h_3 - h_b|$, meters
5. Relative error
6. Traverse along the Konda and the Irtysh Rivers
7. R- ...
8. R-1 (Leushi)
9. R-1 (Nakhrachi)
10. R-1 (Froly)
11. Shaimskiy Rayon
12. Tolumskoye uplift
13. Severo-Teterevskoye uplift
14. Semividovskoye uplift

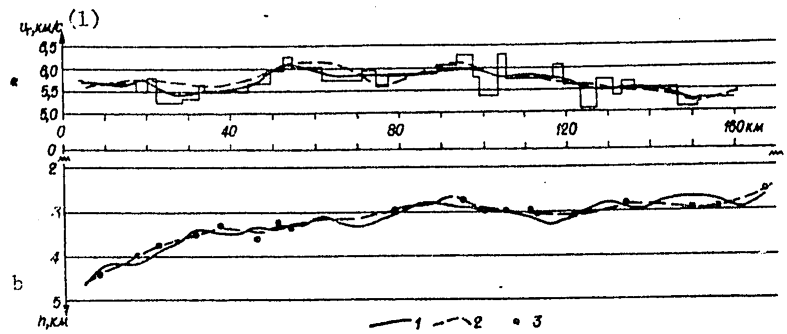

Figure 58. Comparison of the results of the correlation method of refracted waves and spot soundings in the vicinity of Tarskoye Priirtysh'ye (Western Siberia)
a -- graphs of the boundary velocity $v_{boundary}$: 1 -- for averaging of the results of the KMPV refracted wave method (stepped line) on a 10 km base, 2 -- average graph with respect to the spot sounding data; b -- seismic section: 1 -- according to the KMPV data, 2 -- according to the spot sounding data, 3 -- depths to the basement surface by soundings.

Key:
1. $v_{boundary}$, km/sec

Comparison with the KMPV Refracted Wave Method Data. The boreholes reveal the basement in the investigated region primarily in the uplift zones, and therefore the results of the comparison made above can turn out to be insufficient for the characteristics of the possibilities of the sounding procedure in the deep trough zones of the basement surface accompanied by the appearance of new series in the lower parts of the platform section. Accordingly, comparisons were made with the results of the detailed profile KMPV operations in the vicinity of Central Priob'ye [119], Tarskoye Priirtysh'ye [47] and in other sections with deep (4 km or more) downwarps of the basement surface. In all cases in the sections obtained by the sounding data, all of the significant peculiarities of the surface relief of the basement and distributions of the boundary velocity on the surface isolated with respect to the KMPV research results are recorded.

Thus, in the standard profile in the vicinity of Tarskoye Priirtysh'ye (Fig 58) the mean square magnitude of the divergences in the boundary velocity is 0.24 km/sec, and on averaging the KMPV results from the 10 km base, 0.13 km/sec. The differences in depths do not exceed 100 meters.

A comparison with the drilling data and the data from the KMPV method indicates that under the conditions of the Western Siberian platform the refracted wave sounding procedure had quite sufficient accuracy for regional studies of the basement surface. The mean values of the depth errors amount to 2-4%, and the boundary velocity, about 3%.

The testing by the deep seismic sounding materials along the traverse in the vicinity of Barabinsk was discussed in detail in reference [63]. The application of the interpretation methods developed in the spot sounding procedure permitted us to obtain more complete information in the given case about the structure of the earth's crust by the available scattered continuous profiling material than could be accomplished by ordinary methods presupposing the presence of the hodograph system.

In the Sverdlovsk deep seismic sounding profile [28, 126] intersecting the exposed Urals in the latitudinal direction and going beyond the limits of the Western Siberian platform (to the city of Ishim), an interpretation was also made of the continuous profiling data obtained by sounding procedures.[1] The results obtained in the western part of the section in Fig 68 are inferior to the continuous detailed profiling data, but they reliably reflect the large-scale peculiarities of the deep structure, including the existence of the "root" in the M boundary relief under the Urals.

Turanskaya Platform

The traverse from Kopetdag to the Aral Sea located in this region was investigated by a dense network of continuous observations with maximum length of the hodograph to 600 km for a distance between blast points of 20-50 km. As a result, a very detailed breaking up of the earth's crust (8 boundaries are isolated in it) was obtained in the upper mantle to depths of about 100 km [105]. During the testing [54], the spot sounding systems were compiled for investigation of three boundaries: the roofs and feet of the consolidated crust and also the boundaries in the upper mantle.

The study of the surface of the consolidated crust (Φ) was made using refracted waves recorded in the first arrivals on soundings with bases from 2 to 40 km. In spite of the relatively sparse sounding network which could be compiled by the available data, a proper representation of the basic structural forms over this surface was obtained (Fig 59): a sharp submersion in the direction of the pre-Kopetdag trough and the uplift with emergence at the day surface in the vicinity of the Amu-Dar'ya River.

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[1] Coworkers of the Geophysics Institute of the UNTs of the USSR Academy of Sciences (N. I. Khalevin, A. I. Bun'ko, E. A. Nezolenova) and the Bazhenovskaya expedition of the Urals Territorial Geological Administration (V. S. Druzhinin) participated in the interpretation.

The study of the Mohorovicic discontinuity (M) was made by materials of two sounding systems with bases equal to 80-100 and 160-200 km respectively. In the first system the reflections near the initial point were traced, and in the second system, the refracted wave at transcritical reflection. The average velocity in the consolidated crust and the boundary velocity on the M surface found by the fields $t(x, \ell_1)$ of the reflected and refracted waves are found to be equal to 6.5 and 8.2 km/sec respectively, which in practice coincides with the continuous profiling results (6.5-6.6 and 8.1-8.2 km/sec). The determinations of the mentioned velocities by the method of combined soundings of reflected and refracted waves turned out to be the closest to the continuous profiling data: the divergences do not exceed 0.2 km/sec and are equal on the average to 0.1 km/sec. The depths and the M boundary relief also are in satisfactory correspondence to the continuous profiling results (see Fig 59). The magnitude of the mean square divergence of the depths is 2.3 km and the maximum is 4.7 km.

The M_1 boundary in the upper mantle (see Fig 59) was studied by the reflected waves by the sounding system with bases of 270-300 km. The times of arrival of these waves were reduced to the foot of the earth's crust. The stratal velocity in the body of the rock between the M and M1 boundaries was found to be equal to 8.3 km/sec. The depths of occurrence of the M_1 boundary by the discrete and continuous observation data are distinguished by no more than 5 km with a mean square deviation of 3 km.

The waves in the first arrivals at distances of 30-60 km from the source were considered as refracted waves. The isoline of the stratal velocity (v=6.3 km/sec) was constructed by them, the position of which agrees with the velocity distribution in the medium by the continuous profiling data.

Areas of the Ukraine

In these areas with varied geological conditions, a significant volume of deep seismic studies have been performed with the application of the continuous profiling systems with increased detail [108, 85]. The sounding procedure was tested[1] on the materials from two profiles through the Donets trough and the Carpathians. The first profile, which intersects the Priazovskiy massif of the Ukrainian crystalline shield, the Donets trough and the Voronezh massif, corresponds to the average conditions of performing operations by the deep seismic sounding method with respect to complexity. The second profile runs through the western edge of the Russian platform (including a section of the Ukrainian shield), the pre-Carpathian trough, the folded Carpathians and the Transcarpathian internal trough,

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[1] This test was performed jointly with the coworkers of the Geophysics Institute of the Ukrainian SSR Academy of Sciences by the recommendations of the international working group of experts with respect to explosion seismology.

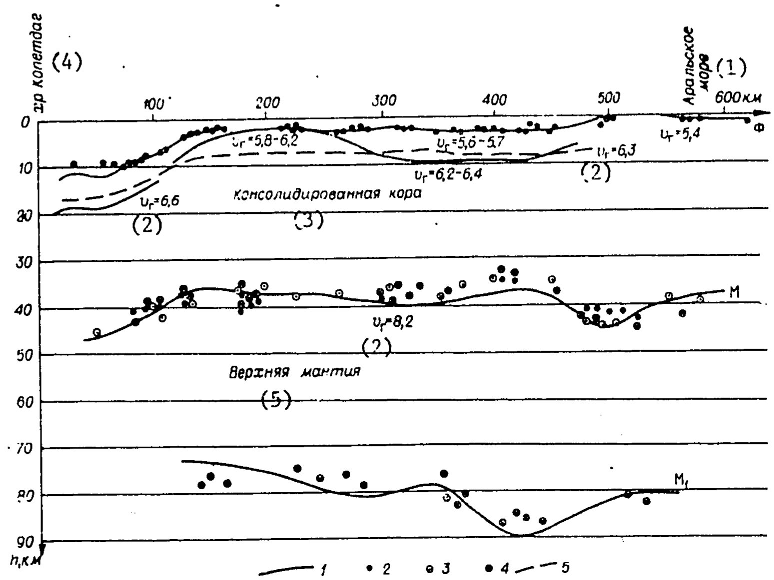

Figure 59. Comparison of the results of continuous profiling and spot sounding by the Kopetdag-Aral Sea profile. 1 -- seismic boundaries by the continuous profiling data. The results of the spot soundings are as follows: 2, 3 and 4 -- depths with respect to the refracted wave data (2), critical (3) and transcritical (4) reflections; 5 -- velocity isolines. The velocity is given in km/sec.

Key:

1. Aral Sea
2. $v_{boundary}$= ...
3. Consolidated crust
4. Kopetdag Ridge
5. Upper mantle

The variety of geological structures intersected by this profile is accompanied by great complexity and inconstancy of the subsurface and surface conditions.

The surface relief of the crystalline basement and the velocity distribution along it with respect to the profile through the Donetsk trough were studied by soundings designed to record the refracted waves in the first arrivals. The sounding bases were from 10-20 to 100 km. The spacing between their centers is on the average equal to 10 km. The separation of the refracted waves from the surface of the basement and from the boundaries in the sedimentary series was performed in the field $t(x, \ell_j)$ with respect to the magnitude of the boundary velocity (Fig 60). The sections of the time field with a velocity of 5.9-6.1 km/sec belong to the wave from the basement. The region with significantly smaller values of the velocity (4.6-5.5 km/sec) corresponds to the waves propagated only in the body of the sedimentary rock.

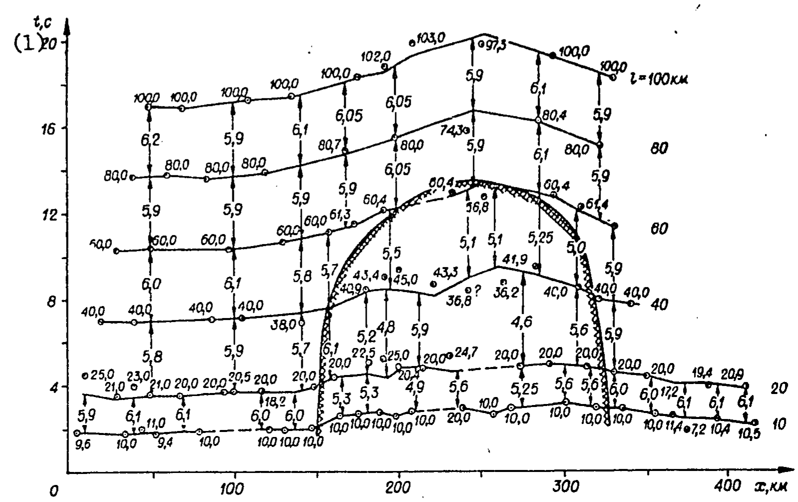

Figure 60. Wave time field in the first arrivals for the deep seismic sounding profile through the Donets trough.

Key:
1. t, sec

In the investigated regions the Mohorovicic discontinuity is predominantly studied by reflected waves which usually are detected the most clearly at distances of 80-130 km from the source. The soundings with these values of the bases were set up on the average every 20-30 km.

A comparison of the sections of the earth's crust (Fig 61) constructed considering all of the continuous profiling data and by the compiled sounding systems indicates the existence of differences in detail of the representation of the geometric peculiarities of the crustal structure and the velocity distribution in the medium. By the continuous profiling results a more detailed dismemberment of the section vertically was obtained, more detailed differentiation of the boundary and mean velocities with respect to profile was established, and a dense fracture network was discovered. The M discontinuity was characterized not as one sharp boundary, but as the concentration zone of reflecting areas having a thickness of several kilometers.

The indicated differences pertain to the quite thin peculiarities of the subsurface structure. The coarse structural features, which are significant for the reconnaissance prospecting phase of the operations are in practice identical with respect to the data of the two procedures. Both the boundary and the average velocities, if we consider the values for the extended profile intervals, differ from each other by no more than 0.1-0.2 km/sec.

According to the sounding data the Mohorovicic discontinuity is approximately in the middle of the zone of clustering of the reflecting areas established by the continuous profiling procedure. As a result of the soundings, the thickness of the earth's crust, its regional variations and the structures of the M boundary with horizontal dimensions of several tens of kilometers or more are reliably reflected. In the Carpathian profile a sharp thickening of the earth's crust is obtained in the vicinity of the folded Carpathians, and it thins under the Pannonskaya basin.

There are theoretical divergences in the depiction of the large features of the surface relief of the crystalline basement, including the transition section from the Russian platform to the pre-Carpathian trough (Fig 61, b). Here, the deep fracture zone obviously reaching the tops of the mantle is marked by the sounding results. The depth of occurrence and morphology of the bottom of the Donets trough are reliably determined, the lateral zones of the fractures are noted in the sections of articulation of the trough with the Ukrainian shield and the Voronezh massif (Fig 61, a).

Generalizing the data from comparing the results of the spot soundings with the results of deep drilling and highly detailed operations by the continuous profiling procedure with respect to all of the investigated areas, we arrive at the following estimates.

The mean square magnitude of the divergences of the unit determinations of the depths by the M boundary is 2.2 km. This divergence is comparable to the probable error and the results of the continuous profiling. When studying the basement surface under relatively favorable conditions (Western Siberia) the depths are determined with an accuracy to 100 meters; under more complex conditions (the pre-Carpathian trough, the Donets trough) the divergences increase, but as a rule, they do not exceed 100 m. The divergences in the values of the velocities (their unit determinations) usually are 0.1-0.25 km/sec.

The estimates obtained indicate that the accuracy realized in the spot sounding procedure when determining the depths and velocities is entirely sufficient for the reconnaissance prospecting of the earth's crust and the tops of the mantle under various seismogeological conditions.

§2. Comparison of the Labor Consumption of Spot Soundings and Continuous Profiling

Above, when testing the spot sounding procedure using continuous profiling materials it was demonstrated that it permits discovery of the basic features of the subsurface structure by the reference seismic boundaries with sufficient accuracy for the regional phase of the investigations. Let us compare the labor consumption of the operations by these methods.

A comparison of the labor consumption of the continuous and discrete observation systems for operations of different detail will be made by the number of sources (blast points) and the required seismic recordings. By the seismic recording we mean the recording of the oscillations on one seismic channel with one position of the source. Having data on the number of recordings and the sources, it is possible with consideration of the specific conditions to arrive at the cost of the field operations. Let extended reflecting and refracting boundaries exist in the section of the given region which correspond to the stable waves in some range of distances from the source. It is necessary to find the number of sources and seismic recordings for each type of observation for investigation with the given detail of the boundary configuration and velocity distribution (mean or boundary depending on the type of wave) in the same profile. The compared observation systems will be constructed beginning with the following requirements.

1. The systems must provide for the construction of the boundary and determination of the velocities in the entire profile at points, the average distance which does not exceed the given value.

2. The location of the sources and their receivers must satisfy the wave correlation conditions by the corresponding rules.

3. The observation systems must be economical, that is, contain the minimum number of sources and receivers of oscillations.

Continuous Observation Systems. We shall consider that in the profile of length $2x_0$ the region of tracing the investigated wave is included in the distance range from the source $(L-\Delta L, L)$. For simplicity let us assume that the profile $(2x_0)$ and maximum recording distance (L) contain an integral number of segments (ΔL).

Let us consider the reflected wave observation system. In order to determine the depths and the velocities throughout the entire profile in this case it is sufficient to have a continuous single tracing of the reflected waves so that in the generalized plane the projection of the system of correlation paths on the observation line will coincide with the investigated profile. For continuous tracing of the wave, each correlation path must have common (mutual) points with the adjacent paths. The density of the receivers established by the requirement of reliability of the position correlation of the waves, as a rule, is appreciably higher than that required for

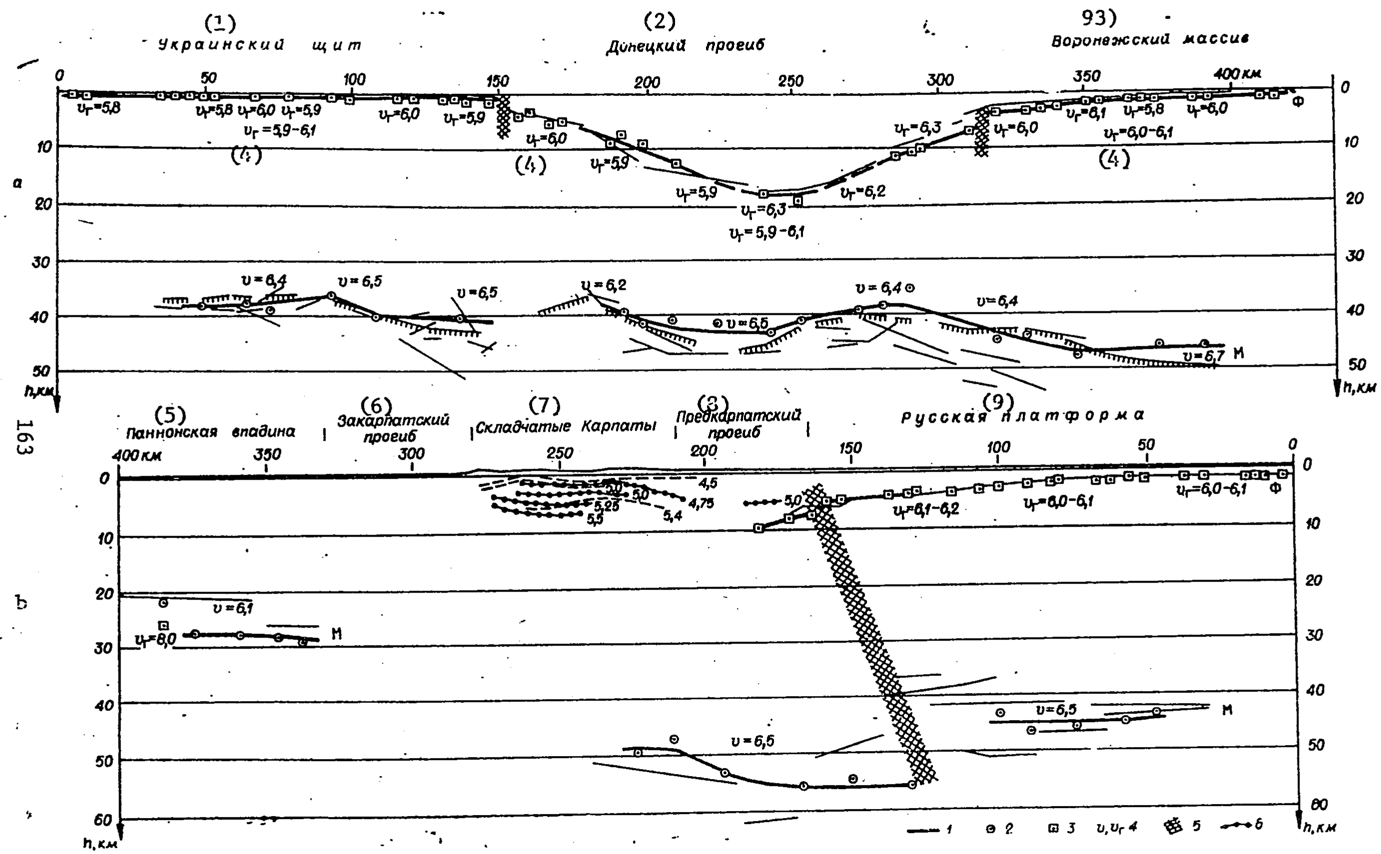

Figure 61. Comparison of the results of continuous profiling and spot sounding by the deep seismic sounding profile through the Donetsk troug. (a) and the Carpathians (according to the materials of the Geology Institute of the Ukrainian SSR Academy of Sciences) (b).

[See p 164 for legend and key]

[Legend and key to Fig 61, p 163]:

1 -- seismic boundaries; 2 -- depths with respect to the data from the reflected waves and 3 -- depths by the data from the refracted waves; 4 -- mean and boundary velocities, km/sec; 5 -- proposed deep fracture zone; 6 -- stratal velocity isolines, km/sec.

Key:

1. Ukrainian shield
2. Donets trough
3. Voronezh massif
4. $v_{boundary}$
5. Pannonskaya basin
6. Transcarpathian trough
7. Folded Carpathian
8. Precarpathian trough
9. Russian platform

determination of the parameters of the medium with required detail. Consequently, the required detail of the prospecting will be insured. The restrictions imposed on the continuous observation systems by economic arguments were investigated by I. I. Gurvich [25]. The systems are optimized by using the same sources for both direct and inverse correlation paths with maximum possible length of each path.

The reflected wave observation systems constructed in accordance with the investigated conditions are depicted in Fig 62, a, b. The first of them is obtained for $L>2x_0$, and the second, for $L\leqslant 2x_0$.

In the case of refracted (head) waves for the construction of the boundary and determination of the boundary velocity over the entire profile it is necessary to have direct and counter summary hodographs tied at mutual points. This system is realized for several direct and inverse correlation paths having no less than one common point. Let us limit ourselves to tying the paths in one direction by the criterion of parallelness of the overlapping hodographs when the position of the binding counter path is not required for construction of the summary hodograph. The conditions of economicalness of the observation system are the same as for the reflected waves. The observation systems of the refracted waves for the cases of $L>x_0$ and $L\leqslant x_0$ (Fig 62, d, e) have common receivers for the direct and return paths.

The following expressions were obtained in reference [61] for determination of the number of sources (q_n) in the investigated continuous observation systems.

In the case of reflected waves

$$q_n = \frac{3x_0 + \frac{L}{2}}{\Delta L}\left|\frac{-x_0 + \frac{L}{2}}{\Delta L} - \frac{1}{2}\right| - \frac{1}{2} = \begin{cases} 4\frac{x_0}{\Delta L}, \text{ for } L > 2x_0, \\ 2\frac{x_0 + L}{\Delta L} - 1, \text{ for } L \leqslant 2x_0. \end{cases} \quad (V.1)$$

For the refracted waves

$$q_n = \frac{3x_0 + L}{\Delta L} - \left| \frac{-x_0 + \Delta L}{\Delta L} - \frac{1}{2} \right| - \frac{1}{2} = \begin{cases} 4\frac{x_0}{\Delta L}, \text{ for } L > x_0, \\ 2\frac{x_0 + L}{\Delta L} - 1, \text{ for } L \leqslant x_0. \end{cases} \quad (V.2)$$

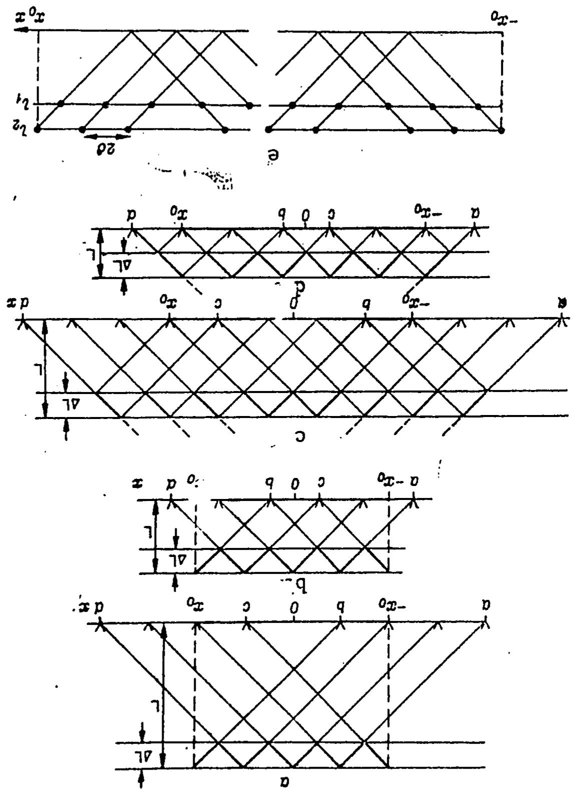

Figure 62. Schematic of continuous (a, b, c, d) and spot (e) observations.

From the summary it follows that the number of sources is determined by the values of the ratios x0/L and L/ΔL (Fig 63, a).

The number of seismic recordings (S_n) in the investigated continuous observation systems in the case of reflected waves is [61]:

$$S_n = \frac{4x_0}{\Delta L}\left(\frac{\Delta L}{\Delta x} + 1\right), \quad (V.3)$$

where Δx is the seismic channel step size.

The number of recordings in the case of refracted waves considering elongated overlapping hodographs will be

$$S_n = \frac{4x_0}{\Delta L}\left(\frac{\Delta L}{\Delta x} + 1\right) + 2\left(\frac{L}{\Delta L} - 1\right)\frac{f}{\Delta x}, \quad \text{(V.4)}$$

where f is the extent of the overlap section of the overlapping hodograph.

Sounding Systems. In order to construct the seismic boundary (reflecting or refracting) and for determination of velocities in the medium it is necessary to have two isolines of the time field over the entire profile. By the observed values of the times on any isoline the depth of occurrence of the seismic boundary can be found. Therefore in order to insure the required density (δ) for determination of the depths it is sufficient that on each isoline the times will be found every 2δ interval. The substantiated density of the calculation points for the velocities will be half as much. The observation density obviously must not contradict the reliability conditions of the discrete correlation. Usually this contradiction is not obtained inasmuch as the decrease in detail of the investigations, the requirements on the accuracy of the wave correlation are reduced simultaneously.

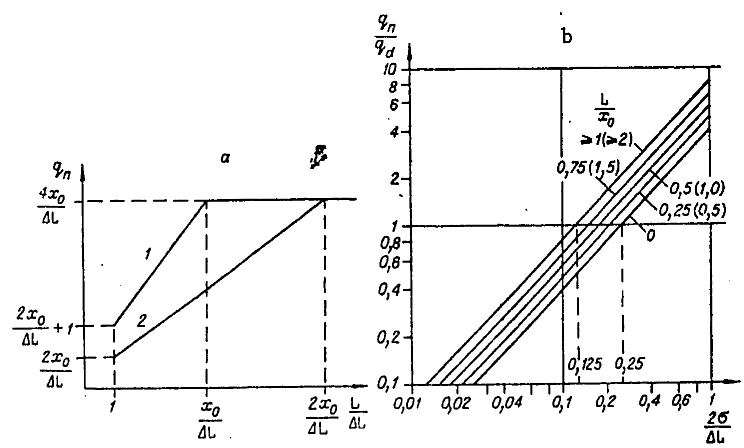

Figure 63. Comparison of the labor consumption of continuous spot observations.
a — ratio of the number of sources in the continuous observation systems by refracted (1) and reflected (2) waves; b — comparison of the number of sources for continuous and spot observations; c) the values of L/x_0 are given in parentheses for the reflected waves).

The requirement of economicalness of the sounding system usually reduces to the minimum number of source; it is also not necessary to set off repeated blasts at each point. These requirements are satisfied if each source is made common for four soundings. Shifting the source along the profile with a mean step size 2δ, we obtain the required observation density.

The sounding system for the reflected and refracted waves corresponding to the discussed conditions is presented in Fig 62, c. The number of sources in this system will be

$$q_d = \frac{1}{2}\left(\frac{x_0}{\delta} + 1\right). \quad (V.5)$$

The number of seismic recordings (S_d) will be determined, assuming that each sounding contains a device with n channels (usually n=6).

$$S_d = 2n\left(\frac{x_0}{\delta} + 1\right). \quad (V.6)$$

Comparison of the Continuous Observation and Sounding Systems. Let us find the magnitude of the ratio of the number of sources in the systems. In the case of reflected waves using formulas (V.1) and (V.5), we obtain

$$\frac{q_n}{q_d} = 2\frac{(2x_0 + L - \Delta L)\,\delta}{\Delta L\,(x_0 + \delta)} \quad (V.7)$$

or neglecting the small values of δ/x_0 and $\Delta L/x_0$,

$$\frac{q_n}{q_d} \approx 2\frac{\delta}{\Delta L}\left(2 + \frac{L}{x_0}\right). \quad (V.7')$$

In the case of refracted waves, using formulas (V.2) and (V.5), we find:

$$\frac{q_n}{q_d} = \frac{2\delta}{x_0 + \delta}\left(\frac{3x_0 + L}{\Delta L} - \left|\frac{-x_0 + L}{\Delta L} - \frac{1}{2}\right| - \frac{1}{2}\right); \quad (V.8)$$

$$\frac{q_n}{q_d} \approx \frac{2\delta}{\Delta L}\left(3 + \frac{L}{x_0} - \left|-1 + \frac{L}{x_0}\right|\right) = \begin{cases} \frac{8\delta}{\Delta L}, \text{ for } L > x_0, \\ 4\frac{\delta}{\Delta L}\left(1 + \frac{L}{x_0}\right), \text{ for } L \leqslant x_0. \end{cases} \quad (V.8')$$

In both cases (reflected and refracted waves) the ratio q_n/q_d depends on the values of $\delta/\Delta L$ and L/x_0. In the coordinate system q_n/q_d, $2\sigma/\Delta L$, on the double logarithmic scale this function is depicted in the form of a family of parallel straight lines with the parameter L/x_0 (see Fig 63, b). The ratio of the number of sources in the continuous observation and seismic systems increases with an increase in the values of $\delta/\Delta L$ and L/x_0. For $\delta/\Delta L > 0.25$ and for any values of the parameter L/x_0, the sounding system will contain fewer sources ($q_n/q_d > 1$). When $\delta/\Delta L < 0.125$, the continuous observation system has the same advantage ($q_n/q_d < 1$). In the intermediate region, the ratio q_n/q_d assumes values from 0.5 to 2. The parameter L/x_0 has no strong effect on the value q_n/q_d; for the fixed value $\delta/\Delta L$, the ratio of the number of sources can vary by no more than 2 times as a result of the variation of L/x_0.

Let us proceed to a comparison of the number of seismic recordings. In the case of reflected waves, the ratio of these values defined by the formulas (V.3) and (V.6) will be

$$\frac{S_n}{S_d} = \frac{\delta\left(1 + \frac{\Delta x}{\Delta L}\right)}{3\Delta x\left(1 + \frac{\delta}{x_0}\right)}. \qquad \text{(V.9)}$$

In practice the values of $\Delta x/\Delta L$ and δ/x_0 usually are much less than one. Neglecting them, we obtain

$$\frac{S_n}{S_d} = \frac{\delta}{3\Delta x}. \qquad \text{(V.9')}$$

For the refracted waves, considering the overlap sections of the overlapping hodographs, we find by using formulas (V.4) and (V.6):

$$\frac{S_n}{S_d} = \frac{\delta}{n\Delta x\,(1 + \delta/x_0)}\left[2\left(1 + \frac{\Delta x}{\Delta L}\right) + \frac{f}{x_0}\left(\frac{\Delta L}{L} - 1\right)\right] \qquad \text{(V.10)}$$

or neglecting the small values of $\Delta x/\Delta L$ and δ/x_0,

$$\frac{S_n}{S_d} \approx \frac{\delta}{3\Delta x}\left[1 + \frac{f}{2x_0}\left(\frac{\Delta L}{L} - 1\right)\right]. \qquad \text{(V.10')}$$

In all the investigated cases the value of S_n/S_d is directly proportional to the ratio of the required density of determination of the depths to the step size of the seismographs. In practice the latter ratio is always appreciably greater than one, and for low-detail studies it reaches several hundreds. Correspondingly, the number of seismic recordings for operations by the sounding procedure can be smaller than in the case of continuous observations by approximately two orders.

Table 3

Investigation	(1) Длина профиля $2x_0$, км	(2) Шаг сейсмографов Δx, км	(3) Детальность исследований δ, км	(4) Дальность регистрации L, км	(5) Область регистрации ΔL, км	(6) q_n/q_d	(7) S_n/S_d (при n=8)
I. Study of the foot of the earth's crust:							
Reconnaissance prospecting							
Refracted waves (p=2 km)	500	0.1	25	250	50	4	83
Transcritical reflection	500	0.1	25	250	50	3	83
Detail							
Refracted waves (p=2 km)	500	0.1	5	250	50	0.8	17
Transcritical reflections	500	0.1	5	250	50	0.8	17
II. Study of boundaries in the consolidated crust:							
Reconnaissance prospecting							
Refracted waves	500	0.1	25	100	50	2.8	83
Reflected waves	500	0.1	25	100	50	2.4	83
Detail							
Refracted waves	200	0.1	5	100	50	0.8	17
Reflected waves	200	0.1	5	100	50	0.6	17
III. Study of the basement surface of the platforms by refraction waves (the conditions of th Western Siberian lowland):							
Reconnaissance prospecting	500	0.05	5	15	5	4	33
Detail	100	0.05	0.5	15	5	0.5	3.3
IV. Study of the sedimentary mantle by reflected waves:							
Search for the second order structures	500	0.02	5	1	1	20	83
Search for the local uplifts	200	0.02	2	1	1	8	83
Prospecting of local uplifts	25	0.02	0.25	1	1	1	4.2

Key:

1. Length of profile $2x_0$, km
2. Spacing of the seismographs Δx, km
3. Detail of the investigation δ, km
4. Recording range L, km
5. Recording region ΔL, km
6. q_n/q_d
7. S_n/S_d (for n=6)

The relations obtained permit us to give a comparative estimate of the labor consumption of the field operations with respect to the continuous observation and sounding systems. The results of the calculations for various types of studies are presented in Table 3.

Thus, for the continuous observations systems the requirements following from the condition of reliability of the position correlation of the waves are appreciably more rigid than those which are caused by the necessary detail of determination of the parameters of the medium. This noncorrespondence is especially great in the case of reconnaissance operations -- the number of seismic recordings on the profile can be several orders higher than the required number of points of determination of the depths and velocities. As a result, during the reconnaissance prospecting operations using continuous observation systems, significant redundant information is obtained not required to solve the standing problem. This lowers the rates of investigation and increases their cost.

During the operations by the sounding procedure it is possible to construct observation systems in complete correspondence to the required detail of the investigation of the medium. The discrete correlation of the reference waves imposes no strict restrictions on the observation density. Therefore the studies of a reconnaissance prospecting nature can be made with appreciably less volume of field operations and in shorter times. By comparison with the continuous systems when using soundings in the reconnaissance prospecting phase, a gain of several times in the number of sources of oscillations and the number of seismic recordings by many tens of times is possible. On making the transition to detailed studies, the advantages of the soundings are lost.

Consequently, the subsurface seismic investigations are expediently carried out in steps, using the sounding procedure for the reconnaissance prospecting operations and converting to the continuous observation systems for increased detail. The relations found above will help to select the appropriate form of observations under specific conditions for the given detail of the study.

§3. Spot Soundings, Dash and Dot Profiling

The dash and dot profiling briefly characterized in the introduction is being widely used at the present time by foreign researchers for low-detail studies of the earth's crust and the tops of the mantle. A comparative analysis is presented below which does not claim to completeness of encompassing all the problems of this version of the subsurface seismic studies (in the form in which it is used for operation abroad on the dry land) and the spot sounding procedures to compare the possibilities of these procedures for solving the problems of the reconnaissance prospecting phase of the operation.

The observations systems used abroad, as a rule, are simple and relatively low-labor consuming, often being a combination of dash and dot profilings; along with the short longitudinal installations of the seismograph, isolated single-channel recorders are used. The route along which the sources and oscillation receivers are located must be rectilinear. This restriction, from which the spot sounding procedure is to a significant degree free, can cause significant difficulties during operations in inaccessible terrain.

The important difference in the compared observation systems consists in approaching the selection of the oscillation recording intervals. For the dotted profile the receivers are relatively uniformly distributed, beginning with the source of oscillations to a defined distance (to 200-300 km). In the sounding procedure, the wave field is recorded only on the intervals of removal from the source where the waves from the basic boundaries are most reliably generated. This reduces t e number of seismic recordings and increases the effectiveness of studying the principle (for the reconnaissance prospecting phase of the operations) peculiarities of the structure of the medium. The uniformity of the recording with a dotted profiling insures natural transition from the reconnais ance prospecting observations to the detail path of simple clustering of the receiver network. However, considering the problems of the reconnaissance prospecting phase, it becomes significant that the information about the structure of the medium which can be reliably obtained in the case of low-detail studies, is distributed non-uniformly in the wave field at different distances from the source. Therefore the uniformity of the receivers leads to obtaining a significant number of low-informative seismic rec lings to the loss of studying the wave field sections which could be effect ly used for interpretation.

Let us compare the labor consumption of the spot soundings and the dotted profiling, taking the parameters of the corresponding observation systems in the Baykal region [56] and in the United States [148] as characteristic examples. Let us state the problem of studying the earth's crust to its entire thickness along the profile with length $2x0=500$ km with the detail which is used for the investigations in these areas.

For the operations by the procedure of spot soundings under the investigated conditions, two observations systems are required: one with sounding bases of 40-60 km is used for studying the internal structure of the consolidated crust with simultaneous tracing of the reflected and refracted waves, and the other for recording the refracted and reflected waves from the M boundary at distances of about 200 km from the source. The average distance between the centers of the adjacent soundings in both systems is equal to $\delta=25$ km. The six-channel recorder ($n=6$) is used for each sounding. The oscillation sources are common to both sounding systems. For simultaneous use of eight recording stations, one blast at each point is sufficient. Substituting the presented parameters in formulas (V.9) and (V.10), let us find the total number of sources (q_d) and seismic recordings (S_d) in the spot sounding systems: $q_d=5$, $S_d=264$.

Let us determine the number of sources (q_p) and seismic recordings (S_p) for the standard system of dotted observations on the 500-km profile, which usually looks like the following. For blasts on both ends and in the middle of the profile two pairs of counter hodographs are obtained in the distance interval of 0-250 km from the source. The average distance between the seismographs will be taken equal to 5 km (in a number of cases it is several times greater). The simple calculations lead to the following results: q_p=3, S_p=200.

For a limited number of simultaneously operating recorders, the repetition of the blasts at the same point can be required.

Consequently, the spot sounding and dotted profiling systems are close with respect to labor consumption of the field observations. The dotted profiling is several times more economical, especially with respect to the number of oscillation sources. However, considering that on comparison the condition of obtaining equivalent information with respect to reliability and completeness about the subsurface structure has not been stated, it is necessary to consider other aspects of the compared procedures.

The identification of the waves, which to a very highly significant degree influences the results obtained, differs significantly in the compared procedures. As has already been noted (§3, Chapter II), the conditions of discrete correlation in the sounding procedure are more favorable, for the oscillation recording is done in specially selected intervals of distances from the source optimal for detection of the given wave or group of waves. In addition, effective procedures are used to monitor the correlation with respect to a set of recordings with the introduction of quantitative estimates of the reliability of the detection of the waves.

By the dotted profiling data, waves are quite reliably traced in the first arrivals. The analysis of the subsequent part of the recording is usually difficult. When using single seismic routes, the attribute of apparent velocity important to the wave identification is lost; the random oscillations with small correlation radius can be erroneously taken as the regular wave. As a result of the significant (5 km or more) distances between the single recordings it is impossible with sufficient effectiveness to use the basic criteria of the position correlation: the cophasalness of the oscillations, smooth variation with respect to the amplitude profile and other characteristics of the shape of the recording of the traced wave. The transposition correlation (identification of like waves by the recordings from different sources) is also complicated, for as a result of significant (150-300 km) distances between the blast points, as a rule, for the majority of waves, the correlation bound system of hodographs is not created. The mutual points usually have only hodographs of refracted waves from the M boundary. The hodographs of the waves from the intracrustal boundaries are not connected to each other.

The foreign researchers, in all probability, to a more significant degree than occurs during continuous profiling operations and spot sounding in the USSR, use the previously adopted concepts of the model of the medium when isolating and tracing the waves. They strive to match the theoretical hodographs at least in the rough approximation corresponding to these models with the observed wave field, as a rule, without proper consideration of the horizontal nonuniformities of the medium which in practice are always present. The theoretical hodographs superposed on the seismogram montage presented in a unit time scale are investigated as correlation lines. Usually significant nonuniformity of the wave correlation occurs by the dotted profiling materials, especially in the subsequent part of the seismograms where in the given case there are no substantiated criteria for tracing one wave or another from one path to the other. The necessity for having sufficiently extended hodographs forces the interpreter to try to trace the waves also in unfavorable intervals for isolation of them where the correlation cannot be realized reliably and is carried out with a high degree of subjectiveness.

The methods of determining the parameters of the medium by the spot sounding materials investigated in detail in Chapter IV will permit us to determine the geometric characteristics of the section and the velocity distribution in the medium with accuracy and detail sufficient for the solution of the problems of the reconnaissance prospecting phase of the studies. This is confirmed by comparing the results obtained with the continuous profiling data under various conditions, including with sufficiently complex subsurface structure.

Without specially discussing the interpretation procedures used abroad for the subsurface seismic studies, let us discuss in brief some of the most significant peculiarities characteristic of the low-detailed dotted profiling and caused by the systems of observations used and the wave correlation conditions.

It has already been noted that as a result of incompleteness of the observation systems during operations abroad usually the system of hodographs is obtained which is not correlation-wise connected to each other. Therefore in order to determine the parameters of the medium often studies are made of the individually taken signal hodographs by which in the case of head and refracted waves it is impossible sufficiently correctly to consider and discover the effect of the horizontal nonuniformities of the medium, even if the latter have a linear nature. In this situation the interpreter is forced to take a model of the medium in which the elastic parameters vary (smoothly or discontinuously) only along the vertical. The representation of the variations of the elastic wave velocities and the geometric parameters of the medium along the profile are obtained as a result of interpolation of the data with respect to the sparse network of determinations by single hodographs significant distances from each other (to 200 km or more).

A consequence of these peculiarities is not always sufficient (even for reconnaissance prospecting) detail of the study of the horizontal nonuniformities of the medium and the relatively low reliability of discovery of the vertical variations in the velocity inside the earth's crust. When solving the latter problem abroad efforts are often made at very detailed breakdown of the section, including with isolation of the wave guide layers in the crust.

It is of interest to determine the errors in the parameters of the medium if in the case of real inclined boundaries the interpretation is made under the assumption of horizontal occurrence.

Let us consider the layered model in which the boundaries between the individual layers make an angle ϕ with the x-axis identical for all boundaries. The sign of ϕ is positive in the direction of drop. Let us assume that the thicknesses of all k layers (k=1,2,3,..) are identical, and the velocities built up from layer to layer uniformly, that is,

$$v_2 - v_1 = v_3 - v_2 = \ldots = v_n - v_{n-1}.$$

The effect of omission of the layers will not be observed in this model. The expressions for the errors in depth and velocity can be written [98] in the form:

$$\frac{\Delta h_k}{h_k} = \varphi\Phi_1\left(\frac{v_1}{v_2}, k\right),$$

$$\frac{\Delta v_k}{v_k} = -\varphi\Phi_2\left(\frac{v_1}{v_2}, k\right).$$

The graphs of the functions Φ_1 and Φ_2 are depicted in Fig 64.

Let us consider the numerical results for the seven-layer model of the earth's crust. The variation of the velocity with depth takes place from 5.5 to 8.0 km/sec; the total thickness will be 42 km. The selected parameters of the velocity section are characteristic of the average continental section of the earth's crust (Fig 65). Let us analyze the possible errors in the interpretation if the experimental data are presented in the form of a single hodograph, two overlapping hodographs and two counter hodographs.

1. Single hodograph. The errors when determining the boundary velocity increase for all deeper horizons and for ϕ=2P constitute 1.65, 2.52, 2.94, 3.43, 3.87 and 4.25% respectively (see Fig 65). With a slope of 5°, for the same boundaries they are equal to 4, 5.83, 7.24, 8.57, 9.73 and 10.70%.

The errors in the depths to the refracting horizons are characterized by somewhat different distribution. Both for ϕ=2° and for ϕ=5° the maximum error occurs determining the depth to the first refracting horizon and it is equal to 7.62 and 19% respectively. On making the transition to deeper horizons, the sign of the error changes, and its own type of compensation takes place. With a slope of 2° the errors are 3.1, 1.7, 0.9, 0.03;and 0.04%, for ϕ=5°, 7.2, 4.3, 2.25, 0.8 and 0.1%

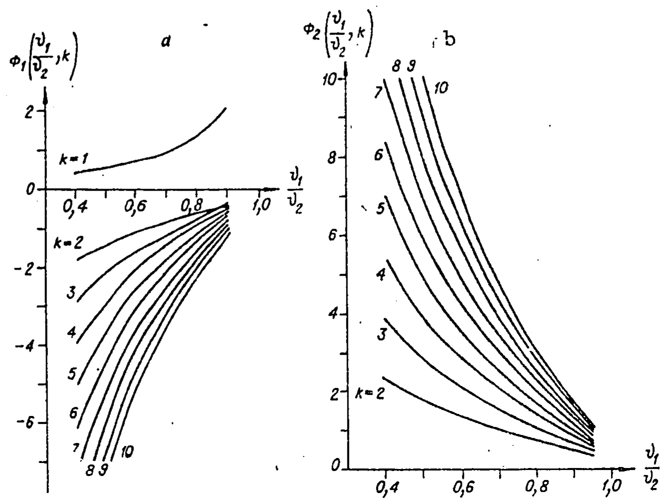

Figure 64. Graphs of the functions: a -- $\Phi_1(v_1/v_2, k)$ and b -- $\Phi_2(v_1/v_2, k)$.

2. Overlapping Hodographs. It is proposed that in the first step, the boundary velocities and the depths to the refracting horizons were determined independently by each of the hodographs. In this case the errors will be the same as when interpreting a single hodograph. Then the velocity isolines were drawn through two velocity columns. For angles of $\phi=2°$, 5° the slope of the isolines in practice does not differ from the theoretically given values, and the errors in the velocities are approximately the same as for a single hodograph.

3. Counter Hodographs. The interpretation of the counter hodographs was made just as in the case of overlapping hodographs. For each of the hodographs the errors are characterized by opposite signs; therefore the equal velocity isolines can also be characterized by opposite slopes, that is, significant distortion of the structural forms occurs. Thus, for $\phi=2°$ the slope of the first refracting horizon coincides with the given one; the second and third horizons have already been significantly distorted, and the slopes of the fourth and subsequent boundaries have opposite sign by comparison with the initial one (see Fig 65). Still more expressed distortions of the structural forms are observed for $\phi=5°$. Here the first refracting horizon is characterized by the opposite sign of the slope by comparison with the initial one.

The performed analysis indicates that the use of the simplest systems of single hodographs or pairs of overlapping and counter hodographs for

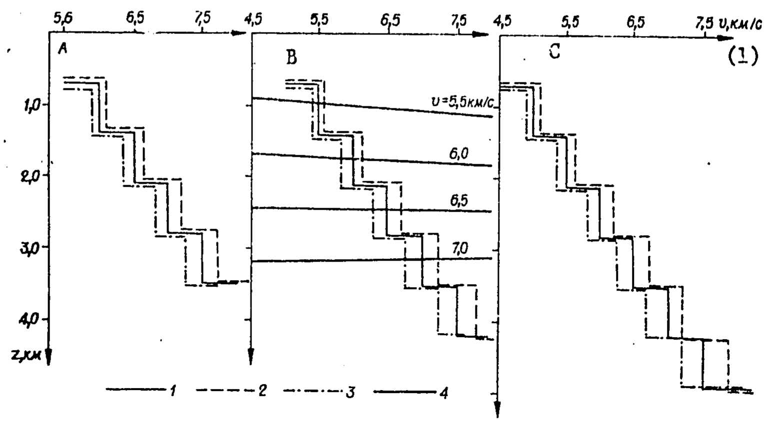

Figure 65. Example of distortions in depths and velocities connected with failure to consider the slope of the refracting interfaces. The seven-layer model of the earth's crust with identical thickness of each layer equal to 7 km and the velocity gradient between layers of 0.5 km/sec was taken as the initial model.
1 — initial vertical section; 2 -- velocity columns obtained when processing the hodograph in the direction of fall correspondingly with sources of the points A, B, C; 3 -- the same in the direction of ascent; 4 -- lines of equal velocities obtained as a result of independent processing of the two counter hodographs with sources at the points B and C.

Key:
1. v, km/sec

independent processing of them leads to highly significant errors in depths, slope angles and velocities even for very small slope angles of the interfaces.

Under actual conditions obviously the monoclinal occurrence is observed most frequently in relatively small segments of the profile hardly exceeding approximately 100 km. However, at the same time the local slopes can change sign, which leads to an apparent increase in the differentiation of the section with respect to velocities and distortions in the structural forms of approximately the same order as the ones obtained above for the monoclinal occurrence.

The sections of the earth's crust obtained by the data for the compared procedures differ somewhat. As a result of the dash and dot profilings usually more broke earth's crust is obtained along the vertical, for the wave field is recorded relatively uniformly with respect to the entire interval of distances from the source. Therefore there is the possibility of the isolation a quite large number of waves with one degree of reliability or another with stable characteristics within the limits of one or two counter hodographs. Here, however, not all of the waves (and, consequently, the boundaries corresponding to them) can be identified in the entire investigated profile.

The spot sounding procedure, which is inferior to dash profiling in vertical breakdown of the section permits us to obtain more detailed and reliable information about the horizontal nonuniformities of the medium, its block structure with isolation of the abyss . fracture zones. The increased reliability of studying the horizontal nonuniformities in the sounding procedure is insured by tracing only the clearest waves from the reference boundaries. By the data obtained in this way both the morphology of these boundaries and the basic peculiarities f the variation of the elastic wave velocities along the investigated traverses are determined quite reliably.

When selecting the specific method of reonnaissance prospecting, an important role is played by the conditions of performing the field operations. The dash and dot profiling can turn out to be economically more advantageous in easily accessible areas where the blasting at a large number of points is complicated for one reason or ano her. In inaccessible areas such as Siberia and the Far East with forested, swampy or mountainous terrain, the spot sounding procedure has indisputable advantages.

CHAPTER VI. RESULTS OF USING THE SOUNDING PROCEDURE

The procedural and equipment development discussed in the preceding chapters have led to the creation of an effective method of regional seismic operations in inaccessible areas, which has made it possible to resort to systematic studies of the structure of the deep structure over broad territories of Siberia with the solution of two basic problems: 1) regional investigation of the basement of the Western Siberian platform and the Siberian platform, primarily in connection with the requirements of petroleum and gas geology; 2) the study of the deep structure of the earth's crust in the tops of the mantle. The procedure is exploited by a number of production organizations. In particular, in the territory of the Tyumen' Oblast these operations are performed on profiles along the basic river basins (Ob', Irtysh, Konda, Kazym, Dem'yanka, Pyaku-Pur, Vakh, and so on), where large-scale petroleum and gas formations were later discovered. In the vicinity of the Shaimskiy structural swell, large-scale area surveys have been performed over an area of 2750 km^2, and the results were completely confirmed by detailed seismic operations by the reflected wave method and drilling.

The study of the basement surface by the sounding procedure started at the end of the 1950's in the Tyumen' Oblast has been developed broadly since the middle of the 1960's initially in the Western Siberian platform and then on the Siberian platform (in the vicinity of the Tungusskaya syneclise, the Nepskiy arch, Yakutia). The extent of the investigated traverse reaches 25,000 km; the area surveys have been performed in individual regions. Recently we have converted to area studies not only in the basement surface, but also the inside structure of its upper 5 to 10 kilometer thickness. These operations performed in the southern part of the Western Siberian platform over an area of 100,000 km^2 are important in connection with the problem of studying the Paleozoic deposits of this region.

The studies of the entire earth's crust and the tops of the mantle along the regional traverses and in individual cases, in the form of the area surveys were the first application of seismology of blasting when studying the deep structures of Siberia. The operations were performed in the central and southern parts of the Western Siberian platform, in the southern and eastern regions of the Siberian platform, within the Altaye-Sayan and Baykal folded regions, and in the vicinity of the Baykal rift.

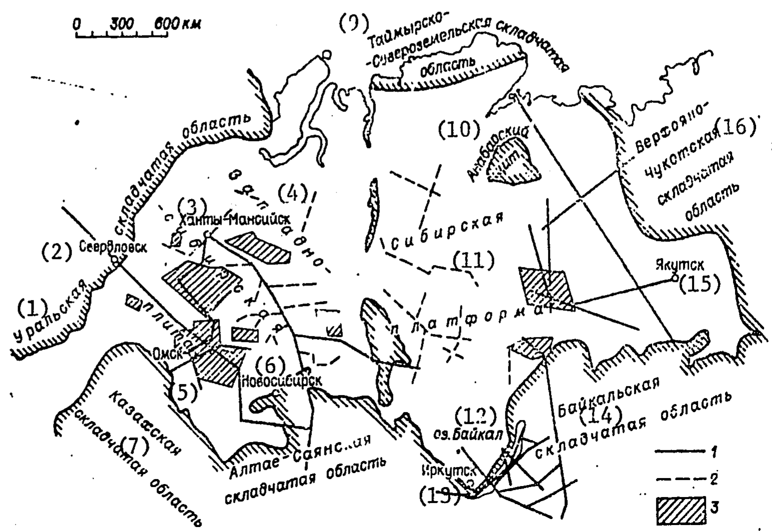

Figure 66. Schematic of the basic traverses and areas of regional seismic research in Siberia
1 -- deep seismic sounding profiles; 2 -- profiles made to study the basement; 3 -- sections of area studies of the basement.

Key:

1. The Urals folded region
2. Sverdlovsk
3. Khanty-Mansiysk
4. Western Siberian platform
5. Omsk
6. Novosibirsk
7. Altaye-Sayan folded region
8. Kazakh folded region
9. Taymyrsko-Severozemel'skaya folded region
10. Anabarskiy shield
11. Siberian platform
12. Lake Baykal
13. Irkutsk
14. Baykal folded region
15. Yakutsk
16. Verkhoyano-Chukotskaya folded region

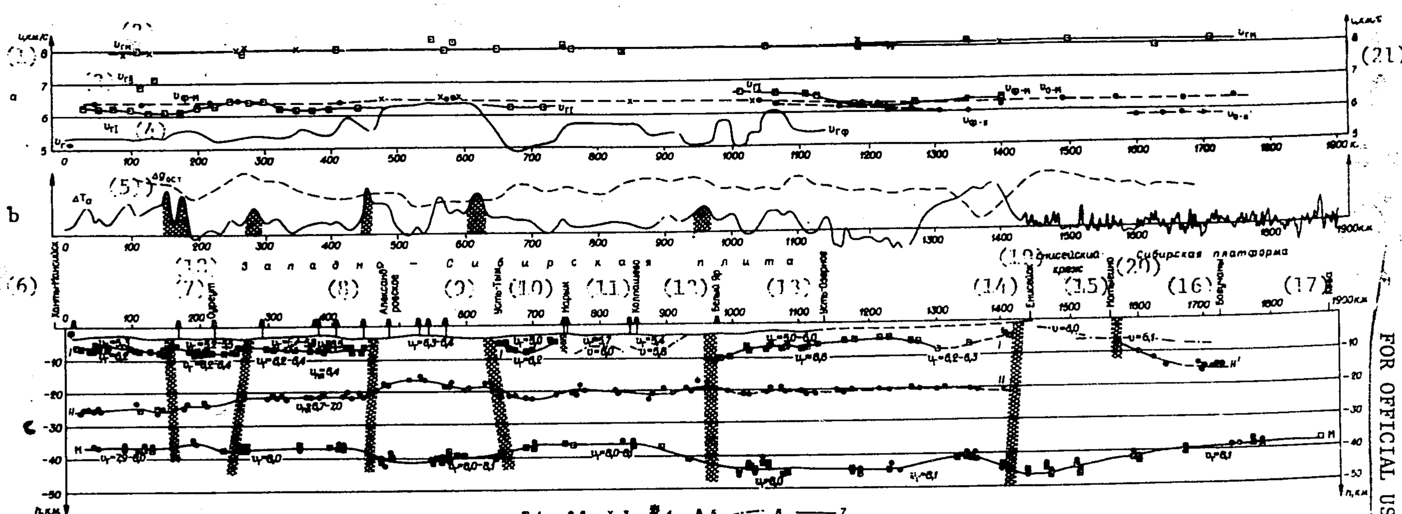

Figure 67. Seismic traverse through the central and eastern parts of the Western Siberian platform:

a -- velocity graphs for elastic waves. $v_{boundary\ \phi}$, $v_{boundary\ I}$, $v_{boundary\ II}$, $v_{boundary\ M}$ are the boundary velocities for the Φ, I, II, M boundaries. $v_{\Phi-II}$, $v_{\Phi M}$, v_{0-M} are the mean interval velocities in the rock between the corresponding seismic boundary; b -- graphs of $\Delta g_{residual}$ are the residual gravitational anomalies, ΔT_a are the anomalies of the intensity of the magnetic field (the anomalies that are extended in plan view or cross hatched); c -- seismic section. 1 -- depths and velocities by the refracting wave data; 2 -- the same by the reflected wave data; 3-- velocities by the data from joint processing of reflected and refracted waves from one boundary; 4 -- abyssal fracture zone; 5 -- boreholes; 6 -- velocity isolines by the refracted wave data; 7 -- sections of the M boundary with anomalous ratio of the refracted and reflected waves (Fig 68 and 69, b)

Key: 1 -- v, km/sec; 2 -- $v_{boundary\ M}$; 3 -- $v_{boundary\ II}$; 4 -- $v_{boundary\ I}$; 5 -- $\Delta g_{residual}$; 6 -- Khanty-Mansiysk; 7 -- Surgut; 8 -- Aleksandrovskoye; 9 -- Ust'-Tym; 10 -- Narym; 11 -- Kolpashevo; 12 -- Belyy Yar; 13 -- Ust'-Ozernoye; 14 -- Yeniseysk; 15 -- Motygino; 16 -- Boguchany; 17 -- Keva; 18 -- Western Siberian platform; 19 -- Yenisey Ridge; 20 -- Siberian platform; 21 -- v, km/sec.

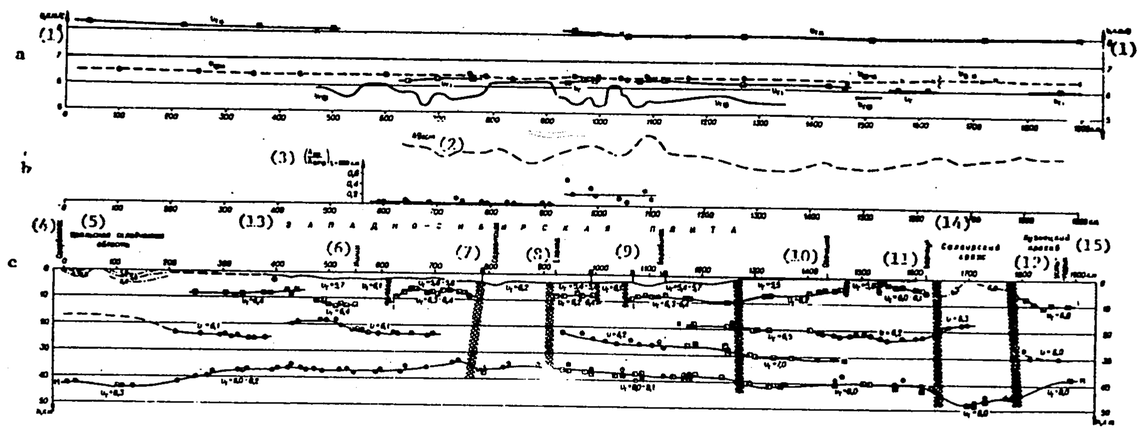

Figure 68. Sverdlovsk-Ust'-Naryk traverse. For the provisional notation, see Fig 67.

Key: 1 -- v, km/sec; 2 -- $\Delta g_{residual}$; 3 -- $A_{refracted}/A_{reflected}$; 4 -- Sverdlovsk; 5 -- Ural folded region; 6 -- Ishim; 7 -- Sargatskoye; 8 -- Yelanka; 9 -- Barabinsk; 10 -- Obechkino; 11 -- Barnaul; 12 -- Ust'-Naryk; 13 -- Western Siberian platform; 14 -- Salairskiy ridge; 15 -- Kuznetsk trough.

The results obtained are sufficiently representative both with respect to volume of research (16,000 km of traverses) and with respect to encompassing of various geological situations. In addition, the new procedure was used for the seismic study of the subsurface structure of Antarctica performed first by Soviet researchers, and it was used when interpreting the materials of the blast seismology obtained by the American geophysicists in the vicinity of Verkhniy Lake (the Canadian field).

The results obtained are the result of relatively low-detail operations of the reconnaissance prospecting phase. Their purpose was expressed discovery of the large-scale deep structures of broad regions. In the sections of greatest interest, detailed studies must be made. The distribution of the traverse and area operations by the sounding procedure in Siberia is illustrated in Fig 66.

The statement of the indicated operations was preceded by testing the new method on the materials from high-detail seismic studies of different depths under various geological conditions.

§1. Deep Seismic Studies in Western Siberia

The basic geological structure in the investigated territory is the epihercinic Western Siberian platform, in the sedimentary mantle of which the richest oil and gas reserves have been discovered. The platform is surrounded by Paleozoic folded structures of the Urals, the Kazakh mountain areas, Altay and Sayan; in the east it is bounded by the ancient Siberian platform.

Information about the structure of the deep parts of the earth's crust and the top of the mantle in Western Siberia were highly schematic before the deep seismic sounding operations. This information had been obtained primarily on the basis of gravitational and magnetic data. Before the deep seismic studies of the reconnaissance prospecting phase, the goal was set of discovering the general laws of the structure of the folded basement, the deep zones of the earth's crust and top of the mantle, the regionalization of the territory with respect to the deep structural peculiarities with isolation of the large crust-mantle blocks and the abyssal fracture zones. The deep seismic sounding data had to be used as the reference for a profound geological interpretation of the entire set of geophysical materials.

In this region the first studies by the deep seismic sounding method were performed in 1959 (SNIIGGiMS Institute, the Novosibirsk Geophysical Trust [82]) in a 300-kilometer continuous profile to the southeast of Barabinsk. In 1962-1970, the Novosibirsk, Tomsk Main Administrations and the IGiG Institute of the Siberian Department of the USSR Academy of Sciences used the procedure of spot seismic soundings to study the structure of the earth's crust and the top of the mantle by a series of traverses connected to each other with a total extent of 6000 km [60, 110, 97, and so on] (see Fig 66). In the inaccessible part of the region for the seismic traverses in practice all of the navigable rivers south of the latitudinal course of the Ob' were used.

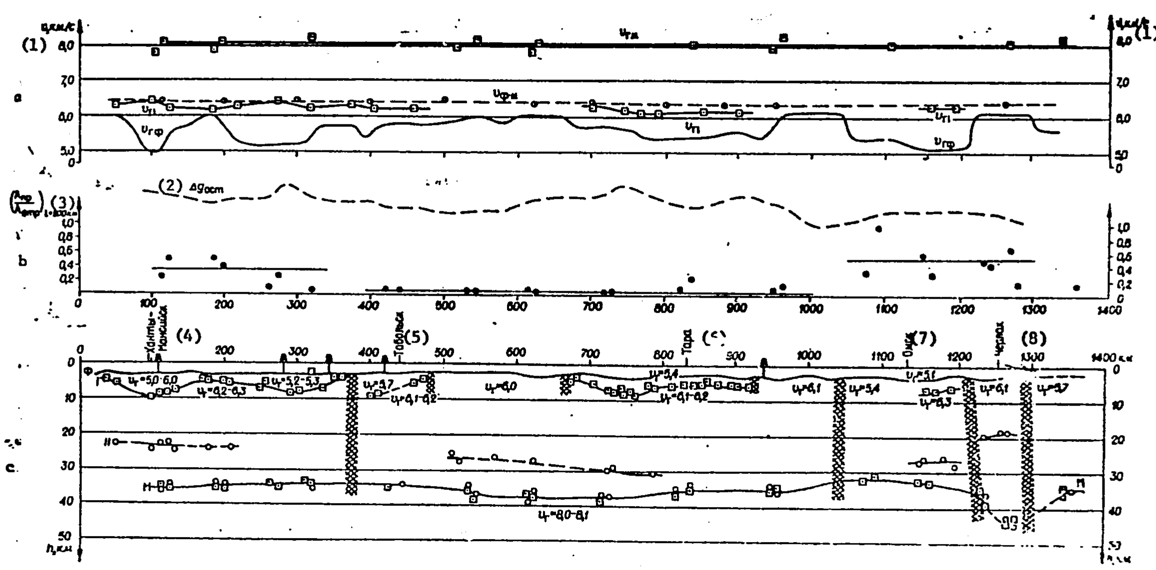

Figure 69. The Khanty-Mansiysk-Cherlak traverse. The provisional notation is the same as in Fig 67.

Key:
1 -- v, km/sec; 2 -- $\Delta g_{residual}$; 3 -- $A_{refracted}/A_{reflected}$; 4 -- Khanty-Mansiysk; 5 -- Tobol'sk; 6 -- Tara; 7 -- Omsk; 8 -- Cherlak

The basic resultant structures investigated below are seismic sections with respect to five connected regional traverses[1] (Fig 67-71) and the block diagram compiled on the basis of them (see Fig 72). If possible these data characterize the large-scale structural features of the earth's crust and the top of the mantle in the central and southern parts of the Western Siberian platform and its folded frame in parts of the Yenisey Ridge, the Altaye-Sayan Oblast and Northern Kazakhstan. For characterization of the properties of the deep rock, the sections are accompanied by graphs of the mean and boundary velocities along the corresponding traverses.

Structure of the Upper Part of the Consolidated Crust

The seismic studies of the upper part of the consolidated crust were made with detail permitting discovery of the velocity anomalies in the medium and the deep structures a few tens of kilometers or more across. In order to compile the seismic model of this part of the section, some of the results of the operations by the reflected wave method were used. Let us characterize the basic seismic boundaries.

The reflecting boundary f traced by the reflected wave data lies in the lowest part of the Mesozoic-Cenozoic platform mantle and can be considered its foot with sufficient approximation for regional operations.

Refracting Surface Φ. The refracted and exchanged (PPS type) waves from it in the internal parts of the Western Siberian platform usually are recorded on soundings with bases of 10-25 km. On the arches of the uplifts, this boundary coincides with the foot of the platform mantle (with a boundary f). In the troughs the indicated boundaries diverge by 1-2 km. The layer included between them has an elastic wave velocity to 4.5-4.8 km/sec and, in all probability, corresponds to the sedimentary-vulcanogenic rock of supposedly Triassic and Lower Jurassic age. On making the transition through the Φ boundary, the propagation rate of the elastic wave increases sharply, as a result of which clear refracted waves are formed on it. The sharpness of the gradient of the elastic properties on this boundary is confirmed by the occurrence in it of sufficiently intense refracted and transmitting exchanged waves. The boundary Φ in the exposed regions coincides with the day surface, in the internal regions of the Western Siberian platform it submerges to 4.4 km, and in the north and the northeastern part of the platform (the Pur River, the lower course of the Yenisey River) reaches 6-7 km. The distribution curve of the boundary velocity ($v_{boundary}$) is characterized by a wide range of variations and has a complex 2-modal form with peaks at values of 5.7 and 6.1 km/sec. The noted peculiarities indicate significant

[1]When compiling the sections, the results of the deep seismic sounding with respect to continuous profiles through the Central Urals (the UTGU Administration, the Geology Institute of the UNTs of the USSR Academy of Sciences) and the Barabinsk-Ovechkino profile (SNIIGGiMS, NTGU) were also used.

petrographic nonuniformity of the rock emerging to the Φ surface. The next, deeper boundary I is also isolated by the refracted wave data in soundings with bases of 30-60 km. In the investigated territory its maximum submersion reaches 11 km. The boundary has discontinuous propagation and a typically block form of relief. The extended sections of comparatively gently sloping occurrence of it are disturbed by multikilometer scarps, along which it rises to the level of the Φ surface or is exposed on the day surfaces in the vicinity of the Salairskiy and the Yenisey Ridges). The magnitude of the boundary velocity is more sustained than on the ϕ surface, and it is 6.0 to 6.6 km/sec. The problem of whether the boundary I is accompanied by a sharp velocity discontinuity or smooth variation of the velocity properties in some depth range cannot be given an entirely defined answer for the entire investigated territory by the available data. In some cases (the vicinity of the Kuznetsk trough) clear exchanged waves are recorded (refracted and transmitted) from this boundary; consequently, there is a quite sharp velocity discontinuity. In other regions (the latitudinal course of the Ob' River) such waves have not been obtained, and the problem of sharpness of the boundary remains to a significant degree indeterminate.

According to the set of data on the configuration of the seismic boundaries Φ and I and the velocity distribution in the medium in the investigated territory of Western Siberia it is possible to isolate three types of structure of the upper part of the earth's crust shown in Fig 73 in the form of schematic columns. It is possible to determine the propagation of the various types of structure by the block diagram in Fig 72.

Let us classify the sections a first type where the boundary I occurs 2 to 10 km below the Φ surface. In such sections the propagation rate of the elastic saves on the Φ surface is somewhat reduced, and usually it is 5.0 to 5.6 km/sec, that is, it corresponds to the left maximum of the distribution curve $v_{boundary}$. This type of structure is extended to 70% of the total extent of all of the deep seismic sounding profiles. The territory of the Kuznetsk trough is characterized in the folded frame zone by this type of section.

The second type of section does not contain the I boundary. A high value of the boundary velocity on the Φ surface is characteristic (6.1-6.4 km/sec). In the given case on this surface, in all probability, rocks are detected which usually occur under the I boundary. The noted structural characteristics are encountered within the limits of the Western Siberian platform (for example, in the section of the Ob' traverse between the villages of Aleksandrovskoye and Ust'-Tym) and in the exposed regions (Salairskiy Ridge).

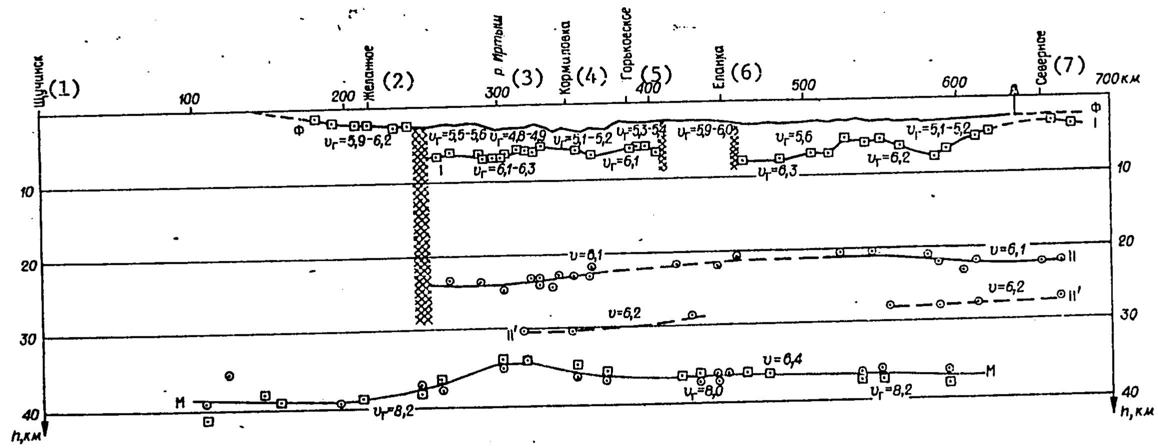

Figure 70. Seismic section along the traverse through the northern part of the Kazakh folded region and the southern part of the Western Siberian platform. For the provisional notation see Fig 67.

Key:
1 -- Shchuchinsk; 2 -- Zhelannoye; 3 -- Irtysh River; 4 -- Kormilovka; 5 -- Gor'kovskoye; 6 -- Yelanka; 7 -- Severnoye

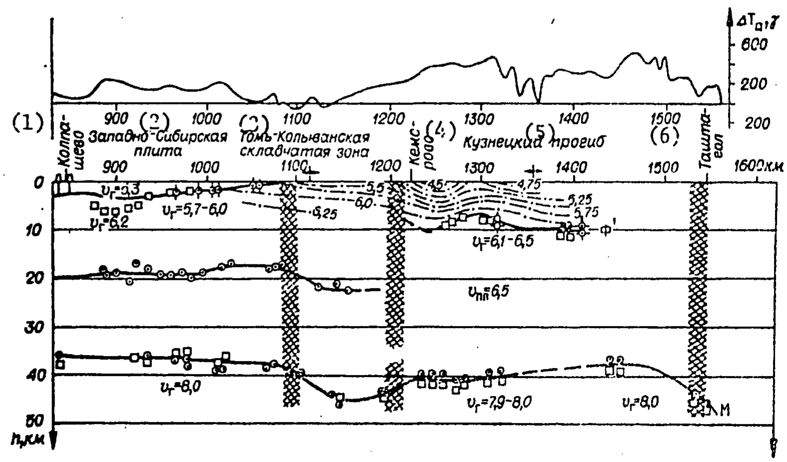

Figure 71. Kolpashevo-Tashtagol traverse.
For the provisional notation see Fig 67.

Key:

1. Kolpashevo
2. Western Siberian platform
3. Tom'-Kolyvanskaya folde' zone
4. Kemerovo
5. Kuznetsk trough
6. Tashtagol

The third type of section, also without the I boundary, was established in the exposed Tom'-Kolyvanskaya folded zone and in the section north of it up to the vicinity of Kolpashevo. In contrast to the second type section, here the velocity on the Φ surface is 5.3-5.9 km/sec, and the lower series of rock about 5 km thick is in the first approximation the gradient medium in which the velocity increases on the average by 0.05-0.15 km/sec for each kilometer of depth. The maximum increase in velocity is characteristic of the exposed sections.

The indicated three types of seismic section correspond to three types of basement blocks delimited by the deep fractures and forming a complex mosaic structure in plan, which in the southern regions of the Western Siberian platform have been studied by the procedure of the area type seismic soundings.

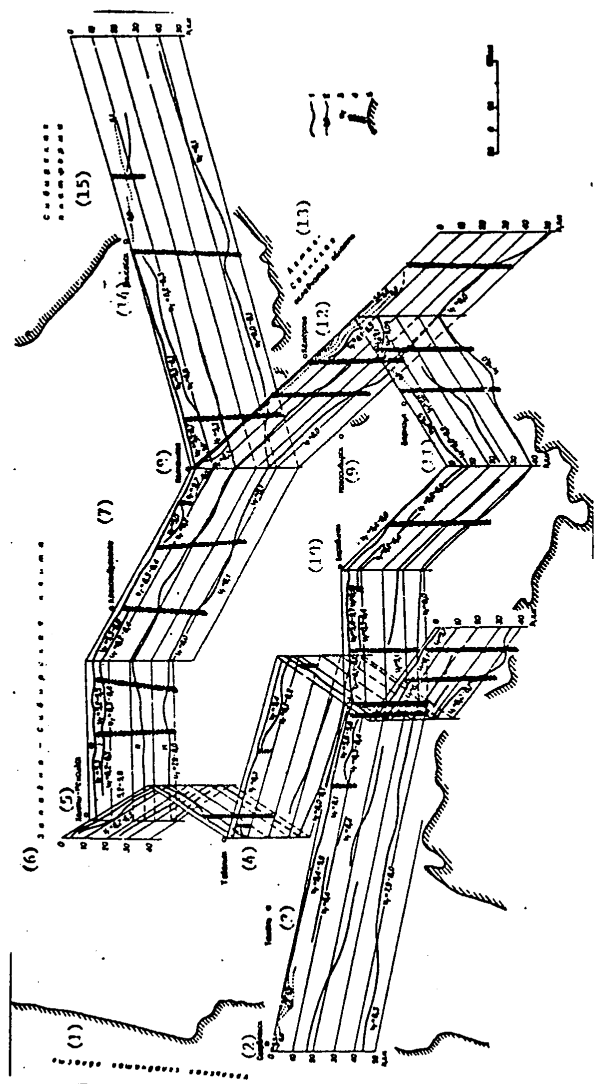

Figure 72. Block diagram of the structure of the earth's crust in Western Siberia

[see p 189 for legend and key]

[Legend and key to Fig 72]:

1 -- seismic boundaries: Φ -- basement surface (refracting boundary), I -- refracting boundary inside the basement, II -- reflecting boundary in the crystalline crust, M -- foot of the earth's crust; 2 -- isolines of the stratal velocities, km/sec according to the refracted wave data; 3 -- boundary velocity, km/sec; 4 -- abyssal fracture zone; 5 -- boundary of the folded framing of the Western Siberian platform.

Key:

1. Urals folded region
2. Sverdlovsk
3. Tyumen'
4. Tobol'sk
5. Khanty-Mansiysk
6. Western Siberian platform
7. Aleksandrovskoye
8. Kalpashevo
9. Novosibirsk
10. Barabinsk
11. Barnaul
12. Kemerovo
13. Altaye-Sayan folded region
14. Yeniseysk
15. Siberian platform

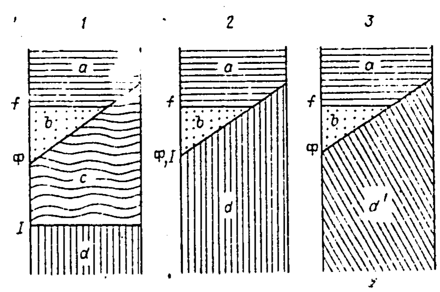

Figure 73. Types of seismic sections of the upper part of the earth's crust in the southern part of the Western Siberian platform

a -- platform mantle; b, c, d' -- layers with the velocity v_{Π}, km/sec: b≈4.5-4.8 (Triassic and Lower Jurassic rock), c≈5.0-5.6, possibly made up of slightly metamorphosed Paleozoic rock, d≈6.0-6.4; d' -- vertical gradient medium (v_0≈5.5 km/sec, dv/dz≈0.1 sec^{-1}). f, Φ, I -- reference seismic boundaries.

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APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200020008-9

Deep Zones of the Earth's Crust and the Tops of the Mantle

The structure of the deep parts of the section was studied in less detail with discovery of the deep structures about 100 km or more across.

In the central part of the section of the earth's crust at depths of 15-30 km by the reflected wave data recorded at distances of 40-70 km from the source, the II boundary was established. The recordings of the refracted waves corresponding to it were obtained only in the region east of Khanty-Mansiysk, the boundary velocity here is about 7 km/sec. The boundary is traced discontinuously with a different degree of reliability. In the scattered sections, various seismic surfaces were possibly traced. The most reliable data were obtained along the Khanty-Mansiysk-Kolpashevo-Kemerovo traverse, and on the low end of the profile along the Irtysh River. The slope angles of the investigated boundary usually do not exceed 2° with the exception of the sections of sharp flexural bending. In such sections with more detailed investigations multikilometer scarps with a discontinuity will possibely be established.

The Mohorovicic discontinuity (M) has been studied by the reflected and refracted wave data on soundings with bases of 170-220 km. The characteristics of this boundary are of special interest, for they permit determination of the properties of the tops of the earth's mantle.

The depths of occurrence of the M boundary in the investigated territory of Western Siberia vary from 32 to 52 km. The mean value of the depths for the Western Siberian platform is 8-10 km less than the adjacent regions of the folded frame.

The surface relief of the mantle depicts the block nature of the latter. In the internal part of the platform, sections of almost horizontal occurrence of the surface predominate. The transitions from section to section are accompanied by sharp variations in depth to the surface of the mantle. The minimum depths (32 km) have been established in the vicinity of Omsk, the maximum depths (44-45 km), in the eastern Yenisey part of the platform.

Block features also appear in the distribution of the slope angles of the M boundary. Along with predominance of the small angles (0-3°) increased values of them are noted which are characteristic of the sections of relatively sharp flexures and possibly the mantle surface scarps. The amplitudes of the flexures (scarps) are usually several kilometers, reaching 8 to 10 km in individual cases.

The mean value of the boundary velocity on the M boundary for the Western Siberian platform is close to the normal value and is equal to 8.0 km/sec. The sustaining of the velocity within the limits of the entire investigated territory of the platform is characteristic -- systematic deviations from the mean values do not exceed ± 0.1 km/sec. The transition to the folded framing regions, as a rule, is accompanied by an increase in the velocity in the tops of the mantle.

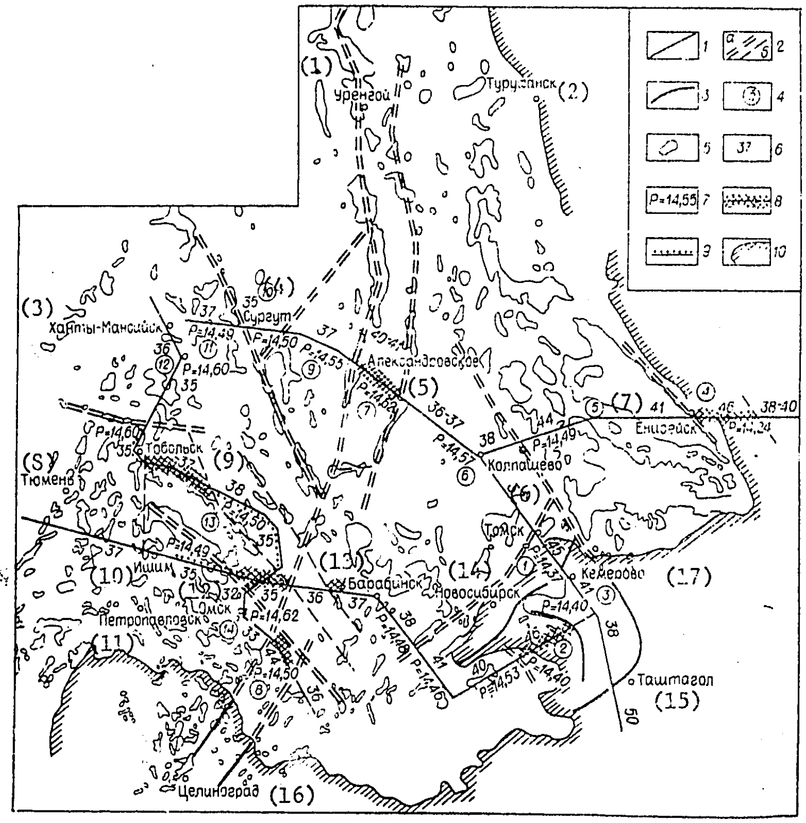

Figure 74. Diagram of the blocks of the earth's crust in Western Siberia

1 -- deep seismic sounding profile; 2 -- abyssal fracture zones according to the deep seismic sounding data (tracing by the magnetic and gravitational field anomalies): a -- fractures encompassing the entire crystalline crust; b -- fractures appearing in the upper part of the crust; 3 -- abyssal fractures according to geological data; 4 -- block numbers; 5 -- positive magnetic field anomalies; 6 -- thickness of the earth's crust; 7 -- pressure (in kilobars) at a depth of 50 km; 8 -- sections with high (6.0-6.4 km/sec) velocities on the basement surface; 9 -- sections with anomalous properties of the tops of the mantle; 10 -- boundary of the folded frame of the Western Siberian platform.

Key:

1. Urengoy
2. Turukhansk
3. Khanty-Mansiysk
4. Surgut
5. Aleksandrovskoye
6. Kolpashevo
7. Yeniseysk
8. Tyumen'
9. Tobol'sk
10. Ishim
11. Petropavlovsk
12. Omsk
13. Barabinsk
14. Novosibirsk
15. Tashtagol
16. Tselinograd
17. Kemerovo

The differences with the regions of the Urals and Northern Kazakhstan are especially significant, where the velocity is 0.3-0.4 km/sec more than in the territory of the Western Siberian platform.

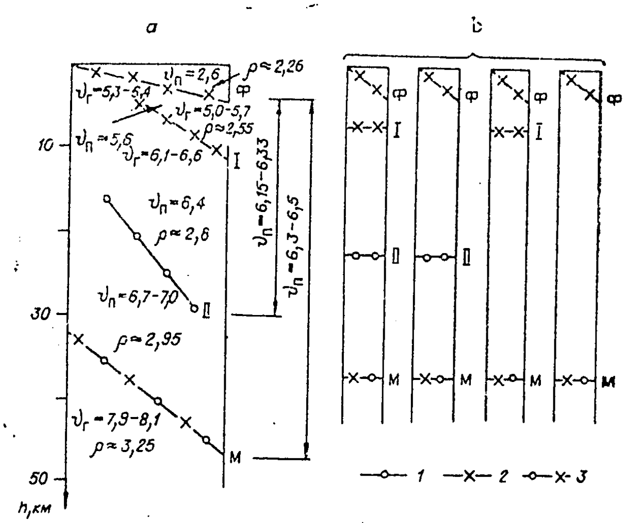

Figure 75. Diagrams of the dismemberment of the earth's crust in Western Siberian according to elastic properties

a -- generalized scheme; b -- schemes for individual regions. Φ -- basement surface; M -- Mohorovicic discontinuity; I and II -- boundaries inside the consolidated crust. 1 -- reflecting boundary; 2 -- refracting boundary; 3 -- reflecting and refracting boundary. v_Γ, v_π -- boundary and average stratal velocities, km/sec; ρ -- density, g/cm^3.

The positive information about the properties of the upper part of the mantle itself were obtained by the dynamic characteristics of the reflected and refracted waves from the Mohorovicic discontinuity. The magnitude of the amplitude ratios of the mentioned waves recorded on one seismogram with fixed distance from the source (200 km) in the greater part of the investigated territory fluctuates within the limits of 1.5-10, and it is equal on the average to 4. The anomalous, sharply increased values with a mean value of about 26 and a range of variation of 10-50 were obtained in the southwestern part of the Western Siberian platform near the cities of Tobol'sk, Omsk and Ishim (Fig 74). A comparison of these experimental data with the results of theoretical calculations for a number of models of the medium will permit the proposition that in the greater part of the territory the velocity under the M boundary will increase with depth on the average 2-5 m/sec for each kilometer of depth. In the anomalous region the magnitude of the velocity gradient is in practice equal to zero. Thus, along with sustaining the propagation rate of the elastic waves along the surface of the mantle within the limits of the entire southern half of the Western Siberian platform, the tops of the mantle are nonuniform with respect to magnitude of the vertical velocity gradient.

By the set of data from the deep seismic sounding method characterized above, the basic features of the deep structure in the investigated territory of Western Siberia are formulated as follows.

1. Along with the regionally sustained seismic boundaries -- the surface of the basement and the Mohorovicic discontinuity -- intermediate boundaries which do not extend everywhere have been isolated in the earth's crust. As a result of their discontinuity and wedging out of the sedimentary series, the earth's crust is broken down into different numbers of layers in different sections (with identical detail of the studies) -- from one to four layers. The generalized data on the breakdown of the section with respect to the elastic properties are presented in Fig 75.

2. The basement surface of the Western Siberian platform on the regional level has relatively little broken relief with predominance of the slope angles of 1-2° and highly complex distribution of the boundary velocity with amplitude of its variation of more than 1.5 km/sec. All of the lower boundaries are characterized by the block form of relief -- extended sections of gently sloping occurrence a angles of 0-3° are disturbed by sharp flexures or scarps with shifting of several kilometers.

3. The surface of the mantle under the Western Siberian platform is characterized by a sustained value of the boundary velocity of 7.9-8.1 km/sec. In adjacent parts of the folded frame the velocities increase to 8.2-8.4 km/sec. In the southwestern part of the platform, in the section with horizontal dimensions of several hundreds of kilometers, an anomaly was discovered in the dynamic characteristics of the elastic waves from the M boundary. The probable cause of the anomaly is a reduced value of the vertical velocity gradient in the rock making up the upper part of the earth's mantle itself.

Laws of the Deep Structure of Western Siberia

Let us begin the analysis of the general relations by comparing the geometric characteristics of the basic seismic boundaries and layers occurring at different depths.

For quantitative evaluation of the deep structural nonuniformities let us consider the mean square deviations of the depths of occurrence of the boundaries (σ_h), their slope (σ_ϕ) and also the thicknesses of the layers (σ_H). The deviations are taken from the mean values of the corresponding parameters characterizing the dismemberment of the relief of the seismic boundaries and variability of the thicknesses of the layers. The corresponding data for the Φ, I, II, M boundaries in increasing order of their average depths (h) are presented below. The data pertain to the Khanty-Mansiysk-Kolpashevo-Kemerovo traverse where all of the interfaces are reliably traced out. The traverse passes through the central and lateral part of the Western Siberian platform, it intersects the closed section of the Tom'-Kolyvanskaya folded zone. Each parameter is calculated by 20 to 30 values averaged on a 50 km base:

Граница (1)	$\bar{h}$, км	σ_h, км	σ_φ	Слой (2)	σ_H, км
Φ	2,7	±1,1	±0°55′	0—Φ	±1,1
I	5,6	±1,8	±2°40′	Φ—I	±1,8
II	21,0	±2,8	±1°50′	I—II	±2,0
M	38,3	±2,8	±2°20′	II—M	±4,8

Key:

1. boundary
2. layer

The presented data indicate the general trend of an increase in the geometric nonuniformities of the structure from the upper boundaries and layers to the lower ones. The surface relief of the basement (Φ) and the thickness of the layer of sedimentary deposits (0-Φ) are the least variable -- all of the compared parameters for the deeper parts of the section have 2 to 4 times greater values. The platform mantle of the Western Siberian platform, as is known, is very slightly dislocated. For example, the fluctuations of the contact surface of the Cretaceous and Paleogenic deposits do not go beyond the depth range of 0-800 meters for regional slopes of only 0° to 0°12'. The day surface is characterized by still less dismemberment: along the investigated traverse the minimum and maximum altitudes of the relief are +50 and +300 meters respectively.

Let us proceed with a comparison of the lateral nonuniformities on different levels of the section, using the data on the elastic wave propagation rates along the reference refracting boundaries Φ, I and M, the average depths of occurrence of which are 3.7 and 38 km. The corresponding boundary velocities (v_Γ) carry information about the properties of the rock making up the upper part of the consolidated crust and the upper mantle. The initial information is sufficiently representative: in Western Siberia on the profiles about 6000 km long, several hundreds of single determinations of the boundary velocity were obtained which are close with respect to accuracy.

As the measure of lateral nonuniformity of the medium by the values of $v_{boundary}$ let us take the mean square deviations ($\sigma_{v_{boundary}}$) of the velocity from the mean value of it for each boundary. The values of $\sigma_{v_{boundary}}$ for the Φ, I and M boundaries are equal to 0.32, 0.13 and 0.12 km/sec respectively.

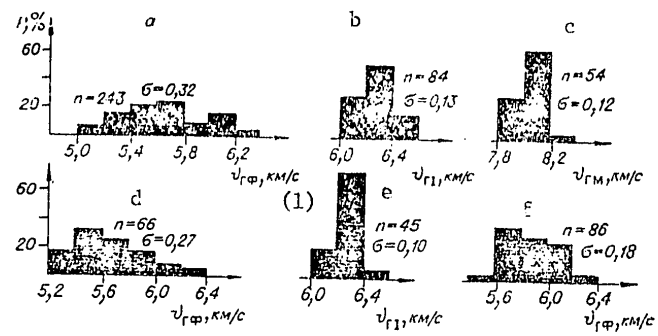

Figure 76. Histograms of the boundary velocity at the Φ, I and M boundaries.
The data for the Φ boundary: a -- initial values, d -- average values on a 100 km base, f -- the same with reduction to the thermodynamic conditions near the surface of the mantle. The data for the I boundary: b -- initial values, e -- average values on a 100 km base, c -- initial values for the M boundary.

Key:

1. km/sec

The corresponding histograms are presented in Fig 76, a, b, c. These values are determined not only by the actual nonuniformity of the medium, but also different detail of the study of the different boundaries inasmuch as, as has already been noted, for the used method of seismic operations the boundary velocity on the M surface will be about 100 km long for its sections, and the averaging interval of the properties of the boundary Φ approximately 10 times less. In order to obtain comparable characteristics, the initial data on $v_{boundary}$ along the Φ and I boundaries were correspondingly average on a 100 km base (Fig 76, d, e). Here, of course, information on the nonuniformities with dimensions of less than 100 km is lost. After this operation the values of $\sigma_{v_{boundary}}$ for the Φ, I and M boundaries have become equal to 0.27, 0.10 and 0.12 km/sec, respectively.

Consequently, the most nonuniform with respect to elastic properties is the series of rock occurring directly under the Φ boundary. With an increase in depth, the degree of nonuniformity quickly decreases: on the level of the I boundary, it becomes 2 to 3 times less. The nonuniformities of the upper part of the mantle itself is almost the same as for the rock in the consolidated crust near the I boundary, that is, at depths of 7-10 km. The latter conclusion is in contradiction to the widespread concept of significantly greater homogeneity of the mantle by comparison with the consolidated crust. The possible cause of this contradiction is failure of the preceding researchers to consider the differences in detail of the seismic and other geophysical information obtained on the crustal and mantle boundaries. It is also necessary to remember that the data that we obtained pertain only to large inhomogeneities with horizontal dimensions of more than 100 km.

Let us try to go from the above-investigated inhomogeneities in the velocity distribution of the elastic waves to the approximate estimates of the inhomogeneity of composition of the rock at different depths. For this purpose it is necessary to consider the influence of the thermodynamic conditions which differ significantly at the investigated levels of the section on the elastic wave velocity. Using the relations known by laboratory experimental data [84] for the velocity as a function of the pressure and temperature, let us reduce the values of $v_{boundary}$ at the Φ and I boundaries to the M boundary conditions, taking a pressure of 9000 kg/cm^2 and a temperature of 500°C for it. The velocity distribution obtained at the Φ boundary (see Fig 76, f) varies significantly, and for the I boundary it remains in practice unchanged. After this reduction the values of $\sigma v_{boundary}$ can be considered as the approximate indirect characteristics of the nonuniformity of the rock position on the corresponding levels of the section. For the Φ, I and M boundaries these values were found to be sufficiently close: 0.18, 0.10 and 0.12 km/sec, respectively.

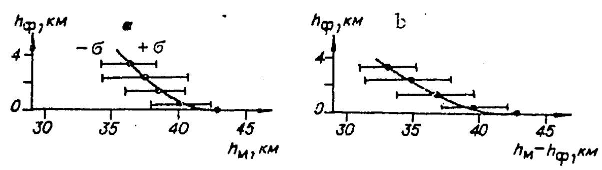

Figure 77. Depths to the Mohorovicic discontinuity (a) and thickness of the consolidated crust (b) as a function of depth to the surface of the basement in Western Siberia.

Let us consider the relations of the geometric parameters for the regionally propagated boundaries Φ and M. The correlation boundaries (see Fig 77) for the depths of occurrence of these boundaries, the thicknesses of the sedimentary layer and the thickness of the consolidated crust (the layer between the Φ and M boundaries) each were constructed by 85 pairs of values taken every 50 km in the seismic profiles within the limits of the entire investigated territory. The average values are indicated in the figure for the kilometer intervals of the vertical axis. The segments of the horizontal straight lines correspond to the mean square deviations (σ) from these mean values. The investigated values are related by the inverse correlations. The submersion of the basement surface from 0 to 4 km is accompanied by a rise of the Mohorovicic discontinuity from 43 to 36 km. A decrease in thickness of the consolidated crust from 43 to 32 km corresponds to an increase in the thickness of the sedimentary mantle to 4 km. Consequently, the giant depression of the Western Siberian lowland exhibited in the upper layers of the section corresponds to just as broad an uplift of the surface of the earth's mantle with approximately twice the amplitude and with a reduction in thickness of the consolidated crust by more than 10 km.

The presented correlations are characterized by great dispersions; consequently, in addition to the above-noted laws characteristic of the Western Siberian platform and its framing as a whole, there are significant nonuniformities of the deep structure within the boundaries of the large structures.

Relations for the Internal Part of the Western Siberian Platform. In order to attenuate the effect of the above-investigated regional relations connected with variation and thickness of the sedimentary mantle, let us limit ourselves to the data of the areas with relatively sustained (in the range of 2-4 km) depths to the Φ surface. For this purpose let us select the corresponding sections on the south end of the Irtysh traverse and on the Khanty-Mansiysk-Kolpashevo-Tomsk traverse. The reference points of the depths will be selected every 50 km.

The correlation graphs for the depths of occurrence for the I, II and M boundaries are presented in Fig 78. It is demonstrated that the depths to the Φ boundary differ little at all points. Between the depths h_I and h_M and also h_{II} and h_M there are quite close mutual correlations (see Fig 78, b, c). The correlation coefficients (r) are equal to -0.84 and -0.79 respectively; the mean square devi[illegible]ions (σ) from the regression lines are ±1.1 and ±1.8 km. The increase in depths h_M corresponds to a decrease in the value of h_I and h_{II}, that is, the inversion relation is established for the forms of the surface relief of the mantle with the higher-lying boundaries inside the consolidated crust. The de[illegible]ths of the boundaries I and II (Fig 7, d) are related by a direct correlation (r=+0.79, σ=±1.9 km), that is, these surfaces occur in general matched.

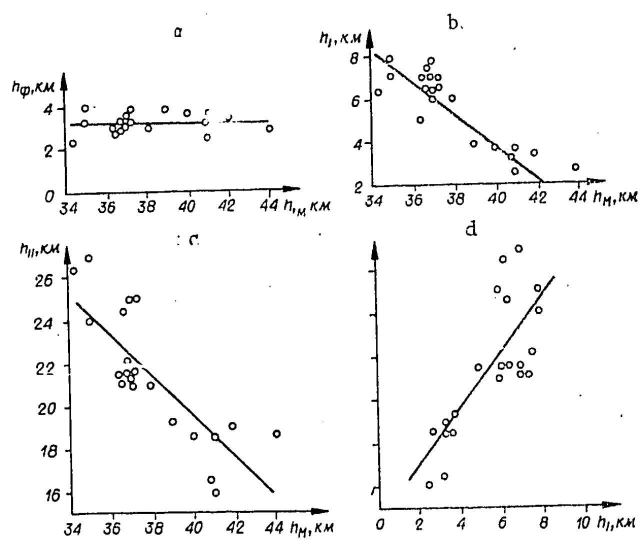

Figure 78. Correlation graphs of the depths of occurrence of the seismic boundaries (inside of the Western Siberian platform)

Let us consider the correlations of the thicknesses (H) of the layers Φ-I, I-II and II-M as a function of the total thickness of the earth's crust (Fig 79). The thickness of the upper layer (Φ-I) varies discontinuously from 0 to 2-4.5 km. The zero values correspond to the complete wedging out of the investigated layer and they are coordinated with the sections with thickened crust (39-44 km). The second group of values is characteristic for the crust 34-38 km thick.

The thickness of the second layer (I-II) has a weak tendency (r=-0.49) toward some decrease with an increase in thickness of the crust (see Fig 79,b). The mean square deviations from the mean value (~15 km) is ±2 km, that is, the thickness of the layer is relatively sustained.

A very close relation is established between the thickness of the lower layer (II-M) itself and the total thickness of the crust (r=0.94, σ=±1.8 km). The thickening and thinning of the entire earth's crust in its lower layer coincides (see Fig 79, c). As a result of the inversion relation of the relief of the II and M surfacea, the thickness of the layer bounded by them is most invariant. The total scale of its oscillations is approximately 2 times more than for the entire thickness of the earth's crust and it exceeds by 3 to 4 times the variations for any other layer.

Thus, in the internal part of the Western Siberian platform with relatively sustained thickness of the sedimentary mantle there are inverse (inversion) relations of the depths of occurrence of the surface of the mantle with the higher-lying boundaries of the consolidated crust. The most inconstant is the thickness of the lower layer of the earth's crust, and its thickness varies in general in accordance with the variation in thickness of the entire crust, but with approximately twice the amplitude.

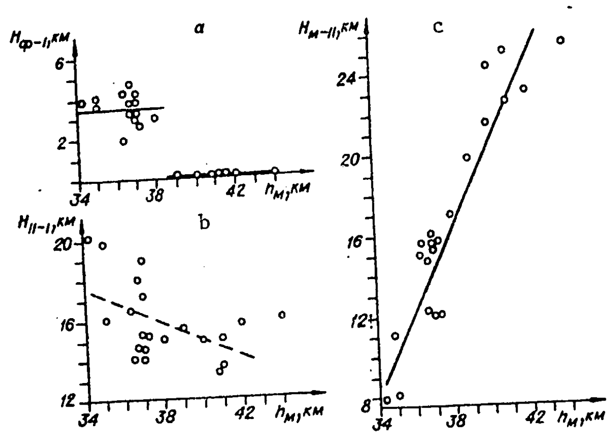

Figure 79. Correlation graphs for thicknesses of the layers of the earth's crust (the inside part of the Western Siberian platform)

The relations for the lateral zone of the Western Siberian platform, that is, for the sections of transition to the mountain frame, are important in connection with the discovery of the causes of formation of an enormous depression in the territory of the Western Siberian lowland.

It was demonstrated above that on making the transition from the exposed areas to the inside sections of the platform, a reduction in thickness of the entire earth's crust takes place, especially its consolidated series. Let us consider what changes occur inside the crust in this case.

The variation in thickness of the layers of the earth's crust in the section of articulation with the exposed Tom'-Kolyvanskaya folded zone in the vicinity of Tomsk consists in the following (see Fig 71). For submersion of the Φ boundary from the level of the day surface to a depth of 3 km, the thickness of the upper layer of the consolidated crust bounded by the Φ and II surfaces (the I boundary was not established in the investigated section), remains, in practice, invariant, for the Φ and II boundaries occur matched. The thickness of the lower layer (II-M) decreases regularly from the exposed part to the inside zone of the platform. The reduction in thickness of this layer is about 6 km and within the limits of accuracy of the initial data coincide with the decrease in thickness of the consolidated crust (the Φ-M layer). Consequently, the variation in thickness of the consolidated crust takes place wholly as a result of its lower section. The buildup of the layer of the platform sediments to 3 km only half compensates for this effect; therefore the total thickness of the earth's crust decreases in the direction of the internal zone of the platform.

The variations of the deep structure close to the ones discussed above are also visible in the schematized section through the Sverdlovsk intersection (see Fig 67). The eastern submersion of the surface of the exposed folded rock in the Urals is accompanied by a reduction in thickness of the earth's crust basically as a result of its lower layer. On the profiles to the south of Barabinsk (see Fig 68) and in section adjacent to Northern Kazakhstan (see Fig 70), the thickness of the crust is also reduced in the direction of the submerged part of the platform; the upper layers occur almost matched, with an increase in depth, inversion of the structural forms takes place.

The discussed characteristics of the relation of the seismic boundaries at different depths make it possible to propose the probable cause of formation of the broad Mesozoic-Cenozoic depression made by sedimentary rock in the territory of the Western Siberian platform. The Mohorovicic discontinuity and series of deep boundaries inside the earth's crust, in the opinion of the majority of researchers [14, 125, and so on], are secondary and superposed. During the course of geological development, the displacement of these boundaries to other hypsometric levels and the variation of their shapes are possible. The cause can be reconstruction of the lower part of the earth's crust in the territory of the modern depression. The Mohorovicic discontinuity and the boundaries of the lower part of the crust were shifted to higher levels. As a result, the rock density increased in the transformed part of the section, and the isostatic equilibrium of the broad territory was disturbed. This led to gradual downwarping of the earth's crust over an enormous area accompanied by filling of the depression formed by sediment.

The inversion relation existing at the present time for the relief of the upper and lower boundaries of the crust can be explained by the fact that the amplitude of the depression was less by comparison with the initial displacement of the lower horizons upward along the section. For this reason, the thickness of the earth's crust remained diminished. The total magnitude of the ascending displacement of the Mohorovicic discontinuity can be approximately determined by the difference in thicknesses of the consolidated crust within the limits of the Western Siberian platform and in its mountain framing regions which is on the average equal to 10 km.

The basic results of analyzing the structural peculiarities and the properties of the consolidated earth's crust in Western Siberia at different depths consisted in the following.

1. The variability of the depths of occurrence of the seismic boundaries and the thicknesses of the layers of the earth's crust, as a rule, increases, with depth. The nonuniformity of the natural distribution of the elastic wave velocities decreases sharply with an increase in depth only in the very upper part of the section (between the Φ and I boundaries). The deeper zones of the earth's crust, if limited to the investigation of nonuniformities with horizontal dimensions of more than 100 km obviously do not differ significantly from the upper part of the mantle with respect to degree of homogeneity of the elastic properties.

2. The common relation for the entire territory is the inverse relation between depths to the basement surface and the Mohorovicic discontinuity. The broad depression of the Western Siberian platform which in the investigated area over the basement surface has amplitude of about 4 km, corresponds to uplift of the surface of the mantle with almost double amplitude and reduction of the thickness of the consolidated crust on the average by 10 km with respect to the folded framing regions. In the majority of cases, the inversion relation of the relief of the mantle surface and the higher-lying boundaries in the consolidated crust is noted.

3. The thickness of the lower ("basaltic") layer is most inconstant and varies in accordance with the thickness of the entire earth's crust, However, the thicknesses of the layers of the upper ("granite" and "sedimentary") part of the section frequently vary correspondingly, and their total thickness fluctuates by up to 10 km,

4. On the basis of the peculiarities of the variation of the deep structure on making the transition from the mountain frame to the Western Siberian platform it appears probable that the cause of downwarping of the platform territory during the Mesozoic and Cenozoic Ages was reconstruction of the

lower part of the earth's crust as a result of the ascending displacement of the Mohorovicic discontinuity with conversion of part of the crustal rock to mantle material. The disturbance of the isostatic equilibrium that occurred led to the formation of a broad, long-lived sedimentary basin over the area of the modern Western Siberian lowland.

Block Structure of the Earth's Crust in Western Siberia

Isolation of Blocks and Fractures. The following peculiarities lead to the concept of the block structure of the earth's crust. Over the extended (100 km or more) sections of the profiles the depths of occurrence of the seismic boundaries, the thickness of the earth's crust, and its dismemberment vertically, the thicknesses of the individual layers and the elastic wave velocities vary little. In the narrow zones of articulationof such sections throughout the entire series of cons lidated crust, all or the majority of the mentioned parameters vary sharply. Frequently these zones are the tracing boundaries of certain seismic surfaces. The amplitudes of the sharp variations in relief of the seismic boundaries (in the form of flexures or with discontinuities) usually are 3-7 km. The thicknesses of the layers can vary still more. The discontinuities of the boundary velocity and the basement surfaced reached 0.5-1 km/sec. In some cases the average and stratal velocities vary noticeably.

The sections with sustained deep structure are considered as blocks of the earth's crust. In the articulation zones of the blocks, in all probability, large abyssal fractures have bee developed, many of which penetrate the entire thickness of the crust a.d possibly the tops of the earth's mantle. The majority of abyssal fractures appeared in the gravitational and magnetic fields in the form of extended zones of intense positive magnetic anomalies, gravitational "steps" and a change in structure of the anomalous fields. This permits more certain isolation of the zones of the probable abyssal fractures and tracing of them to significant distances from the seismic traverses.

By the set of indicated attributes for a significant part of the Western Siberian platform and certain regions of its folded frame, a diagram of the blocks of the earth's crust was drawn (see Fig 74), where the large blocks which appear throughout the entire thickness of the earth's crust and are delimited by fractures reaching the tops of the mantle are isolated. At a number of points, the finer blocking is reflected which was discovered only in the upper part of the consolidated crust. The intersecting zones of abyssal fractures in the northwesterly and northeasterly directions predominate, and fractures are noted with almost meridional and latitudinal strikes. As a result, an important characteristic of the structure of the earth's crust has been traced: the presence of a mosaic system of large angular blocks with horizontal dimensions of 100 km or more. Let us briefly characterize the individual blocks.

The Altaye-Sayan folded region has been studied by the seismic method in sections of the Tom'-Kolyvanskaya zone, Salair, the Kuznetsk trough and partially in Gornaya Shoriya. The earth's crust in the Tom'-Kolyvanskaya folded zone which corresponds to the individualized block I was up to 45-46 km thicker and exceeds the adjacent blocks by 5 to 7 km with respect to thickness. The reflecting boundary II inside the earth's crust lies at a depth of about 22 km, that is, 4 km deeper than in the adjacent part of the Western Siberian platform.

The higher-lying part of the section does not contain clear elongated boundaries and can in the first approximation be considered as the gradient medium with velocity buildup from 5.5 km/sec near the day surface to 6 km/sec at depths of 3-5 km.

Block 2 corresponds to the exposed part of the Salair anticlinorium and the adjacent section of the Western Siberian platform. The block is bounded by abyssal fractures 20 km east of Barnaul and at the boundary with the Kuznetsk trough. The inversion relation of the M and II seismic boundaries is characteristic: the foot of the crust is downwarped to depths of about 40 km, and the II boundary is uplifted. The uppermost part of the section is made up of rock with high elastic wave velocity (6.0-6.3 km/sec).

Block 3 coincides with the territory of the Kuznetsk trough. The thickness of the earth's crust is 38-41 km, that is, 5-10 km less than in the adjacent mountain regions, the articulation with which takes place with respect to the abyssal fracture zones. The refracting boundary I in the upper part of the crust is characterized by variable values of the boundary velocity (6.1-6.5 km/sec) and depths of occurrence (7-10 km) in all probability corresponding to the surface of the intensely metamorphosed folded base of the trough. The structure of the sedimentary series above the I boundary is characterized by the stratal velocity isolines according to the refracted wave data.

The Yenisey ridge and the western edge of the Siberian platform are intersected by the seismic profile with respect to the latitudinal course of the Angara River. The Yenisey ridge (block 4) borders with the Western Siberian platform along the abyssal fracture. On making the transition to the ridge, the thickness of the crust increases from 41 to 47 km, and the seismic surfaces I and II cease to be traced. The propagation rate of the elastic waves in the upper part of the crust of the Yenisey ridge increased (6 km/sec). The mean velocity in the entire thickness of the crust in the meridional direction is approximately 0.2 km/sec more than in the latitudinal direction, which together with the absence of the sustained boundaries inside the crust probably indicates the latitudinal development in it of submeridional disjunctives propagated to the depth.

On making the transition to the western edge of the Siberian platform the thickness of the earth's crust decreases smoothly to 38-41 km, and at depths of 8-15 km the reflecting boundary was established which can correspond to the surface of the Archean base of the platform.

The Western Siberian platform is also broken down into a series of large blocks with different deep structure of the earth's crust.

The extreme eastern block 5 is located between the Yenisey ridge and a continuation of the Kuznetsk-Altay zone of abyssal fractures. The thickness of the crust is increased (to 44-45 km) by comparison with the adjacent sections of the platform. At depths of 20-22 km, the reflecting boundary II is traced. The higher refracting surface I has a sharply dismembered, obviously, block relief (4-11 km) and variable values of the boundary velocity (6.2-6.6 km/sec). Obviously this boundary corresponds to the surface of the day crystal basement. The layer between the I and Φ boundaries probably is moderately dislocated, weakly metamorphosed sedimentary rock from the Paleozoic discovered in the given region by deep wells under the Meso-Cenozoic platform mantle. The inside structure of the eastern block is nonuniform. In the section of the Kaska basin '' . I boundary is downwarped by 3-4 km, and the Mohorovicic discontinuity is uplifted to 41 km. In the same section reduction of the values of the boundary velocity is noted at the I surface and the mean velocity to the II boundary.

Block 6 in the east is bounded by the Kuznetsk-Altay fracture zone, in the west, by the fracture in the vicinity of the mouth of the Tym River, and in the southeast it is articulated with the exposed Tom'-Kolyvanskaya zone. The southwestern continuation of the block has not been investigated. The thickness of the earth's crust is 37-38 km. The II boundary occurs in the depth range of 20-22 km. The refracting surface I in the basement has been established only in two limited sections, being the bottom of the basins with downwarp amplitude of 3-4 km and no more than 100 km across made up of relatively weakly metamorphosed rock. Over the remaining territory of the block the upper part of the basement is a gradient medium, just as within the limits of the Tom'-Kolyvanskaya folded zone.

Blocks 7 and 8 which are sharply detected by the structural peculiarities have been established correspondingly on the Ob' (the section between the villages of Aleksandrovskoye and Ust'-Tym) and the Irtysh (the vicinity of Cherlak) traverses. There is much in common in the deep structure of these blocks: rock with high (6.1-6.4 km/sec) elastic wave velocity goes to the surface of the basement, the earth's crust has a thickness of more than 40 km and is thickened by 4-8 km with respect to the adjacent sections. The inversion of the structural forms is clearly exhibited: downwarps with respect to the M boundary correspond to uplifts of the II and I surfaces. The western boundary of both blocks is the Omsk fracture zone intersecting the entire Western Siberian lowland. With respect to magnetic field peculiarities, the block 7 is traced to the north to the Arctic Ocean, and block 8, to the region of exposed structures in Northern Kazakhstan where it is the uplifted part of the Caledonian structures. Possibly the investigated blocks form a single buried structure extending several thousands of kilometers 100-200 km across, which cuts through the basic mosaic system of angular blocks. At approximately the latitude of Omsk, this structure is disturbed by the transverse fractures of northwesterly strike; the complex structure of the earth's crust was discovered here which differs from that described above.

Blocks 9, 10 and 11 were studied along the latitudinal course of the Ob' River. The thickness of the crust varies little (36-37 km). The II boundary rises successively from block to block from 25-26 km in the west to 21 km in the east. The refracting boundary I with sustained depths of occurrence (6-8 km) and a boundary velocity of 6.2-6.4 km/sec has been established in all the blocks. The velocity at the surface of the basement is somewhat lowered, and it varies little (5.2-5.6 km/sec).

Block 12 is bounded on the south by the sublatitudinal fracture in the vicinity of Tobol'sk, and it is traced to the north to Khanty-Mansiysk. On making the transition through the southern fracture, the structure of the upper part of the consolidated crust (see Fig 74) and the nature of the recordings of the elastic waves from the M boundary vary. The thickness of the crust of the block is equal to 35-36 km. The reflecting boundary II is noted only in its northern half at depths of 22-23 km. The upper part of the consolidated crust is nonuniform: the boundary velocity on the basement surface varies from 5 to 6 km/sec, and the depths of occurrence at the refracting boundary in the body of the basement are sharply variable (4-10 km). Significant differences in the structure of the upper part of the consolidated crust do not permit joining of this block with the block adjacent to it to the east of Khanty-Mansiysk.

Block 13 was established in the central part of the Irtysh traverse; in the southeast it is adjacent to the Omsk fracture zone and is divided into the eastern and western parts bounded by the fracture which appeared only in the upper part of the crust. In the east, the velocities at the basement surface are reduced (5.4 km/sec), and at depths of 5-8 km the refracted boundary I occurs. In the west the I boundary does not exist, the velocity at the basement surface is high -- 6.0 to 6.1 km/sec. The seismic boundary I in the eastern section obviously corresponds to the bottom of the large (with an amplitude of up to 5 km) downwarp in the basement filled with relatively weakly metamorphosed sedimentary rock. The mantle surface is submerged by 35-38 km. The velocity buildup with a depth in the rock of the mantle obviously takes place appreciably more slowly than in other sections.

In the vicinity of Omsk, block 14 has minimum thickness of the earth's crust -- 32 to 34 km -- for the entire investigated territory. The upper part of the basement is made up of rock with low elastic wave velocity (5.1 to 5.4 km/sec). Inside the crust two boundaries have been established; reflecting at a depth of 27 km and refracting at the 6-7 km level.

The peculiarities of the velocity distribution connected with the block structure of the earth's crust, in addition to the procedural significance, are important as valuable information about the properties of the deep structures within the limits of the inhomogeneous blocks.

Initially we shall consider the resultant data on the mean velocity obtained by the corresponding recalculation [115] of the effective velocities determined by the reflected and refracted waves. Fig 80 shows the mean velocity as a function of depth $\bar{v}(h)$ for standard blocks. The graphs pertain only to the consolidated crust. The origin of the coordinates for the depths is matched with the Φ boundary which in the exposed regions coincides with the day surface

By the functions $\bar{v}(h)$ the blocks with different structure of the tops of the consolidated crust are most sharply distinguished. The blocks for which the high-velocity (6.0-6.4 km/sec) rock reaches the Φ boundary are characterized by the largest values of the mean velocity and the minimum values of its vertical gradient (see Fig 80, 1). In the mountain frame, they include the section of the Salair ridge, within the limits of the Western Siberian platform, blocks 7 8 and others denoted by the dotted line in the diagram (see Fig 74).

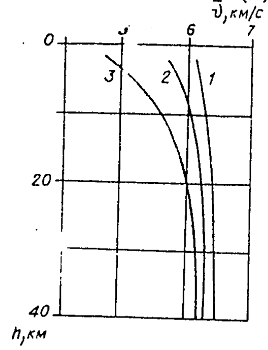

Figure 80. Characteristic graphs of the average velocity in the consolidated crust as a function of depth:
1 -- in block 7 (the Western Siberian platform); 2 -- in the blocks of the Western Siberian platform containing a series of low-speed rock under the Φ boundary; 3 -- within the limits of the Kuznetsk trough.

Key:
1. $\bar{v}$, km/sec

The blocks which are widespread in the territory of the platform with a layer of relatively low-speed (5.0-5.7 km/sec) rock bounded by the Φ and I surfaces are characterized by lower values of the mean velocity at all depths and higher vertical velocity gradient (Fig 80, 2). The noted peculiarities of the function $\bar{v}(h)$ are still more sharply manifested for the block corresponding to the Kuznetsk trough (Fig 80, 3). Here the upper layer has a very great thickness (about 10 km), and the velocities are still lower. The latter obviously is basically caused by the absence of the compression effect within the limits of the platform as a result of the thick platform mantle.

The separation of the consolidated crust into the "granite" and "basaltic" part is widespread. This provisional provision by the geophysical data permits approximate determination of the large differences in the petrographic composition of the crust in different sections inasmuch as the rock of basic (basaltic layer) and acid (granite layer) composition is characterized by different velocities and densities. The traditional separation of the indicated layers by the deep seismic sounding data reduces to the fact that one of the intracrustal seismic boundaries is taken as the so-called Conrad surface separating these layers. This choice usually is provisional: for detailed seismic studies several discontinuities which are similar with respect to their properties have been often established, and the stratal velocities in the isolated layers do not remain constant. All this leads to significant difficulties and ambiguity in the comparison of the various blocks with respect to thicknesses of the granite and basaltic layers with traditional isolation of them.

Below, another approach is used to the separation of the consolidated crust into two provisional layers. In the lower (basaltic) layer the velocity is assumed to be constant and equal to 6.8 km/sec. The higher-lying part of the crust to the Φ boundary is joined to the upper ("granite") layer. The velocities in it are taken equal to 6.4 km/sec below the I boundary, and in the interval between the Φ and I boundaries, in accordance with the actual data for the investigated section of the profile. Knowing the thickness of the entire consolidated crust and the mean velocity in it, it is possible to calculate the value of the ratio of the powers (q) of the upper and lower layers. The absolute value of q depends on the selection of the velocity in the lower layer, and therefore it is provisional. However, when comparing these values for different blocks, it is possible to determine the difference of the latter with respect to their "granite" and "basaltic" parts. The values of q for large blocks in Western Siberia were described in the diagram (see Fig 81).

Significant differences of the blocks connected with the deep structure with respect to magnitude of the thickness ratio of the granite and basaltic layers which varies from 1.1 to 3.3 have been established. The low values (2.0-2.6) are characteristic for a large group of blocks (the first group) with a layer of relatively low-velocity rock under the Φ boundary. The minimum value of q=1.1 is characteristic of the Kuznetsk trough where this layer has maximum thickness. For the blocks of this group, decreased thickness of the crust by comparison with the adjacent sections is also characteristic.

The high values of q=3.0-3.3 were obtained for the second group of blocks with high (6.1-6.4 km/sec) velocity on the Φ surface. For the majority of such blocks, the total thickness of the earth's crust is relatively increased (Salair and Yenisey ridges, blocks 7 and 8 in the Western Siberian platform). The noted peculiarities are explained by the characteristic sections through the different type blocks (Fig 82): in the blocks of the first group the provisional "basaltic" layer is thicker, and its surface has a grown-over form with respect to the intracrustal boundaries.

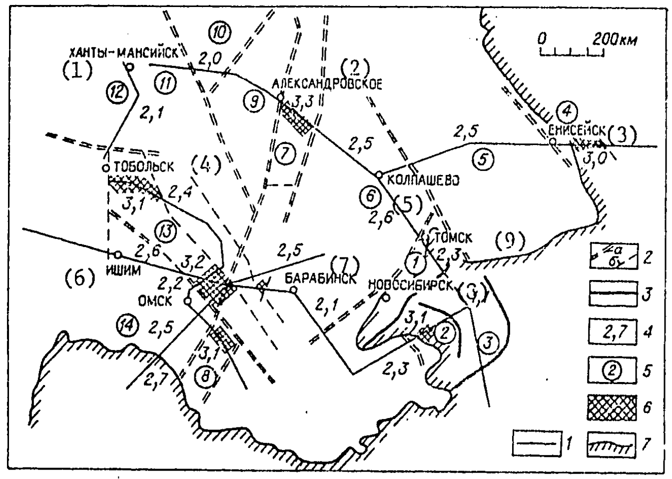

Figure 81. Diagram of the thickness ratio of the granite and basaltic layers
1 -- deep seismic sounding profile; 2 -- crustal-mantle fractures (a) and fractures in the tops of the basement (b); 3 -- abyssal fractures with respect to geological data; 4 -- ratios of the thicknesses of the "granite" and "basaltic" layer; 5 -- numbers [illegible] the block; 6 -- sections with high velocity on the bas[illegible]nt surface; 7 -- boundary of the folded frame of the Western Siberian platform.

Key:

1. Khanty-Mansiysk
2. Aleksandrovskoye
3. Yeniseysk
4. Tobol'sk
5. Kolpashevo
6. Ishim
7. Barabinsk
8. Novosibirsk
9. Tomsk

Let us try to give the possible geological interpretation of the presented data. The blocks of the first group with an increase in the "basaltic" layer and higher position of the M boundary experienced relative subsidence in the premesozoic time, which was recorded by the formation of a layer between the Φ and I boundaries, and in the Kuznetsk trough, its sedimentary execution. The second group of blocks characterized by thinner "basaltic" layer and deeper M boundary, were uplifted at the same time, as a result of which the deep rock with high elastic velocity reached the Φ surface, and in the exposed regions, the day surface. The possible cause of vertical movements of the blocks leading to significant changes in the upper part of the consolidated crust could be the nonuniform conversion of the lower part of it to the mantle material, disturbing the equilibrium of adjacent blocks.

In the blocks of the first group this transformation was manifested more strongly; the Mohorovicic discontinuity turned out to be appreciably uplifted, and the higher-lying rock of the earth's crust increased in weight. The latter is recorded by increased thickness of the "basaltic" layer, the thickness of which in this interpretation is considered as an index of the degree of conversion of the lower part of the crust itself.

The estimation of the isostatic equilibrium of the blocks of the earth's crust is of interest for determination of the tectonic activity of the individual regions of the investigated territory. It is known [5, 7, and so on], that the disturbance of the isostatic equilibrium can be considered as an indication of the modern activity of the given section of the earth's crust. Usually the study of isostasy is made by the gravimetric data; there are examples of using the results of deep seismic soundings for this purpose [21, 121, 134]. Below, the second of the mentioned approaches is used which permits calculation of the pressure on the selected level for each block. The use of the seismic data permits not only estimation of the differences in pressure, but also discovery of the peculiarities of the deep structure which lead to one isostatic effect or another.

Using the seismic data on the structure of the earth's crust and the known [5] relation of the rock density to the elastic wave velocity, the pressures (p) at a depth of 50 km were calculated. The calculations were performed by the formula

$$p = \sum_i \rho_i H_i,$$

where ρ_i and H_i are the densities and thicknesses of the layers respectively averaged for the given block. The mean values of the density in the layers are presented in Fig 75. On variation of the velocities in the medium, the corresponding corrections were introduced to the densities.

The pressures obtained are applied in the schematic of the blocks (see Fig 74). The probable error in the pressure is estimated at 0.02-0.04 kbars.

The pressure averaged for the entire investigated territory of Western Siberia at a depth of 50 km is 14.54 kbars, which is close to the corresponding values obtained by Yu. G. Yurov [134] for the Caucasus (p=14.6 kbars) and A. G. Gaynanov and S. A. Ushakov [21] for the transition zone from the Asian continent to the Pacific Ocean (p=14.4 kbars).

On the whole the Western Siberian platform is characterized by somewhat increased values of the pressure (14.54 kbars) by comparison with the folded framing regions (the Yenisey ridge, 14.24 kbars, the Tom'-Kolyvanskaya zone, 14.37 kbars). The excess pressure in the vicinity of the territory is approximately 0.2-0.3 kbars.

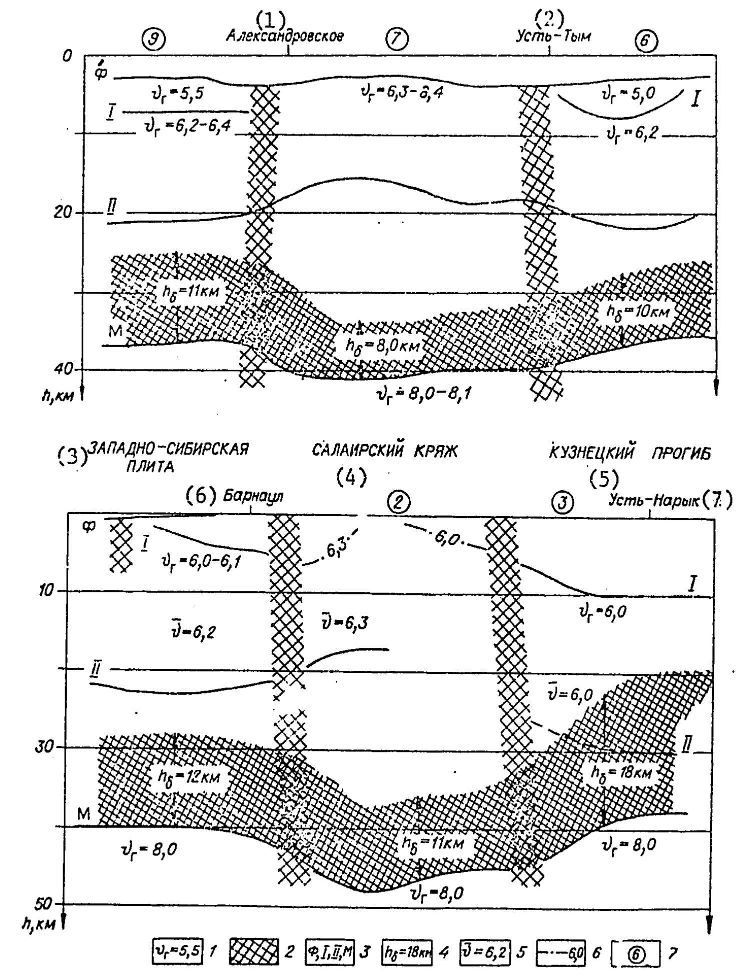

Figure 82. Characteristic seismic sections with provisional "basaltic" layer (crosshatched).
1 -- boundary velocity, km/sec; 2 -- abyssal fracture zone; 3 -- seismic boundary; 4 -- thickness of the "basaltic" layer; 5 -- mean velocity, km/sec; 6 -- velocity isolines; 7 -- numbers of the blocks of the earth's crust.

Key:

1. Aleksandrovskoye
2. Ust'-Tym
3. Western Siberian platform
4. Salair ridge
5. Kuznetsk trough
6. Barnaul
7. Ust'-Naryk

Within the limits of the platform itself the pressure at the selected level is appreciably more sustained; it does not go out of the range of 14.47 to 14.62 kbars. The difference in values for adjacent blocks exceeds 0.1 kbars rarely. Let us present comparative data with respect to the tectonically active region of transition from the Asian continent to the Pacific Ocean [21]. Here the deviations from the average pressure are 0.3-0.4 kbars, and they reach 0.9 kbars for the Kurilo-Kamchatka Arc and the adjacent deep-water trench. The corresponding deviations for the Western Siberian platform are almost 10 times less. Consequently, it is possible to consider that the blocks of the earth's crust of the Western Siberian platform are in a condition very close to the isostatic equilibrium. The level of pressure compensation is located immediately under the mantle surface; therefore the isostasy of the blocks is caused by the peculiarities of the mass distribution inside the earth's crust. Some nonequilibrium is noted in the boundaries with the regions of folded framing of the Western Siberian platform. Let us formulate the basic conclusions pertaining to the block structure of the earth's crust in the territory of Western Siberia.

1. The earth's crust in the Western Siberian platform and adjacent exposed regions has a mosaic-block structure. Within the limits of each block the thickness of the crust, its layering, the depths of occurrence of the seismic boundaries, the thickness of the layers and the elastic wave velocities are relatively sustained. The blocks have horizontal dimensions from 100 to 200 km to many hundreds of kilometers, and they are bounded by fracture zones reaching the tops of the mantle. The boundaries of the blocks in the majority of cases have appeared in the magnetic and gravitational field anomalies, which has made it possible to interpolate the data to large distances from the seismic profiles and to obtain a concept of the spatial structure of the earth's crust in a significant area. In the exposed sections the seismic blocks and fracture zones are a deep continuation of the geological structures known near the surface.

2. The ratio of the thicknesses of the provisionally isolated "granite" and "basaltic" layers is in regular relation to the block structure of the region. The "basaltic" layer is thickened in the blocks with a thick layer of low-velocity rock in the upper part of the basement and with relatively reduced thickness of the crust. A possible cause of the differentiated vertical movements of the blocks in the premesozoic time essentially changing the structure of the upper part of the basement was nonuniform conversion of the bottom of the crust to mantle material.

3. In spite of the significant nonuniformities in the deep structure, the investigated territory of Western Siberia is in a condition which is close to isostatic equilibrium -- the pressure fluctuations at the compensation level (~50 km) are appreciably lower here than in the tectonically active regions. The blocks of the earth's crust within the boundaries of the Western Siberian platform are the closest to equilibrium. Some nonequilibrium of the platform territory with respect to sections of its folded frame is noted.

4. The discovered peculiarities of the block structure of the consolidated crust constitute the basis for more reliable tectonic regionalization of the basement of the Western Siberian platform with respect to the entire set of geological-geophysical data, which, in addition to independent prospecting significance, in accordance with the principle of inheritance of geological development, is important for discovery of the laws of the tectonics of the platform mantle and the regional variations of the lithologic-facies composition of the components of its sedimentary complexes containing oil and gas deposits.

§2. Studies of the Basement of the Western Siberian Platform

Information about the structure of the basement is needed for reliable tectonic regionalization, on which the scientifically substantiated prospective planning of the prospecting for various minerals is based to a significant degree. Accordingly, it is necessary to note two basic aspects of the study of the basement.

First, in the near future the required increase in oil and gas reserves will be realized not by prospecting produc ive complexes of rock in the platform mantle, but, possibly, as a result of discovering new oil and gas-bearing formations in the more ancient deposits. For the southern part of the Western Siberian platform, finding Paleozoic oil under the Meso-Cenozoic platform mantle is already now urgent.

Secondly, the study of the basement presupposes the use of the principle of inheritance of the geological development of the platform mantle and the basement. The inheritance is most clearly manifested in the young platforms, to which the Western Siberian platform belongs, where the discontinuity in time between the formation of the mantle and the postgeosynclinal folding of its base is relatively small. The regional differences in the structure and the development of the basement in accordance with the principle of inheritance can cause significant peculiarities of the tectonic conditions and the conditions of sediment accumulation of the platform formations, which are the reservoirs for the oil and gas; therefore the tectonic regionalization of the basement must be given special attention.

Until recently, this regionalization of the basement of the Western Siberian platform remained to a great extent ambiguous, based primarily on the analysis of the gravitational and magnetic anomalies with extrapolation of the layer established in the mountain frame of the platform, to the internal closed regions. The role of the most exact geophysical method -- seismic prospecting -- was relatively small. The tedious studies by the correlation refracted wave method (KMPV) were basically limited to the local sections and did not give an idea of the regional structure of the basement.

The regional studies of the surface of the basement by the sounding procedure in the traverse version were actually carried out along all of the navigable rivers of Western Siberia in the 1960's. The total extent of the investigated traverses reaches 15,000 km. The Novosibirsk, Tomsk and Krasnoyarsk Main Administrations, subdivisions of the Glavtyumen'geologii Administration, the IGiG Institute of the Siberian Department of the USSR Academy of Sciences, and the ZapSibNIGNI Institute participated in the work. In recent years, area studies of the basement have been made in the southern parts of Western Siberia in order to study not only the surface of the prejurassic basement, but also its internal three-dimensional structure to a depth of up to 10 km.

A discussion is presented below of the basic results of the work in the Tyumen' Oblast and in the southern part of Western Siberia.

Studies in Tyumen' Oblast

In this largest oil and gas-bearing region the spot soundings by the refracted wave method (Chapter II, §4) were used to study the basement surface by the regional traverses (the Glavtyumen'geologii crews made about 5,000 km of river traverses, the ZapSibNIGNI Institute investigated the ground traverse along the Tura-Tobol-Irtysh Rivers); small and large-scale area surveys were made of the basement surface.

Sounding systems of the B and E type were used (see Fig 23) with careful introduction of corrections for the oscillation phase (considering the characteristic features of the form of the wave recording), the depth of submersion of the explosive charge, the low-velocity zone, the relief and the displacement of the blast and observation points from a rectilinear profile. All of this insured increased accuracy of determining the parameters of the medium -- on comparison with the drilling data (see §1 of the given chapter) the error in the depth to the basement surfacd was 2-2.5%. Along with the depths and boundary velocities, values were determined for the vertical velocity gradient of the upper part of the basement, using the method [78] based on investigation of the nonparallelness of the elements of the overlapping hodographs.

In addition to the solution of the regional problems, the procedure for soundings by refracted waves was tested to discover the possibility of its application for finding and preliminary study of the local structures with respect to the basement surface.

Traverse Regional Studies. For characterization of this type of operation, let us consider the results with respect to the standard Pecherakh-Froly traverse (Fig 83), by the Konda seismic crew 46/63 along the Konda and Irtysh Rivers.

In the western part of the profile (60-140 km) the large anticlinal bend is clearly fixed which corresponds to the intersection of the Shaimskiy structural nose. The amplitude of the bend is 450-500 meters with a width of 80 km; the angles of dip of the wings are about 40', Then, between 140 and 170 km of the profile, an anticlinal bend is noted which corresponds to the Bol'she-Tapskiy swell. Its dimensions with respect to the given intersection are about 30 km, and the amplitude is on the order of 400 meters. The dip angle of the western wing of the Tapskiy swell is about 1°, and the eastern wing, is significantly steeper, about 3°50'. With respect to value of the boundary velocities of 4.2-4.4 km/sec in this profile interval, the basement is represented by the deposits of the II structural stage. In the same section of the profile, an increased vertical velocity gradient is observed. By the deep drilling data the basement in this region is represented by deposits which are standard for the II structural-tectonic stage and are claasifiable as the Turinskaya series.

The Lugovskaya basin which is isolated in the 170-200 km section of the profile has an extent on the order of 30 km with a magnitude of the downwarp of about 300 meters. The dip angle of the eastern and western sides of the basin are 2°12' and 3°50', respectively.

The Leushinskiy swell (200-260 km) previously isolated by the TT survey data, is depicted in the TZ MPV refracted wave section as an anticlinal bend with a width of 55 km, an amplitude of 700 meters and dip angles of the wings of 2°10' and 1°10'.

East of the Leushinskiy swell, a monoclinal of submersion of the basement surface to the center of the Mansiyskaya basin complicated by positive and negative structures with horizontal dimensions of 20-30 km and amplitudes of several hundreds of meters is noted. In the eastern section of the traverse, in view of the small volume of operations, only the order of the depths to the refracting horizon which experiences a rise from a depth of 3350 to 3207 meters is obtained. The R-1 Frolovskaya well encountered limestone, from the roofs of which the refracting horizon is identified.

When comparing the TZ MPV refracted wave data with the results of continuous profiling by the reflected wave method by the river procedure, satisfactory comparison of the results is observed on the whole. Some divergence of these data is explained obviously by the incomplete matching of the MOV [reflected wave method] and TZ MPV refracted wave profiles in plan view. In general, by the data from the refracted wave method the regional and local peculiarities of the relief of the basement surface are depicted more sharply and in greater contrast than it is possible to determine by the data of the reflected wave method which, given the depths to the reflecting horizons in the sedimentary mantle, gives many peculiarities of the structure of the section in clear form. The individual details of the basement relief, even small in magnitude, find reflection in the above-lying reflecting boundaries. For example, two anticlinal bends in the vicinity of the 430 km profile with small horizontal displacement are fixed to a depth of 2000 meters.

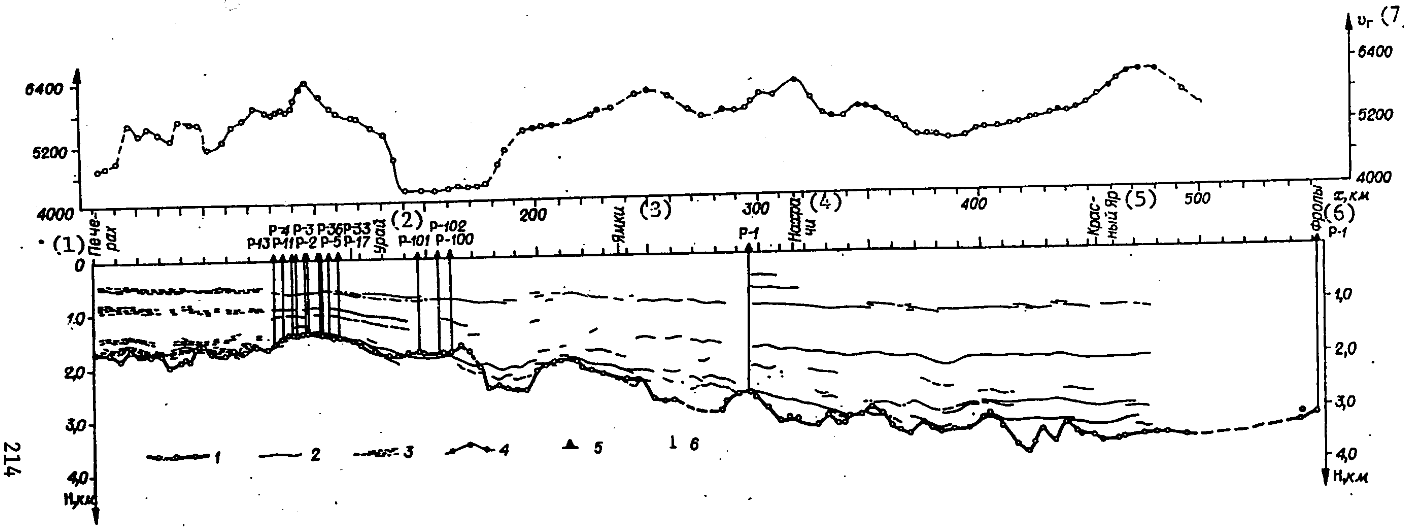

Figure 83. Seismic section through the Pecherakh-Froly profile.
1 -- depth to the surface of the basement according to the refracted wave data; 2 -- reflecting boundaries; 3 -- the same by the unreliable data; 4 -- value and graph of the boundary velocity; 5 -- deep prospecting holes; 6 -- depth to the basement according to the drilling data.

Key:
1. Pecherakh
2. Uray
3. Yamki
4. Nakhrachi
5. Krasnyy Yar
6. Froly
7. $v_{boundary}$

The small-scale area regional operations with the goal of studying the basement surface by the TZ MPV procedure were carried out during two field seasons by crews 36/64 and 17/65 on the Khanty-Mansiyskiy geophysical trust in the Khanty-Mansiyskiy, Surgutskiy, Konda, Uvatskiy and the Tobol'skiy Rayons. The total survey area in two generalized sections contains 153,00 km^2 with an average density -- one determination of the depth to the basement surfaces per 2,200 km^2. The operations were performed by air.

Let us present the basic geological-geophysical results with respect to the most interesting area in petroleum-bearing respects located in the Surgutskiy and the Khanty-Mansiyskiy Rayons. Here the aeromagnetic and gravimetric surveys and the aviation seismic soundings by the reflected wave method were performed, by the materials of which jointly with the results of the detailed work using the reflected wave method and drilling, the structural and tectonic diagrams of the Mesozoic-Cenozoic mantle were compiled. The absence of data on the basement surface served as a basis for stating the TZ MPV refracted wave operations, inasmuch as it was recognized that the clearest representation of the tectonics of the Mesozoic mantle could be obtained, having a map of the basement surface available.

A comparison of the results of the TZ MPV surveys with the previously constructed structural-tectonic map of the basement surface compiled by the surveys by the reflected wave method on a 1:1000000 scale and the gravimagnetic data indicates comparison of the majority of structural elements. Here the surface relief of the basement according to the refracted wave data appears in sharper form. The majority of positive structures (the Lyaminskiy Arch, the Trom"yeganskiy, Chernorechenskiy and Vyngapurskiy dome uplifts) correspond to intense positive gravitational fields, although other more complex relations exist.

The map of the boundary velocities constructed on the 1:2 500 000 scale gives defined information about the material composition of the underlying rock. On the whole the boundary velocity field is divided into two sections. In the western part of the area, an increased value of the boundary velocity is observed. The isoline of 6.3 km/sec outlines the most uplifted part of Lyaminskiy arc. Within the limits of the Chernorechenskoye and Trom"yeganskoye uplifts the boundary velocity decreases to 4.9-5.1 km/sec.

The vertical velocity gradient (β) was determined by many of the soundings. The nature of the field β is analogous in general features to the nature of the boundary velocity field. In the vicinity of the Lyaminskiy arc, the velocity gradient is minimal, and in the most uplifted part it is close to zero. The maximum value of β (0.06-0.07 1/km) is noted on the arcs of the Trom"yeganskiy and the Chernorechenskiy dome-type uplifts. In the depression zones of the basement, the velocity gradient is somewhat less, on the order of 0.03-0.04 1/km.

The complex interrelation of the various geophysical fields to the values of the boundary velocity is discovered. In spite of the small volume of research that has been performed, some laws are noted. In the operations territory it is possible to isolate two zones distinguished by the nature of the geophysical fields. The first zone corresponding to the Lyaminskiy arc and the region adjacent to it is characterized by the sign-variable magnetic field, the maximum value of $v_{boundary}$ and the minimum value of β. It is possible to propose that the foundation of this zone is complicated by monolithic rock, probably, crystalline shales or silicified limestones and dolomites characteristic of the late Baykal geosynclinal complex.

The second zone coincides with the most uplifted part of the Surgutskiy arc and is characterized by the minimum values of the boundary velocities, maximum β, quite intense anomalous positive magnetic field and negative gravitational anomalies. Obviously, within the boundaries of the Surgutskiy arch, the basement is represented by weakly metamorphosed formations of stage II with the development of effusives of basic composition.

The results of these operations indicate the significant prospectiveness of the development of such studies in enormous territories still not covered by seismic exploration to the north and south of the latitudinal course of the Ob' River. Considering these results, the Glavtyumen'geologiya Trust and the Ministry of Geology of the USSR are planning the soundings by the refracted wave method in 1977-1980 over an area of 150,000 km^2. Defined possibilities are opened up in using such data for interpretation of the gravitational and magnetic field anomalies.

The large-scale prospecting work by the spot sounding method using refracted waves was carried out in the Shaimskiy oil-bearing region within the limits of the so-called Shaimskiy structural nose. The work was performed during two summer field seasons by the efforts of the ZapSibNIGNI Institute (1963) and production crew 44/64 of the Shaimskaya petroleum prospecting expedition (1964) with the goal of testing the procedures for finding and preliminary study of local structures. Some 292 physical observations were made in an area of 2650 km^2, which made it possible to compile a structural map of the surface of the basement on a 1:200000 scale with an isohypse cross section of 100 meters (see Fig 84).

As a result of the TZ MPV refracted wave operations, the general regional submersion of the basement surface from southwest to northeast to a depth from 1600 to 1900 meters was established. In the general submersion zone the structural element of II order is clear -- the Shaimskiy structural nose previously noted by the data from the gravimagnetic surveys and bounded on the west, the north and the east by the 1800 meter isohypse.

A number of local order III structures have been isolated (see Fig 84). In the southern part of the area the northern periclinal of the Severo-Teterevskaya structure was discovered. Then to the north the Tolumskoye local uplift was discovered and outlined. It is a brachyanticlinal fold extended in a meridional direction, The dimension of the structure with respect to the long axis is 10-12 km, and by the short axis, 6-7 km. The amplitude of the uplift within the limits of the closed loop is 120 meters. The depth to the basement surface in the arch part is 1580 m. The Tolumskoye uplift is separated from the Severo-Teterevskaya structure by a downwarp.

North of the Tolumskaya anticlinal structure, the Semividovskaya local structure is noted which has dimensions with respect to the outlining isohypse of 1700 meters, 9x6 km with an amplitude of 50 meters. Northeast of the Semividovskoye uplift is the small (5x2.5 km) brachyanticlinal fold of the northeastern strike with an amplitude of about 40 meters.

The western and eastern wings of the Shaimskiy structural nose are made up of a number of local bay-like troughs, local depressions and uplifts. In particular, on the western wing, a small uplifted zone called the Double Local Structure is noted.

A comparison with the detailed area operations by the reflected wave method performed after taking the TZ MPV surveys indicates that even insignificant structural peculiarities noted in the TZ MPV refracted wave method, essentially only qualitatively find good confirmation during beachhead operations. The detailed seismic prospecting operations by the reflected wave method have confirmed the Severo-Teterevskaya, Tolumskaya, Semividovskaya and the Dvoynaya structures.

Of course, the constructions by the TZ MPV refracted wave method and by the area surveys using the reflected wave method in individual details sometimes do not coincide, which is entirely natural in connection with the different observation density for the detailed area surveys by the reflected wave method and the prospecting TZ MPV refracted wave method.

After performing detailed seismic work on the Severo-Teterevskaya and the Tolumskaya structures, prospecting drilling was started leading to the discovery of two oil fields (Severo-Teterevskoye and Tolumskoye). The drilling results confirm the high accuracy of determining the depths to the basement surface by the sounding procedure (see Chapter V, §1, Table 3).

The presented results indicate that the TZ MPV refracted wave method of course cannot replace the reflected wave method (the continous profiling), but even under the complex conditions of the Shaimskiy district the complexing of these general methods will permit the most efficient selection of the areas for prospecting and outlining local structures with smaller expenditures of time and means.

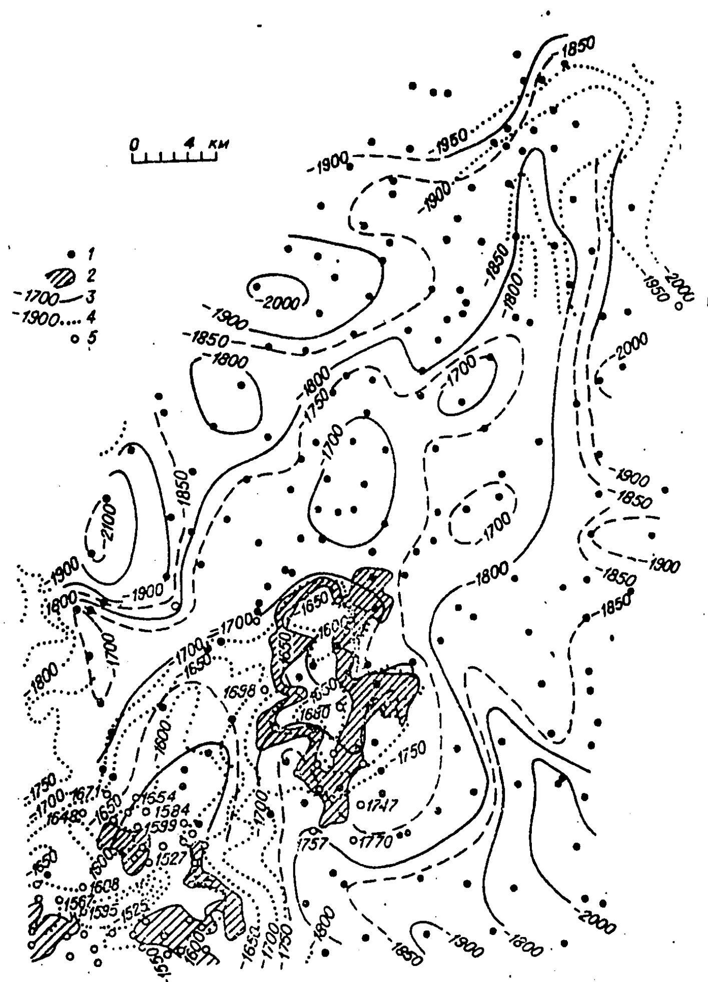

Figure 84. Comparison of the results of the TZ MPV refracted wave method with the data from detail seismic proszpecting by the reflected wave method and drilling
1 -- sounding centers in which the depths to the surface of the foundation are obtained; 2 -- outline of the petroleum deposits by the condition on 1 January 1967; 3, 4 -- isolines of the basement surface with respect to the data of the TZ MPV refracted wave method (3) and by the data from the detail operations by the reflected wave method of the Shaimskaya and the Khanty-Mansiyskaya oil prospecting expeditions (4); 5 -- the reconnaissance prospecting drilling wells and absolute depths to the crystalline basement.

Area· Studies of the Internal Structure of the Basement in the Southern Part of the Western Siberian Platform

These studies were performed by the central complex geophysical expedition of the Novosibirsk territorial geological administration jointly with the IGiG Institute of the Siberian Department of the USSR Academy of Sciences over an area of 100,000 km^2 within the limits of the Novosibirsk, the Omsk and the Kurgan Oblasts in connection with the problem of discovering the prospects of oil-bearing Paleozoic depotis [64, 113]. The operations were basically performed during the summer with motor transportation.

The seismic model of the upper part of the basement and the choice of the reference waves for the regional area studies are based on the results of the traverse operations discussed in the preceding item by the method of deep seismic sounding and on the experience of studying the bottoms of the platform mantle by the reflected wave method.

The reflecting boundary f, occurring in direct proximity to the foot of the Mesozoic-Cenozoic platform mantle is traced by the reflected wave method using the ordinary procedure.

The refracting surface Φ is studied in an area sounding network with bases of 10-25 km with average density of the points of determination of the depths and the boundary velocity of 7x7 km. The discontinuous layer b (see Fig 73) between the boundaries f and Φ obviously corresponds to the sedimentary-vulcanogenic rock of Triassic and lower Jurassic age included by a number of researchers in the composition of the II structural stage.

The refracting boundary I is also traced in the area sounding network. The sounding bases are 40-60 km, and the spacing between their centers is 2-3 times greater than when studying the boundary f. The refracting method I supposedly belongs to the surface of intensely metamorphized rock of the geosynclinal complex, and the layer c between the Φ and I boundaries for the interpretation which is in need of confirmation by deep drilling data, can be considered as the lower (Paleozoic) series of rock in the structural phase II. The basic prospects of oil-bearing Paleozoic in the southern part of the Western Siberian platform are connected with this series.

The indicated seismic surfaces and the layers bounded by them are encountered in various combinations. By the set of data on the configuration of the seismic boundaries and the velocity distribution in the medium, three types of seismic sections of the basement are isolated which are investigated in detail in the preceding item (see Fig 73).

The areas with different types of section are blocks of the basement separated by almost vertical abyssal fracture zones. The problem of the area regional seismic studies include the study of the Φ and I reference boundaries to obtain data on the spatial structure and properties of the basement to depths of about 10 km with separation and tracing with respect to the area of different blocks and the deep fractures separating them.

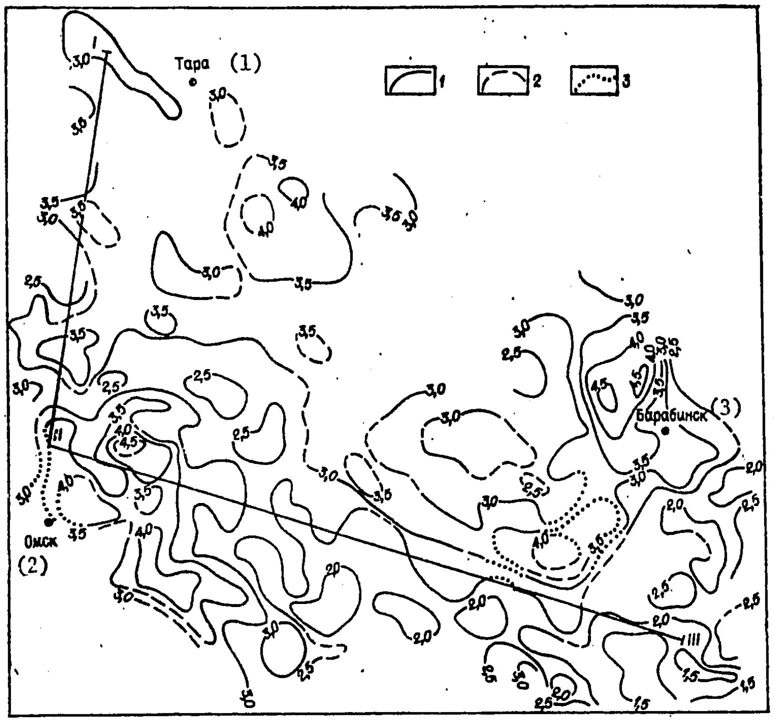

Figure 85. Structural map of the Φ boundary
1 -- isohypses, km; 2 -- isohypses by the uncertain data and
3 -- proposed.

Key:
1. Tara
2. Omsk
3. Barabinsk

The resultant constructions are presented in the form of three maps and the section explaining them (see Figures 85-88). The maps obtained contain the following information.

1. The relief of the refracting surface Φ with detail sufficient for determination of the regional structures and their complicating uplifts and troughs with horizontal dimensions of more than 10 km.

2. Area distribution of the boundary velocities in the rock underlying the Φ surface.

3. The contours of the propagation of great thicknesses (more than 0.5 km) of the layer b between the boundaries f and Φ identified with the upper series of sedimentary-vulcanogenic rock of the intermediate structural stage.

4. The thicknesses of the layer c between the Φ and I boundaries, the discontinuous spread of which is controlled by the fracture zones.

By the set of these data it is possible to determine the spatial layered-block structure and the properties of the rock with a total thickness up to 5-6 km, which is the basement of the platform mantle. The regionalization of the basement with respect to types of its internal structure shown in Fig 73 is possible. Let us consider the general laws of the seismic structure of the basement.

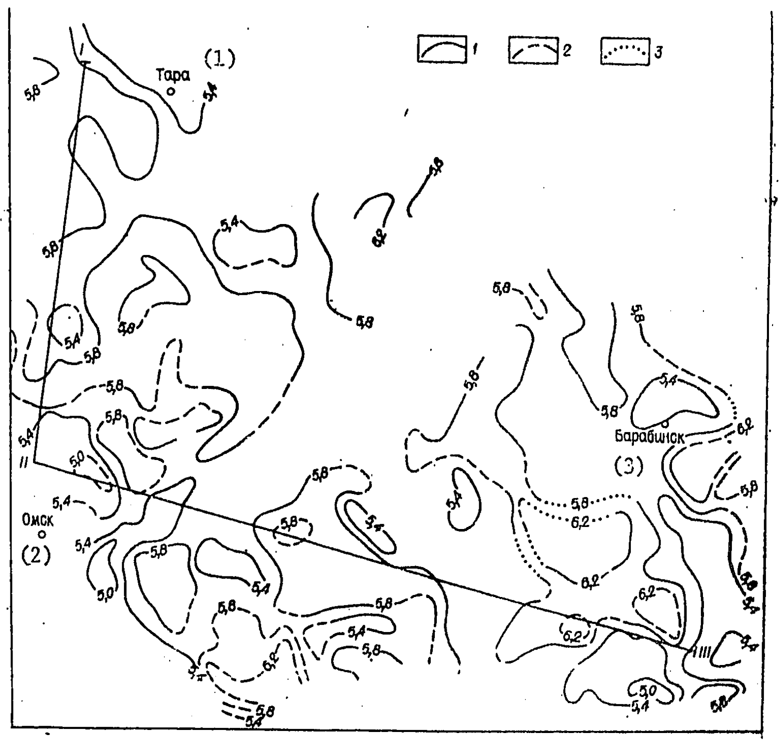

Figure 86. Velocities through the Φ boundary
1 -- velocity isolines, km/sec; 2 -- isolines by the unreliable data and 3 -- proposed.

Key:
1 -- Tara; 2 -- Omsk; 3 -- Barabinsk

The refracting boundary Φ divides the investigated series of basement rock into two parts distinguished with respect to elastic properties (and, consequently, with respect to rock composition) and structural characteristics.

The upper part -- the seismic layer b probably corresponding to the Triassic and lower Jurassic formations -- is characterized by relatively smooth variation of thickness in the 0-2 km range. The maximum thicknesses are coordinated with the deep depressions, the zero thicknesses are coordinated with the uplift arches with respect to the Φ surface. The thickness of the layer is basically determined by the relief of this boundary, for the surface of the layer (the boundary f) lies appreciably more gently sloping. The lower (under the boundary Φ) part of the basement section has higher propagation rates of the elastic waves, as a rule, more than 5 km/sec. A characteristic feature of this part is the block structure. The limits of the blocks (fractures) are in the sections with sharp variation of the depths and velocities on the Φ boundary where discontinuous uplift of the surface I takes place to the level of the Φ boundary, as a result of which the layer c between them is completely wedged out. The transverse dimensions of the isolated blocks amount to no less than 10-15 km. Their strike is different, and on the whole it agrees with the strike of the structures over the Φ surface. The blocks predominate with the c layer (the first type of structure in Fig 73), in which the boundary velocity at the Φ surface is relatively low, about 5.6 km/sec or less.

The blocks with thick (several kilometers) low-speed layer c spread to 60-70% of the investigated territory are of significant interest in connection with estimation of the prospects of oil-bearing Paleozoic in the southern part of the Western Siberian platform, for it is possible to propose that this layer in a number of cases corresponds to the slightly altered sedimentary Paleozoic formations making up the buried petroleum-bearing basins. Accordingly, during further studies, along with the expansion of the area of the investigated regional seismic operations, a problem of primary significance is the discovery of the geological nature of the layer c by the set of drilling and geophysical data. The seismic method faces the problem of the breakdown of this layer and the study of its internal structure to find possible petroleum-controlling structures.

Let us proceed with the geological interpretation of the basic seismic data on the structure of the upper part of the consolidated crust. The main problem consists in determining the geological analogs for seismic boundaries Φ and I and the layer of rock between these boundaries.

As has already been noted, in the basement of the Western Siberian platform covered with Mesozoic and Cenozoic platform mantle, two structural stages are isolated. Stage I, or the folded basement itself, is a complex of Paleozoic and more ancient formations undergoing the geosynclinal phase of development and represented by the folded, metamorphosed rock saturated with various intrusions. Stage II (otherwise called the pre-mantle, intermediate or parageosynclinal) is formed of Paleozoic and Lower Mesozoic sedimentary and vulcanogenic-sedimentary rock occurring discontinuously between the Mesozoic-Cenozoic platform mantle and folded basement.

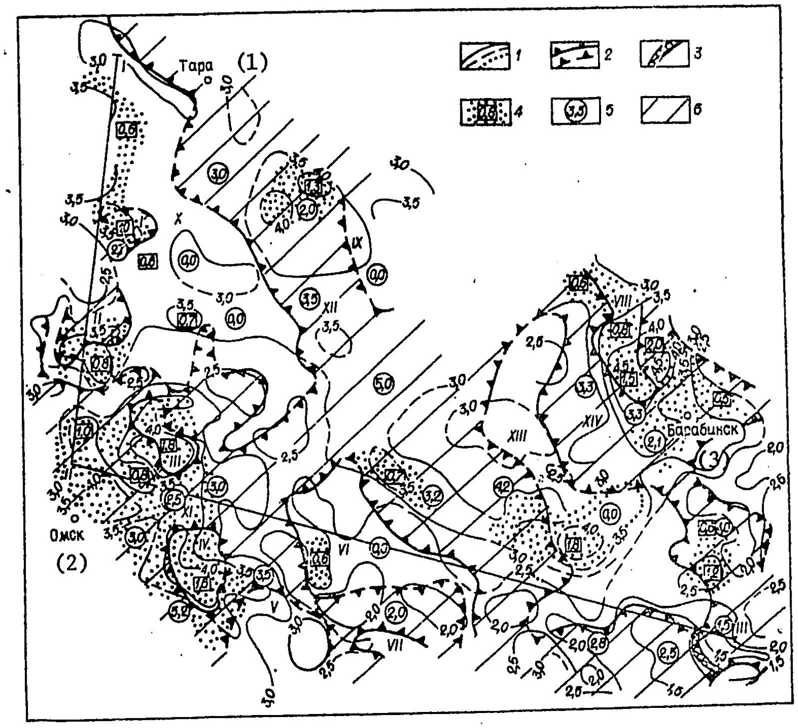

Figure 87. Diagram of the internal structure of the prejurassic deposits of the Western Siberian platform
1 -- isohypses, km; 2 -- boundaries of the blocks (proposed fracture zones); 3 -- sections of sharp variation of the boundary velocity along the Φ surface; 4 -- sections of spread of the layer b (see Fig 73) more than 0.5 km thick; 5 -- thickness of the layer c, km; 6 -- propagation sections of the layer c.

Key:
1. Tara
2. Omsk
3. Barabinsk

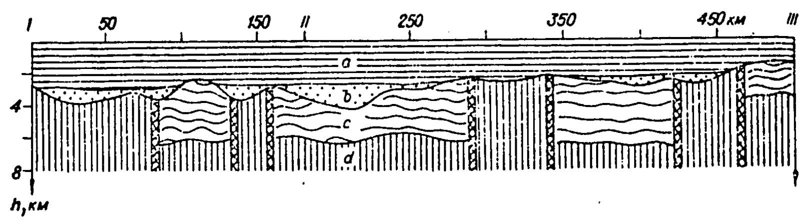

Figure 88. Seismic section characterizing the internal structure of the basement of the Western Siberian platform by the I-II-III profiles (see Fig 85-87). For the provisional notation see Fig 73.

The structural stage II includes complexes of deposits of different age, composition and conditions of occurrence. A. L. Yanshin [136] divided them into three groups: the molasse formations of the edge downwarps and the intermontane hercinian basins, the epigeosynclinal Middle and Upper Paleozoic deposits within the regions of Caledonian folding, Triassic and Lower Jurassic deposits known in the Chelyabinsk graben and in the northern part of the Turgayskiy trough. In the regions with more ancient folded basement the deposits of stage II can be semiplatform and platform facies of the Lower and Middle Paleozoic. According to V. S. Surkov [116], such conditions are probable primarily for the eastern part of the platform. Many problems pertaining to the structural stage II remain under discussion. Thus, the Triassic and Lower Jurassic deposits (the Turinskaya and the Chelyabinsk series of suites) were classified as stage II by N. N. Rostovtsev who considered their local spread, their dislocation and uncoordinated overlap by the sediments of the platform mantle. A. L. Yanshin [136] classified the same formations as platform mantle.

The problem of the geological nature of the refracting boundaryΦΦ has been investigated by many researchers, but the nonuniformity of the complexes of rock combined under the name of the second structural stage was not taken into account to the required degree here. In addition, before performing the operations by the deep seismic sounding method data were not available in the required volume or on the structure below the Φ boundary. These facts led to contradictory solutions: the boundary Φ was identified either with the surface of the prejurassic basement or only with the surface of the folded basement.

At many tens of points of the spot seismic sounding traverses the platform mantle was completely penetrated by drilling wells. In practice in all of these points the boundary Φ coincided with the foot of the platform mantle. However, this coincidence is insufficient for complete solution of the investigated problem inasmuch as the wells almost always are drilled in uplift zones where usually there is no rock of the second structural stage. With respect to the surface Φ, the deep depressions are established in which, judging by its relation to the layers in the bottoms of the sedimentary mantle, the appearance of new series of rocks is highly probable. These series can be Triassic and Lower Jurassic formations, especially if they are represented by the Chelyabinsk series of suites joined by interlayers of effusives and similar with respect to elastic properties to the lower layers of the platform mantle. According to D. B. Tal'virskiy [118], this variety of rock in the second structural stage is characterized by the velocities of the elastic waves near 3-4 km/sec. The discontinuity between the platform mantle and the Triassic-Lower rock has been reliably established during detailed KMPV [correlation refracted wave method] operations, but it can hardly be determined reliably by the data from the sounding procedure although such efforts have been made.

Consequently, in the uplift zones the boundary Φ corresponds to the foot of the Mesozoic and Cenozoic platform mantle, and in the deep depressions may drop to the foot of the Triassic and Lower Jurassic formations, the structural-tectonic regionalization of which, as was noted above, is interpreted differently by different researchers. It is expedient more precisely to define the solution of the problem for the depression zones in specific cases by the KMPV studies on continuous profiles and by operations using the reflected wave method.

The complexes of rock of the second structural stage of the Paleozoic Age have been studied in the basins of Central Kazakhstan, in the Minusinskiy and Kuznetsk troughs and in other sections. By comparison with the Triassic and Lower Jurassic formations, a high degree of compacting and higher velocities of the elastic waves are characteristic for them. Thus, the rock of the Kuznetsk trough (see Fig 71) near the day surface has a velocity of 4.5-5.0 km/sec. If the analogous series of rock is overlapped by the platform mantle 2-3 km thick, then the velocities in them as a result of the compression effect increase to values of about 5.0-5.5 km/sec. The contact of the investigated rock with the platform mantle in all probability will correspond to the refracting boundary Φ. In this case the deeper seismic boundary I can be considered as the surface of the folded (geosynclinal) basement, and the layer between the Φ and I boundaries, as the separate structural stage complicated by the Paleozoic formations.

As a result of the analysis, the basic characteristics of the structure of the upper part of the consolidated crust of the Western Siberian platform can be represented as follows.

The Φ boundary is with respect to its geological nature, a composite boundary: it coincides with the surface of the second structural stage if it is represented by Paleozoic rock and wherever Paleozoic rock is absent, with the surface of the folded (geosynclinal) basement. The Φ surface has sharply dismembered relief; the development of Triassic and Lower Jurassic formations is probable in its deep depressions.

The internal structure of the foundation below the Φ boundary is non-uniform and can be schematically divided into three types. The most widespread type of section is two structural stages: the intermediate stage made up of different parageosynclinal and platform Paleozoic formations, and geosynclinal stage. The data from the seismic method on the probable propagation of the indicated formations of the Paleozoic supplement the previous structures [104, 117, 124]. It has been established that the thickness of these formations, which in a number of cases reaches 6 to 10 km, is greater than previously assumed.

The sections of the second type distinguished by high elastic wave velocities on the Φ surface (6.0-6.6 km/sec) are characteristic of the uplifted, deeply eroded blocks of folded basement, and obviously, they are to a great extent analogous to the exposed part of the Salair anticlinorium.

The third type of section with relatively smooth velocity buildup in the medium under the Φ surface has local spread corresponding apparently to a continuation of the geosynclinal formations of the Tom'-Kolyvanskaya folded zone deep in the Western Siberian platform.

The presented geological interpretation of the seismic data, which is unavoidably schematic, in all probability correctly characterizes the general features of regional structure of the basement of the southern half of the Western Siberian platform. The seismic boundary I cannot be associated with the surface of the folded basement in all parts of the investigated territory. In particular, the vicinity of the latitudinal course of the Ob' River constitutes an exception. This boundary possibly reflects the secondary alterations of the elastic properties of the basement rock as a result of regional metamorphism. These difficult problems must be solved by special, significantly more detailed seismic observations.

§3. Regional Seismic Studies in the Siberian Platform

The ancient Siberian platform is one of the most prospective regions of our country where the richest oil and gas formations, diamonds and other minerals have been discovered after broad regional geophysical studies, primarily by the seismic method. The inaccessible terrain, the presence of permafrost, high elastic wave velocities in Paleozoic platform mantle saturated with trapped bodies in a number of regions -- all of this presents great difficulties to the regional seismic operations which actually have not been performed to any significant extent to the present time. The study of the basement surface has been carried out only in individual restricted profiles by the correlation refracted wave method. No deep seismic sounding operations have been carried out in general.

The development and introduction of the methods of spot (differential) soundings with the Tayga system, improvement of the methods of exciting the oscillations have to a significant degree made it possible to overcome the noted difficulties and proceed with a regional study of the basement and the deeper parts of the section in the vicinity of the Siberian platform. The basement (about 8000 km of traverses) has been studied in the Tungusskaya syneclise; in the southern platform they have been performed in the vicinity of the Nepskiy arch and started in the diamond-bearing areas of Yakutia. The study of the entire thickness of the earth's crust has been performed in the territory of Yakutia (5000 km of profiles) still with respect to relatively incomplete sounding systems which in a number of sections needs additional observations planned for the near future.

In addition, the deep seismic sounding traverses when studying the Western Siberian platform in the Baykal rift zone will reach the extreme western and southern parts of the Siberian platform. The results of these traverses are investigated in §2 and 5 of this chapter.

Tungusskaya Syneclise

The Tungusskaya syneclise, the largest (about 1 million km^2) suprasequential structure of the Siberian platform, puts this territory in the category of prospective for petroleum. Along with the extremely difficult surface conditions for geophysical operations, a characteristic feature of this area is the broad development of the trap formation rock represented by stratal and intersecting bodies, saturating and crossing the sedimentary mantle in which numerous conducting trap channels and dislocations with a break in continuity of different depths of occurrence are observed. All of this greatly complicates the natural geophysical fields and leads to low reliability of their geological interpretation without support on the results of the regional seismic work. The concepts of the thickness of the platform mantle and the structure of the basement until recently were primarily based on the results of interpreting the magnetic and gravitational field anomalies, and they were highly contradictory.

Since 1969, the Krasnoyarskneftegazrazvedka Trust and the SNIIGGiMS Institute have been conducting scientific studies in the northern, central and southern parts of the syneclise by the refracted and reflected wave spot sounding procedure as a regional study of the upper part of the earth's crust to a depth of up to 10-15 km. The studies are performed by the Tayga equipment and using blasts of large groups of small charges in boreholes 1 meter deep (see Chapter IV, §1). Four thousand km of regional traverses have already been run.

In order to study the wave picture, isolate the reference waves and determine the seismic model of the medium, 20 uniformly distributed parametric soundings have been made. It was discovered that for sounding bases to 10-20 km, the former have recorded refracted waves from the boundaries in the sedimentary mantle; then up to distances of about 60 km, in the first arrivals refracted waves from the boundaries have been recorded with high (6.1-7 km/sec) boundary velocity associated with the surface of the basement. In the subsequent arrivals reflected waves were isolated (basically at the critical angle). The most stable of them pertain to the surface of the basement (10-40 km base) and to the boundary inside the basement at a depth of 10-15 km (sounding base 40-60 km). On the basis of these data, sounding systems have been given on the regional traverses.

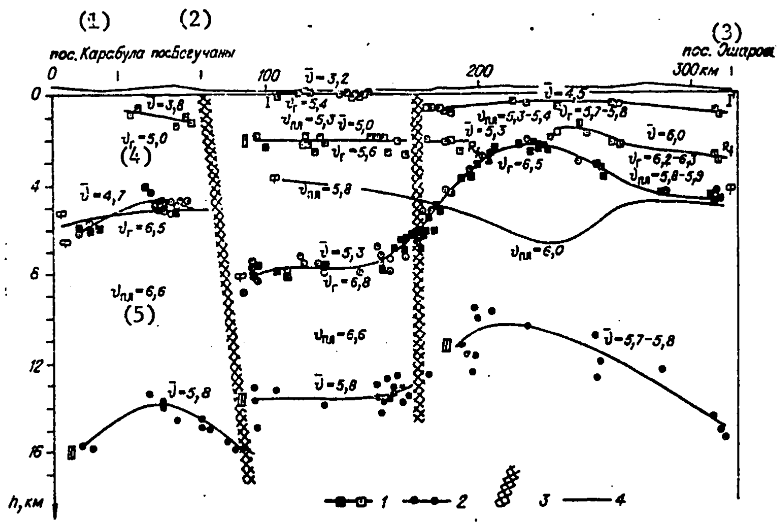

Figure 89. Seismic section through the profile of the Karabula-Osharovo settlements (Tungusskaya syneclise).
1 -- refracting boundaries; 2 -- reflecting boundaries; 3 -- proposed fracture zones; 4 -- basement surface by the data from the complex interpretation of the gravimagnetic materials [36]. The velocity is presented in km/sec.

Key:
1. Karabula settlement
2. Boguchany settlement
3. Osharovo settlement
4. $v_{boundary}$
5. $v_{stratal}$

The Karabula-Osharovo traverse (Fig 89) has been investigated as a standard traverse. It characterizes the deep structure of the southern part of the investigated territory in the sections of the Kansko-Taseyevskaya and Vel'minskaya basins.

At depths to 16 km, four seismic boundaries were isolated. The Φ and III boundaries were the most sustained. The stratigraphic time of the seismic boundaries was realized using data on the deep wells in the northern section of the traverse -- boundary I corresponds to the deposits of the Bel'skaya suite, boundary R_f is coordinated with the roofs of the Riphean deposits. In the center of the traverse boundary I pertains to the top of the Angara suite, and boundary II is provisionally tied to the Riphean deposits.

The refracting and reflecting boundary Φ pertains to the basement surface. Inside the basement the reflecting boundary III is traced. The mean velocity in the sedimentary mantle varies with respect to the profile in the range of 4.7-5.3 km/sec. The boundary velocity on the Φ surface is 6.5 to 6.8 km/sec. The mean velocity to the boundary III is 5.7-5.8 km/sec.

According to the data on the configuration of the boundaries and the distribution of the boundary, stratal and mean velocities, three blocks have been isolated which are separated by the proposed fracture zones through which the seismic boundaries are shifted by an amount to 3 km.

The central modulus characterized by the greatest depths to the Φ boundary, the highest values of the boundary velocities and the least thickness of deposits included between the Φ and III boundaries. The northern block is distinguished by the least depths to the Φ surface -- 2-5 km; the stratal velocity between the Φ and III boundaries is decreased to 6 km/sec. The increased thickness of the layer between the Φ and III boundaries is characteristic of the southern block.

The blocking, which is most clearly expressed in the lower part of the section, is depicted also in a separate part. The refracting boundary I, I', II and R_f in the central and northern blocks have essentially different boundary velocities for close depths of occurrence. In the southern block in the upper part of the section only one refracted boundary is isolated.

Comparing the seismic structures with the results of the preceding interpretation of the complex of geological-geophysical materials [36] without being supported on seismic data (see Fig 89), it is possible to see the significant noncoincidence in the depth and morphology of the basement surface. Along this surface directly opposite structural forms and differences in depths of 3-4 km were obtained. In the preceding structures, the block structure of the basement was not reflected at all. One of the causes of this divergence obviously is connected with the fact that the gravitational field anomalies serving as the base when calculating the depths to the basement are determined not only by the thickness of the sedimentary mantle, as was assumed, but to a greater degree by the physical properties of the basement rock. This is confirmed by the distribution of the boundary and stratal velocities obtained -- the lowering of the depths to the Φ surface coincides with a section of the central block where increased values of the seismic velocities in the basement rock were established.

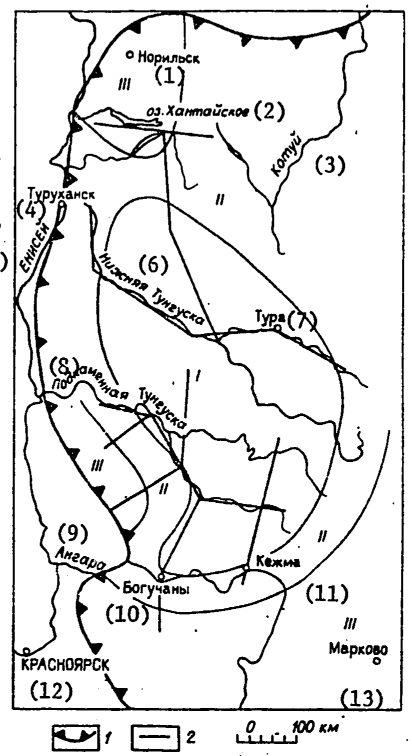

Figure 90. Schematic map of the boundary velocities through the surface of the basement of the Tungusskaya syneclise.

1 -- boundary of the Siberian platform; 2 -- seismic profile, The regions with significant velocity, km/sec: I -- $v_{boundary}$=6.6 to 6.8; II -- $v_{boundary}$=6.3 to 6.5; III -- $v_{boundary}$=6.1-6.2.

Key:

1. Noril'sk
2. Khantayskoye Lake
3. Kotuy
4. Turukhansk
5. Yenisey
6. Nizhnyya Tunguska
7. Tura
8. Podkamennaya Tunguska
9. Angara
10. Boguchany
11. Kezhma
12. Krasnoyarsk
13. Markovo

The summary constructions with respect to the entire set of investigated seismic traverses (Fig 90) provided new information about the regional structure of the upper, for example, 15-kilometer, series of the section of the Tungusskaya syneclise.

By the values of the boundary and the stratal velocity, the regional zonality of the properties of the upper series of the basement is noted. In the central part of the syneclise, a highly dense core is isolated characterized by increased values of velocity -- to 6.6-6.8 km/sec (see Fig 89). The peripheral sections of the syneclise are distinguished by lower (6.1-6.2 km/sec) velocities. This zonality of the properties of the basement must be taken into account when interpreting the regional gravitational anomalies and the complex geological-geophysical structures.

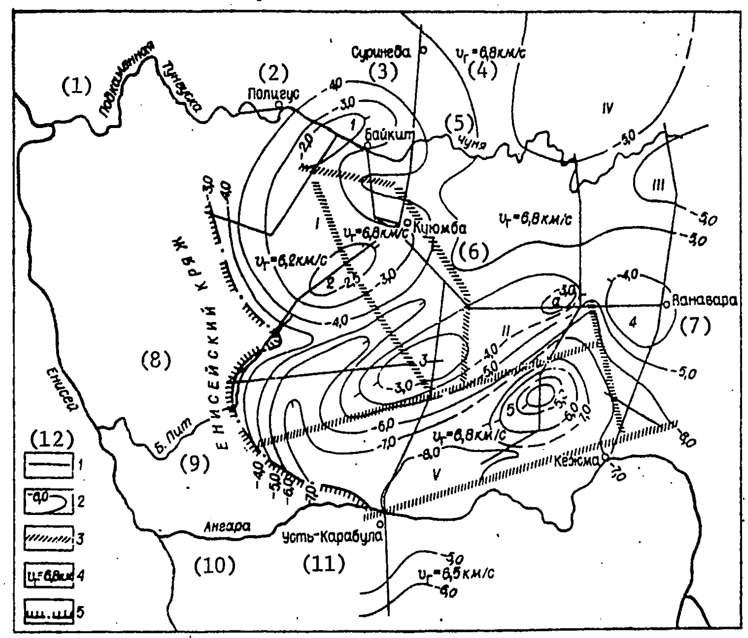

Figure 91. Structural-tectonic diagram of the southern part of the Tungusskaya syneclise with respect to the crystal basement surface (according to the data from the seismic soundings of the basement).

1 -- seismic profiles; 2 -- isohypses to the crystalline basement, km; 3 -- fractures according to the sounding data; 4 -- boundary velocities of the refracted waves, km/sec; 5 -- boundary of the Yenisey ridge. The uplifted zones: I -- Baykitskoye domed uplift; II -- Nizhne-Tayginskaya, III -- Chunskaya, IV -- Yuzhno-Turinskaya, V -- Priangarskaya basin. Swells: 1 -- Baykitskiy; 2 -- Kuyumbinskiy; 3 -- Nizhne-Tayginskiy. Oskobinskaya large-scale local structure, domed uplift; 4 -- Vanavarskoye, 5 -- Chadobetskoye.

Key:

1 --Podkamennaya Tunguska; 2 -- Poligus; 3 -- Surineva; 4 -- $v_{boundary}$ =6.8 km/sec; 5 -- Chumya; 6 -- Kuyumba; 7 -- Vanabara; 8 -- Yenisey ridge; 9 -- B. Pit River; 10 -- Angara River; 11 -- Ust'-Karabula; 12 -- Yenisey

By the data obtained it has been established that the thickness of the sediments within thé boundaries of the syneclise varies from 2 to 8 km. In a number of regions the thicknesses of the Riphean deposits are defined, and the zones of their regional wedging out are planned.

In the northern part of the syneclise the position of the Ayanskiy arch and its amplitude (more than 2 km) are determined for the first time over the surface of the basement; the position of the Dyupkunskaya and Kochechumskaya basins is more precisely defined.

In the southern part of the Tungusskaya syneclise, including the interfluve of the Angara and the Nizhnyaya Tunguska, the profile network made it possible for the first time to construct the structural-tectonic scheme over the surface of the basement on a 1:2500000 scale by the seismic data (Fig 91).

In the northwestern part of this territory the -4.0 km isoline is used to outline the large Baykitskiy arch with an amplitude of 2 km and horizontal dimensions of 250x200 km. The arch occupies an area of about 50,000 km^2. In the southwestern part this arch is separated from the Yenisey ridge by a narrow trench 40 km wide with maximum depths to the basement of about 5 km.

The structural plan of the Baykitskiy arch is made up of two swell type domes -- Baykitskiy and Kuyumbinskiy.

In the central part of this territory (the 4.0 km isoline) is the Nizhne-Tayginskaya swell type uplifted zone extended in the northeasterly direction. The amplitude of the uplift is more than 1 km, and the horizontal dimensions are 75x250 km. Within the boundaries of the uplifted zone, two uplifts are isolated: the Nizhne-Tayginskiy swell directly and the Oskobinskaya large local structure. The amplitude of each of these uplifts is about 1 km. Both structures have an elongated shape subordinate to the overall strike of the uplifted zone. The area of the Nizhne-Tayginskiy swell is 3000 km^2, and the Oskobinskiy, 1200 km^2. The Nizhne-Tayginskaya uplifted zone is separated in the west from the Baykitskiy arch by a deep and quite narrow trough. In the east it is bounded by a submeridional fracture.

In the eastern part of the territory the -4.0 km isolines separates the Vanavarskoye dome uplift. The uplift amplitude is more than 1 km, and the area is about 4000 km^2. The Vanavarskoye uplift is separated from the Nizhne-Tayginskaya uplifted zone by a deep (more than 6 km) trough, which in the southern part of the territory is rotated to the wide Priangarskaya graben-like depression elongated in the sublatitudinal direction. In the south this depression is bounded by a fault in the uplifted block of the basement. The maximum depths in the Angara basin reach 8 km or more. Within the boundaries of the basin, almost in its central part, an autonomous Chadobetskoy uplift is located with an amplitude of more than 3 km. The area occupied by the uplift along the -7.0 km isoline is about

6000 km^2. The maximum depths to the basement at its limits is 3.0 meters.

In the northern part of the area the -5.0 km isolines mark off the Chun'skaya and the Yuzhno-Turinskaya uplifted zones.

Within the limits of this territory, an entire system of faults is isolated, part of which is determined by the Kuyumbinskiy block. The Kuyumbinskiy swell and the Nizhne-Tayginskoye uplift are located within its limits. The distinguishing feature of this block is the reduced values of the boundary velocities along the surface of the basement (6.5 km-sec), whereas in the zones arriving from the north and south they amount to 6.8-7.0 km/sec. It is possible on the basis of this to propose that the basement of the Kuyumbinskiy block is made up of less dense rock than the blocks surrounding it. The basement of the Yenisey ridge and also the southern part of the Baykitskiy arch is characterized by boundary velocities of 6.0 to 6.2 km/sec, and it is probably represented by less dense acid rock.

Nepskiy Arch Region

The Nepskiy Arch is located in the southern part of the Siberian platform and is a large buried uplift of northeasterly strike with dimensions of 800x200 km, and an amplitude in the transverse cross section to 800 meters. The arch is complicated by a number of positive structures. The sedimentary mantle and the basement are penetrated by a series of fractures with which the trap intrusions are often associated. For proper orientation of future petroleum prospecting operations the most important goal in the given phase of the investigations is the study on the regional level of the surface of the crystalline basement and its relation to the lower horizons of the sedimentary mantle.

The operations by the refracted wave spot sounding procedure to study the basement in the Nepskiy Arch have been performed since 1974.

The Eastern Geophysical Trust jointly with the IGiG Institute of the Siberian Department of the USSR Academy of Sciences has introduced a new procedure and has studied an area of more than 30,000 km^2. The basic volume of this work is concentrated in the least studied southeastern slope of the arch.

The refracted wave from the basement surface was recorded in the first arrivals in the traverse and area sounding systems with bases of 30-60 km. The Tayga equipment was used. The oscillations were excited by group blasts in shallow natural bodies of water. Air transportation was used.

The operations in this region are continuing. The materials already available indicate high effectiveness of the procedure and theoretical significance of the results obtained.

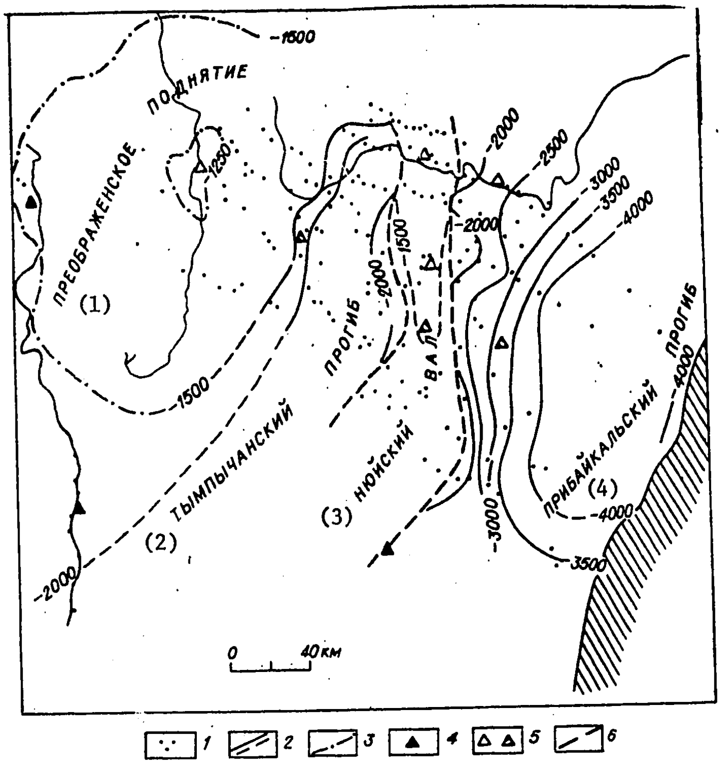

Figure 92. Nepskiy Arch. Structural diagram of the basement surface in the basins of the Nizhnyaya Tunguska-Peleduy-Lena Rivers.

1 -- sounding center; 2 -- isohypses of the basement surface with respect to the TSZ MPV refracted wave method; 3 -- isohypses of the basement surface according to the reflected wave method, the common depth point method and by drilling; 4 -- the deep drilling areas; 5 -- recommended areas of deep parametric drilling (crosshatched -- the primary drilling areas); 6 -- proposed tectonic disturbances according to the geophysical data.

Key:

1. Preobrazhenskoye uplift
2. Tympychanskiy trough
3. Nyuyskiy swell
4. Pribaykal'skiy trough

As a result of processing the materials from the spot seismic soundings and complex interpretation of the geological materials available over the area, a structural diagram of the basement surface for the southeastern part of the Nepskiy Arch (Fig 92) and the deep sections were compiled, one of which is presented inFig 93. In the structural diagram the

Preobrazhenskoye uplift, the Nyuyskiy swell and the Tympychanskiy and Pribaykal'skiy troughs bordering on them are clearly isolated.

The Preobrazhenskoye uplift occupies the central part of the Nepskiy Arch, and it is traced 120 to 130 km in the latitudinal direction. The basement surface marks are -1400-1500 meters. The roofs of the Nizhnemotskaya subsuite (M_2 horizon) traced by the seismic exploration by the reflected wave method within the limits of the Preobrazhenskoye uplift in practice coincides with the basement surface.

The Nyuyskiy swell is a sharply expressed structural element of the basement surface on the southeastern slope of the Nepskiy Arch. It has submeridional strike, and it has a width of 20 to 60 km. The swell is traced 150 km. The basement surface marks are -1100 to 1300 meters.

The Tympychanskiy trough separates the Nyuyskiy swell from the Preobrazhenskoye uplift. The absolute marks of the basement surface in the trough are -2000 to 2200 meters. The M_2 horizon here lies practically horizontally at the level of 1200 to 1300 meters. The total thickness of the sedimentary mantle by comparison with the Preobrazhenskoye uplift increases by 600-800 meters.

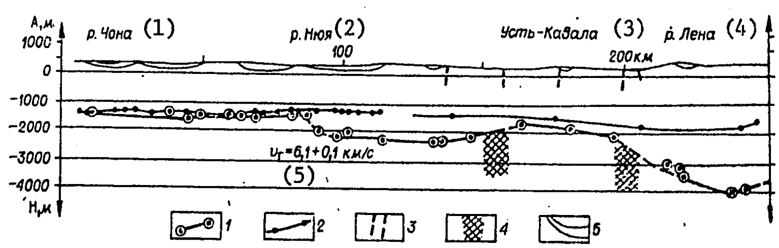

Figure 93. Geological-Geophysical Section (Chona River to Ust'-Kadala settlement).

1 -- depths over the basement surface according to the refracted wave data from spot sounding; 2 -- depths to the reflecting horizon M_2 (roofs of the Nizhnemotskaya subsuite according to the seismic exploration data of V. I. Pompik, 1974); 3 -- tectonic disturbances by the geological map; 4 -- proposed tectonic disturbances by the geophysical data; 5 -- surface outcrops of the rock of the Upper Cambrian, Jurassic and Ordovician.

Key:

1 -- Chona River; 2 -- Nyuya River; 3 -- Ust'-Kavala; 4 -- Lena River; 5 -- $v_{boundary}$=6.1+0.1 km/sec.

The eastern part of the investigated area is occupied by the Pribaykal'skiy trough, the width of which within the limits of the investigated territory is 70-100 km. A strip 20 km wide east of the Nyuyskiy swell is a zone of sharp gradients of submersion of the basement from the -2000 to 3500-4000 meter marks. The thickness of the sedimentary complex increases by 2000 meters or more.

The increase in thickness of the sedimentary mantle in the deep troughs (see Fig 93) takes place as a result of an increase in thickness of the terrigenic deposits of the Motskaya suite and, primarily, as a result of the appearance in the section of the Wend and the Upper Proterozoic terrigenic-carbonaceous deposits with a low degree of metamorphism. In the direction of the internal parts of the platform the total thickness of these deposits is quickly reduced and wedges out. These wedging-out zones located in the natural parts of the Nepskiy Arch are of interest as an independent object of oil and gas prospecting.

As a result of the work that has been done, the data on the structure of the southeastern slope of Nepskiy Arch have become theoretically significant for the first time. The most important results of the studies reduce to the following.

1. It has been established that the basement surface is characterized by dismemberment of the relief, the morphology of which frequently does not find reflection in the structure of the lower Cambrian deposits. The basic elements of the arch -- the Preobrazhenskoye uplift, the Tympychanskiy trough, the Nyuyskiy swell and the Pribaykal'skiy trough -- have been isolated with respect to the basement surface.

2. On the slopes of the noted uplifts, on the outside of the Pribaykal'skiy trough, wedging-out of the lower Cambrian and the late precambrian deposits has been discovered everywhere with which the zones of regional petroleum and gas accumulation are connected.

3. The discovery of the indicated tectonic and structural-lithologic laws with respect to the basement surface and the deep horizons of the sedimentary mantle is one of the most important bases for estimating the high prospects of the oil and gas-bearing nature of the Nepskiy Arch, which permits successful orientation of the prospecting work. The recommendations with respect to the location of the primary parametric deep wells are reflected in Fig 92.

Regions of Yakutia

In the eastern parts of the Siberian platform, the Geological Institute of the Yakut branch of the Siberian Department of the USSR Academy of Sciences and the Yakut TGU Administration (the Yakut Complex Geophysical Expedition and the Amakinskaya Geological Prospecting Expedition) have performed deep seismic studies by the spot sounding method. In 1968-1974, work was done [110] along a number of traverses by the deep seismic sounding method over an extent of about 5000 km (see Fig 66) within the limits of the Vilyuyskaya syneclise, the Botuobinskaya saddle, and the Aldan and Anabarskaya anteclises. Before the seismic soundings there was only an approximate representation of the structure of the deep horizons of the earth's crust using the data from magnetotelluric sounding and gravitational field anomalies.

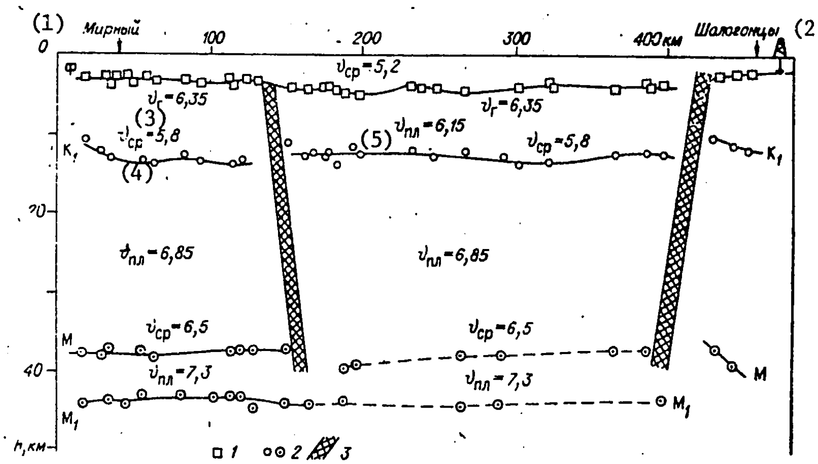

Figure 94. Seismic section along the Mirnyy-Sholosgontsy traverse.
Depths according to the wave data: 1 -- refracted; 2 -- reflected; 3 -- abyssal fracture zone

Key:
1. Mirnyy
2. Shalogontsy
3. $v_{boundary}$
4. v_{mean}
5. $v_{stratal}$

The conditions of performing the seismic work are difficult: the taiga and marshy terrain, and developed permafrost. In the high-speed sedimentary mantle there are trap formations, and kimberlite magmatism.

The oscillations were recorded by the Tayga equipment. In the initial phase of the operations, bombing from an aircraft was tested for excitation of the oscillations. The experiments were performed using waves from industrial open-pit mining blasts. The basic volume of the observations were made for blasts in the shallow natural bodies of water. The sounding systems were designed to study the earth's crust to its entire thickness. The observations performed in recent years are planned to be supplemented for more reliabl determination of the parameters of the medium in the more interesting sections. In addition, additional observations are needed at large (about 200 km) distances from the source, obtaining recordings of the refracted waves from the deep boundaries, including the surface of the mantle. Now this part of the section is characterized basically only by the reflected wave data.

In the seismic sections and the generalizing systems constructed calling on the data on the anomalous natural geophysical fields, large features of the stratified-block structure of the earth's crust have found reflection within the limits of the Aldan and Anabar anteclises, the Vilyuyskaya syneclise, and the Botuobinskaya saddle. The standard seismic section is presented in Fig 94.

The surface of the crystalline basement (Φ) investigated by the refracted wave data has a boundary velocity of 6.1-6.4 km/sec, and it occurs in a wide range of depths -- from several tens of meters to 13 km. The mean velocity in the platform mantle varies within the limits of 3.9 to 5.2 km/sec.

As a result of constructing the deeper boundaries and determining the velocities in the consolidated crust, it is divided into the provisional "granite" and the "basaltic" layers, the mean stratal velocities in which are equal to 6.1-6.4 and 6.7-6.9 km/sec respectively. In the predominant part of the territory the thicknesses of these layers are commensurate and equal to 9-25 and 13-34 km respectively. In the vicinity of the Botuobinskaya saddle and the adjacent parts of the Anabar anteclise and the Tungusskaya syneclise where the magmatic rock of basic composition is widely developed, great thickness (24-34 km) and shallow occurrences (9-13 km) of the "basaltic" layer were obtained. Its thickness here exceeds by approximately 3 times the thickness of the "granite" layer.

The M surface with respect to the reflected wave data over the entire investigated territory of the eastern part of the Siberian platform occurs in a narrow range of depths of -38 to 40 km although it is impossible to exclude the possibility of the appearance of zones of complicated occurrence of the surface of the mantle and significant variations of its properties with respect to area in more detailed work. The mean velocity in the entire body of the crust is 6.3 to 6.5 km/sec.

The total thickness of the earth's crust remains in practice invariant over the entire territory. However, the thickness of the consolidated crust (between the Φ and M boundaries) varies within broad limits -- from 25 to 39 km (Fig 95). The minimum thickness is established in the depressions of the Vilyuyskaya syneclise, and the maximum thickness, near the Aldan shield and the Anabar massif.

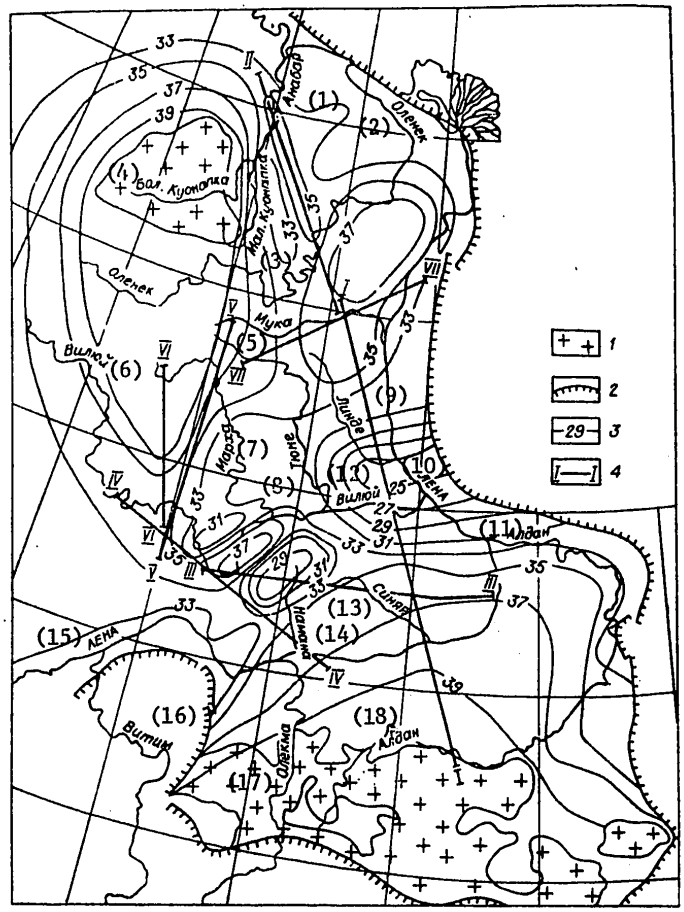

Figure 95. Schematic of the thicknesses of the consolidated crust in the eastern part of the Siberian platform
1 -- outcrop of crystalline rock at the day surface; 2 -- edge seams; 3 -- isopachous lines, km; 4 -- deep seismic sound-traverses

Key:

1.	Anabar	10.	Lena
2.	Olenek	11.	Aldan
3.	Malaya Kuonapka	12.	Vilyuy
4.	Bol'shaya Kuonapka	13.	Sinyaya
5.	Muka	14.	Namana
6.	Vilyuy	15.	Lena
7.	Markha	16.	Vitim
8.	Tyung	17.	Olekma
9.	Linde	18.	Aldan

Below the M surface by 6-9 km another reflecting boundary (M_1) is traced. The approximate estimates of the velocity in the layer between this boundary and the M surface give a value of 7.3-7.8 km/sec. This layer is considered [10] as a transition zone from the crust to the mantle of the earth.

As has already been noted, in the vicinity of Yakutia, the lower part of the section of the earth's crust and the top of the mantle still has been investigated only by the reflected wave method. Later the plan calls for additional work on the previously laid profiles recording the refracted waves to obtain more complete information about the physical state of the mantle material and the material at the bottom of the crust, which is extremely important for studying the kimberlite magmatism located here. It is also necessary to execute reference profiles with detailed observations systems.

In 1974 deep seismic studies were started in the area network of profiles in the kimberlite magmatism sections (Malo-Botuobinskiy and Daldyno-Alakitskiy Rayons) in order to study the surface of the crystalline basement, the deep parts of the earth's crust and the transition zone from the crust to the mantle.

§4. Deep Seismic Sounding of the Earth's Crust and Upper Mantle in the Baykal Rift Zone

The ocean and continental rift zones are the most important tectonic elements of our planet. Their study has primary importance in connection with knowledge of the deep processes inherent in the deeper parts of the earth's mantle and actively manifested in the near-surface parts of the earth's crust. The Baykal rift is the largest element in Eurasia of the world rift system. Until recently the deep seismic studies mad here were based on recording predominantly natural physical fields: gravitational, electromagnetic, thermal, and the seismic earthquake fields. In all of these fields significant deviations from the normal values have been established, indicating the anomalous properties of the deep material and characterizing the active tectonic process from different sides. However, the concepts of the deep structure of the Baykal rift without the deep seismic sounding reference data remained to a great extent hypothetical and contradictory. Even the problem of the position of the principal reference deep geophysical boundaries -- the Mohorovicic surface -- was until recently the subject of sharp discussion.

The seismic operations by the deep seismic sounding method in the spot (differential) seismic sounding version in the Baykal region have been conducted since 1968 by the Eastern Geophysics Trust and the IGiG Institute of the Siberian Department of the USSR Academy of Sciences. The goal of of the first (recognition) phase of these operations was a study of the large-scale features of the structure of the earth's crust and the top of the mantle within the limits of the entire rift zone and in the regions of the Siberian platform, Transbaykal and eastern Sayan adjacent and not touched by riftogenesis. At the present time studies have been made over an area of 400,000 km^2 with a total extent of the seismic traverses of 4000 km basically in the central part of the zone (Fig 96). In addition, area seismic soundings have been made to study the spatial structure of the mantle surface, including under the Baykal Lake. The materials on the seismology of earthquakes [49] have been used which permit an increase in depth of study of the top of the mantle. The study of the flank regions of the rfit zone has been started, including the region of construction of the Baykal-Amur railroad. In spite of the imperfection of the work that has been done (recently work has been done in both flanks of the zone), the degree to which the deep structures of the Baykal zone have been studied at the present time by the deep seismic sounding method is the greatest by comparison with other (foreign) continental riftogenesis zones.

Peculiarities of the Operations Technique

When planning the operations in the Baykal region, the following circumstances were kept in mind.

1. The riftogenesis was caused by deep mantle processes; therefore it was important to obtain the most information possible about the structure and properties of the tops of the mantle.

2. The complex deep structure characteristic of the rifts cannot always be reliably approximated by the two-dimensional seismic models even in the regional investigation stage. Therefore along with the ordinary traverse observations in the most complex sections of the Baykal rift, area sounding systems were used.

3. For the rift zones not only the complex configuration of the deep structures, but also anomalous physical condition of the deep material are characteristic. Therefore special attention was given to the study of the seismic velocities in the medium with discovery of the waveguide layers and mapping of the velocity anomalies with respect to area.

In order to detect clear, stable waves which are suitable for discrete corelation, initially observations were made on the piecewise-continuous parametric profiles (in the southern part of the Siberian platform and in the Baykal folded region). In both sections observations were made for one oscillation source obtaining hodographs to distances of about 200 km. By the results of studying the wave picture, two sounding systems were given: the first (distances between the source and the receiver 40-70 km) was used to record the reflected and the refracted waves from the intracrustal boundaries every 20-25 km of profile; the second was designed for recording the waves from the Mohorovicic discontinuity with sounding centers every 20-50 km.

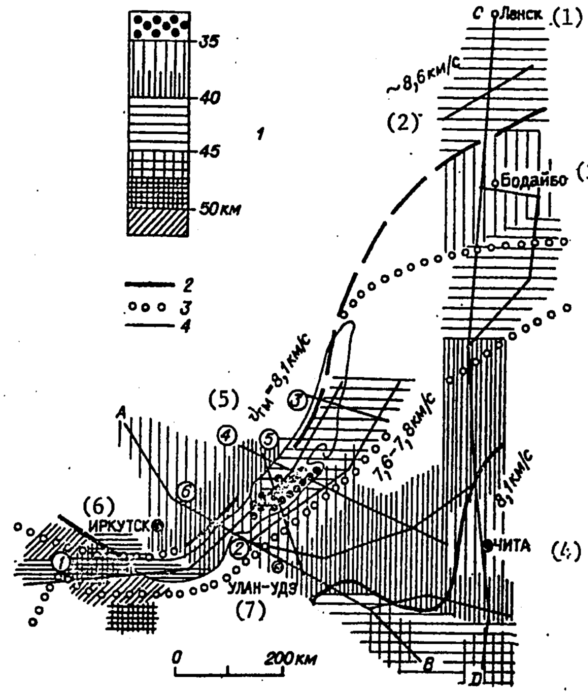

Figure 96. Diagram of the surface structure of the mantle in the Baykal region.

1 -- depth scale to the M boundary; 2 -- boundary of the region with anomalously low velocity on the surface of the mantle. The values of the boundary velocity with respect to the surface of the mantle in individual sections are written out; 3 -- the outline of the rift zone according to the geological data; 4 -- the deep seismic sounding traverses. The figures in circles denote the seismic sections presented in Figures 97-98.

Key:

1. Lensk
2. ~8.6 km/sec
3. Bodaybo
4. Chita
5. $v_{boundary\ M}$=8.1 km/sec
6. Irkutsk
7. Ulan-Ude

In all of the traverses the waves from the Mohorovicic discontinuity (M) differ insignificantly with respect to kinematic and dynamic characteristics. On the sounding seismograms with 180-250 km bases the former records the refracted waves, and every 0.5-2.0 seconds, the transcritical reflection. The mean values of the apparent velocities of these waves are 7.6-8.2 and 6.5-7.0 km/sec respectively. By comparison with the refracted wave, the reflected wave is characterized by values of the amplitude increased by 5-10 times and clearly reduced visible oscillation frequencies.

The waves from the intracrustal boundaries in the sections of the Siberian platform and Baykal folded region differ significantly. Within the limits of the Siberian platform at distances of 20-80 km from the source in the first arrivals the refracted wave is recorded from the surface of the crystalline basement. For this wave, low intensity, and apparent velocity of 6-7 km/sec are characteristic. For distances of 40-70 km in the subsequent part of the seismograms reflected waves from the deeper boundaries in the earth's crust are isolated. The waves have increased in intensity and large values of the apparent velocities (7-8 km/sec). In the Baykal folded region the first waves with respect to arrival time at distances of 20-100 km from the source correspond to the refracted wave penetrating to a depth of up to 10 km. The waves in the first arrivals here are more intense, and the reflections from the intracrustal boundaries are less clear than in the Siberian platform.

When determining the velocity parameters, special attention was turned to discovery of the variations of the boundary and the mean velocities along the traverses by the recordings of waves from the M discontinuity. Initially the mean velocities were determined in the earth's crust by the reflections from this boundary. The distribution of the boundary velocities on the surface of the mantle was found by two procedures: by the refracted wave field and with joint use of the reflected and refracted waves from the M boundary.

The convergence of the values obtained for the depths and the velocities at near points, and the theoretical calculations permit estimation of the error in a single determination of the velocity at 0.1-0.15 km/sec. When determining the depths to the M boundary preference is given to the reflected wave data. The accuracy of the constructions is estimated at 0.3 km for the surface of the basement and 1-2 km for deeper boundaries, including the M surface.

Let us discuss some peculiarities of the procedure connected with the study of the specific characteristics of the deep structures of the rift zone. It appeared extraordinarily important to solve the problem of the existence of the waveguide layers in the earth's crust. For this purpose use was made of the recordings of refracted and reflected waves considering the distorting effect of the horizontal nonuniformities of the medium. In the specially geologically homogeneous sections, sounding profiles were made, the bases of which varied relatively uniformly with a step size of 10-20 km in the range of 10-200 km. The soundings with minimum bases made it possible to control the effect of the nonuniformities of the upper part of the section. With respect to the time field of the first (refracted) waves, the function $t(\ell)_{x=const}$ was obtained, which is an analog of the hodograph of the common depth point known in seismic exploration. This function, which is influenced by the deep horizontal nonuniformities in attenuated form was used for finding the dependence of the true velocity on depth [73]. In order to estimate the velocity in the waveguide layer, recordings of reflected waves from the boundaries in the middle part of the crust were used. The results obtained were controlled by solving the direct kinematic problem.

The structure of the M boundary under the Baykal depression is highly complex, sharply variable both across and along the strike of the rift. The transition necessary under such conditions to the area study of the M boundary was realized by the scheme illustrated in Fig 39. This system of soundings made it possible to obtain data on the area distribution of the boundary velocity on the surface of the mantle and the mean velocity in the entire body of the earth's crust. The depths to the M boundary are determined at almost 50 points over a significant part of the lake and its shores. The analogous area observations were made on the flanks of the rift zone. The high effectiveness of the area observations was achieved as a result of mass application of the portable Tayga equipment transport on helicopters.

The first operations by the deep seismic sounding method in the vicinity of the Baykal rift established the anomalously low values of the boundary velocity on the surface of the mantle. Accordingly, the problem arose of increasing the depth of the studies to determine the thickness of the layer with anomalously low velocity and discover its relation to the asthenospheric mantle layer of Gutenberg characterized by almost the same values of the longitudinal wave velocities. As a result of limited power of the artificial oscillation sources used during deep seismic sounding, the recording range achieved in the Baykal region was insufficient for reliable solution of the indicated problems using refracted waves. Accordingly, a joint interpretation was made of the seismic recordings of the blasts and local earthquakes [49]. The hodographs of the first waves from 20 sufficiently powerful earthquakes recorded on a network of stationary and portable stations with epicentral spacings of 200-1000 km by matching with the available deep seismic sounding data were reduced to the surface source conditions. A statistical determination was made of the times. Then, by the set of deep seismic sounding data and seismology, an average reduced hodograph was compiled up to 1000 km in length, which was used to estimate the seismic parameters of the upper part of the mantle in the rift zone. The penetration of the waves into the body of the mantle by several tens of kilometers is insured in this way.

Results of the Studies

Let us characterize the principal peculiarities of the regional structure of the earth's crust and the tops of the mantle discovered by deep seismic studies in the rift zone and in adjacent sections of the Siberian platform and the Baykal folded region.

The area and traverse observations were used to study the basic features of the distribution of the thickness of the earth's crust within the rift zone and also in adjacent regions not subjected to riftogenesis. In the summary diagram of the M surface (see Fig 95) compiled with respect to the entire set of data obtained, it is established that in the central part of the Baykal rift the thickness of the earth's crust varies within appreciably larger limits than in the adjacent inactive regions. The ranges of variation of the depths are as follows: 34-48 km in the rift zone, 37-39 km in the southern part of the Siberian platform and 39-41 km in the regions of Transbaykal adjacent to the rift.

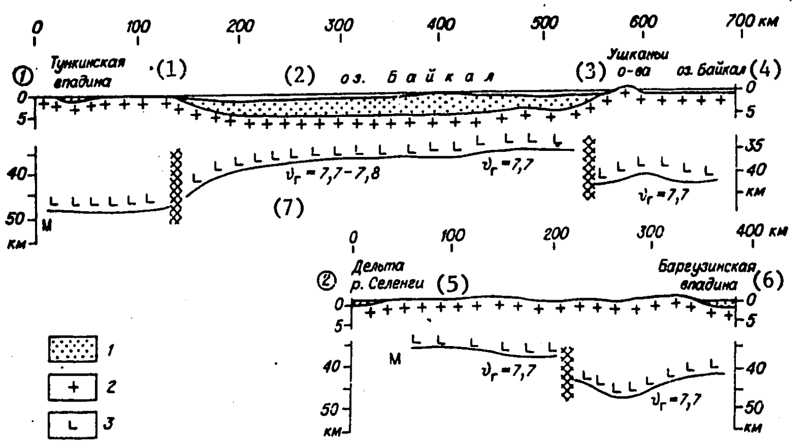

Figure 97. Seismic sections along the Baykal rift (velocity given in km/sec).
1 -- sedimentary execution of the Baykal basin; 2 -- upper and 3 -- lower part of the consolidated crust.

Key:
1. Tunkinskaya basin
2. Baykal Lake
3. Ushkan'i
4. Baykal Lake
5. delta of the Selenga River
6. Barguzinskaya basin
7. $v_{boundary}$

Significant differences noted in the thickness of the crust under the southwestern (the deeper water) and northeastern parts of Lake Baykal: 34-36 and 40-44 km respectively. The articulation of these sharply differing blocks takes place near the island of Ol'khon and the Svyatoy Nos Peninsula where probably there is a large abyssal fracture zone which is transverse with respect to the rift. The indicated differences in the thickness of the earth's crust are traced not only under Baykal itself, but also along its southeastern shore (Fig 97).

The structure of the mantle surface is different also in different transverse cross sections of the rift (Fig 98).

In the extreme northern cross section (section 3 in Fig 98) the M boundary occurs approximately on the same level (41-43 km) under the eastern extreme edge of the Baykal basin, the Barguzinskaya basin and the Barguzinskiy ridge separating them.

Cross section 4 runs in the region of articulation of the northern and southern basins of Baykal. The M surface forms a deep trough here which in its central part is complicated by a sharp uplift, that is, there is a type of combination of opposite structural forms -- "root" and "antiroot" -- with highly contrasting variation in thickness of the crust within the range from 35 to 44 km.

Two cross sections (5 and 6, Fig 98) through the southern Baykal basin in the vicinity of the island of Ol'khon and the Selenga River delta have theoretically similar, but contrast-wise different form of the M boundary. In both cross sections under the northwestern side of the Baykal basin where the Obruchevskiy fault runs, a scarplike uplift of this boundary by 3-6 km in the direction of the lake is noted.

Thus, the data obtained by the deep seismic sounding method on the morphology of the M boundary characterized as the highly complex, sharply variable surface not only across, but also along the strike of the rift. The Baykal rift does not correspond with respect to this surface to any single structural form in the form of the previously proposed "root" or "antiroot." The discrepancies with the earlier schematics with respect to the thickness of the earth's crust and its gradients reach large values.

The peculiarities of the internal structure of the earth's crust in the Baykal region must be considered to include the differences in the degree of its stratification with respect to elastic properties and the different sections and the velocity inversion with respect to depth.

The regular seismic layering with several clear horizontal boundaries has been established in the earth's crust in the southern part of the Siberian platform in the vicinity of the city of Chita. In the remaining territory, including the rift zone and the regions of Transbaykal adjacent to it,

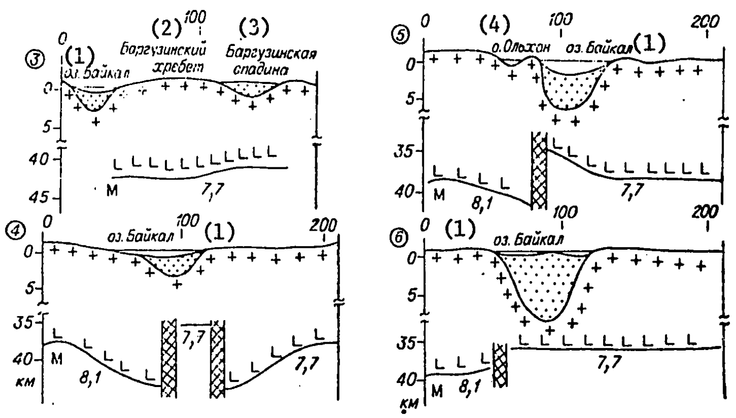

Figure 98. Seismic sections across the strike of the Baykal rift (the velocities are given in km/sec). The provisional notation is the same as inFig 97.

Key:
1. Lake Baykal
2. Barguzinskiy ridge
3. Barguzinskaya basin
4. Ol'khon Island

the intracrustal seismic boundaries can be continuously traced only in individual short sections of the traverses.

The problem of the existence of the waveguide layers in the earth's crust is extremely important inasmuch as under the defined conditions these layers can correspond to sections of the medium with increased plasticity having high significance for the analysis of the deep geodynamic conditions and distribution of the earthquake centers. Accordingly, in three sections (on the southeast shore of Baykal and also 150 km south of it and along the Tunkinskaya basin) special observations were made of the refracted and reflected waves considering the effect of the horizontal inhomogeneities of the medium.

In all of the sections, in practice identical results were obtained: a seismic waveguide was discovered in the depth range of 12-17 km with a decrease in the velocity by 0,2-0,3 km/sec with respect to the surrounding medium. The relation of the discovered seismic waveguide to the distribution of the other geophysical characteristics established by the data from the magnetotelluric soundings, seismology and magnetometry has been noted. The layer with reduced seismic wave velocity is made up in all probability of rock with high electrical conductivity, and the basic mass of the magnetically active bodies and the earthquake centers is located above this layer. Possibly the overall reason for this is increased heating and partial fusion of the deep material.

The section of the upper mantle in the Baykal zone made up from the seismology data on blasts and earthquakes is characterized by the following peculiarities of the velocity distribution of the longitudinal waves vertically (Fig 99).

The section of the mantle begins with the layer with anomalously low velocity of 7.6 to 7.8 km/sec. The vertical velocity gradient in the upper part of this layer estimated by the ratio of the amplitudes of the reflected and refracted waves from the M boundary [58] will be 0.003 to 0.005 sec^{-1}, which is insufficient for a smooth transition to the normal values of the velocity at great depths. The lower boundary of the layer with reduced velocity was found by the summary 1000-kilometer hodograph of the first waves from the blasts and the earthquakes [49]. On this hodograph at a distance of about 350 km from the source exchange takes place of the refracted mantle waves with velocities of 7.7 and 8.1 km/sec. The thickness of the layer with a velocity of 7.7 km/sec was found to be equal on the average to 17 km, the depths to its upper and lower edges are 38 and 55 km. On the eastern flank of the rift the thickness of the anomalous layer is estimated by the deep seismic sounding data and it is about 8 km [77].

Although the parameters obtained for the anomalous layer of the upper mantle are averaged for a large section of the Baykal rift zone, they have theoretical significance for the discovery of its deep structure. It has been established that the anomalous layer is disconnected from the asthenospheric Gutenberg channel, where the velocities are approximately the same, and the depth to its upper edge in the investigated region is approximately 100 km according to the seismological data [4]. The relation to the asthenospheric channel can be assumed only in the form of a narrow vertical connecting strip most probably located under Baykal and then in a strip of intensive Baykal-Vitim gravitational minima.

The region of propagation of the layer with anomalously low velocity has been mapped at the present time over an enormous area of 200,000 km^2 (see Fig 96, 100). Beyond the limits of this region the velocity on the surface of the mantle has normal values of 8.1-8.2 km/sec, increasing to 8.6 km/sec in the vicinity of Lensk. The boundaries of the anomalous region occupy an intersecting position with respect to the ancient geological structures, although they are controlled in a number of sections by the deep seams known by the geological data. The region of the anomalous mantle is 2 to 3 times broader than the Baykal rift zone itself which has been mapped by the surface geological attributes and the seismicity distribution. The central section of the rift zone (the Baykal basin) is located under the northwestern edge, and the eastern flank of the zone, above the central part of the anomalous mantle region.

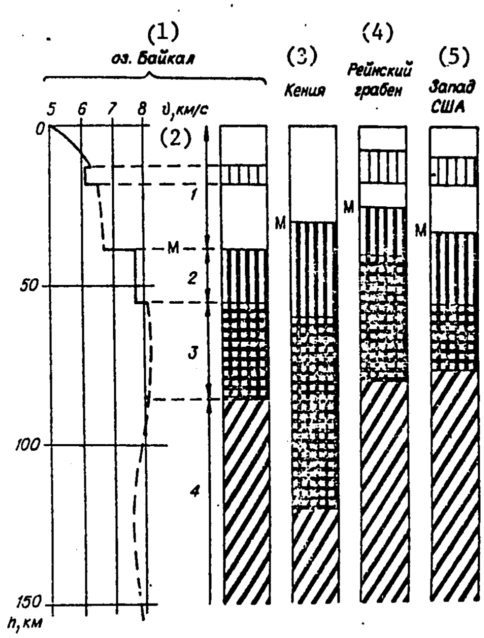

Figure 99. Velocity columns for Baykal and other continental rifts.
1 -- earth's crust; 2 -- anomalous mantle; 3 -- normal mantle; 4 -- areduced velocity zone in the upper mantle

Key:
1. Lake Baykal
2. v, km/sec
3. Kenya
4. Rhine graben
5. Western part of the United States

Comparison with Other Continental Rift Zones

The purpose of comparing the results of the seismic studies of the deep structures of the Baykal region with the corresponding data with respect to other zones of the continental riftogenesis is discovery of the common features of their deep structure connected with the latest tectonic activity.

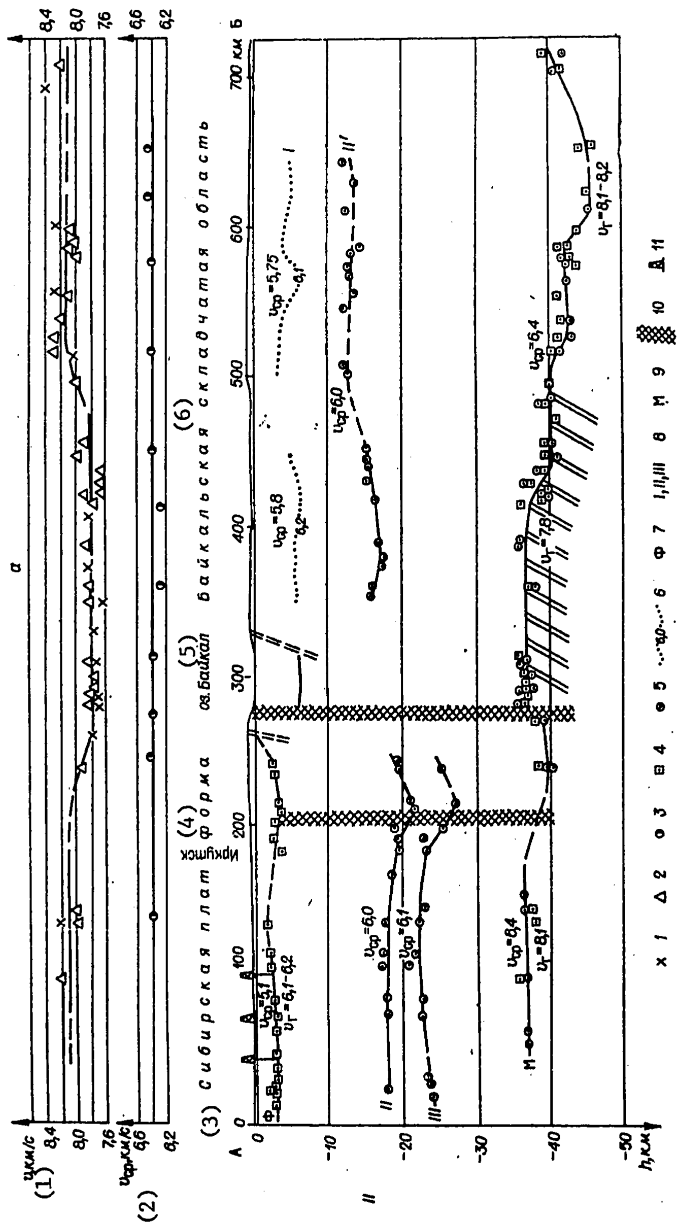

Figure 100. [See p 251]

Key:
1. v, km/sec
2. v_{mean}, km/sec
3. Siberian platform
4. Irkutsk
5. Lake Baykal
6. Baykal folded region

b

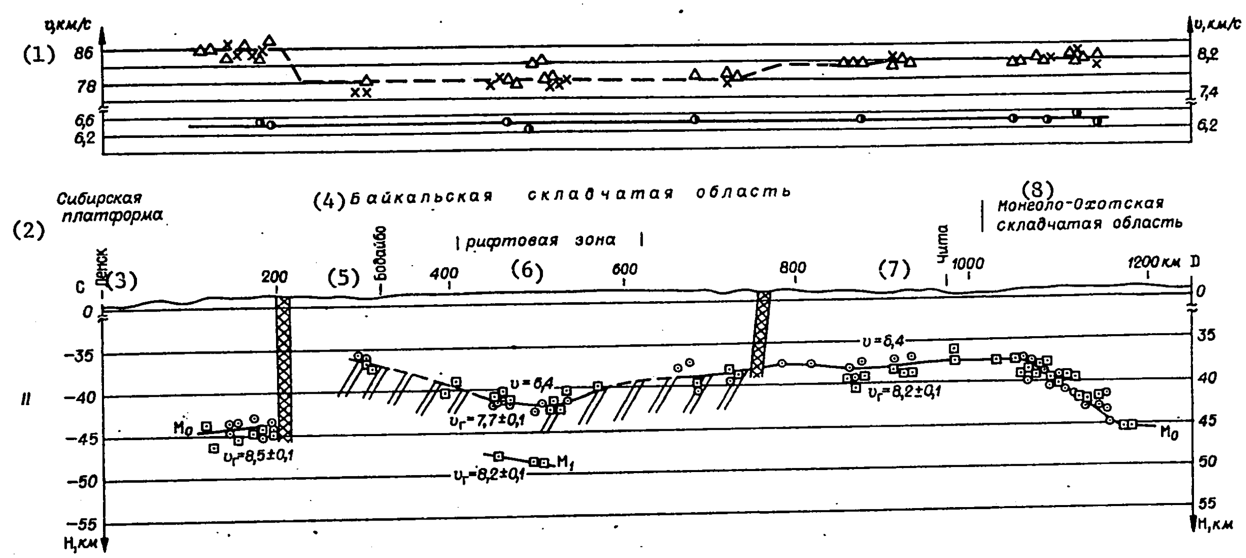

Figure 100 [continued]. Seismic traverses A-B (a) and C-D (b) (see Fig 96) across the southern part of the Siberian platform, the Baykal rift, the Baykal folded region. I -- boundary velocity $v_{boundary}$ on the M surface according to the refracted wave data (1) and with joint use of the reflected and refracted waves (2); mean velocity in the earth's crust v_{mean} according to the reflected wave data (3); II -- section; 4, 5 -- depths with respect to the refracted and reflected waves; 6 -- velocity isoline, km/sec; 7 -- surface of the basement of the Siberian platform; 8 -- reflecting boundary in the crust; 9 -- Mohorovicic discontinuity; 10 -- abyssal fracture zones; 11 -- boreholes

Key:

1. v, km/sec
2. Siberian platform
3. Lensk
4. Baykal folded region
5. Bodaybo
6. rift zone
7. Chita
8. Mongolian-Okhotsk folded region

When comparing the data on the earth's crust, let us consider only its general characteristics, the determination of which is influenced to a low degree by the differences in the seismic investigation procedures in the various regions. Some decrease in thickness of the earth's crust noted under the Rhine graben and in the North American province of basins and ridges probably is not common to all continental rift zones. In the Baykal zone this effect is not sufficiently clearly manifested.

For continental rifts, in all probability, the intracrustal seismic wave guides are typical which can be caused by increased heating of the deep material. In addition to the Baykal zone, the existence of waveguides in the earth's crust is noted under the Rhine graben and in the western part of North America.

In a number of sections of the world rift system (Iceland, the axial graben of the Red Sea) high velocities (6.5-7.0 km/sec) were discovered in the upper part of the earth's crust explained by the introduction of deep rock. For the intracontinental rifts a similar phenomenon has not been established. The velocities in the crust, as a rule, differ little here from the value in the adjacent inactive sections.

For the objective comparison of the seismic characteristics of the upper mantle, just as for the Baykal region, summary hodographs of the first mantle waves from the blasts (chemical and nuclear) and local earthquakes recorded at great distances from the sources of oscillations in the regions of East Africa, the North American basin and ridge province and the Rhine graben were compiled [57] by the data published for the first time. The summary hodographs of the first waves for all regions are surprisingly similar in their primary features. In all cases, beginning with distances of 120-180 km from the oscillation source, the refracted wave was recorded first with a velocity of about 7.7 km/sec. The extent of the region of its recording in the first arrivals is 100-300 km. Then comes a break in the hodograph, and the wave with a velocity of 8-8.2 km/sec arrives first. The reality of the noted peculiarities in the hodographs is unquestioned, although their quantitative characteristics must be more precisely determined by more representative experimental data.

From the similarity of the hodographs we have similarity of the primary features of the velocity distribution of elastic waves in all of the investigated continental riftogenesis zones (see Fig 99). In the uppermost part of the mantle there is a layer everywhere with anomalously low velocity equal approximately to 7.7 km/sec. The average thicknesses of this layer in the various regions are 15-30 km. The velocity in the anomalous layer and the mantle waveguide of Gutenberg are almost identical, but these objects are not geometrically a united whole, for they are separated by a series of rock with a velocity of 8-8.2 km/sec.

Thus, as a result of comparing the Baykal rift with sections of other continental zones of modern riftogenesis studied by seismic methods, their theoretical similarity is established with respect to certain characteristics of the seismic section of the earth's crust and especially the upper mantle to the Gutenberg waveguide. The common characteristics of the continental rifts, in addition to the previously known reduction of velocity in the uppermost part of the mantle, should include the fact that the layer with anomalously low velocity is not very thick and can be in communication with the asthenospheric Gutenberg waveguide only in local sections.

Nature of the Layer with Anomalously Velocity in the Rift Zones

Under all of the ocean and continental rift systems investigated by the method of blast seismology, a thick layer (to several tens of kilometers) with anomalous velocities of the longitudinal waves equal in the majority of cases to 7.3-7.8 km/sec and not typical of either the crust or the tops of the mantle is discovered. For the rift of the midoceanic ridges and Iceland basically values of 7.0-7.6 km/sec are characteristic. In the continental zones (Baykal, East Africa, Rhine, North American basin and ridge province), as has already been noted above, obviously higher values predominate (7.6-7.8 km/sec). The anomalous layer is underlain with rock with normal velocity of 8.1-8.2 km/sec for the top of the mantle.

The problem of the physical nature of the anomalous seismic layer can be formulated as follows: is it a part of the mantle, the earth's crust or does it correspond to an intermediate crust-mantle series? There is no united opinion on this subject, for seismic data alone are insufficient for a solution of the problem, and this leads to various interpretations of the results of blast seismology regarding the subsurface structure of the riftogenesis zones. In particular, in these zones the position of the global geophysical discontinuity -- the M boundary -- is determined fiferently.

A more defined determination of the probable nature of the anomalous layer can be made by joint investigation of the most widespread properties of the medium in subsurface geophysics -- the seismic wave velocity, density and specific electrical resistance. Using these properties, it is possible to compile three-parameter, geophysical models corresponding to the competing hypotheses regarding the nature of the anomalous layer and to compare them with the geophysical data in specific regions. Let us consider the following basic hypotheses.

1. The heating of the upper mantle material. The high values of the thermal flux in the rift zones indicate increased heating of their deep structures. Therefore a reduction in the velocity in the tops of the mantle as a result of weakening of the intercrystalline bond when heating the deep material is possible.

2. Partial melting of the upper mantle material. When the temperature reaches 1100 to 1200°C at the depths of occurrence of the anomalous seismic layer, melting of the basaltic component of the rock in the upper mantle is possible with a corresponding decrease in the velocities in them.

3. The serpentinization of the ultrabasic rock. This process, which is possible at a temperature below 500°C, was proposed by H. Hess as an explanation for the formation of the ocean crust. With a relatively low degree of serpentinization, velocities can be obtained which are observed in the anomalous layer.

4. The partial eclogitization of the "basaltic" layer. At the bottom of the continental crust thermodynamic conditions for phase conversion of gabbro to eclogite are possible. The "basite-eclogite" layer formed under these conditions has "crustal-mantle" seismic wave velocities.

5. The crustal-mantle mixture is a hypothetical formation, which is the result of shifting of the mantle rock and the "basaltic" layer proposed by K. L. Cook to explain the reduced velocities in the tops of the mantle in tectonically active regions.

The hypotheses are divided into three groups: the first two (heating and partial melting) put the anomalous seismic layer in the mantle; the third and fourth (serpentinization and eclogitization) put the anomalous seismic layer in the crust; the hypothesis of a crustal-mantle mixture puts them in the transition region. Correspondingly, the position of the M boundary is interpreted differently.

The physical model of the anomalous layer corresponding to the hypothesis of heating of the upper mantle material was presented in the form of a single-component solid medium having the properties of olivinite. The model of the partially molten metal was simulated by a two-phase medium in which liquid basalt is found in the solid olivinite skeleton; a study is made of the cases of different degree of binding of the liquid inclusions. The models of the crustal-mantle mixture, eclogitization and serpentinization were represented as two-component solid mixtures made up of gabbro and olivinite, gabbro and eclogite, serpentine and peridotite, respectively. By varying the temperature (in the single-component model) and the ratio of the volumes of the components (in the two-component media), pair relations were calculated for each model for the three parameters: velocity-density, velocity-electrical resistance and density-electrical resistance. The calculation procedures and the assumed initial data are discussed in reference [46].

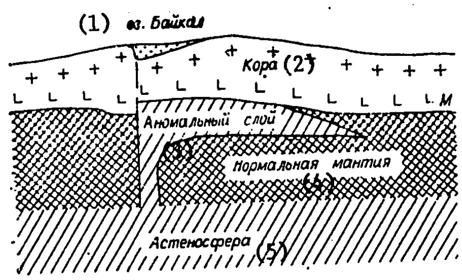

Figure 101. Schematic explaining the proposed process of the formation of the Baykal rift

Key:
1. Lake Baykal
2. Crust
3. Anomalous layer
4. Normal mantle
5. Asthenosphere

The investigation of the three-parameter geophysical models of the anomalous layer presented in the form of the indicated relations obtained here indicates that they permit three possible proposals regarding its physical nature to be distinguished: heating of the upper mantle material, partial fusion of this material and an unresolved group of solid mixtures (crustal-mantle, basite-eclogite, serpentine-peridotite). Consequently, it is possible to determine whether the anomalous layer is part of the mantle or not. However it is impossible to separate the assumption of its "crustal" and "crustal-mantle" adherence.

By the results of blast seismology, gravimetry and magnetotelluric sounding for a number of rifts (Baykal, Kenya, Iceland, the basin and ridge province), estimates are known for the velocities, the density and the electrical resistance of the anomalous layer. On comparing these data with the theoretical curves for the indicated parameters the following is established. Only the curves corresponding to the hypotheses of partial fusion and heating of the upper mantle material go into or close to the probable values of the physical parameters of the anomalous layer. Consequently, only these hypotheses can be taken as probable, and the hypotheses of the crustal-mantle mixture, eclogitization and serpentinization are unsuitable for explanation of the nature of the anomalous seismic layer in the investigated rift zones. For the western parts of the United States the heating and partial fusion of the upper mantle material are equally probable. In the regions of the Icelandic, Kenya and Baykal rifts, the hypothesis of partial fusion of the top of the mantle is preferable. Here the volumetric proportion of the molten basalt does not exceed 5-10%.

Consequently, by the set of geophysical parameters (velocity, density, electrical resistance) the M boundary in the rift zone corresponds to the roof of the anomalous seismic layer, which in all probability, is complicated by the partially molten rock of the upper mantle.

Considering the data discussed above on the peculiarities of the subsurface structure of the continental rift zones and the nature of the anomalous properties of the upper mantle material it is possible to put together a general concept of the probable causes of the formation of the Baykal rift (see Fig 101). The uplift of the heated and partially molten plastic material of the asthenospheric layer took place along a weakened zone to the edge of the Siberian platform. The spread of this material at the foot of the earth's crust with the corresponding effect on the country rock was directed away from the stable crustal-mantle blocks of the ancient Siberian platform, playing the role of a type of support. The introduced material of the asthenosphere in the form of a layer with a velocity of 7.6-7.8 km/sec caused the formation of a broad gently sloping uplift of the earth's crust -- the regional Baykal arch. The horizontal spread of this material in the southeasterly direction created tensile stresses in the earth's crust which became the cause of the formation of asymmetric (with steep northwestern sides) grabens of the Baykal rift zone in the previously nonuniform and disturbed sections near the edge of the Siberian platform.

§5. Studies in Foreign Areas

In addition to studying the Siberian regions the spot sounding procedure was used for the first deep seismic sounding operations in two parts of Antarctica. It was also used for interpretation of the materials from blast seismology obtained by the American geophysicists when studying the earth's crust of the Canadian shield in the vicinity of Verkhniy.

Deep Seismic Studies in Antarctica

Soviet geophysicists have the priority in seismic sounding of the earth's crust to its entire thickness on the Antarctic continent. The success of this work, which up to now has been the only work on the sixth continent, was promoted to a significant degree by the use of the spot seismic sounding method and the experience in studying inaccessible regions of Siberia.

The work was done during the research by the 14th and the 18th Soviet Antarctic expeditions. In 1969 the group of coworkers of the Scientific Research Institute of Geology of the Arctic headed by A. L. Kogan performed studies in the eastern Antarctic on the coast of Queen Maud Land [40]. The spot soundings were performed with standard seismic prospecting equipment. In 1963 the Scientific Research Institute of Geology in the Arctic, the Institute of Geology and Geophysics of the Siberian Department of the USSR Academy of Sciences and the Eastern Geophysical Trust investigated the Amery Ice Shelf [41] (Fig 102). A study is made below in the second of the regions where the possibilities of the spot sounding procedure with the Tayga system has been realized to the full extent.

This region is located within the epiproterozoic Antarctic platform. The deep seismic sounding traverse intersects the principal tectonic structure of the region -- the gigantic graben filled with the Lambert Glacier and the Amery Ice Shelf making up the largest reserve glacier in the world. On both sides of the graben, metamorphic and ultrametamorphic rock of granulitic facies were detected which belong to the Archean crystalline basement of the platform. The sedimentary deposits making up the Upper Paleozoic mantle of the platform emerge from under the ice cover only in individual sections. In the platform basement numerous intrusions of gabbroids and granitoids of different ages are noted, and in the deposits of the mantle rare sills of alkaline-ultrabasic rock of Mesozoic Age are encountered.

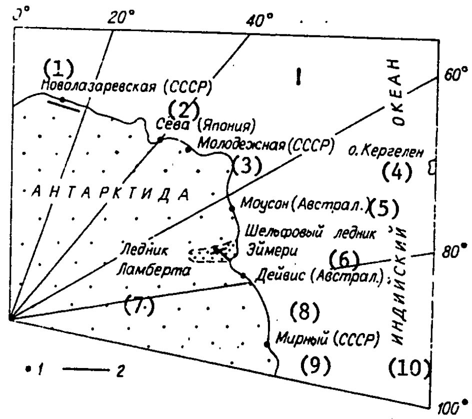

Figure 102. Diagram of the deep seismic sounding traverses in the eastern Antarctica
1 -- Antarctic stations; 2 -- deep seismic sounding traverses

Key:

1. Novolazarevskaya station (USSR)
2. Sova (Japan)
3. Molodezhnaya station (USSR)
4. Kerguelen Islands
5. Mawson station (Australia)
6. Amery Ice Shelf
7. Lambert Glacier
8. Davis (Australia)
9. Mirnyy (USSR)
10. Indian Ocean

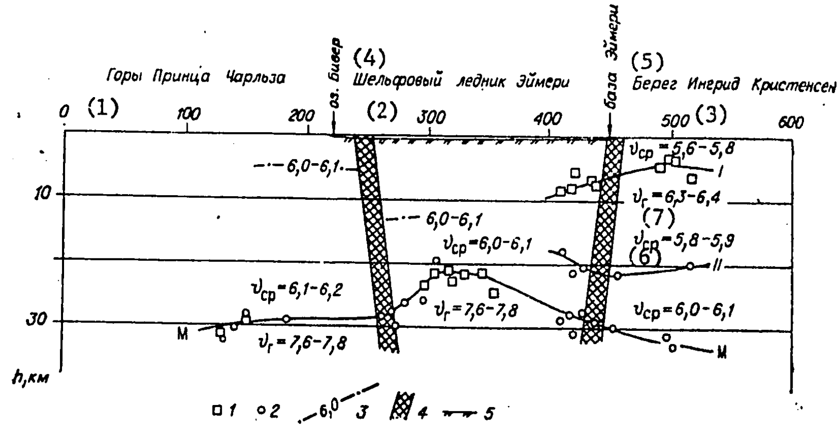

Figure 103. Seismic section of the earth's crust in the coastal region of Eastern Antarctica
1 and 2 -- depths according to the reflected and refracted wave data; 3 -- velocity isolines according to the refracted wave data (the velocities are given in km/sec); 4 -- zones of proposed abyssal fractures; 5 -- bottom of the ice

Key:
1. Prince Charles Mountains
2. Amery Ice Shelf
3. Ingrid Christensen Coast
4. Beaver Lake
5. Amery Base
6. v_{mean}
7. $v_{boundary}$

Characteristic Features of the Procedure. In order to record the elastic waves, 12 Tayga recorders were used simultaneously. The recorders were adjusted to operate at low temperature. They were placed in special thermostats with internal heating maintaining an invariant temperature of about 0°C for 2-3 days.

The equipment was remotely controlled from an aircraft and helicopter, where the 150 watt radio transmitter was placed insuring reliable remote switching within a radius of no less than 250-300 km.

The oscillations were introduced by detonating scattered charges weighing a total of 1-2.5 tons in lakes 60-100 meters deep.

The seismic observation systems used were similar to those used for operations in Siberia. In the first phase of the investigations, parametric piecewise-continuous observations were made in the distance range of 0-220 km from the source. These observations made it possible to study the wave picture in the new region and substantiate the subsequent sounding systems, the bases of which were selected equal to 40-60 km to study the intracrustal boundaries and 160-220 km, to study the surface of the mantle by reflected and refracted waves. The recordings of the subsurface waves characterized in detail in reference [41] do not differ significantly from the standard recordings in the continental regions.

The basic sounding traverse about 600 km long intersected the Amery Ice Shelf, along which an additional traverse was run.

The results of the investigations are presented in the section (Fig 103) cutting across the geomorphological elements: the Prince Charles Mountains, the Amery Ice Shelf under which there is an extended graben, and Ingrid Christensen Coast.

In the seismic section it is possible quite clearly to distinguish three block sections, within which the earth's crust is characterized by welded constancy of the mean and boundary velocities, thicknesses between individual intracrustal horizons and depth to the Mohorovicic discontinuity. On the surface these blocks coincide with the enumerated geomorphological elements. At the boundaries of the blocks a sharp change takes place in the thicknesses of the layers of the individual seismic boundaries, the total thickness of the earth's crust and the velocities, that is, the articulation of the blocks takes place along abyssal fracture zones within which there are sharp variations of the seismic characteristics of the earth's crust. The structure of the earth's crust in the blocks appears to be as follows.

Prince Charles Mountains Block. The total thickness of the earth's crust here is 29-31 km. Thickening of the earth's crust in the southeasterly direction is noted with respect to a relatively small number of observations. The boundary velocity at the Mohorovicic surface is 7.6-7.8 km/sec. The mean velocity in the entire thickness of the earth's crust is 6.1-6.2 km/sec.

Amery Ice Shelf Block. This block is characterized by sharp thinning of the earth's crust. The depth to the Mohorovicic discontinuity decreases to 22-24 km. With respect to thickness the earth's crust occupies an intermediate position between the continental and oceanic types of crust. The western contact of the block along the Mohorovicic boundary probably appears not as a smooth uplift of this boundary, but in the form of a sharp scarp with an amplitude of 7-9 km. In the northeasterly direction the thickness of the earth's crust increases to 30 km. The submersion of the Mohorovicic discontinuity obviously takes place in a series of scarps. The mean velocity with respect to the entire earth's crust is 6.0-6.1 km/sec. The boundary velocity on the surface of the mantle is 7.6-7.8 km/sec. As a result of the compressed times for the field operations it did not appear possible to study the internal structure of the crust in the central part of the block. The refracting horizon I was traced on the northwestern boundary of the block at depths of 7-8 km. The problem of the nature of this horizon still remains unexplained. One of the probable propositions must be considered to be absence in this section of a thick series of high-velocity sedimentary rock, which is confirmed by the geological survey data.

Ingrid Christensen Coast Block. This block has a crust thickness of 30-32 km. The mean velocity in the crust is 6.0 to 6.1 km/sec. The Mohorovicic boundary was studied here only by the reflected wave data; therefore there is no information about the boundary velocity. In the upper part of the crust the refracting boundary I is submerged to a depth of 4-5 km. The reflecting boundary II constructed with mean velocity of 5.8-5.9 km/sec is located at depths of 20-22 km and is uplifted in the direction of the Amery Ice Shelf.

The performed studies demonstrated the possibility of the successful use of the spot seismic sounding procedure to study the layered-block structure of the earth's crust under the severe specific conditions in Antractica. The experience gained is important for planning subsequent deep seismic sounding operations in the coastal and internal regions of this little-investigated continent and also when studying Arctic regions.

Interpretation of the Materials Obtained in the Vicinity of Verkhniy Lake

In this part of the ancient Canadian shield American geophysicists have performed spot seismic observations using a dense network and obtaining a system of extended hodographs [147]. By the wave hodographs in the first arrivals a number of researchers [139, 144, 146] have constructed several versions of the seismic section of the earth's crust with two refracting boundaries. One of them occurs at depths of 5-10 km, and the second corresponds to the M surface (Fig 104). We performed a second interpretation of the seismic materials obtained here by the spot sounding procedure to compare their possibilities with the methods used by the foreign researchers.

The initial data for the interpretation were the time tables of the first arrivals published in reference [147]. From the entire set of data, the times of arrival of the waves at distances of 250-300 and 50-100 km were selected. The fields $t(x, \ell)$ were constructed by them for the refracted waves corresponding to the Mohorovicic discontinuity and the upper refracting boundary. Using the method of recalculating the field with a decrease in bases (Chapter II, §2), isolines were calculated with bases close to the x-axis of the initial point of corresponding waves. The latter made it possible to find the boundary velocity distribution and depth distribution without resorting to rigid assumptions regarding the model of the medium. The boundary velocities for the upper boundary were found by the lines ℓ=0 and ℓ=50 km; the depths to it were determined by the line ℓ=50 km. The Mohorovicic discontinuity was constructed by the line ℓ=100 km, and the boundary velocity (3.1 km/sec) was calculated by the lines ℓ=100 and 150 km. The seismic section (see Fig 109) is not inferior with respect to completeness of information about the structure of the crust to the sections obtained by the other researchers, although no more than 5 to 10% of the total number of observations were used for its construction.

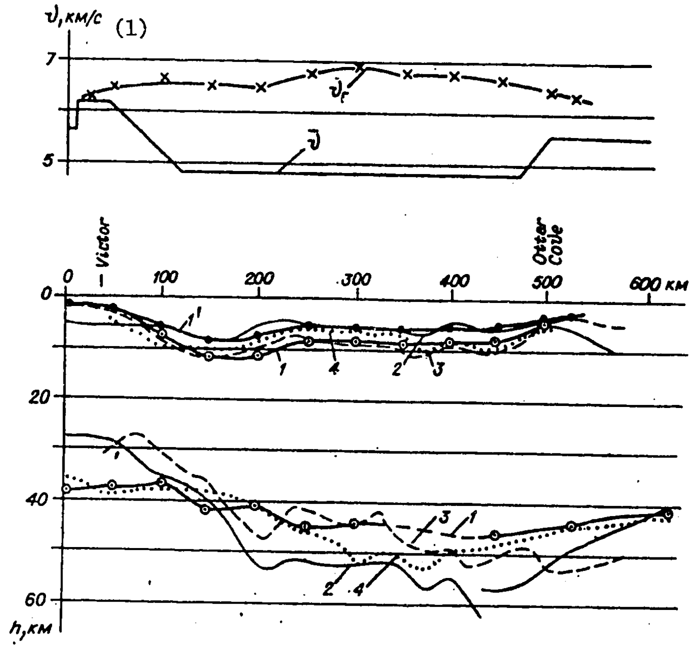

Figure 104. Comparison of the section of the earth's crust in the vicinity of Verkhniy Lake (the Canadian shield) obtained by the spot sounding procedure (1, 1', with the results of Berry, et al. [139] (2), Smith, et al. [146] (3) and O'Brien [144] (4). 1 -- the boundary was constructed with constant mean velocities; 1' -- the same with variable velocity (see the graph $\bar{v}$ in the upper part of the figure). $v_{boundary}$ is the boundary velocity for the upper boundary according to the spot sounding data.

Key:
1. v, km/sec

The construction by the sounding procedure, especially at the M boundary diverge with certain versions of the sections published by American geophysicists (Fig 104). The divergences are most significant with the results of the "travel time" method [139, 146], based on a number of simplifying assumptions about the model of the medium. This method was used to obtain very sharp variations in thickness of the earth's crust -- from 24 to 60 km -- which does not agree with the relatively little disturbed field of gravitational anomalies in the investigated region (0-40 mgl, according to the data of [149]). The best agreement of the section, according to the sounding data, is noted with the O'Brien version [144] obtained by a quite correct method which is similar with respect to its basis to the method of conjugate points of the head wave.

The investigated example indicates that the spot sounding procedures using special time fields is expediently used for interpretation of the blast seismology data along with the methods based on using systems of hodographs, especially in cases where these systems are inadequate for proper realization of the strict methods.

CONCLUSIONS

The main results of this paper are the following: theoretical and experimental substantiaion of a special procedure for performing regional seismic studies of the earth's crust and the top of the mantle in inaccessible regions; the creation of an original design of equipment for recording oscillations of the soil and subsequent processing of the information; obtaining the new data about the subsurface structure of Siberia on the regional level required for mineral prospecting.

About the Procedure

1. The expediency of the step execution of the regional seismic studies of all types (including the study of the folded basement, the deep zones of the earth's crust and the upper part of the mantle) with subsequent transition from the reconnaissance prospecting (low-detail) operations over broad territories to the high-detail operations in the sections of greatest interest is demonstrated. The problem of the reconnaissance prospecting phase is the study of the three-dimensional deep layered-block structure and distribution of the seismic velocities in the medium with details sufficient for characterization of the regional geological structures and discovery of the nature of the large-scale anomalies of the natural geophysical fields. The procedure of reconnaissance prospecting operations must insure express traverse-area study of broad territories, including inaccessible territories; the required accuracy and quality composition of the information must be obtained not as a result of complication of the observation systems, but by joint use of the waves of various types from the seismic reference boundaries.

2. The theory of the seismic soundings initially created for the refracted waves on the basis of the traditional hodographic approach was developed for certain monotypic waves (reflected, head, refracted) and arbitrary traverse and area observation systems used in inaccessible areas. The theory of the special two-dimensional and three-dimensional time fields which are a generalization of the concept of the seismic hodograph to the case of an arbitrary system of sources and receivers was created, which has great significance for the further development of the methods of seismic prospecting of any detail. The discrete correlation of reference seismic waves recorded in the sounding system was substantiated.

3. The procedure was proposed and developed in practice for field operations in the versions for profile (traverse) and area seismic sounding systems. These systems, made up of elementary soundings (the oscillation source and compact linear or area receiver), are effectively realized under complex surface conditions using river and air transportation. The seismic oscillations are induced by group blasts in bodies of water or large (to 1000 individual charges) groups of boreholes about 1 meter deep. The methods of determining the density of the seismic observations for the solution of the specific problems are substantiated.

4. The procedures were developed for interpretation of the experimental data for reflected, head and refracted waves, including the joint use of waves of different types from the same boundary. The discrete correlation procedures for the reference waves based on the a priori data and data obtained during the course of the operations on the wave field, the geometric and physical properties of the medium are substantiated; the process of wave identification was formalized, obtaining quantitative estimates of its reliability. The methods of solving the inverse problems using time fields have been developed both for simple models of the media with local-plane boundary and for more complex models: multilayered media with curvilinear boundaries, media with sharp surface inhomogeneities, with horizontal and vertical velocity gradients. The proposed methods permit sufficiently proper (for the problems in the reconnaissance prospecting phase) interpretation of the experimental data, obtaining information both about the configuration of the seismic boundaries and the velocity distribution of the elastic waves in the medium.

5. An objective estimate of the reliability and accuracy of the results of the spot sounding procedure was obtained by comparison with the deep drilling and continuous seismic prospecting data under various geological conditions -- from the areas of the ancient shields and platforms to the sections with Alpine age of the folding. The comparison demonstrated that in the results of the sounding procedure significant surface structures of the basement and the Mohorovicic discontinuity are correctly depicted for the reconnaissance prospecting phase of the operations and also basic characteristics of the velocity distribution in the earth's crust. The depths to the basement surface are determined with accuracy of approximately 100 meters (under the conditions of the Western Siberian platform); the accuracy of the constructions with respect to the deeper boundary, including the M surface, is about 2 km; the errors in the velocities usually do not exceed 0.2 km/sec.

About the Equipment

1. The requirements on the equipment for regional seismic studies in inaccessible areas are substantiated, the basic ones of which are as follows: high portability and reliability with small size and weight; broad dynamic and frequency ranges; reliable time coordination of the blasts and seismic information on a large number of scattered autonomous

recorders operating without service personnel at the observation stations; successive recording of the oscillations from several blasts without preparatory operations, except remote control at a distance of up to several hundreds of kilometers. The existing Soviet and foreign seismic recorders do not fully correspond to these requirements.

2. The original, portable remote controlled Tayga seismic system was developed which is specially designed for operations in inaccessible areas. A highly economical magnetic recording channel for recording seismic signals using simple tape drives with a dynamic range of more than 50 decibels was built for the first time in the USSR. The noise-proof system for radio remote control of scattered seismic recorders was built which insures reliable time gridding of the information received at the blast time.

3. As a result of the field testing, the correspondence of this equipment to the proposed requirements was demonstrated. The Tayga system has found broad production application during regional seismic studies in various parts of the USSR, including in the most inaccessible parts of Siberia and the Far East where previously such operations were in practice impossible. The application of this equipment has greatly increased the productivity of the field operations.

Results of Using the New Procedure and Equipment

1. The development of the new procedure and equipment, their broad introduction into practice have made it possible to begin systematic regional seismic studies of the basement, the entire earth's crust and the top of the mantle over the broad inaccessible expanses of Siberia where previously such operations, extremely necessary to determine the deep structural laws and for mineral prospecting, were actually never performed.

2. In the southern half of Western Siberia a frame network of regional deep seismic sounding traverses has been created with a total extent of 6000 km. Within the Western Siberian platform and its mountain frame seismic stratification of the depths under the large crustal-mantle blocks separated by abyssal fracture zones have been discovered. The data obtained are important for more correct solution of the problems of tectonic regionalization and serve as the basis for deep geological interpretation of the entire set of geophysical materials.

3. In the territory of the Western Siberian platform in the broad (15000 km) network of regional refracted wave sounding traverses and in the individual areas work has been done to study the morphology and physical properties of the basement surface which are important in connection with oil and gas prospecting. In the Omsk and Novosibirsk Oblasts over an area of 100000 km^2 a study has been made of the internal three-dimensional structure of the basement with isolation of the low-velocity layers prospective for finding Paleozoic petroleum.

4. In the Siberian platform the regional study of the basement (about 8000 km traverses) was made under extraordinarily complex surface and subsurface conditions of the Tungusskaya syneclise and also in the southern (Nepskiy arch) and eastern (Yakutia) regions. Theoretically new data were obtained on the structure of the basement and the bottom of the sedimentary mantle required for proper orientation of future petroleum prospecting work. The first informationabout the laws of the deep structure of the earth's crust and the top of the mantle in the area of development of kimberlite magmatism was obtained for Yakutia.

5. In the Baykal rift zone, which is the largest structure of its type in Eurasia, the greatest degree of seismic study of the deep structures by comparison with other (foreign) continental riftogenesis zones was achieved in a short time (1968-1975). The traverse (more than 4000 km) and area studies encompassed the central part of the zone, its flanks (including the region where the Baykal-Amur railroad is being built) and adjacent parts of the Siberian platform, Eastern Sayan and Transbaykal. Along with the general features of the deep layered-block structure, the characteristics were discovered which are connected with the active tectonic process: the presence of a broad (more than 200000 km^2) upper mantle region with anomalously low seismic wave velocity (7.7-7.8 km/sec) characterized by an average thickness of about 20 km and not having a continuous connection with the asthenospheric Gutenberg channel; coordination of the Baykal basin with the complex faulted zone above the edge of the anomalous region; the existence of an intracrustal seismic waveguide, apparently to a significant degree controlling the course of the geodynamic processes and the seismicity distribution in the given region.

In addition to studying the Siberian regions, significant work was done using the new procedure in two parts of the east coast of Antarctica (the work of the 14th and 18th Soviet Antarctic Expeditions). The first and still only seismic data for the sixth continent about the structure of the entire earth's crust and top of the mantle were obtained. Valuable experience was gained in performing studies under the severe polar conditions with a solid ice cover. As a result of using the sounding procedures to interpret the blast seismology material for the vicinity of Verkhniy Lake (the Canadian shield) the expediency of using this material in the case of incomplete hodograph systems insufficient for proper realization of ordinary strict procedures, is demonstrated. The introduction of the sounding procedure and the Tayga equipment was started in the Far East.

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