STRUCTURES AND GRAVITY ANOMALIES OF CRYOGENIC ORIGIN IN THE BAIKAL REGION

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and

MAXIMUM DEPTHS OF PERMAFROST

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STRUCTURES AND GRAVITY ANOMALIES OF CRYOGENIC ORIGIN IN THE BAIKAL REGION

by

A.P. Bulmasov

In this paper we deal with certain structures, very widely distributed in the Baikal region, that are related to permafrost beds, and we describe their physical properties. Examples are given to show the ineffectiveness of the geomorphological method of investigating deep structure, an ineffectiveness due to the absence, in permafrost zones, of any inheritance of structural form in depth.

A distinct relationship is noted between gravity anomalies and features of the geological structure in permafrost zones. It is shown that for positive [uplifted] structures related to permafrost, negative gravity anomalies are characteristic.

Permafrost occupies approximately half the territory of the USSR, and is well-developed on the territories of many other nations. In permafrost zones there exist proper conditions for the application of various geophysical methods to the solution of geological problems. The process of heat exchange in the system formed by the earth's crust and atmosphere --- the process which leads to the development of permafrost --- proceeds uninterruptedly; the energy level of this system varies in time and in space, with the consequence that in some areas of the globe new permafrost beds are being formed, while in others the permafrost is in a state of relative thermal equilibrium, or is decaying.

The direction and character of tectonic movements in some degree affects (promotes or hinders) the formation of new permafrost beds, or determines the conditions of their decline. The freezing and thawing of some varieties of frozen and non-frozen ground is accompanied by change in the ground texture and structure, which also is a fact to be taken into consideration in studying the in-depth structure of permafrost regions.

There are, it must be said, many features in the permafrost strata that have been very little studied, and this is in some measure explained by underestimation of the part played by the permafrost phenomenon in shaping the structure of the upper crustal horizons.

On the example of the Baikal region we shall try to show how great is the role of permafrost in forming the surface relief and the textures and structures of the component soils or rocks, and how this is reflected in the character of the gravity anomalies caused by permafrost. The phenomena in question, definitely related to permafrost, are on so large a scale that without profound study of them it is impossible to understand the history of the formation of the crustal structure in the permafrost beds in this Baikalian region, which is so interesting in so many respects. Some of the features we have noted in the distribution of thicknesses, composition and structure of the permafrost beds, and also in the gravity anomalies produced thereby, will undoubtedly occur in other similar regions of the Soviet Union. We hope that the present paper will be of interest to researchers working in the permafrost areas of Siberia, the Far Eastern Province, and the Far North of the USSR.

GEOCRYOLOGICAL FORMATIONS AND CRYOGENIC STRUCTURES OF THE BAIKAL COUNTRY

P.F. Shveçov suggested that the principle on which the geocryological zoning of the USSR should be carried out is the discrimination and identification of the permafrost soil formations. Permafrost, he writes, is "a frozen stratum of the earth's crust, typical of a given locality, area or region, comparatively uniform in composition, structure, thickness, depth from ground surface, degree and character of spatial discontinuity, composition, water content and water penetrability of the underlying ground. The qualitative and quantitative characteristics of geocryological formations as a whole reflect features of the physico-geographical and geological conditions under which they were developed and under which they presently exist; these in their turn are reflected, at the ground surface, in the character and composition of the soils and vegetation, in specific cryogenic processes and phenomena of physical geography, and furthermore --- as a result of these processes --- in the form of the microrelief, in the deformation of structures, and so forth." [14]

For the greater part of the permafrost area in the USSR, the permafrost stratum has been as yet so little studied that to speak of identifying geocryological formations for the whole territory of the USSR is out of the question. For some individual areas we already have sufficient material on the structure and properties of the permafrost beds, so that here it is possible to carry out a zoning, even if only schematically, on the basis of identifying the typical geocryological formations. Among such regions we may count the Baikal country, where, through long years of geophysical work carried out for the purpose of studying the deep geological structure of the area and for mineral prospecting, it has *incidentally* happened that details of the permafrost distribution and structure have been, at some points, brought out.

And now a few words about current ideas of the Baikalian permafrost. Sumgin [9, 10], for instance, includes the Baikal country among those areas where permanent (or long-term) freezing of the ground exists in relatively small "islands". Such islands are found in the extreme southwest and northeast of the area. In the central part of the area, permafrost is said to be absent. Baranov, in his geocryological map of the USSR [1, 2] --- which according to his ideas should reflect not only the distribution but also the composition and other cryogenic characteristics of the Baikalian permafrost --- gives just as schematic a description as does Sumgin. According to Baranov's findings, the greater part of the Baikal country is characterized by mean annual soil temperatures approaching $0^{\circ}C$ at depth 1-2 m, which excludes the possibility of any thick permafrost beds forming here. Only in the southwest and northeast of the Baikal country does he allow the existence of a permafrost stratum with thicknesses of as much as 25-50 m, the ground temperatures here being of the order of -1°C at depth 1-2 m. [But] he believes that even in Central Baikalia there might be preserved thick beds of a type that he classes as relict permafrost and buried permafrost [1].

Utilizing data from geophysical researches carried out over very great areas in the Baikal country, the author of the present paper will attempt to describe in somewhat more detail the permafrost strata of this region.

In the Baikal country the mountain ranges are for the most part made up of dense, mainly crystalline eruptive and metamorphic rocks, while the intermontane depressions are filled with loose and plastic formations (sands, sandy loams, loams and clays). The highly dissected relief has in some measure determined the vertical distribution of permafrost, which may be divided into two geocryological formations. The first formation --- let us call it the *high geocryological formation* of the mountain ranges and watershed areas of Baikalia --- comprises the permafrost beds of the upper topographic level. The second formation --- the *low geocryological formation* of the Baikalian intermontane depressions --- comprises the thick permafrost beds that have developed in the valleys. Spatially these two formations are separate in both horizontal and vertical directions and, it seems, are nowhere united.

The permafrost strata of the *high formation* are found mainly on the northern, northwestern and northeastern slopes of the mountain ranges and watersheds. On the opposite slopes, permafrost is found in local depressions of the relief (in the valleys of creeks and small rivers, and in dry valleys). The microclimate in these regions is characterized by negative mean annual temperatures of the order of -2 to -3°C. The topsoil cover is slight, with the result that thermally conducting ground is in contact with the atmosphere, and thermal exchange proceeds, it seems, quite energetically. The depth of seasonal freezing is 1 to 3 m (this depth has been fixed by electrical survey in many areas). The thickness of the permafrost layer is 25-30 m, or more. For instance the thickness of the permafrost bed at the Bokson bauxite deposits is as much as 30-40 m; on the northwestern slope of the Shore Ridge it is 10-20 m (opposite Bayandai).* In plan, the permafrost lenses are seen as long and narrow strips. Such strips have been noted on the northwestern slopes of the Shore Ridge, the Ikat Ridge, the Upper Angara Ridge and other mountain ranges.** As the slopes become milder in transition to the foothills of the mountains, the permafrost becomes thinner. It does not join up with the permafrost in the depressions. The rock textures and structures of this high formation have remained almost unaltered by the freezing of the water, since the mechanical bonds between the mineral particles of the igneous and metamorphic rocks apparently have a strength exceeding the pressure of the congealing water. The physical properties of the frozen ground also have remained without marked alteration, aside from the fact that the electrical resistance is increased from 2000-6000 to 10,000-20,000 ohm·m. On the whole, the soils or rocks of the high geocryological formation are little different in composition and properties from those in the unfrozen state.

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* Bokson, 51°58'N 100°20'E; Bayandai, 53°04'N 105°30'E. [Translator.]

** See map, DRB translation T 435 R, Fig. A; also footnotes, Pages 1 and 2. [Translator.]

More interesting in the *low geocryological formation* of the Baikalian intermontane depressions. In this case electrical survey work has almost everywhere revealed comparatively thick beds of permafrost, of close to lenticular form. The number of permafrost lenses in a depression is determined by the number of sub-basins making up the depression. Thus the Tunka and Barguzin Depressions each consist of five basins, * with which are associated five lenses of permafrost. The Bargoi and Gusinoye Ozero * Depressions have each been found to possess a single lens of permafrost. The number of permafrost lenses in the Ivolga, ** Upper Angara and certain other depressions has not yet been determined, since not all of the area of these depressions has been covered by electrical survey operations. In the Lake Baikal basin the presence of permafrost beds has, so far, been established only in the delta of the Selenga River. It seems that permafrost may also be found on the Chivyrkui isthmus and in the Tankhoi area. ***

The thickness of the permafrost beds in the depressions varies quite markedly: as a rule, the thickenesses are maximum near the centers of the depressions and decrease to zero toward the rims. If in the interior of a depression there is a comparatively high uplift of the crystalline basement, then either the thickness of the permafrost stratum is here reduced, or there is no permafrost at all. In fact, the lower boundary of the permafrost follows, in general outline, the relief of the basement surface. The behavior of the upper boundary is much more complicated.

Two types of conformity, for the upper and lower boundaries, are observed. In some parts of the depressions the upper boundary reproduces the relief of the lower boundary, but with less contrast. In this case the shape of the permafrost deposit approximates that of a concavo-convex lens with the concavity downwards. In other cases the permafrost zone is in the form of a biconvex lens, the upper convexity being the shape of the top of the permafrost and the lower convexity that of the permafrost base. In this sort of lens the upper horizons of the frozen ground form an anticline, below which the slopes of the horizons become less and less, and finally *invert*, forming a syncline. In the concavo-convex lenses the frozen ground horizons lie conformably [to the two boundaries].

Spatially the two types of permafrost lenses are associated with different areas in the depressions, marked by different speeds of vertical movements. Thus the areas of rapid downwarping of a depression have concavo-convex lenses of permafrost associated with them, while areas that are somewhat lagging behind in the subsiding movement have the biconvex type of permafrost lens.

The depth of the upper permafrost boundary varies within relatively narrow limits and depends on the type of permafrost deposit. In areas of relatively rapid subsidence in the depressions (concavo-convex lenses) the

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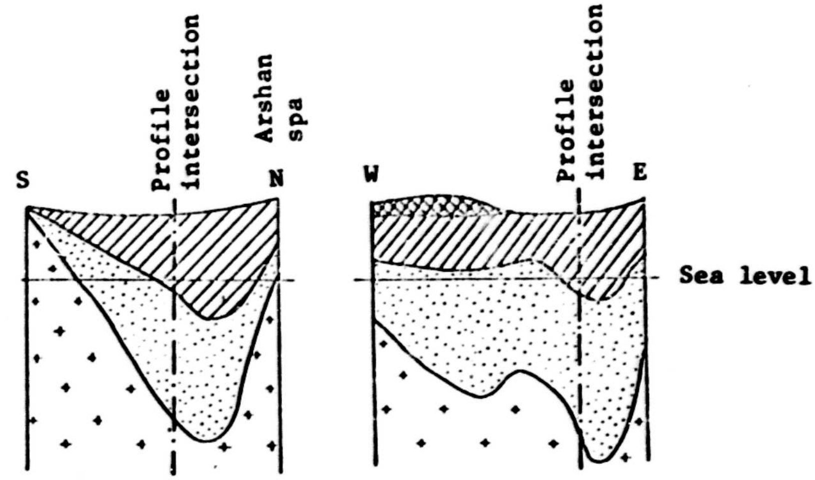
* Tunka and Barguzin Depressions: see DRB translation T 435 R, page v and map, Fig. A.
Borgoi or Bargoi, 50°45'N 105°50'E; Gusinoye Ozero (Goose Lake), 51°N 106°30'E. [Translator.]

** Ivolga, 51°45'N 107°14'E. [Translator.]

*** Chivyrkui Bay, 53°45'N 109°10'E; Tankhoi, 51°33'N 105°07'E. [Translator.]



Scale Horizontal, 1 : 500,000
Vertical, 1 : 50,000

Fig.1. Transverse and longitudinal sections of Tunka Depression.

Zones of interbedding of permafrost and non-frozen ground, lying conformably to the underlying non-frozen ground and to the basement relief.

Bed of non-frozen ground.

Crystalline basement.

Anticlinal permafrost structure in Baidary area.

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permafrost lies, as a rule, at a depth of 1 to 2 m from the ground surface and merges with the active layer. But in areas lagging behind in the downward movement (biconvex lenses) the permafrost is at depths from the low tens of meters to a hundred or more meters. Thus in all the sub-basins of the Tunka and Barguzin Depressions the permafrost in the areas of rapid subsidence starts from depths in the first few meters, while in these same basins there are areas where the depth to the permafrost zone is 10-20 m (Baidary, in the Tunka Depression) and even 100-150 m (Verkhnii Kuitun, in the Barguzin Depression) (Fig. 1). The directions of the vertical movements and their speeds, in the different areas of the basins, are well-established, both from the changes in the surveyed heights of the relief and from the rates of swamp-formation in the downwarping areas.

The first data forthcoming from geophysical investigations of the permafrost thicknesses in the Baikalian depressions raised doubts in the minds of many geologists; the thicknesses seemed to be exaggerated. But subsequent boring confirmed the findings.

The maximum permafrost thickness determined from the geophysical data in the area of greatest downwarping in the Tunka Depression was 1200-1300 m. When a deep borehole was drilled in this area, a frozen core of friable material, copiously impregnated with ice, was extracted from a depth of 1100 m. Upon thawing, this core turned into a sludge. *

In the Verkhnii Kuitun area the thickness of the permafrost zone was determined (by electrical survey) as 150-200 m, and the depth to its upper boundary as 100-150 m. Drilling here revealed frozen friable material in the interval from 150 to 250 meters depth.

We have already pointed out that in the depressions the permafrost takes in only the plastic clays and clay loams, along with the friable sandy loams and sands --- materials with only slight differences of physical properties. All of these we shall from now on call "friable soils". The freezing of these soils, both in the Baikalian depressions and elsewhere, is known to take place through afflux of water from outside, from the ground enclosing the permafrost bed. Because of the capillarity of the friable soils, the particle-surface film of ground water migrates to a certain extent into them and, furthermore, if the freezing is accompanied by subsidence of the locality, some of the ground-surface water, converted into ice, gets buried in the permafrost strata, with the consequence that the structures of the non-frozen ground and the frozen ground become considerably different. The frozen ground, as a rule, is characterized by a natural ice content *higher than the natural water content of the non-frozen ground.*

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* The very considerable depth found for the permafrost in the Tunka Depression does not mean that in all the 1000-meter depth interval the soils or rocks are in a frozen state. In the sub-basin in question, effusions of basalt have occurred repeatedly, and these basalts are interlayered with friable formations, the temperatures of which are everywhere above freezing. It seems that because the thermal conductivity of the basalts is higher than that of the friable formations, these constitute channels conducting heat into the permafrost stratum, which thus becomes broken up and discontinuous.

The formation of permafrost beds in the depressions takes place under conditions particularly favorable for the burying of large amounts of ice, since in these depressions the areas of freezing are at the same time areas of downwarping and of swamp-formation. In summer the thermal conductivity of swampy soils is less than in winter, so that the seasonal freezing of the ground penetrates to greater depths than the seasonal thawing, and each year there is an increase in the thickness of the permafrost layer.

Comparison-cores of non-frozen, frozen and thawing soils extracted at Baidary have shown that the degree of saturation with water is subject to large variations. Non-permafrost soils in the natural state of humidity have a density of 2.2 g/cm^3. The very same soils when frozen, but without any marked alterations of texture, have a density of about 2.1 g/cm^3. And finally, soil *sludges* from the thaw-zone are characterized by a density of 1.6 g/cm^3. Since the permafrost beds of the depressions indubitably contain a great amount of ice, the *sludge density*, it would seem, should be about right for the density of the permafrost as a whole. Other data, discussed infra, confirm the very low density and high ice-content of the soils in the permafrost stratum.

From the above it may be concluded that during the subsidence of the Baikalian depressions there were formed, in these depressions, concavo-convex lenses of frozen soil, *buried permafrost*, abundantly saturated with ice.

Since the downwarping of the depressions is proceeding so rapidly that gravitational forces are unable to bring the frozen ground/non-frozen ground system into equilibrium, the result is the formation of mass-deficiencies in the depressions during their subsidence. If in a depression some area having an already-formed stratum of permafrost lags somewhat behind the surrounding areas in its subsiding movement, then the conditions for the formation of new permafrost layers are ruled out, and in this case the weight-forces will bring the system into gravitational equilibrium. The process of establishing equilibrium in the non-frozen ground/frozen ground system is in many respects similar to the process of isostatic equilibration of the earth's crust, floating in its heavier substratum. In our case a similar rôle to that of the crust is played by the permafrost, while the rôle of the substratum is taken by the non-frozen ground. For this system to equilibrate itself it is necessary that the non-frozen ground beneath the permafrost be displaced, lifting the frozen bed. Obviously the uplift of the permafrost will be the greater in amplitude, the greater the density-difference between the permafrost and the non-frozen ground and the greater the thickness of the permafrost bed. In the general case, the amplitude of the upheaval will be determined by Archimedes' Principle and will amount to

$$A = H\left(1 - \frac{\sigma_1}{\sigma_2}\right),$$

where A is the amplitude of the permafrost uplift,

H is the thickness of the permafrost zone,

σ_1 is the density of the permafrost, and

σ_2 is the density of the non-frozen ground (the before-freezing density).

In the Baikalian depressions, structures of the Baidary and Verkhnii Kuitun type, where the permafrost zones in vertical section have the shape of a biconvex lens, are regarded by us as secondary cryogenic structures, the explanation of which is that at these sites the crystalline basement is lagging behind the subsidence of other parts of the depression, thus creating a *local thermal effect*. In the light of this explanation it is in fact possible to understand the details of how the *inversion* is formed in the permafrost bedding, as between the upper and lower horizons in the lens.

We shall now present some information on the cryogenic structures in the Tunka and Barguzin Depressions.

The Baidary rise [dome] is located in the western part of the Tunka Depression. It measures as much as 15 km across, and the amplitude of the uplift is about 150 m. The structure is prominent in the relief, in the form of a mound rising high above the floor of the basin (see Fig. 1). Florensov [12] and Lamakin [6] found that the Baidary rise was a typical isometric anticlinal structure with a well-expressed slope of the strata from crest to base. Electric survey data confirm the anticlinal structure of the upper part of the rise. But starting from a depth of 150 m the layers are found to be horizontal, and still deeper there is the inverted bedding, with the synclinal amplitude increasing with depth. The crystalline basement under Baidary is deeply downwarped. At one time the notion was current that the Baidary rise, to judge from its tectonic structure, had some petroleum prospects. But geophysical data were obtained in time to discourage the carrying out of costly prospecting operations here; they indicated the synclinal bedding of the deeper horizons in the structure and made clear its cryogenic origin.

The permafrost zone attains its maximum thickness (600 m) beneath the crest of the rise. Toward the periphery the thickness rapidly diminishes to zero. If the amplitude of the rise is 150 m, then with a permafrost thickness of 600 m and a non-frozen ground density of 2.2 g/cm^3, the mean density in the permafrost bed within the area of this structure is close to 1.7 g/cm^3; consequently the permafrost here is abundantly impregnated with ice.

The Verkhnii Kuitun rise [dome] is located in the middle part of the Barguzin Depression. It is about 15 km across and the amplitude of the upheaving of the permafrost bed is as much as 70 m. This structure too was regarded as a tectonic uplift, and oil drilling was started on it. In the course of the drilling, however, the anticlinal structure ceased to be in evidence at depth; the geophysical data indicated an inversion in the lie of the upper and lower horizons, and the cryogenic origin of the formation. Consequently prospecting operations were carried no further. In drilling the borehole, permafrost was found in the depth-interval from 150 to 250 m.

The above-described cryogenic structures, it seems, are not unique and they might well be encountered in other areas where thick frozen beds of friable soils have been formed (Katanga and Lena-Viliui intracratonic depressions, Zeya-Bureya depression, the intermontane depressions of the Transbaikal, the northern regions of the West Siberian Plain, and so forth.) Everywhere their study will be not only of scientific but also of practical interest.

CRYOGENIC GRAVITY-ANOMALIES

The present paper will not give any data on conditions for the application of the various geophysical techniques in permafrost zones. This is a problem that has been little investigated and is not extensively treated in the literature [3, 4, 11, 8, 15 and elsewhere]. It appears that the data are still awaiting publication. In this paper we are devoting our attention only to anomalic gravitational effects that can be caused by permafrost deposits.

Dense soils or rocks, in which the mineral particle bonding is strong and the porosity coefficient small, practically do not change their density in freezing. But friable soils (sands, sandy loams, clay loams and clays) have extremely high coefficients of porosity and very light bonding between the mineral particles (the tensile strength in clays does not exceed 0.8 kg/cm^2 and in sands it is zero); hence water freezing in the pores is well able to thrust the mineral particles apart. (The congelation pressure of the gravitating [non-bound] water may be as high as 1250 kg/cm^2 and that of the film-bound water still higher [7]). Upon freezing, the soil volume increases in proportion to its relative moisture content, which under natural conditions is numerically equal to the porosity coefficient. The increase of volume produces a decrease in the soil density, and if this is not taken into account when analysing gravity data, major errors may be committed in the geological interpretation of gravity anomalies.

We now consider two models for the change of soil density in freezing. In the first of these, the freezing takes place without afflux of water from outside; in the second model, with such afflux.

The mean density of the friable soils in the Baikalian depressions, under their natural bedding conditions, is 2.2 g/cm^3, with a porosity coefficient equal in the mean to 0.3. If all of the water contained in the soil pores before freezing is converted into ice, then the soil density is diminished by an amount

$$\Delta\sigma = \frac{\sigma\beta\varepsilon}{1 + \beta\varepsilon}$$

where σ = density of the non-frozen ground;

ε = coefficient of porosity;

β = coefficient of volumetric expansion of water in passing from the liquid phase to the solid phase (β = 0.0908).

It has been made clear by experiment that in the case of the Baikal country this reduction of the friable soil density has the seemingly small value of 0.064 g/cm^3. But if we take into account the great thickness of the permafrost in the depressions (as much as 350 m, and one area indeed 1100 m), then in determining the Bouguer anomaly the error due to not using the true value of the density in the permafrost stratum will amount to about 0.3 milligal for each 100 m of permafrost thickness. Of course, in the process of the soil's freezing not all the pore water will be converted to ice (even at relatively very low temperatures a large part of the film-bound water remains liquid), but in friable soils this is a small fraction of the total amount of water. Çytovich [13] gives the following laboratory data on the quantity of non-frozen water in soils at different temperatures:-

Temp. °C	Kinel' clay %	Pokrovsk clay %	Clay loam %	Sandy loam %	Sand %
− 0.3	34.3	17.0	12.0	-	0.5
− 1.0	26.0	14.0	9.5	4.5	0.3
− 2.3	19.8	12.3	-	-	-
− 5.0	-	-	7.0	3.5	0.3
−10.0	15.3	9.3	6.5	3.5	-
−20.0	-	-	6.4	-	-
−30.0	-	6.8	-	-	-

In the Baikalian depressions, where friable soils --- sands and sandy loams --- predominate throughout the vertical section of the sedimentary bed, the quantity of non-frozen water in these soils is so small that there is no need to consider it, and we may take the density reduced by 0.064 g/cm^3 as close to the proper value.

This density in the friable-soil permafrost may be regarded as maximum, since in all other cases it will be significantly less. The minimum density value is attained only when the whole of the permafrost is in the form of isolated lenses of ice, the density of which is 0.9 g/cm^3. In the drilling of borehole R-1 in the Barguzin Depression, ice lenses of thickness as much as 12 m were encountered. With a density difference of 1.3 g/cm^3 between non-frozen soil and ice, each 100 m of ice can cause a 5.5 mgal gravity anomaly. *

And so, we have considered the extreme limits of variation for the soil density in the permafrost stratum in the depressions. But what are the probable *mean values* of permafrost density in these Baikalian depressions? They may be determined in several ways. For instance, in the case of those cryogenic structures which in cross-section have the shape of biconvex lenses and which are developed in areas lagging somewhat behind in the subsidence, the density, as we have shown, can be determined from Archimedes' Principle, provided we assume that the permafrost lens has arrived at a state of gravitational equilibrium with the underlying non-frozen ground. In the Badary case the density of the soil formations in the permafrost stratum, determined in this way, was found to be 1.7 g/cm^3, and at Verkhnii Kuitun 1.75 g/cm^3.

The mean density of the soil formations in the permafrost stratum may be determined from the relationship between the so-called residual gravity anomalies and the known thickness of the permafrost stratum. We note that the permafrost stratum density in the Baikalian depressions, thus determined, ranges from 1.2 to 1.9 g/cm^3, that is, it falls within the above-stated limits.

The low values of the mean permafrost density in the Baikalian depressions is evidence that the freezing of the soils does involve a good deal of the above-discussed afflux of water from outside the beds.

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* No widespread distribution of thick lenses of pure ice in the depressions is at all likely.

Let us now turn to the characteristics of the observed gravitational effects that are unquestionably due to the anomalously low density of the frozen ground (cryogenic anomalies, so-called). On ordinary gravity maps the anomalies of cryogenic origin are not adequately brought out, and their presence may be established only by special, rather detailed study.

Figure 2 shows such a gravity anomaly, undoubtedly of cryogenic origin (this was confirmed by drilling), which was discovered in one of the Baikalian depressions. The residual anomaly in the central part of the zone attains a value of 10 mgal. In Figure 3 we have plotted, from electrical survey data for the same terrain, the isopachytes of the permafrost stratum. * Comparison of these diagrams proves their complete resemblance, a fact which emphasizes the indubitable close connection between the two phenomena. In this zone, along with the usual friable frozen soils, ice lenses were revealed. The mean density of the permafrost in the center of the zone is 1.2 g/cm^3 and in its marginal regions 1.9 g/cm^3.

In the Baikal country, it seems, cryogenic anomalies such as described are not isolated occurrences, but the extent to which the region has been geologically studied is insufficient for classifying all observed anomalies as geological or cryogenic. Nevertheless, in applying corrections to the observed gravity anomaly values in the Baikal region, particularly in the depressions, it is absolutely essential to allow for the decrease of density in the permafrost of the depressions. The mean permafrost density for three cryogenic structures that we have studied in detail (Baidary, Verkhnii Kuitun, and the structure shown in Figures 2 and 3) is 1.7 g/cm^3. This density was in fact accepted by us for plotting Baikal region gravity charts recognizing a differentiation of intermediate layer density.

The matter of cryogenic structures and gravity anomalies is of an importance transcending the limits of Baikalia. Similar phenomena are observed in other regions. Thus in 1959 the author reviewed the report of a multi-discipline geophysical group operating in the Taimyr. His attention was attracted to certain linear gravity anomalies, the map positions of which strictly coincided with the valleys of rivers flowing through the survey area. Those in charge of the operations ascribed the said anomalies to faults in the earth's crust. But a conjoint analysis of all the geophysical exploration data (magnetic survey, gravity survey and electrical survey) made it possible to show that the anomalies were caused by linear zones of permafrost decay, and this was why they rigorously corresponded to the river valleys.

In the Lena-Viliui depression there is approximately the same type of relatively-negative anomalies, showing up at a certain distance from the Tatta, Aldan and other rivers. As a rule, the maximum intensity of these anomalies is observed over areas with the greatest thicknesses of permafrost. It seems that the picture here observed is, as in the Baikal country, to be interpreted as due to a regular relationship existing between the permafrost thickness and the amplitude of downwarping of the crystalline basement.

* The permafrost thickness here established from the electrical survey data has been confirmed by drilling.

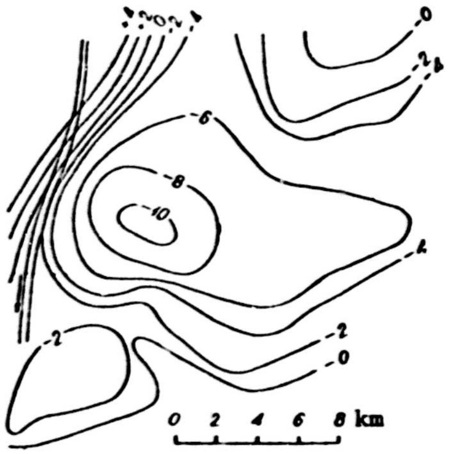

Fig.2. Residual gravity anomalies of cryogenic origin observed in one of the Baikalian depressions.

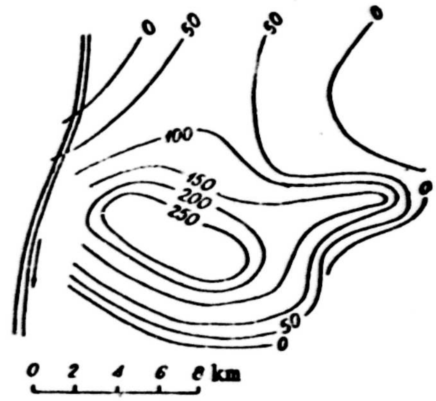

Fig.3. Isopachytes of permafrost in the same Baikalian depression (according to electrical survey data).

All the above gives us grounds for presuming that in the conduct of geological exploration special attention should be paid to the study, and the many-sided study, of permafrost, since proper consideration of phenomena related thereto will, in many cases, significantly improve the efficiency of such exploration in the regions of Siberia, the Far Eastern Province, and the Far North.

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MAXIMUM DEPTHS OF PERMAFROST

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UDC 561.52

Until recently permafrost thicknesses, as most reliably reported, have not anywhere on the globe been greater than 650 m. On the basis of extrapolations of temperatures measured in boreholes at depths up to 500 m it has been suggested that the permafrost thickness in some high-mountain areas may attain 900 m. All such information has been entered in our tabulation of maximum depths to the bottom surface of the permafrost --- which is taken as corresponding to the 0°C isothermal surface. *

Very interesting, when considered against the background of these data, is A.P. Bulmasov's communication [2] ** reporting the recovery of frozen soil (an icy sludge or quicksand) from a depth of 1100 m in a borehole in the Tunka Depression, and stating that the thickness of the permafrost in the area of greatest downwarping of the said depression has been determined, by geological methods, as 1200-1300 m. Somewhat earlier V.P. Solonenko [19] had identified an area in the Sayan-Baikal Engineering-Geological Province where the permafrost is classed by him as of "Baikalian type", comprising two horizons:-

upper horizon --- recent permafrost of "island" type and
lower horizon --- ancient buried permafrost, explored to a depth of 500 m (900 m?).

Bulmasov's depth of more than a kilometer for the permafrost bottom surface is exceptional not only for Siberia but for the whole of the Earth. For establishing the reliability of such data there are in principle many valid criteria, the most important of which are: the method and the duration of the drilling and of the subsequent maturation of the well, the method of measuring the temperature or the state of freezing of the ground, the precision of the instruments employed, and so forth [1, 4-7, 10, 12, 14, 15, 18, 23]. But not infrequently the presence of permafrost is simply inferred on the basis of the driller foreman's report: "from the rate of advance or the operation of the drill, frozen (or thawed) ground is being penetrated". Geophysical methods of surveying thick beds of permafrost and reliable procedure for interpreting the data have not yet been worked out. All methods without exception require that we have some (if only a few) temperature measurements in the boreholes for the purpose of "tying in" the permafrost data.

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* This assumption is arbitrary, since at depths of about 1000 m the temperature of ice formation is reduced to -0.7° by the large hydrostatic pressure. The higher mineralization of ground water reduces this temperature by another 1-2 degrees or more.

** Here translated; see p.1.

MAXIMUM DEPTHS TO BOTTOM SURFACE OF PERMAFROST *
(that is, to 0°C isothermal surface).

Place	Lat. (deg)	Altitude (m)	Mean annual atm. temp. (°C)	Predominant rocks	Rock temperature: Depth (m)	Rock temperature: °C	Depth to bottom of permafrost: By calculation (m)	Depth to bottom of permafrost: By drilling (m)	Method of determination **	Source
					EUROPE					
Amderma	69	< 50	-	Clay shales, limestones	20 100 270	-4.6 -5.3 -3.8	About 500		Geoth. to 270	Yefimov, 1940
					ASIA					
Var'yegan	62	-	-	Silts, sands; Quaternary and Cretaceous			Over 315		Drill, geophys.	Zemçov, 1960
Salekhard	67	About 50	-7	Loams, sands; Quaternary and Cretaceous	20	-4.0	380	350 ***	Drill, geophys.	Baulin, 1962 [14]
Noril'sk	69	About 200	-8	Sandstones, shales; Permian-Triassic	50 320 330	-7.5 -0.3 +0.2	400	325	Geoth. to 330	[13]
Dzhebariki-Khaya	62	215	-11	Sandstones, silts, coal; Jurassic	30 170	-5.5 -3.7	416		Geoth. to 170	[14]
Ust'-Port	69	< 50	-11	Sandstones, clays, sands; Cretaceous	50 330	-3.0 -1.2	500	425	Hydrogeol., geoth., geophys.	[14, 16]
Mouth of R. Viliui	62	About 70	-10	Sands, argillites, sandstones; Cretaceous	20 240	-2.1 -1.2	420		Geoth. to 240	Yefimov, Kozlov, 1960
Magan	62	195	-10	Sandstones, argillites; Jurassic	20 300 400	-3.0 -0.8 -0.5	450		Geoth. to 400	[10]

Namçy	63	80	-10	Sands, silts; Cretaceous	20 200 500	-2.5 -2.2 -1.6	560		Geoth. to 300	Yefimov, Kozlov, 1960
Mirny (Yakutia)	63	300	-9	Kimberlite	15 300 550	-2.7 -1.9 -0.0 (sic)	55	550 ****	Geoth. to 500 hydrogeol., drill	[6]
Kozhevnikova	73	15	-13	Limestones, salt, gypsum, caprock; Paleozoic	15 400	-12.5 -3.6	600		Geoth. to 400; drill	[16]
Tiksi	71	< 20	-14	Sandstones, siltstones	20 200 500	-11.1 -8.8 -4.7		630	Geoth. to 630	[10]
Bykhanai	66	50	-12	Sandstones, silts, sands; Cretaceous	50 500 1000	-3.8 -0.2 +10.4		650	Geoth to 3300	Yefimov, Kozlov, 1960 [10]
Udokan	57	200	-12	Sandstones, shales	50 300 500	-7.5 -5.0 -3.3	900		Geoth. to 500	[10]
					NORTH AMERICA					
Cape Simpson	71	< 100	-12	Clay shales; Cretaceous	42	-9.9		309	Geoth. to 309	[27]
Fort Umiat	69	< 100	-12	Clay shales; Cretaceous	21	-7.3	321	-	Geoth. to 264	[25]
Point Barrow	71	< 100	-12	Clay shales; Cretaceous	179	-6.3	390	-	Geoth. to 180	[27]
Fort Resolute	75	< 100	-15	Clay shales; Cretaceous	16 30 135	-12.2 -13.0 -7.5	387	-	Geoth. to 195	[26, 28]

* See note, p.19.

** "Geoth. to 400" = on the basis of geothermal measurements to depth 400 m; "hydrogeol." = hydrogeological, by presence of subterranean water; "drill" = by drilling, from the advance of the drill and from the icy core; "geophys." = from interpretation of industrial geophysical data.

*** This figure is for the bottom surface of the second (relict) layer of permafrost.

**** Down to 250-300 m the ground is cemented with ice; below this are saline waters cooled below zero centigrade.

In view of the brevity of this paper we shall not give any detailed analysis of Bulmasov's statements [2] concerning the possibility of using a gravimetric method of studying icy permafrost, having a different texture from that of unfrozen ground. For small depths of the order of 20-40 m the proposed method is likely applicable. Usually permafrost bodies of some meters' thickness are associated with the upper part of the Quaternary deposits. For revealing the permafrost bedding conditions to a depth of some hundreds of meters, the success of the gravimetric method is dubious. In the majority of cases the ice at such depths is only dispersed in the frozen ground in the form of isolated crystals and ice-cement, the resulting density difference being half an order of magnitude smaller than indicated by Bulmasov, that is, a difference of no more than 0.02 g/cm^3, which cannot have any important effect in modifying the gravitational field.

Bulmasov incorrectly visualizes the process whereby the texture of frozen ground is formed. He writes that "some of the ground-surface water, converted into ice, gets buried in the permafrost strata, with the consequence that the structures of the non-frozen ground and the frozen ground become considerably different". It is well known that buried ice has a very limited distribution, and that in the principal regions where large masses of subterranean ice are found, buried ice plays almost no part [14]. The texture of permafrost is formed, not by any "burying of surface ice", but by the formation of ice during the freezing of loose, water-soaked ground, and the type of cryogenic texture depends primarily on the genesis of the soils or rocks and on the conditions under which their freezing takes place [15].

The question of how far gravimetry is applicable to the needs of geocryology must be further studied --- particularly as regards determining the minimum ice content in the ground that will make it possible to identify as cryogenic a change in the gravitational field background.

It should be noted that in the case in question the Bouguer anomalies observed by Bulmasov cannot be interpreted unambiguously, since the [stratigraphic] interval with which he was concerned was made up of loose Quaternary sediments of low density. The phase composition of the water in these soils at such considerable depths (500-800 m) is not capable of noticeably affecting the total density in any way. Bulmasov's paper [2] gives very little data from which one could decide how representative the observations were that served as basis for his inferring a great thickness of permafrost. Nor is there any such information in Solonenko's paper [19].

The Cisbaikal, which is in the southern part of the permafrost zone, has until now been described as a region where the maximum permafrost thickness varies within a range of 25-50 m, or under special conditions, within a range of 100-200 m [14].

Consequently the Tunka depression (and also certain other depressions around Lake Baikal), where according to Bulmasov there exist such unusually great thicknesses of permafrost, should be distinguished by some peculiarity in structure and geological history, whereby this "permafrost anomaly" has developed.

The Tunka depression, where the PreCambrian folded bed lies at a depth of 2.5 km, is filled with sediments of only Neogene and Quaternary age [9].

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The two uppermost suites --- a sandy suite (Middle to Upper Pleistocene) of thickness about 400 m and a "recent" suite (Holocene) of thickness about 40 m --- are composed mainly of sands and gravels, alternating with layers of clays and with basalt sheets of no great thickness. These two suites were laid down under cold climatic conditions. Finds of thin interlayers of peat among the frozen clays and sands around the town of Yenarga convincingly support their recent age of formation.

In the three underlying suites --- a peat-bearing suite (Upper Pliocene - Post-Pliocene) of thickness of about 300 m, an ochreous suite (Upper Pliocene) 480 m thick and a coal-bearing suite (Miocene - Lower Pliocene) of thickness of about 1250 m --- the sediments were laid down under warm climatic conditions (broad-leaved flora, magnolia, laurel) [9].

In its structural-tectonic aspect the Tunka depression is a continuation of the Baikal depression, with clear manifestations of a neotectonic activity that is bringing about not only a rejuvenation of ancient deep faults but also the formation of new faults and crustal displacements [22]. The whole Baikal-Sayan region is characterized today by a high seismicity, of intensities 8-9 and higher [19, 21]. There are widely known instances of considerable displacements that have occurred in our times on the shores of Lake Baikal [8].

Along the northern side of the Tunka depression a mighty fault is traced, with associated mineral-water hot-springs. The formation of this fault is referred by N.A. Florensov [22] to post-glacial times. Hence, it seems, the idea also originated that in some areas permafrost strata formed at the ground surface can be displaced downward and buried [2, 19]. The considerable mobility deep in the earth in this area is the primary cause of the rocks' being intensely broken by fissures, both ancient and recent. The markedly fissured character of the carbonate rocks that are widely distributed along the margins of the Tunka depression has led to a development of karst. Loose soils have also, through fissuring, become more penetrable to water. All these factors have produced an above-ordinary abundance of water in the sedimentary fill of the Tunka depression. This abundance is manifested in the multiplicity of groundwater springs, which are characterized by very considerable discharges (up to 1000 m^3/hr), by a variety of chemical and gaseous contents, and by water temperatures of up to 41°C [11, 20].

Characteristic of the artesian basins associated with the Baikal-type depressions, and above all the Tunka basin, is the high permeation of the surrounding hydrogeological massifs and the sediments filling the intermontane depressions. Evidence of this is, for instance, the fact that in the Tunka basin we encounter, right down to the crystalline basement, only fresh waters and carbonate waters (calcium and sodium bicarbonate). Some hydrofer horizons with yields of 1-11 l/sec have been discovered here at depths from 45-70 to 800-1500 m or more. Shveçov [24] cites the Tunka depression as an example of unusually rapid increase of rock temperature with depth (1°C per 18.5 m). This hydrogeological and geothermic activity of the Tunka depression has not favored and does not now favor any deep freezing of the ground, and even less its preservation in the frozen state at great depths for thousands of years.

Let us assume for argument's sake that the permafrost in the Tunka depression extends to great depths --- to 500-900 m according to Solonenko, and to 1200-1300 m according to Bulmasov. If we compare these figures with the stratigraphic column [9], then the [above-said] peat-bearing suite should be found in the frozen state if the permafrost thickness is 500 m, and the ochreous suite if the thickness is 900-1200 m, and even part of the coal-bearing suite if the permafrost thickness is 1300 m. Now these suites were deposited under conditions of warm or temperate-to-warm climate [9, 17]; hence there is no doubt that, if frozen, they must have been *epigenetically* frozen. The freezing, which could have commenced only during the period of deposition of the sandy suite, the basal depth of which is now about 400 m, must have penetrated a bed of minimum thickness as much as 400-800 m.

Indeed the freezing must have been much greater even than this, because during the time that has elapsed since its supposed burying (10-20 thousand years), the permafrost should have thawed out from below for a vertical distance not less than 200-400 m as a result of the internal geothermal flux alone, leaving quite aside the thawing action of ground waters.

To maintain that there exists today a kilometer thickness of permafrost in the Tunka basin, we should need definite confirmation of quite exceptionally severe climatic conditions existing in the Tunka basin during the second half of the Pleistocene. For the epigenetic freezing of the ground to a depth of 1100-1300 m we should have to have a mean earth-surface temperature of the order of 18-20° below zero centigrade and a duration of freezing reckoned in hundreds of thousands of years.

Syngenetic freezing could have occurred, in the Tunka depression, through accumulation of sediments under cold climatic conditions plus a continuous subsidence of the basement. The thickness of the permafrost bed formed in this way would in general be limited to the thickness of the sandy and "recent" suites, namely 400-500 m. As a matter of fact this figure is too high, since the subsiding ground would be freezing from the top and thawing from the bottom, and protracted syngenetic freezing would likely be hindered by the rapid subsidence of large blocks that is characteristic of the tectonics of the Baikalian depressions [3, 8, 22]. Bulmasov [2] gives an unconvincing explanation for the formation of his huge "biconvex and concavo-convex lenses of permafrost". In his opinion there are, in the Tunka depression, basalts which are "interlayered with friable formations, the temperatures of which are everywhere above freezing", and since the "thermal conductivity of the basalts is higher than that of the friable formations, these constitute channels conducting heat into the permafrost stratum, which thus becomes broken up and discontinuous". How is it possible, from statements such as these, to understand just what soils or rocks were frozen, and what remain frozen, and how all this took place?

The above considerations compel us to adopt a very cautious attitude as regards the thesis that permafrost is present in the Tunka depression down to depths of 900-1300 m. Accepting such unprecedented depths of permafrost would make it essential to revise many existing ideas on neotectonics, on the Quaternary paleoclimate, and on the hydrogeological conditions not only of the Tunka basin but also of vast neighboring regions. These are matters of such importance that revision can only be justified after the most careful study of geothermal conditions in the Cisbaikal and the obtaining of incontestable information on the depths of permafrost distribution.

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NOTE: After this paper was written P.I. Mel'nikov, at the Second Geothermal Conference in 1964, reported, on the basis of measurements in a borehole penetrating to the crystalline basement, that on the southern slope of the Anabar Massif, on the upper waters of the River Markha, the permafrost thickness reaches 1500 m. The report of this is being published in the Transactions of the Conference. Our table (pp.14,15) does not show data on the ice thickness in Greenland and in Antarctica, which is as much as 3-5 km. *

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* In the Russian text this Note was the first footnote to the Table (page 15), where we have replaced by a cross-reference. The 1500-m permafrost find seems well established; for a description see N.A. Grave, Priroda, 1968, 1, 46-53 (DRB translation T 499 R). [Translator].

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