DEEP STRUCTURE OF MAFIC - ULTRAMAFIC COMPLEXES IN THE ANADYR' - KORYAK REGION

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ABSTRACT

This paper presents a summary of geophysical investigations of the deep structure of the Anadyr'-Koryak region in northeastern Russia. Rocks of increased density (mafic-ultramafic) were found at shallow depths using quantitative analysis of geophysical data, often including gravitational data. The areas covered by the increased density are several tens of times greater than the total area of known exposures of ophiolite complexes. The geophysical analysis allows us to distinguish between rooted and rootless mafic-ultramafic assemblages. The tectonic role of the mafics and ultramafics in the formation of the regional structure is discussed.

INTRODUCTION

The Anadyr'-Koryak region is located in the extreme northwestern periphery of the Pacific Ocean basin. Geologically, it is considered to be a continental portion of the continent-ocean transition zone. The Okhotsk-Chukotsk volcanic belt (OCVB) separates this region from the continent in northeast Asia.

The structure, in terms of density, of the Anadyr'-Koryak region and the adjacent Russian northeast, at depths of 20, 30, 40, and 60 km, is shown in Fig.1. These horizontal slices are a tomographic representation of the lithosphere obtained as part of a three-dimensional model calculated using vertical sections, horizontal slices, and specialized maps. These slices were subsequently interpreted in terms of petrology. It is possible to make a similar three-dimensional model in terms of layers and blocks (or terranes and plates) using the assumption that the upper and lower boundaries of the density heterogeneities coincide with the horizontal stratification of the lithosphere (Vashchilov, 1985).

The Anadyr'-Koryak region is clearly seen on the 20-km slice, where rocks with densities of 3.00-3.15 gm/cm^3, i.e., mafics and ultramafics, dominate. Rocks with a density of 2.90-3.00 gm/cm^3, typical of mafic rocks, occur to the north and west of this region at the same depth. At a depth of 40 km, the Anadyr'-Koryak region and its surrounding regions become similar. Most ultramafics or eclogitized assemblages, with a density of 3.16-3.30 gm/cm^3, are found in this layer.

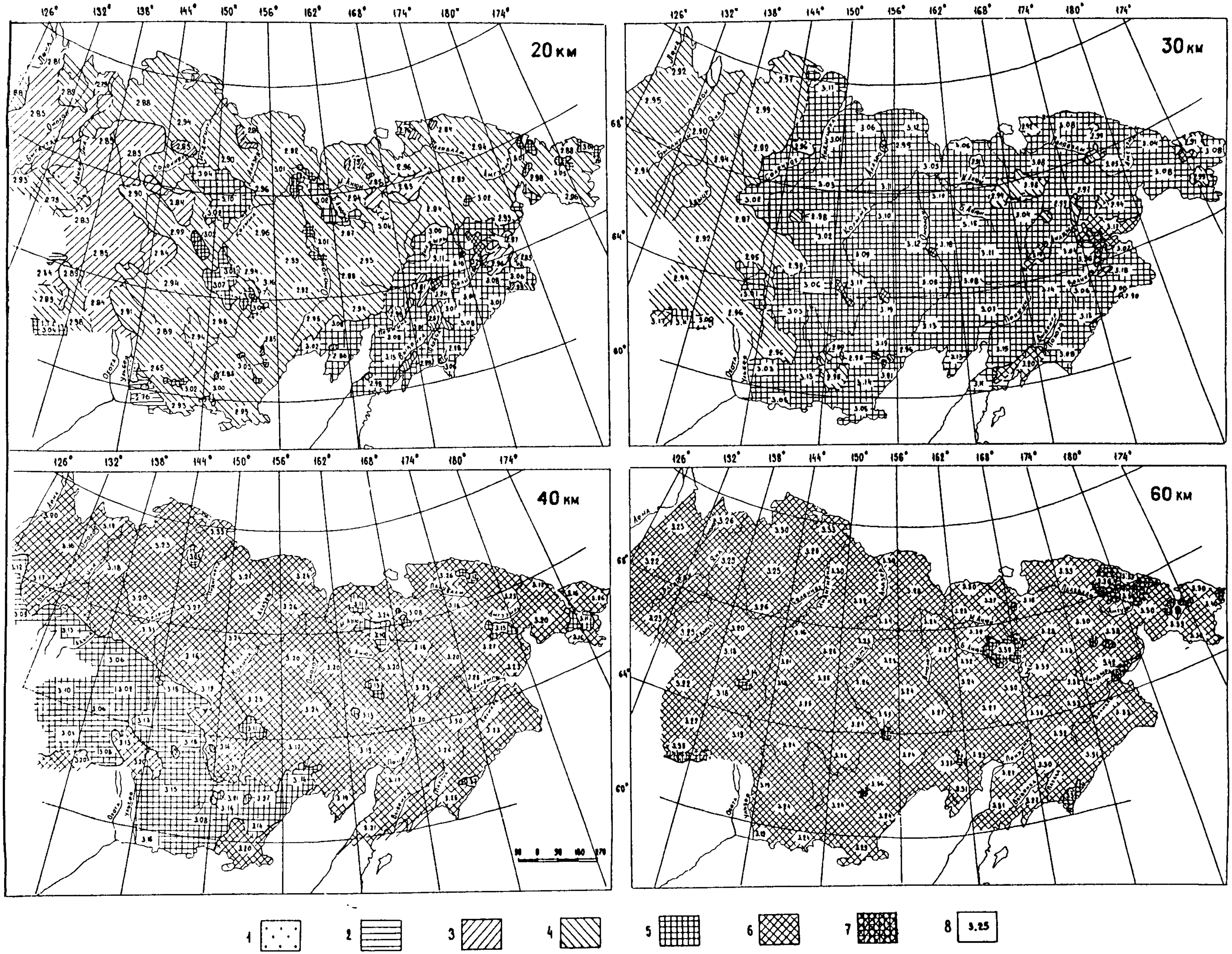
Melanocratic rocks are located close to the earth's surface (Markov, 1975), and this results in the extensive distribution of ophiolitic rocks in the Anadyr'-Koryak region. These ophiolites have attracted the attention of geologists for a long time, and many geological papers have been published (Vashchilov, 1968; Pinus et al., 1973; Aleksandrov, 1974; Aleksandrov et al., 1975; Lavrova, 1980; Markov et al., 1982; Belyi and Anikin, 1985a and b). However, there have been no geophysical publications. Vashchilov (1968) considered the Ust' Belaya massif to be rooted and an outcrop of subcrustal material. Vashchilov (1988) also considered the Tamvatnei ophiolite complex is a thin, laminated, rootless massif. Some geophysical aspects of the composition of the Ust' Belaya massif were considered in Aleksandrov (1974), who showed that the ultramafics have an overthrust nappe and allochthonous nature, but gave no numerical calculations to support this idea. A geological interpretation of geophysical fields was presented in Belyaev et al. (1974), but again there were no quantitative calculations.

OPHIOLITE PETROPHYSICS

We used gravity, magnetic, and magnetotelluric methods of profiling to study ophiolites. Some information on the structure of the host rocks, the regional deep structure, and studies of buried ophiolite complexes with no exposures was obtained using other geophysical methods, including seismic and some variants of electric prospecting.

It is most reasonable to study the mafic-ultramafic complexes using gravity and magnetic methods. Unaltered mafics and ultramafics are characterized by a high density, with the ultramafics being denser than mafics. However, serpentinized ultramafics have a large variation in density from 2.40 to 3.40 gm/cm^3. Thus, in some ophiolite complexes, higher gravity values can be observed above outcrops of banded gabbros within dunites or harzburgites. For example, in the Ust'-Belaya massif, the gravity values above the serpentinized lherzholites and harzburgites along the left bank of the Tamvatvaam River are lower than those of the host sedimentary rocks. The degree of serpentinization of ultramafics can be studied by examining the variations in density. The amount of density decrease in the ultramafics, as compared with unaltered rocks, can help determine the degree of serpentinization. In addition, the quantitative interpretation of the results can help to identify ultramafics of the pyroxenite and dunite-harzburgite series that have not been exposed by erosion.

Fig.1. (Overleaf) Density and inferred lithology of northeast Russia. Horizontal sections at depths of 20, 30, 40, and 60 km. Symbols show calculated densities in gm/cm^3 and their inferred lithology: 1--2.70 (granite and sedimentary rocks); 2--2.70-2.77 (granodiorite, granitogneiss); 3--2.78-2.84 (diorite, diorite-basalt, marmorized limestones, metamorphosed terrigenous rocks); 4--2.85-2.90 (mafics, glaucophane schist, greenschist, serpentinized ultramafics); 5--3.00-3.15 (mafics, ultramafics, gabbro-amphibolites, mafic crystalline schist, eclogitized rocks); 6--3.16-3.33 (ultramafics, eclogitized rocks); 7--greater than 3.33 (eclogite, ultramafics); 8--density values in gm/cm^3.


20 км
30 км
40 км
60 км
1
2
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4
5
6
7
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3.25

Ultramafics of the pyroxenite series are less susceptible to serpentinization.

The density of rocks that contain an ophiolite association varies within a large interval, but it is usually between 2.70 and 2.80 gm/cm^3. The density of sedimentary and sedimentary-extrusive rocks of Cretaceous and Cenozoic age is usually less than 2.40-2.50 gm/cm^3.

The magnetization of mafic-ultramafic complexes is determined by the presence of ferromagnetic minerals, primarily considerable magnetite, pyrrhotite, titanium-magnetite, and some others. The presence of these minerals can explain the high magnetization of gabbro, serpentinite, and serpentinized ultramafics. Ultramafic rocks may not be distinguishable in the magnetic field. However, both serpentinites and gabbros are marked by positive magnetic anomalies. The magnetization of serpentinized peridotite increases as a result of the decomposition of iron-bearing silicates and as a result of the formation of magnetite grains. The iron content of minerals in peridotites increases from harzburgite to wehrlite. Their magnetic properties depend on the presence of ore minerals of magnetite and to a lesser extent on the degree of sulphide mineralization.

The values of the magnetic susceptibility and the density of mafic and ultramafic rocks of some ophiolite complexes in the Anadyr'-Koryak region are presented in Vashchilov et al. (1982).

Finally, viscosity is one of the most important petrophysical characteristics of rocks of the ophiolite association. Although viscosity is not calculated here, it is important to remember that ultramafics have a lower viscosity than the granites, granitoids, and gabbros containing them and most known metamorphic rocks. This is typical of ultramafic complexes in heated, subsolidus conditions, as serpentinized peridotites, and as magmas. The viscosity of peridotitic magma is one hundred million times less viscous than granitic magma. Water affects the creep of peridotites found in cold conditions. Experiments show that even a small amount of water increases the creep of dunites by more than three orders of magnitude (Post, 1977). The lowered viscosity is one of the reasons why ultramafics have a special role in the deep and surficial structure of the crust and upper mantle, and in tectonics. Due to its lowered viscosity, ultramafics are one of the most mobile materials in the lithosphere and are capable of plastic protrusive, non-isostatic displacements.

THE STRUCTURE OF ROOTED AND ROOTLESS OPHIOLITES

The idea of rooted and rootless ophiolite complexes (Vashchilov, 1969) is supported by recent geological investigations and the quantitative interpretation of geophysical data. The Ust'-Belaya ophiolite complex, the largest in the Anadyr'-Koryak region (Fig.2), is an example of a mafic-ultramafic massif whose roots extend to the lower crust and upper mantle. The Pekul'nei horst-anticline extends northeast from this complex. The ultramafics are exposed locally in the hinge of the fold. These ultramafics extend farther to the northeast in similar anticlines. Geologic data suggest that the blocks and layering of the ultramafics are vertical. Gravity measurements unambiguously suggest that there is a large underground buried ophiolite complex along the right bank of the Anadyr' River (Figs.3-5).

A variety of geophysical studies (magnetic, gravity, magnetotelluric) were conducted and their results analyzed with the objective of studying the deep structure of the mafic-ultramafic complex of the Ust'-Belaya massif and the southern, buried part of the Pekul'nei rooted mafic-ultramafic complex and testing the hypothesis of whether they were connected at depth. Available magnetic and gravity maps also were used in the interpretation.

The main geophysical feature of rooted mafic-ultramafic massifs is the increased gravity field within its boundaries. The gravity anomalies were interpreted by the method of Vashchilov (1984) for calculating the attraction of three dimensional block sources. The quantitative interpretation of gravity anomalies uses a three-dimensional density model as a first approximation. It results in a satisfactory convergence between the calculated and observed values of the gravity field within the whole study area; however, it takes considerable time to develop it.

A quantitative interpretation of gravity anomalies can only calculate the relative density contrast along the vertical boundaries of blocks, terranes, or plates. The absolute values required for a geological interpretation are obtained using special methods for density sounding (Vashchilov, 1984). A successful density sounding was made within the Markovo depression, located immediately northwest of the Ust'-Belaya massif and the Talovka-Main anticlinorium. Core samples from a test bore hole on the Grinevetsky structure showed complete agreement with the calculated densities up to a depth of 2,500 m (Vashchilov, 1988). The absolute densities from the Markovo depression were applied to the region of the Ust'-Belaya massif. To do this, we calculated changes in density along the edges of blocks representing density heterogeneities. The density model and magnetic and magnetotelluric sounding data formed the basis for the geologic model composed of a series of crustal slices at the surface and depths of 1.5 and 5 km (Figs.2, 3, and 4). These slices form the basis of density tomography. The geologic interpretation of these slices then become schematic geologic maps at the different depths.

Magnetotelluric sounding within the massif of the Ust'-Belaya Mountains show that the upper layer is 10-15 km thick and electrically conductive. The electrical conductivity of the upper crust depends on the presence of mineralized water. Given the thickness of the electrically conductive layer, one may make inferences about the depth at which serpentinization begins. A second electrically conductive layer is distinguished at a depth of 90-100 km in the asthenosphere.

At a depth of 1.5 km (Fig.3), the Ust'-Belaya massif complex and the southern continuation of the Belaya depression and the Pekul'nei horst are separated and

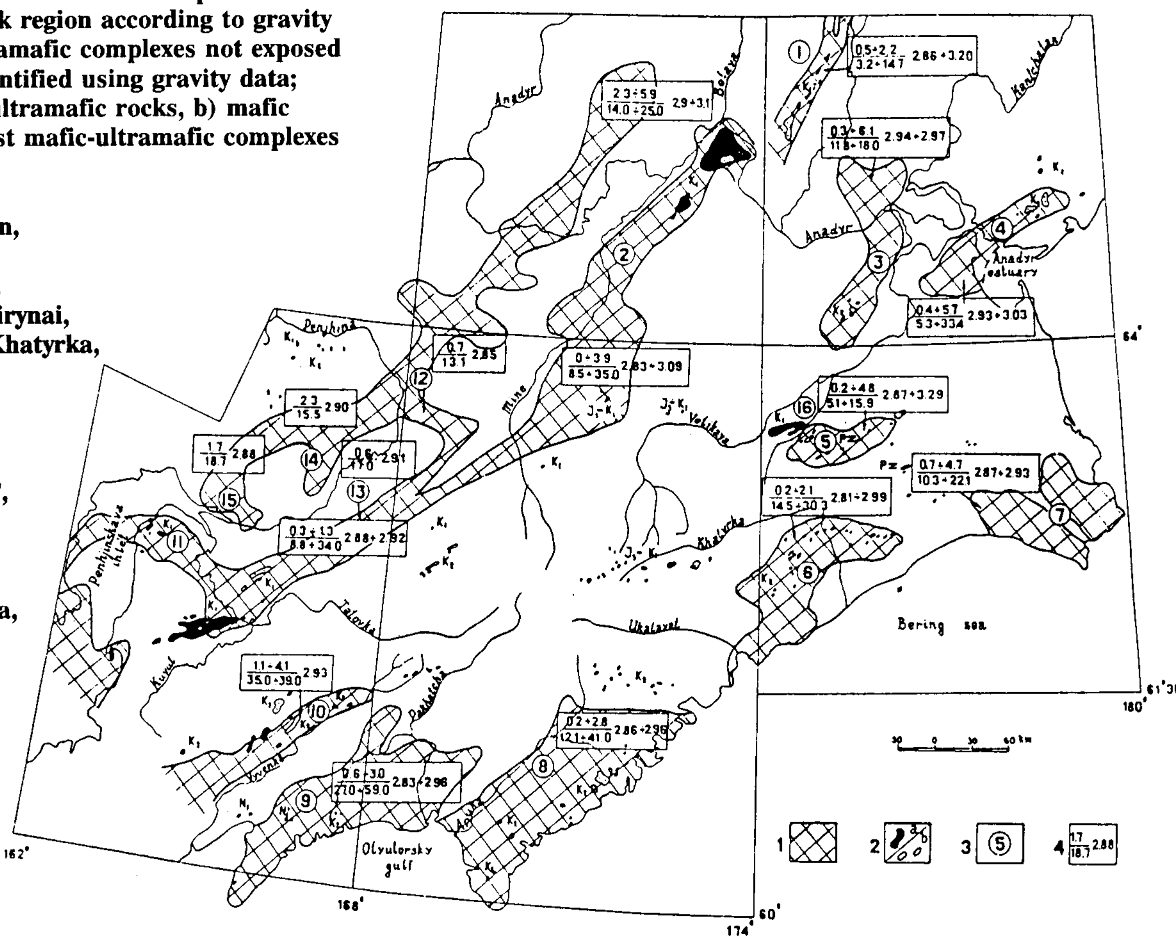

Fig.2. Map of mafic-ultramafic complexes in the Anadyr'-Koryak region according to gravity data. 1--mafic-ultramafic complexes not exposed by erosion and identified using gravity data; 2--outcrops of a) ultramafic rocks, b) mafic rocks; 3--the largest mafic-ultramafic complexes and their names:
1. Pekul'nei,
2. Ust'-Belaya-Main,
3. Rarytkin,
4. Zolotoi-Anadyr',
5. Chirynai-Nauchirynai,
6. Chetkinvayam-Khatyrka,
7. Ukvushvuinen,
8. Olyutorka,
9. Govenna,
10. Vyvenka,
11. Talovka-Kuyul',
12. Slovutnoe,
13. Palmatkin,
14. Oklan,
15. Lower Penzhina,
16. Tamvatnei;
4--parameters of massifs calculated from gravity data, the numerator is the depth to the lower limit in km, density given in gm/cm^3.

different. The Ust' Belaya massif is characterized by the fact that the density of its ultramafics increases from east to west; this is due to their degree of serpentinization. The western Ust'-Belaya massif is composed of extremely serpentinized mafics with a density of 2.67 gm/cm^3. Its eastern portion is composed of denser assemblages (about 3.00 gm/cm^3). High-density unaltered ultramafics or gabbros form the core of the Pekul'nei horst at a depth of 1.5 km. Pyroxenites may dominate here.

One can clearly observe the tendency for the densities of the mafic-ultramafic complexes to decrease with depth by examining the density map at 5 km (Fig.3). This is consistent with a decrease in the degree of serpentinization. Some differences between the eastern, western, and southern regions are maintained. However, the Ust'-Belaya massif becomes more homogeneous at 5- km depth. In addition, differences in density within the ultramafic and mafic complexes of the Pekul'nei Mountains disappear.

The morphology of the Ust'-Belaya massif and its relationship to the Pekul'nei horst-anticlinorium is illustrated in the cross section (Fig.4).

The Ust'-Belaya massif has not been structurally laterally displaced by several tens or several hundreds of kilometers to its present location as proposed by some geologists. It is an outcrop of the mafic-ultramafic layer in the form of a plate about 14 km thick and 40 km wide.

The maximum values of the gravitational anomaly are observed above the gabbro outcrops. Analysis of three-dimensional models shows that the first two units of the ophiolite association in depth (the dunite-peridotite complex and partially banded gabbros) are not located one above the other within the Ust'-Belaya massif, and do not form a small fragment of the upper mantle and the oceanic lower crust. The overthrust nappe and allochthonous character of the ophiolite plates is only an illusion. It is the result of the pressure release of serpentinized ultramafics that moved upward in response to compression and carried upward by the gabbro. The ophiolite associations of the Ust'-Belaya massif and the core of the southern part of the Pekul'nei horst-anticlinorium are quite different in their degree of serpentinization which is expressed by the higher density of the ultramafics in the core of the Pekul'nei horst-anticlinorium.

The rooted type of ophiolite association also forms the cores of the Talovka-Main anticlinorium, Rarytkin Range, the Zolotoi Range, and other anticlinal structural elements of the Koryak-Kamchatka foldbelt (Fig.2).

The Talovka-Main anticlinorium is 15-20 km wide and extends for more than 600 km. The Ust'-Belaya massif is located on the northeastern end of this anticlinorium. The Kuyul' massif and the Mt. Dlinnaya massif are on its southwestern end. They have large gravity anomalies over them, which extend beyond their surficial exposures. Some allochthons of horizontally displaced ultramafics are known to extend beyond their gravity anomalies.

The Tamvatnei allochthon is an example of a rootless ophiolite. The gravity anomaly associated with it covers an area less than the exposures. The massif in the upper course of the Khatyrka River, the Kuyul' massif, and some other small massifs also are rootless (Fig.2). These rootless massifs are located south and southeast of fractures identified using geologic or geophysical data. Geologists have observed thrusts north of the Tamvatnei massif and the massif in the upper course of the Khatyrka River. On the northeast, the Kuyul' massif adjoins the Talovka-Kuyul' mafic-ultramafic complex massif along a semi-vertical fault, which has been identified by gravity data (see below). A characteristic feature of rootless massifs is their higher degree of serpentinization, a wide development on the surface of serpentinite melange, and overthrust nappe complexes.

BURIED OPHIOLITES

Quantitative analysis of gravity data reveals that the Anadyr'-Koryak region has high-density complexes within the lithosphere that do not outcrop on the surface (Fig.1). Their density corresponds to that of the roots of ophiolite associations of the type that includes the Kuyul', Ust'-Belaya, and other massifs. They represent mafic-ultramafic complexes that have been poorly exposed by erosion, e.g., Rarytkin, Zolotoi Range, Upper Khatyrka, and others. It is natural that underground massifs of denser mafic-ultramafic rocks do not include a spilitic component typical of the ophiolite association. They are formed by gabbroids, ultramafics, and relics of host rocks. These rocks are often metamorphosed into the eclogite facies.

Most of the ophiolites of the Anadyr'-Koryak region are located within the outlines of mafic-ultramafic massifs or at their boundaries. However, the upper surfaces of the buried massifs are located at depths of several tens of kilometers.

Buried mafic-ultramafic complexes of the central, northwestern, and northeastern parts of the Anadyr'-Koryak region coincide with anticlinal and horst-anticlinal structures and uplifts identified by numbers 1-7 and 10-15 in Fig.2.

The topmost northeasterly linear zone of increased lithospheric density coincides with the Murgal uplift. Here, at the surface as well as within the entire near-ocean part of the OCVB, granite-diorite massifs are widely developed. The rocks with elevated density are located at a depth of 25 km in the northwest.

The Ust'-Belaya-Main (Fig.2, No. 2) and Talovka-Kuyul' (Fig.2, No. 11) belts are parallel to the Murgal uplift. These belts are part of an extensive belt of mafic-ultramafic rocks that extends to the Sea of Okhotsk through Koni Peninsula. The Talovka-Kuyul' unit of this belt includes the Valizhgen uplift and ophiolitic volcanogennic sedimentary complexes of the Pontonei Mountains.

The most important feature of the Murgal and Talovka-Main buried mafic-ultramafic belts is their structural connection in the Slovutnoe (Fig.2, No. 12) at depths up to 13 km (Fig.2).

The Pekul'nei Range can be considered an en-echelon continuation of the Talovka-Main to the northeast. However, the buried zone of mafic-ultramafic complexes occurs in a crust that is more continental. The buried mafic-ultramafic complexes of the Anadyr'-Koryak region that form the cores of uplifts are marked by gravity maxima. Adjacent to them are regions of gravity minima. Geologically, these latter are regions of subsidence, for example the Penzhina-Anadyr' system of depressions between the Murgal and Talovka-Main buried mafic-ultramafic belts. It should be noted that the extensive belts of buried mafic-ultramafic complexes are structural fissures in the lithosphere up to several tens of kilometers wide. In the southern Anadyr'-Koryak region, along the coast of the Bering Sea near its western deepwater basins, there are the Olyutorka (Fig.2, No. 8) and Govenna (Fig.2, No. 9) buried mafic-ultramafic complexes. These complexes may be considered the relics of recently formed quasi-oceanic crust.

KINEMATIC, DYNAMIC, AND TECTONIC ROLE OF OPHIOLITES

The movement of ultramafics from the earth's interior to the surface seems to contradict the hypothesis of isostasy. In fact, the density of ultramafics is higher than that of the host rocks. The complete melting temperature of ultramafics is very high. Many scientists think that large volumes of ultramafic magma cannot exist close to the surface or in the upper mantle.

There are three mechanisms, and various combinations of them, which can transport ultramafic magma to the earth's surface.

1. *Fissure Mechanism*. Deep fissures appear within the crust and upper mantle initially under conditions of extension. Lowered pressure and tension appear in such a zone of penetrating deformation. Highly plastic and low-viscosity crustal and mantle ultramafics migrate to this zone. When the condition of relative extension are changed to that of compression, subsolidus ultramafics are squeezed out to the surface. This mechanism of squeezing out ultramafics under compression can explain rooted mafic-ultramafic complexes located in lithospheric fissures up to several tens of kilometers wide. It can also explain rootless ophiolites (Kuyul', Yamvatnei, Upper Khatyrka, and some others) that are squeezed out along very narrow faults that are several meters to kilometers in width. Presumably, the pulse of tectonic squeezing came from the north or northwest since rootless ophiolites are bounded on the north by faults, and often by thrusts.

2. *Magmatic Mechanism*. Ultramafics are transported upwards by magma under subsolidus and solidus conditions.

3. *Serpentinization Mechanism*. Serpentinization occurs at depths of less than 10-15 km as a result of

water. The volume of ultramafics increases during serpentinization by a factor of 1.1-1.2, thus resulting in their being squeezed out onto the surface.

The vertical displacement within the crust of ultramafic and mafic units of the ophiolite association result in the deformation of overlying sequences. These deformations are in the form of anticlines with mafics and ultramafics in their cores, i.e., the Talovka-Main anticlinorium. During the application of the fissure and magmatic mechanisms, the ultramafics that are squeezed out to the surface bear great internal tension. Thus "plume" (mushroom-like) structures, serpentinized melange, overthrust nappes, and olistostromes, arise as a consequence of its release. The proximity in nature of the maximum and minimum gravity anomaly values, which are controlled by uplifts and depressions, confirm the compensation mechanism during the formation of the above-mentioned structures. The outflow of matter in the direction of the opening fissures occurs at a specific depth in the crust and the upper mantle.

The subsidences occur in zones of matter outflow. These subsidences are then filled by pyroclastic and terrigenous material from the uplifts.

CONCLUSIONS

The calculation of the dimensions and densities using geophysical fields (preferably gravity) demonstrate the existence of mafic-ultramafic complexes in the Anadyr'-Koryak region. They are located at shallow depths and their base is located in the lower crust and upper mantle. The area of ophiolite complexes exposed on the surface is only several percent of the area outlined by the buried mafic-ultramafic complexes.

Rooted (Ust'-Belaya, Pekul'nei, and others) and rootless (Tamvatnei, Upper Khatyrka, and Kuyul') mafic-ultramafic complexes are identified. The former are outcrops of the lower crust, while the latter are considered to be outliers of the lower crust carried to the surface along faults.

Geophysical studies of ophiolites similar to the Ust'-Belaya massif show that there are no stratified sequences, peridotites-banded gabbro-dike complex-spilite, representing fragments of ancient oceanic crust. While any sequence is possible at a locality, more often they are simply located close to each other.

The structural continuity of the Murgal and Talovka-Main buried mafic-ultramafic belts is demonstrated. The process of serpentinization of peridotite begins at a depth of less than 10-15 km. The wide distribution of ophiolites is related to the position of the mafic-ultramafic layer, i.e., the lower crust. This is supported by gravimetric tomography of northeast Russia. At a depth of 20 km, the Anadyr'-Koryak region is distinguished as a zone of continuous development of mafic-ultramafic complexes. At a depth of 20 km, the Mesozoic foldbelt appears to be a region where mafic rocks are primarily present.

The kinematics of plastic and low-viscosity ultramafic and mafic magma is very important in the formation of structures in the region. It forms anticlines in regions where it is uplifted into the crust, regions of subsidence in areas where there has been the outflow of matter at depth, and thrust complexes on the surface during the compression of ophiolites in fault zones. They play a role very similar to that of granitic magma in the formation of structures in continental crust.

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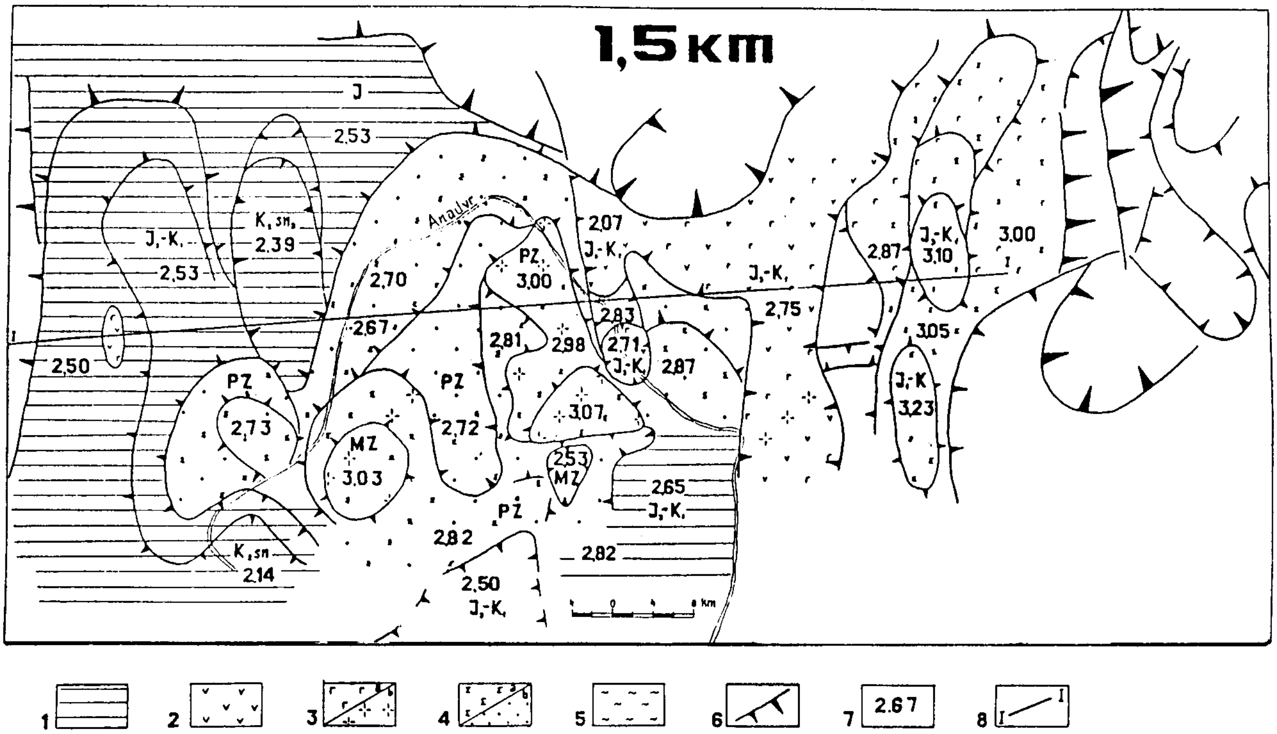

Fig.3. Density section of the Ust' Belaya mafic-ultramafic massif and the southern Pekul'nei horst-anticlinorium at a depth of 1.5 km and its geological interpretation. 1--Mesozoic sedimentary rocks (MZ); 2-- andesite and andesite-basalt; 3--(a) basalt and (b) gabbro; 4--(a) ultramafics and (b) serpentinites; 5-- Paleozoic metamorphic rock (PZ); 6--vertical faults from gravity data; 7--density of rocks from the interpretation of gravity data, gm/cm^3; 8 - location of profile shown in Fig.5.

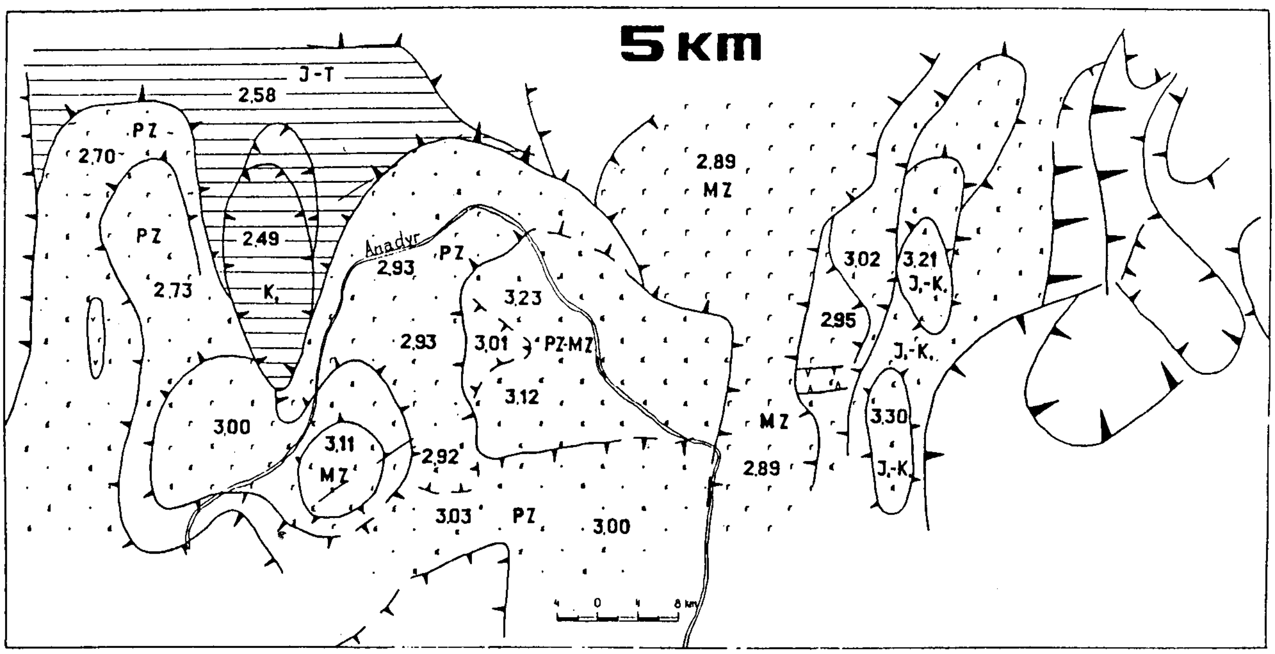

Fig.4. Density section of the Ust' Belaya mafic-ultramafic massif and the southern Pekul'nei horst-anticlinorium at a depth of 5 km and its geologic interpretation. Symbols as in Fig.3.

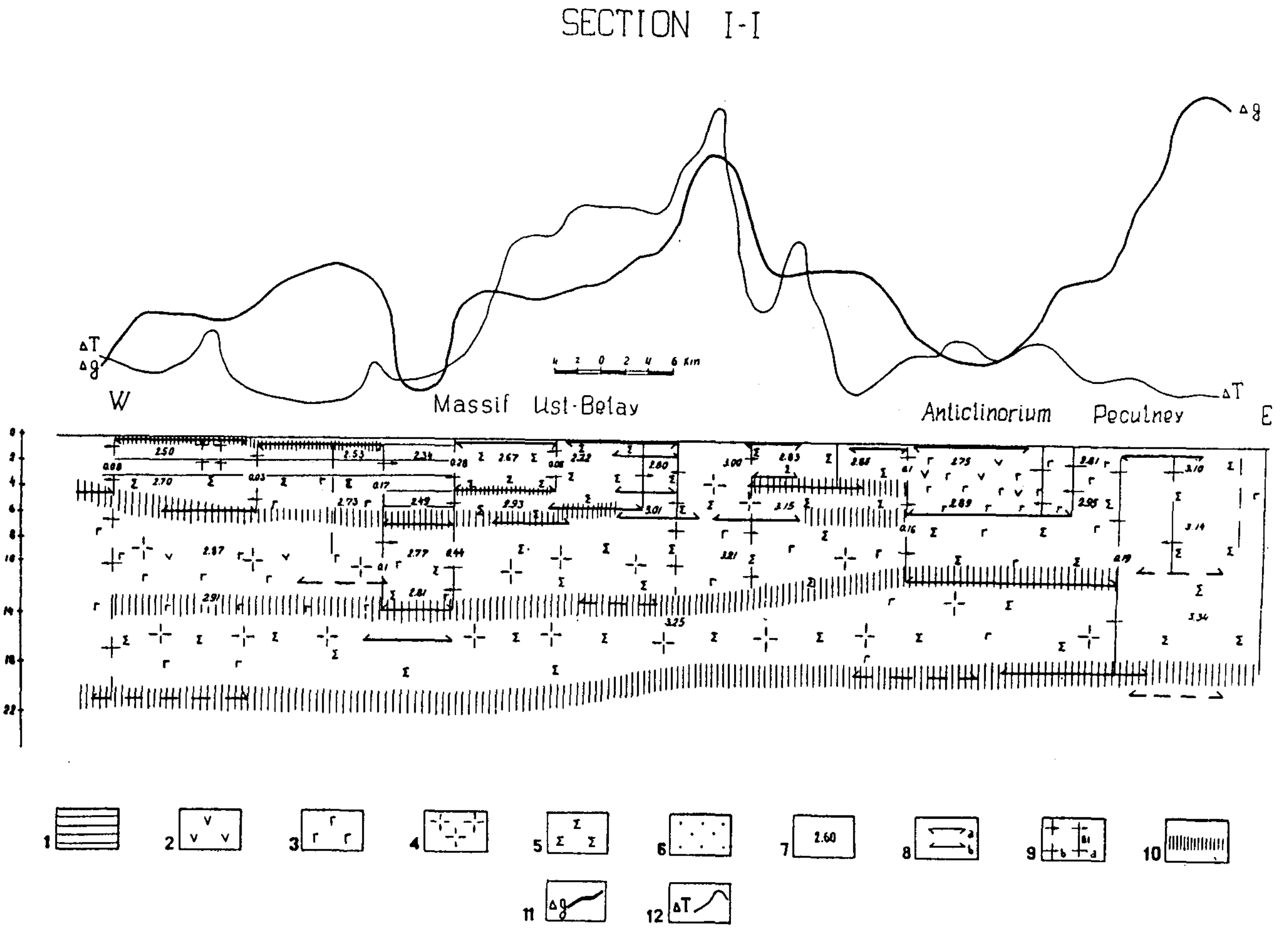

Fig.5. A schematic geologic-geophysical profile of the Ust' Belaya massif and the southern Pekul'nei anticlinorium (see Fig.3 for position). 1--Mesozoic terrigenous deposits (MZ); 2--andesites; 3--mafics; 4-- gabbro; 5--ultramafics; 6--serpentinite; 7--density in gm/cm^3; 8--the (a) upper and (b) lower boundaries of the block density heterogeneities; 9--faults and values of the horizontal change in density; 10--horizontal stratification surfaces; 11--gravity profile; 12--magnetic field anomaly.