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USING SATELLITE INFORMATION ABOUT THE EARTH

THE USE OF SPACE SURVEY MATERIALS RESURS-P, CANOPUS-PSS, ASTER AND LANDSAT FOR FORECASTING URANIUM-MOLYBDENUM AND CHROMITE-PLATINUM MINERALIZATION IN THE POLAR URALS

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Abstract. Methods of complex analysis of the results of space, gravimetric and magnetometric surveys for localization of ore-promising sites in the Polar Urals within the nomenclature sheets R-42, Q-42 have been developed. When decoding the materials of multi-zone satellite imagery of medium (ASTER, Landsat) and high (Canopus-PSS, Resurs-P) resolution, linear, arc and ring structural elements controlling the localization of uranium-molybdenum and chromite-platinum mineralization of the Polar Urals were revealed. The decoding of zones of metasomatically altered rocks in various spectral IR channels made it possible to localize areas for detailed work. Based on high-resolution satellite imagery, large-scale structural and tectonic schemes have been prepared and areas of detail for ground-based verification work have been outlined.

Keywords: *multi-zone satellite imagery, search signs, deposits, chromium, platinum, uranium, molybdenum, Polar Ural*

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INTRODUCTION

Landsat-7 (USA) and ASTER (Japan) multispectral space imagery materials were used for medium-scale interpretation. On their basis, zones of near-ore-altered rocks (berezites, secondary quartzites, sericite-hydrosludic-quartz metasomatites) were identified. The remote sensing bases of prospecting areas were prepared on the basis of multizonal space survey Resurs-P (channels 10, 21–23, 33) and panchromatic imagery Canopus-PSS with 1–3 m ground resolution.

Based on these materials, space surveying and lineament analysis of geological structures were performed. Interpretation of local volcanogenic structures, metasomatic rocks and subvolcanic formations made it possible to outline the areas recommended for ground completion on the basis of space imagery data.

Methodological techniques for predicting mineralization based on remote sensing methods include the use of space data for interpretation of structural elements (lineaments) controlling the spatial location of deposits and ore occurrences, as well as for localization of areas of hydrothermal-metasomatic rocks. Application of GIS-technologies in studying the spatial distribution of ore objects of different levels makes it possible to select new criteria for predicting mineralization. Large arrays of raw data obtained from high- and medium resolution space imagery and geological and geophysical data were processed using ArcGIS, ENVI, Adobe Photoshop software.

GEOLOGICAL STRUCTURE AND RESULTS OF SPACE SURVEY OF THE HAHAREMPE AREA (URANIUM-MOLYBDENUM MINERALIZATION)

The Hakharempe area is located in the western part of the R-42-XXXI sheet. The structure of the R-42-XXXI sheet includes structural-material complexes of 3 structural stages: Riphean-Early Cambrian, Cambrian-Upper Paleozoic and Mesozoic-Cenozoic,

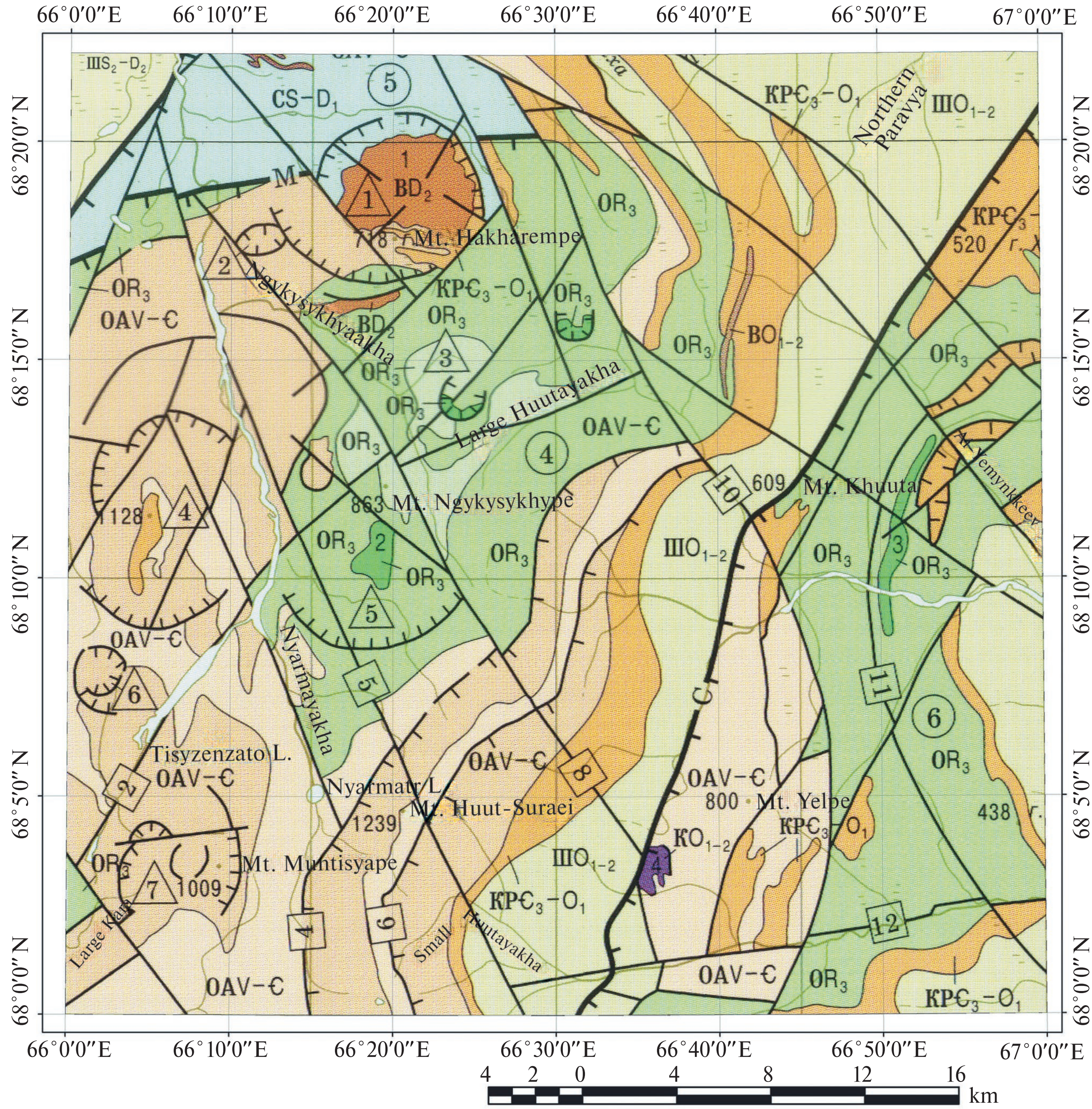


Fig. 1. Tectonic scheme at a scale of 1:500000. R-42-XXXI. The notation in Figure 1a.

corresponding respectively to the Baikal (Kadoma), Caledonian-Varissian and Alpine folding epochs (State..., 2003). They are characterized by different structural plan, separated by angular and azimuthal unconformities, often with major interruptions in sedimentation. The lower structural floor ($R–Є_1$) is composed of metamorphosed rocks of the Ochetyvis, Lyadgean, Syadatinsk, Arkanyr Formation, and is characterized by a complex combination of paleovolcanic and dispersed structural elements. The middle structural floor ($Є_3–P_1$) is composed of metamorphosed (greenshale-greenstone facies) sedimentary, volcanogenic-sedimentary riftogenic, shelf and slope complexes of the Paleozoic in combination with disjunctive and dysplicate structures. The upper structural floor (Mz–Kz) is represented by weakly lithified and friable sedimentary formations of marine and continental types complicated by intraplate

GEODYNAMIC COMPLEXES AND THEIR FORMATIONS

Geodynamic complexes / Structural levels	Intraplate			Continental margin		Subduction		Collisional
	Plate cover	Hot spots	Continental (margin-continental) rift	Shelf	Continental slope	Ophiolites	Active margin of Andean type	
		B	CR	Sh	S	O	MA	C
Paleozoic ($Є_3$–P)		BO$_{1-2}$ Trachireolitic; BD$_2$ Basalt-rhyolite-andesite (volcanomictic)	KPЄ$_3$-O$_1$ KPЄ$_3$-O$_1$ Sandstone and gravel	ШS$_2$-D$_2$ Limestone-dolomitic; ШO$_{1-2}$ Siltstone-sandstone	CS-D$_1$ Limestone-clayey siliceous (carbon-containing)			KO$_{1-2}$ Ultramafic
Riphean–Early Cambrian (R_3–$Є_3$)					Limestone-sandstone-clay (carbon-containing)	OR$_3$ OR$_3$ Basalt-andesite-dacitic; OR$_3$ Gabbro-diorite-granodiorite	OAV-Є Rhyolite-basaltoid; OAV-Є Siltstone-sandstone	

NOTATION

(5) Main structures and their numbers

Anticlinoria

Malokarsky

Blocks: Ochenyrdsky — 4, Lekyntalbeysky — 6

Parautochthons

Karsko-Nyarminsky — 5

(1) Paleovolcanic structures and their numbers:

1 — Khakharemskaya
2 — Malaya Caldera-Pe
3 — Vostochnokyzygeiskaya
4 — Lyadgeyskaya
5 — Kyzygeiskaya
6 — Muntysyapeyskaya
7 — Tiznezashorskaya

Disjunctive Faults

Main Structural Faults: Overlaps; Geological boundaries

Others (a – confirmed, b – suspected): a, b Overlaps; a, b Of Uncertain Kinematics; Faults – constraints of volcano-tectonic structures

Disjunctive Faults

Main (structural faults)

M — Malotalbeysky, S — Saurieyakhinsky

[1] Secondary

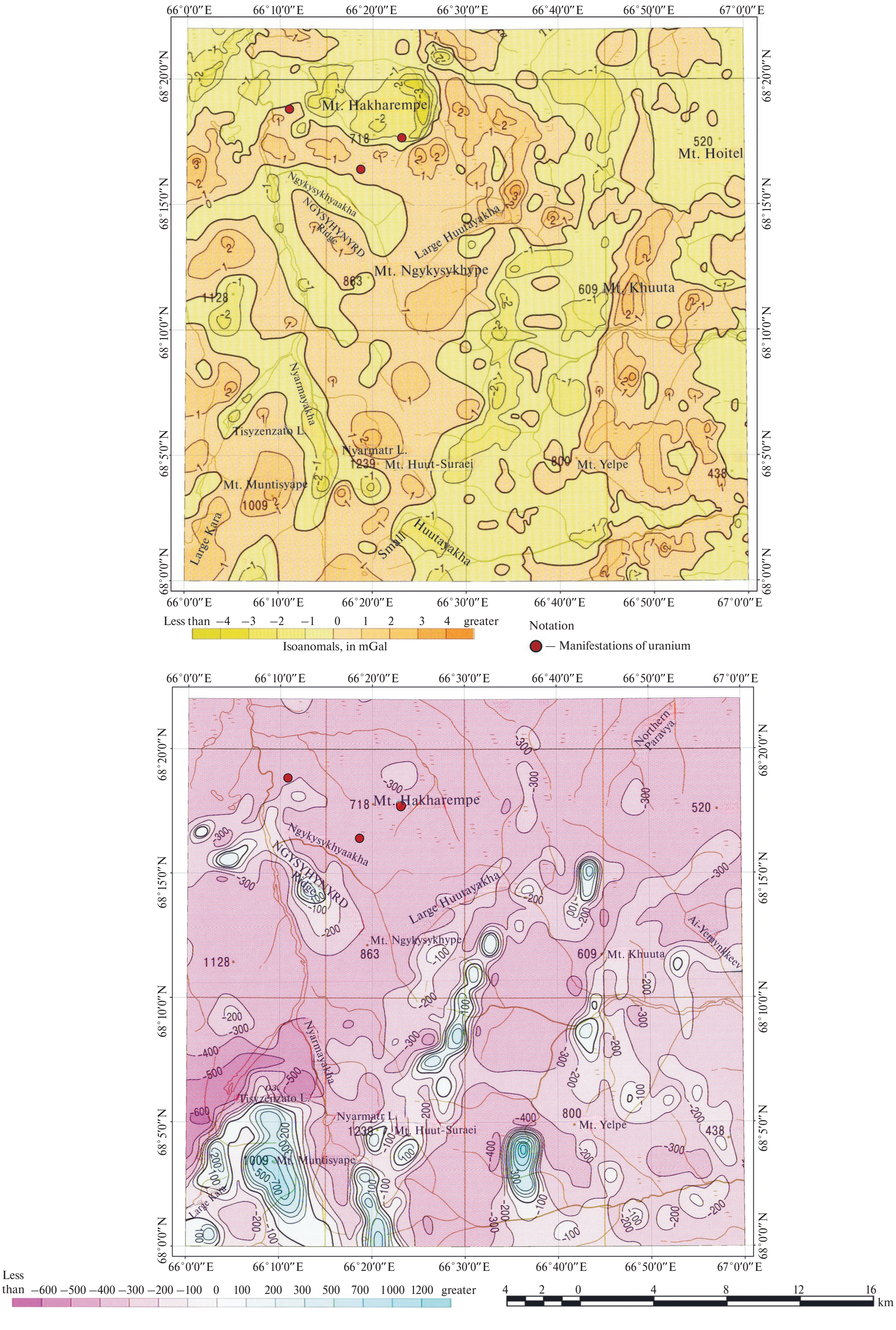
2 — Tiznezatinsky
4 — Verkhnenyarminsky
5 — Nyarminsky
6 — Sangaryakhinsky
8 — Kyzygeisky
10 — Ozyorny
11 — Bedashorsky
12 — Malokhutinsky

Intrusive massifs and their numbers:

1 — Khakharemsky, 2 — Kyzygeisky,
3 — Bedashorsky, 4 — Komsomolsky

Fig. 1a. The notation.

activation processes. The main basement structures are the Ochenirdsky and Lekyntalbeysky blocks (Fig. 1). The internal structure of the Ochenyrdsky block is defined by a system of paleovolcanic structures of central and linear types (Lyadgeysky, Muntysyapeysky, Kyzygeysky, Khakharemsky paleovolcanoes) complicated by a series of paleocraters (Tiznezashorsky, Malaya Caldera-Pe, Vostochnykzygeysky, etc.) in combination with shelf-molassoid sediments of the Ochetyvisky, Lyadgeysky, and Arkanyrsky formations. The latter are often crushed into isoclinal westward-tilted folds with steep (60–70°)


Mt. Hakharempe
718
Mt. Hoitel
520
Ngykysykhyaakha
NGYSYHNYRD Ridge
Large Huutayakha
Mt. Ngykysykhype
863
1128
609 Mt. Khuuta
Nyarmayakha
Tisyzenzato L.
Nyarmatr L.
1239 Mt. Huut-Suraei
800 Mt. Yelpe
438
Mt. Muntisyape
1009
Large Kara
Small Huutayakha
Less than −4 −3 −2 −1 0 1 2 3 4 greater
Isoanomals, in mGal
Notation
— Manifestations of uranium
Northern Paravya
Ai-Yemynkkeey
Less than −600 −500 −400 −300 −200 −100 0 100 200 300 500 700 1000 1200 greater
4 2 0 4 8 12 16 km

← **Fig. 2.** Gravity and magnetic field maps at a scale of 1:500000. R-42-XXXI.

dip of the wings. Paleovolcanic structures are usually broken by a series of circular and radial disjunctives and a system of younger discordant northwestern and submeridional (Nyarminskiy and Kyzygeiskiy faults) structures. The eastern wing of the Ochenyrdsky block is complicated by a system of subparallel thrusts (Verkhnenyarminsky, Sangaryakhinsky), which are characterized by rather steep dip angles of displacements. In the east, the Ochenyrdsky block dips under the Paleozoic littoral-shelf complexes composing the Saurey syncline, complicated by the Saureyakhinskaya collision zone from the east.

The structural feature of the area is a wide development of cover-overthrust dislocations disturbed by a system of subvertical activation structures of dumping-extension type. The Kara-Nyarma paravtochthon, located to the north of the Ochenyrdsky block, is known in the literature as the "Nyarma triangle". It is composed of intensely dislocated carbonate-carbonate-carbonaceous sediments of the Kharot Formation ($S–D_1$) and is bounded on all sides by tectonic faults of the thrust-overthrust type, dipping at angles of 70–80°. The Kara–Nyarma structure and the Ochenyrdsky block are delimited by the Malotalbey structural suture. The internal structure of the suture zone is very complex: it is tectonites, blastomylonites with horizons of pseudoconglomerates. The latter are boudinage structures with mylonitization and disintegration of the strongest rocks.

The Saureyakhinsky structural suture bounds the pre-Paleozoic Lekyntalbey block from the west. Its distinctive feature is saturation of magmatites: serpentinized ultrabasites, gabbroids and dolerites. The length of the Saureyakhin suture is about 50 km. The general strike is northeastern 25–30°. The main seams of the western limitation of the Saureyakhin structure have an eastern dip (dip azimuth 110–120°) at angles of 55–60°.

Structural seams (first-order faults) are fixed in the gravimetric field by lowering Δg values (Fig. 2). The interpretation of potential fields (gravity and magnetic) and their transformations with the use of seismic survey data (GSZ) established the connection between the structure of the gravity field and, especially, its local components and the uplift of the pre-Riphean crystalline basement of the platform (State..., 2003). Positive magnetic field anomalies fix the system of the Verkhnenyarminsk and Sangaryakhinsk faults, the Tiznezashorsk paleovolcanic structure, and the Komsomolsk hyperbasite massif. Among the second-order faults, several groups can be distinguished, differing in direction and shape in plan, time of emplacement and morphology. In terms of direction, they are distinguished as: northwest, submeridional, northeast and sublatitudinal. Faults of north-western and north-eastern directions were laid down in the pre-Paleozoic time. Their distinctive feature is their length and straightness in plan, secant character in relation to the boundaries of structural-formational zones and subzones. As a rule, they are several tens of meters wide zones with complex internal structure and morphology. Sublatitudinal faults are probably also of ancient origin. The modern tectonic structure of the Polar Urals was determined by the development of Mesozoic block tectonics superimposed on Paleozoic and older geological structures.

In the Polar Urals, uranium deposits are known in the western part of the northern periclinal closure of the Lyapinsky anticlinorium and are spatially associated with the Riphean-Cambrian acidic volcanics (Mashkovtsev et al., 2010). Deposits of the molybdenum-uranium formation are characterized by spatial and paragenetic connection with complexes of late-orogenic volcanism, stockwork structure of ore bodies and genetic connection of mineralization with different facies of the metasomatic berezite formation (Boitsov et al., 2008).

The distribution of metasomatic rocks in the study area is subordinate to linear discontinuous structures of northeastern strike (Fig. 3). Metasomatic changes are most clearly manifested in the zone of the Saureyakhinsky structural suture and the Sangaryakhinsky thrust. All the studied types of metasomatites (berezites, propylites, secondary quartzites, sericite-hydrosludic-quartz metasomatites) were determined by cosmodetic survey data in the area of Lyadgeyskaya and Muntysyapeyskaya paleovolcanic structures. The halo of berezites and sericite-hydrosludic-quartz metasomatites was also noted on the southern periphery of the Khakharemskaya paleovolcanic structure. Methodological approaches for the use of ASTER multispectral space imagery to obtain information on different types of metasomatic rocks are outlined in our publications (Milovsky et al., 2023). We used measured and library spectra of reference minerals from free-access sources from NASA et al. (JPL, USGS).

The high-resolution Resurs-P space imagery was used to study the geological structures of the Khakharempe area, within which molybdenite-nasturanium mineralization was previously established. Three uranium occurrences (Valerievskoe III-1-3, Valentinovskoe III-2-1, Andriano-Pavlovskoe III-2-3) are located in the exocontact of the Hakharempe trachyryolite massif and belong to the molybdenite-nasturanic ore formation (Fig. 4). The Andriano-Pavlovskoye uranium occurrence (III-2-3) is the most studied one; it lies in the thickness of volcanogenic-sedimentary rocks of the middle composition of

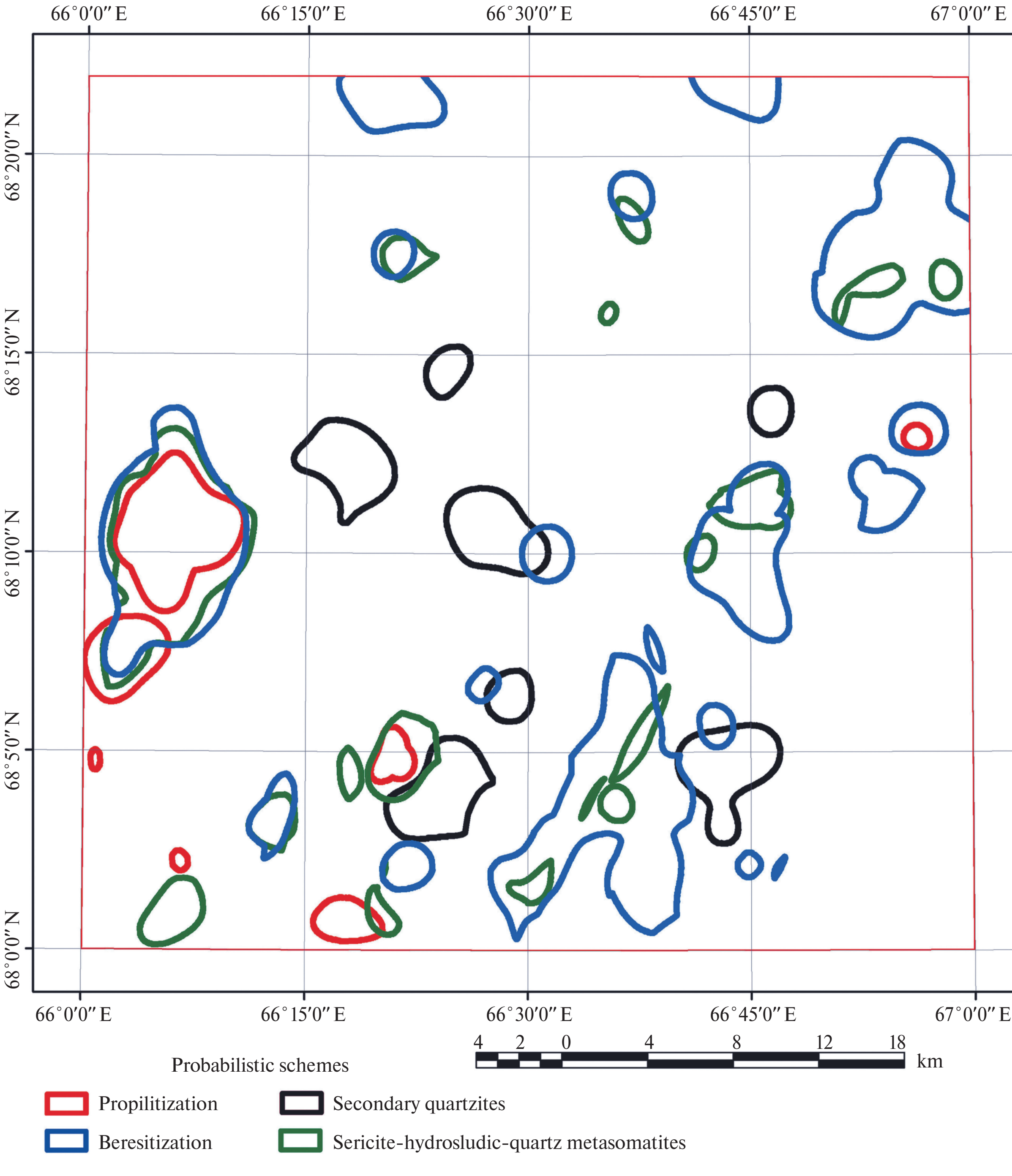
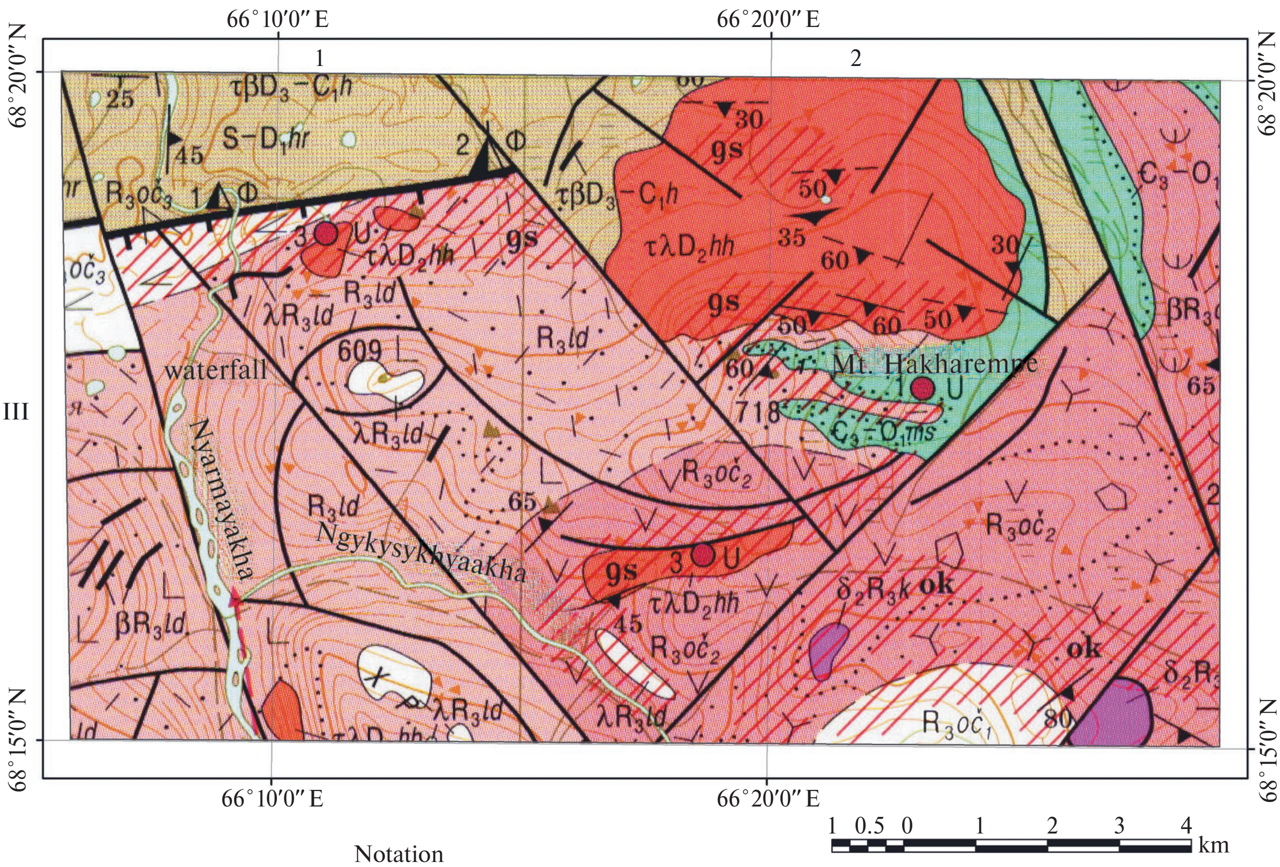


Fig. 3. Map of metasomatic rocks based on ASTER space imagery. R-42-XXXI.

the Ochetyvis Formation (R_3 oč). It is confined to the sublatitudinal body of hydrothermally altered trachyryolites of the Khakharem complex (τλD_3 hh). There are six ore-bearing zones in the body of trachyryolites, controlled by tectonic disturbances of northwestern strike. The ore-bearing zones show vein-embedded ore mineralization of nasturan, pyrite, galena, sphalerite, arsenopyrite. Uranium mineralization is superimposed on polymetallic mineralization.

As a result of processing of space imagery materials (Fig. 5) of the Haharempe area, lineaments of northwestern, northeastern and sublatitudinal direction were identified; local ring structures were identified; the boundaries of lava-pyroclastic and subvolcanic formations were delineated by phototone. Northwest strike-slip faults — Nyarminskiy, Kyzygeiskiy, etc. — are predominantly developed. These faults are complicated by small



Notation

Type	Manifestations	Genetic group of deposits	Ore formations
Uranium	• U	Hydrothermal Plutogenic	Molibdenite-nasturanovaya (rare-metal uranium-molybdenum)

Uranium manifestations:
III-1-3 — Valeryevskoye
III-2-1 — Valentinovskoy
III-2-3 — Andriano-Pavlovskoe

Fig. 4. Haharempe detail area. Mineral map at a scale of 1:200000. R-42-XXXI. See Fig. 4a for notation. 4a.

shear deformations of predominantly northeastern strike. The Malotalbeyskaya suture zone is represented by several subparallel disjunctivities complicated by northwest-trending faults. The structure of the Khakharemskaya ring structure reveals arc and linear discontinuities reflecting the peculiarities of the structure of both the trachyryolite massif and the host rocks. Along the south-southeastern margin of the Hakharemskaya ring structure, the boundary between rhyolitic tuffs of the Lyadgeya Formation (R_3ld) and siltstones of the Miniseya Formation ($Є_3$–O_1ms) was delineated (by phototone). In the southern part of the detailed area, the contours of the intrusive body of diorites of the Kyzygey complex (δ_2R_3k), localized in the field of development of effusive formations (andesites) of the Ochetyviska Formation (R_3 oč$_2$), are delineated by phototone

A more detailed examination of the Khakharempe area on a scale of 1:20000 revealed additional structural elements represented by sublatitudinal and northwestern trending lineaments and arc structures. Local ring structures in the Khakharempe area are established in the field of volcanics of the Ochetyvis and Lyadgean formations. They are complicated by discontinuities and gravitate to large linear disjunctives of northeastern and northwestern strike.

The Valeryevskoye ore deposit (III-1-3) is confined to a trachyriolite stockwork of the Khakharemsky complex in the arc of intersection of northeastern and northwestern strike-slip faults. The Valentinovskoye

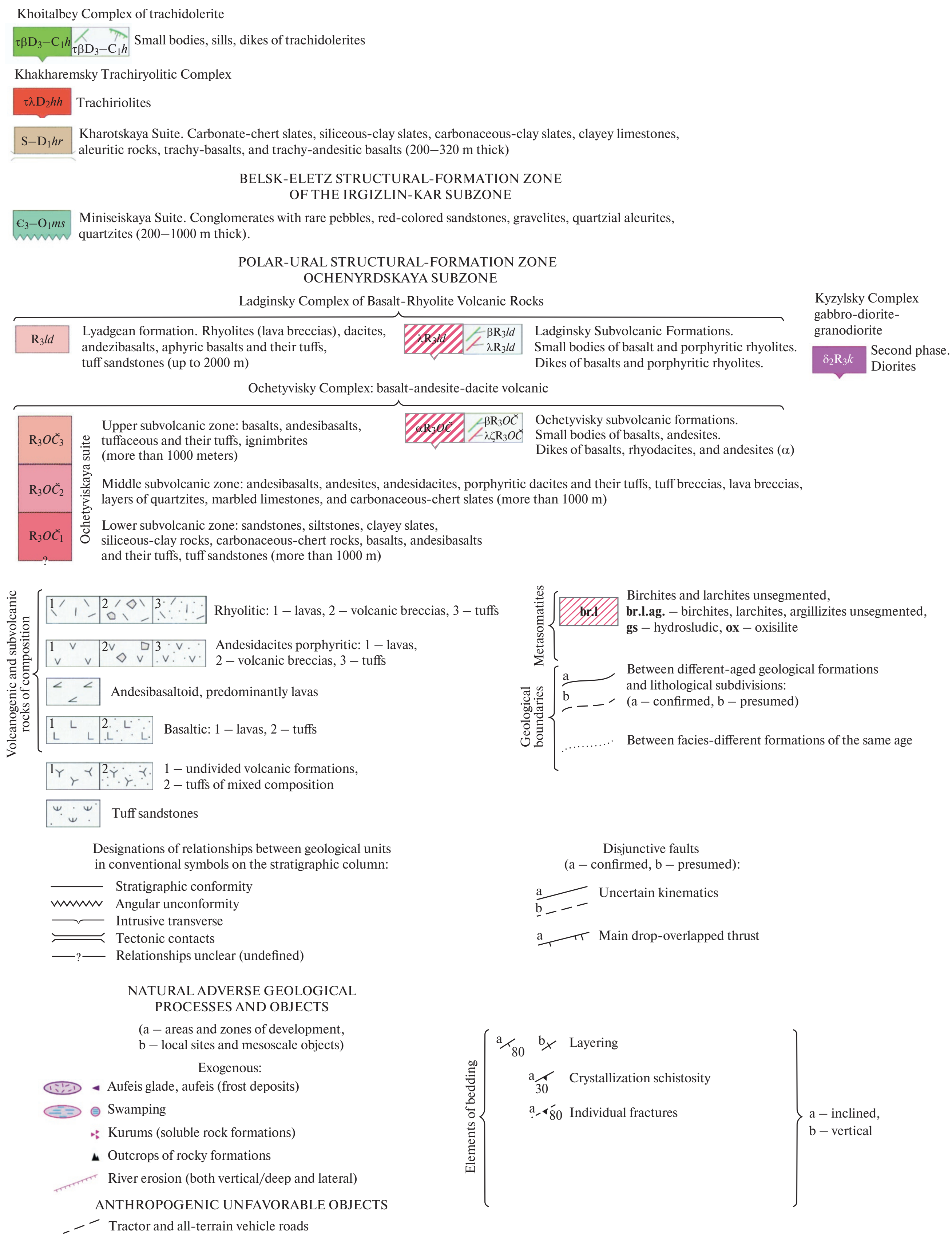


Fig. 4a. Notation to Fig. 4.

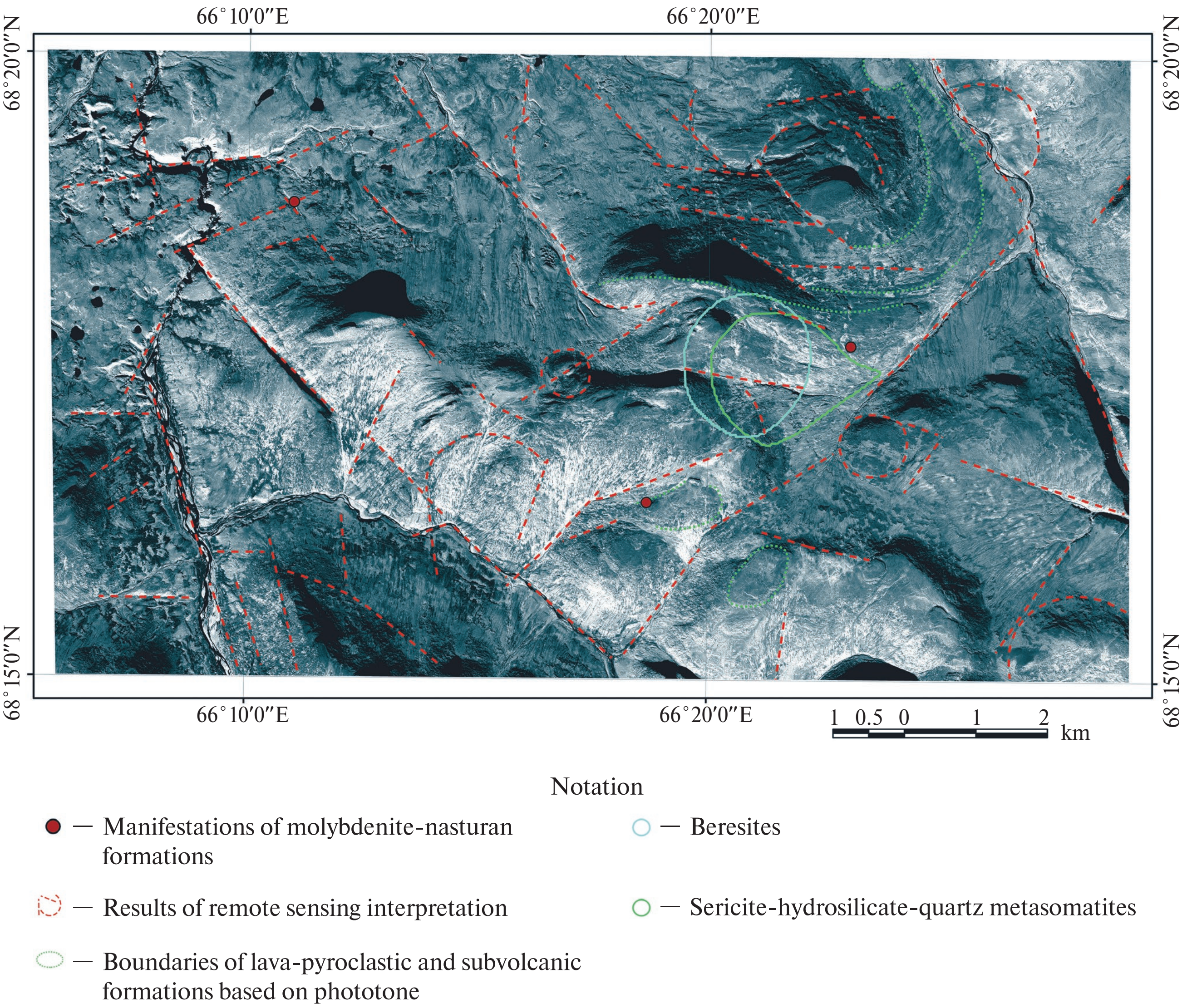


Fig. 5. Haharempe detail area. Space imagery Resurs-P route No. 9861_1. Channel 10. R-42-XXXI.

ore occurrence (III-2-1) gravitates to the northwest strike-slip fault in the area of contact between the Lyadgean and Minisean formations. In this area, the results of ASTER multispectral imaging suggest the presence of berezites and sericite-hydrosludic-quartz metasomatites. The Andriano-Pavlovskoye ore occurrence (III-2-3), as noted above, is confined to a sublatitudinal body of trachyryolites of the Khakharem complex. The contours of this body were delineated by phototone. The central part of the body is displaced by a northwestern strike-slip fault.

Thus, a comprehensive analysis of multi-area space imagery, including high-resolution Resurs-P imagery, has shown that a wide range of prospecting features can be used to predict mineralization on the scale of both ore fields and individual promising areas (deposits), including the structural factor (linear, arc, and ring structures of various grades), the lithological factor (assessment of the lithological composition of ore-bearing rocks by phototone), and the factor of hydrothermal changes (detection of metasomatites of various compositions).

GEOLOGICAL STRUCTURE AND RESULTS OF SPACE SURVEYING OF THE HADATINSKAYA AREA (CHROMITE-PLATINUM MINERALIZATION)

A detailed study of the Lower Tagil-type native platinum deposits discovered in the late 20th century

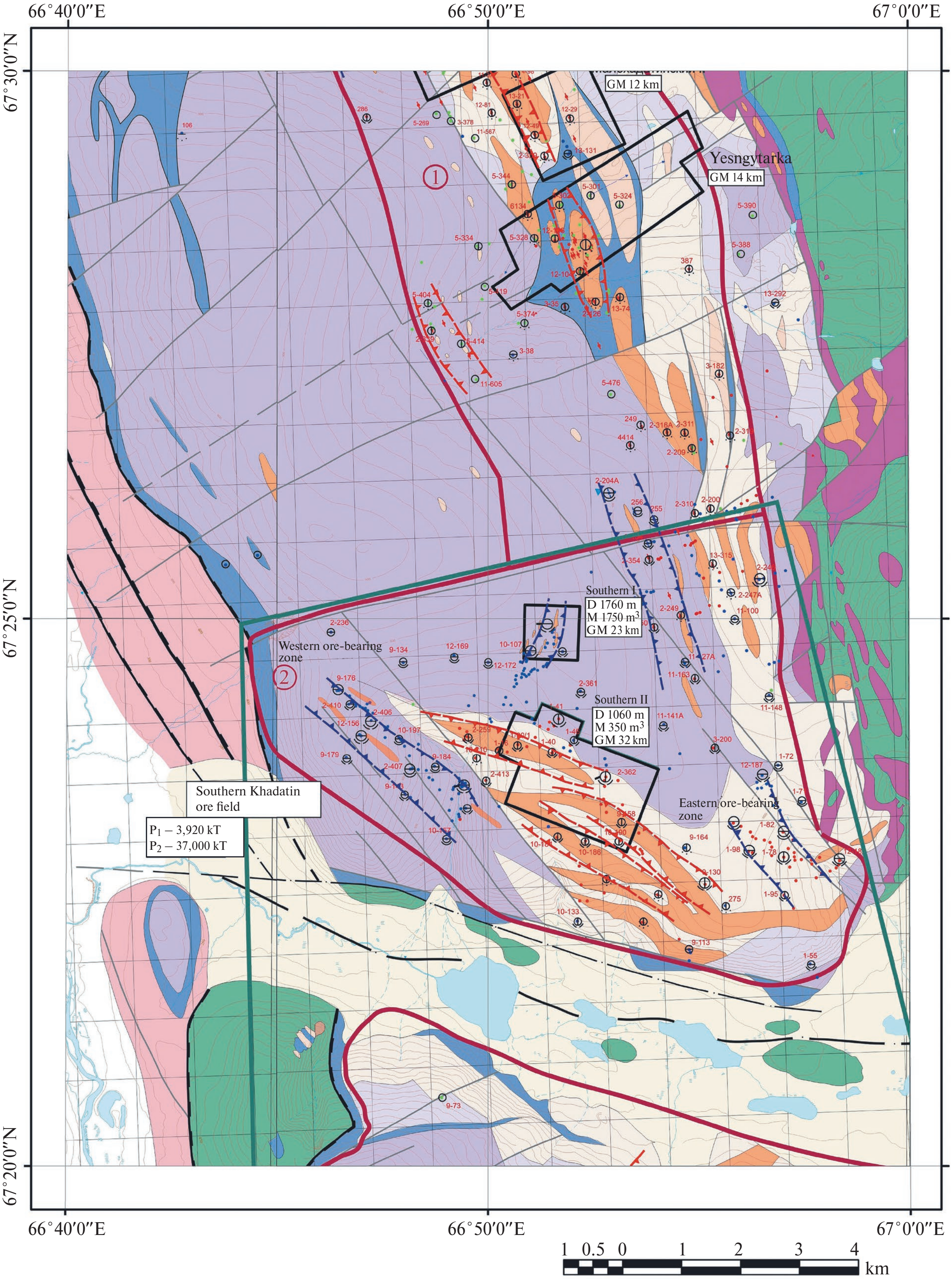


Fig. 6. Geological scheme of the southern part of the hyperbasite massif Syum-Keu with delineation of ore fields. Q-42-I. The notation in Fig. 6a.

NOTATION:

Quaternary undissected deposits (Q)

Nyarovey metamorphic complex (PR_3nr)

Kharampay-Maslovsky gabbro undissected complex (O_3–S_1hm)

MANTYH HYPERBASITIC COMPLEXES (O_3–S_1):
Dunite-verlite clinopyroxenite complex

Undissected dunites, verlites, and clinopyroxenites

Dunites with clinopyroxene

Clinopyroxenites and websterites

Dunite-Gartzburgite complex

Gartzburgites with linear and schlieric dunite segregations up to 10%

Gartzburgites with schlieric-striped dunite segregations 10–30%

Gartzburgites with schlieric-striped dunite segregations over 30%

Dunites

Serpentinite brucite-antigorite varieties

Gradation of chromite ore objects:

1–107 Manifestations (1–107) 1–95 Mineralization points (1–95)

The morphology of ore bodies is flattened-lenticular

Characteristics of chromite ores based on the density of mineralization:

Density-granular and solid

Rare to medium-granular

Sparse-granular

Mineral types of chromite ores:

High-chromium (Cr_2O_3 in chromshpinelide > 46%)

Alumina-rich (Cr_2O_3 in chromshpinelide < 46%, Al_2O_3 > 17%)

A. High-chromium type (red); B. Alumina-rich type (blue)

A B

2-109 5-97 Individual ore points (single fragments of chromite ores)

Over-scale images of jet-striped mineralization

Chromitite zones

Contours of ore fields, their numbers and names:
1. Khadatinskoye ore field
2. South Khadatinskoye ore field

Southern I Contours of detailed sections and their names

Types of geological exploration works:
D. Drilling of prospecting boreholes with a depth of up to 50–150 meters;
M. Mining works (excavation of trenches);
GM. Gravity-magnetic exploration works (observation interval of 20 (10) meters) in a profile setup

Fig. 6a. Notation to Figs. 6, 7, 8, 10.

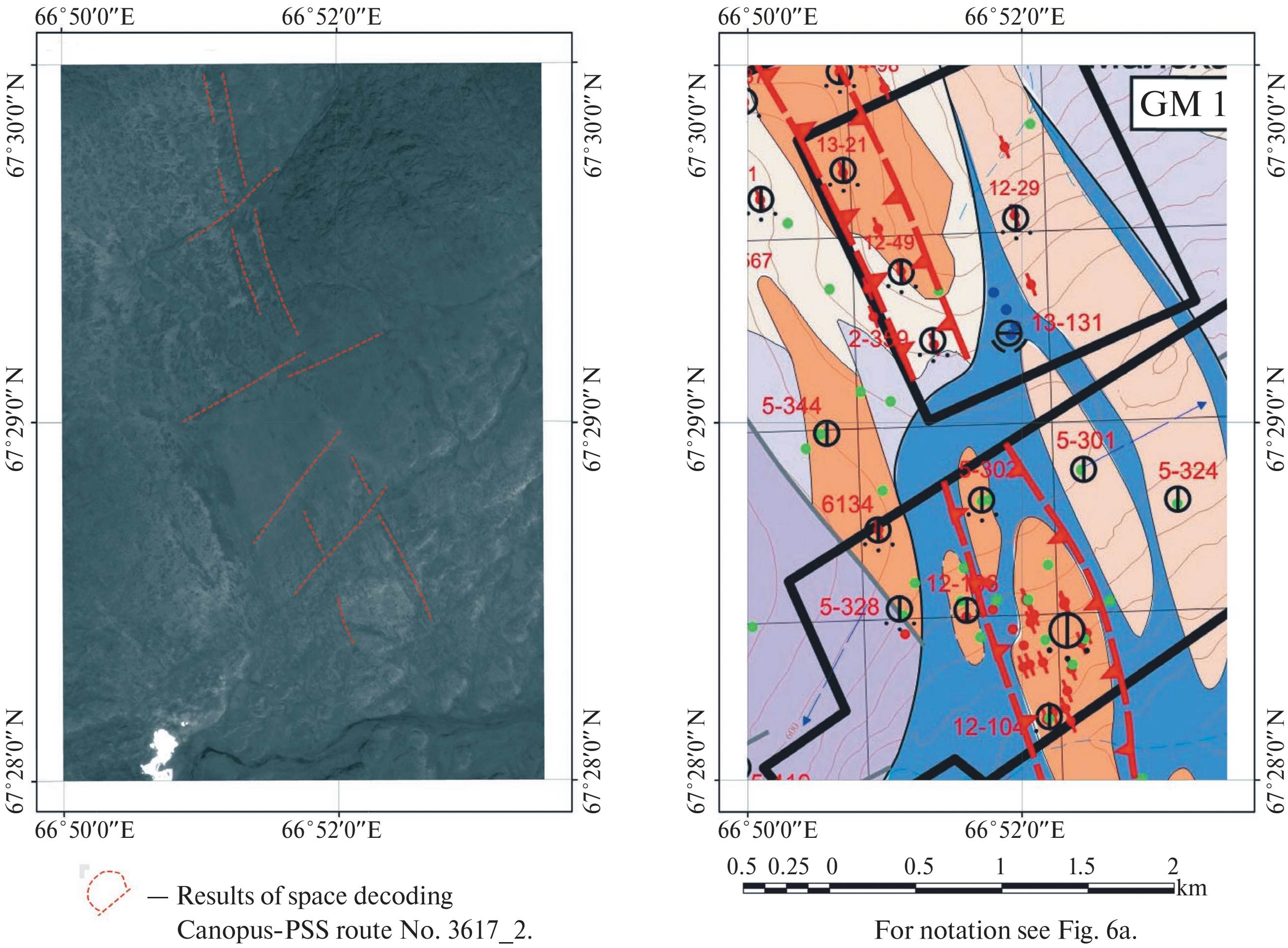
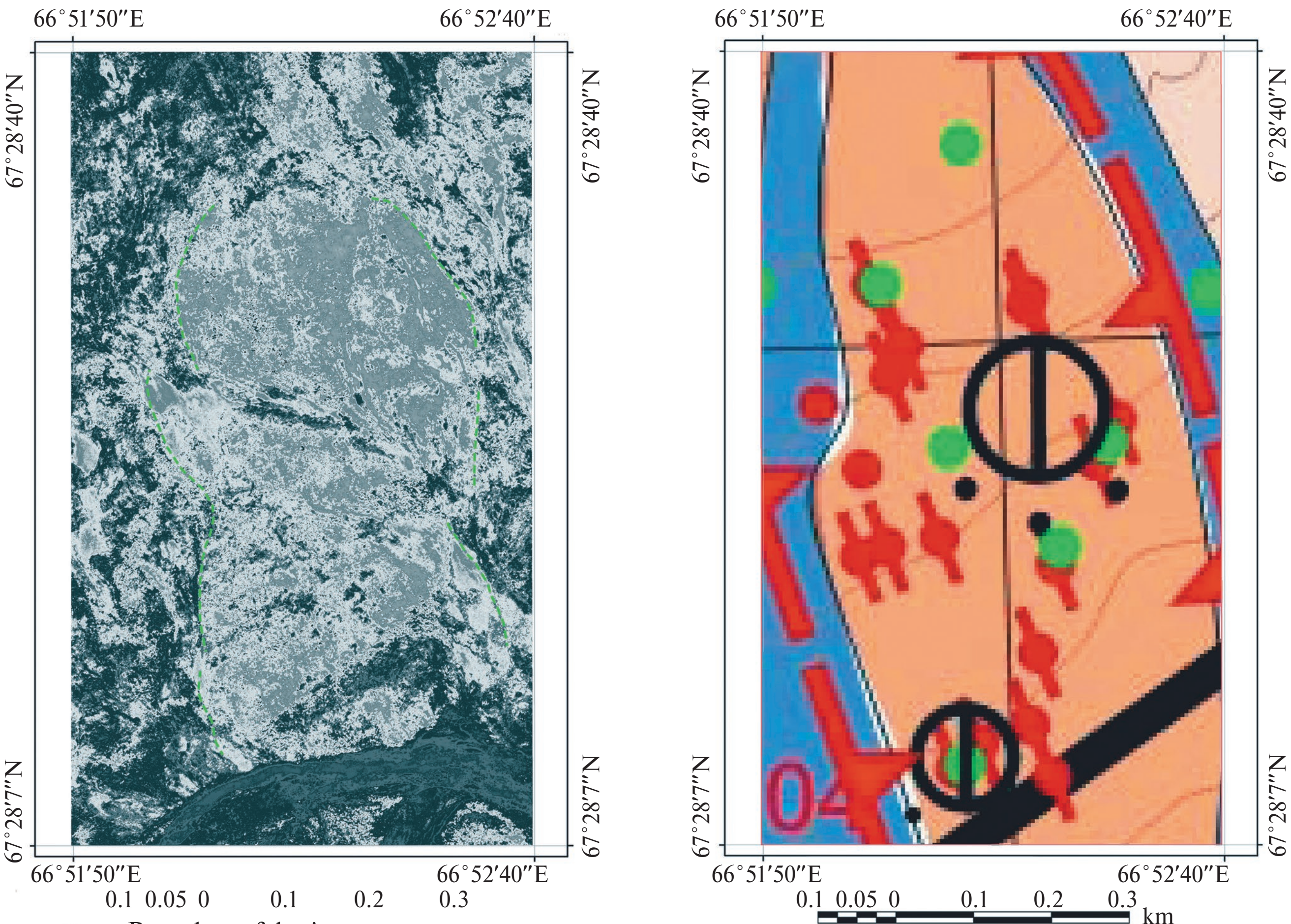


Fig. 7. Khadatinsky detailing site.

showed that the contents of the sum of platinum group metals (PGMs) are related to the iron content of dunite (Dodin et al., 2010). The amount of PGMs in ore zones is 2–10 g/t (sometimes Pt content reaches 20–50 g/t). The metallogenic potential of native platinum of the Lower Tagil type is 19000 tons. In terms of a number of parameters, the Nizhnetagilsky type is similar to the famous Bushveld type. A number of manifestations of this type are established in the Polar and Subpolar Urals, reaching the Rai-Iz and Syum-Keu massifs. The study of platinum content of the Syum-Keu ultramafic massif has revealed two types of platinometallic mineralization associated with chromite ores and sulfide occurrences (Gurskaya et al., 2003). Chromite ores are characterized by the development of three mineral associations: erlichmanite-laurite in high-magnesian chromite ores, sperrylite-irarsite-laurite in aluminous chromite ores, enriched with sulfides, and ferro-platinum in coarse-grained recrystallized dunites with poorly disseminated chromites of high-iron composition.

The Khadata area is located in the southern part of the Syum-Keu hyperbasite massif (Fig. 6). The Early Silurian Syum-Keu intrusion is represented by hyperbasites of the dunite-harzburgite formation (Geological..., 1984; State..., 2014). The Syum-Keu hyperbasite massif is confined to the arc-shaped conjugation in the zone of the Main deep fault separating the eastern wing of the Central Ural anticlinorium from the western wing of the Shchuchya synclinorium. The structure of the Syum-Keu massif includes serpentinites, pyroxenites, peridotites and dunites. Serpentinites are developed on a small scale. They compose the western near-contact part of the Syum-Keu massif. Pyroxenites are mainly recorded in the eastern peripheral part of the Syum-Keu massif, where they compose relatively small bodies (up to 1.5 × 7 km). Inhabited pyroxenites occur quite frequently among peridotites and dunites of the Syum-Keu massif in the form of dikes up to 8–10 m thick. Peridotites are the most widespread rocks of the Syum-Keu massif. Banding in the peridotites is caused by alternation of sections of different compositions. Areas in the form of bands and elongated schlieres, consisting mainly of pyroxene, alternate with the same



— Boundary of dunites.
Resource-P route no. 2960_1.

For notation see Fig. 6a.

Fig. 8. Khadatinsky detailing site. Features of the structure of dunite bodies.

areas consisting of one olivine or almost one olivine. The thickness of bands and schlieres is measured in tens of centimeters or meters. Peridotites are represented almost exclusively by harzburgites and very rarely by verlites. The harzburgites consist of olivine (70–80%) and rhombic pyroxene (15–30%). Verlites occur occasionally in the eastern near-contact part of the Syum-Keu massif. The main rock-forming minerals are olivine and monoclinic pyroxene. Dunites are isolated among the harzburgites both as large elongated bodies and as thin bands and schlieres in banded harzburgites. In serpentinized varieties, a looped or reticulated structure is observed. Gabbro-norites occur in the form of small bodies intruding Syum-Keu hyperbasites and host gabbro-amphibolites.

Within the Khadatinskaya area, two areas — Khadatinsky and Yuzhno-Khadatinsky — representing chromite-bearing zones localized in structures of different spatial orientation have been selected for studies of multizone and high-resolution space imagery (SI) capabilities. The Khadatinsky section includes a discontinuous linear chromite-bearing zone with jet-banded mineralization. Interpretation of the Canopus SI confirmed the discontinuous nature of the ore-bearing zone, which may be due to displacements along northeastern strike-slip faults (Fig. 7). The chromite occurrences are confined to dunites; therefore, it is of interest to determine the boundaries of dunite bodies within the hyperbasite field using high-resolution SI materials. Figure 8 shows the results of delineation of dunite boundaries in the Khadati area using the Resurs SI phototone. Another procedure of the Resurs SI processing was aimed at clarifying the boundaries of the jet-band structure of mineralization within the dunite bodies. The capabilities of the high-resolution multizonal CW resource for predicting chromite mineralization are shown in Figure 9. Two chromite-bearing zones have been identified in the South Khadata area based on geological data. The Resurs SI analysis allows us to identify only one zone of northwest strike in this

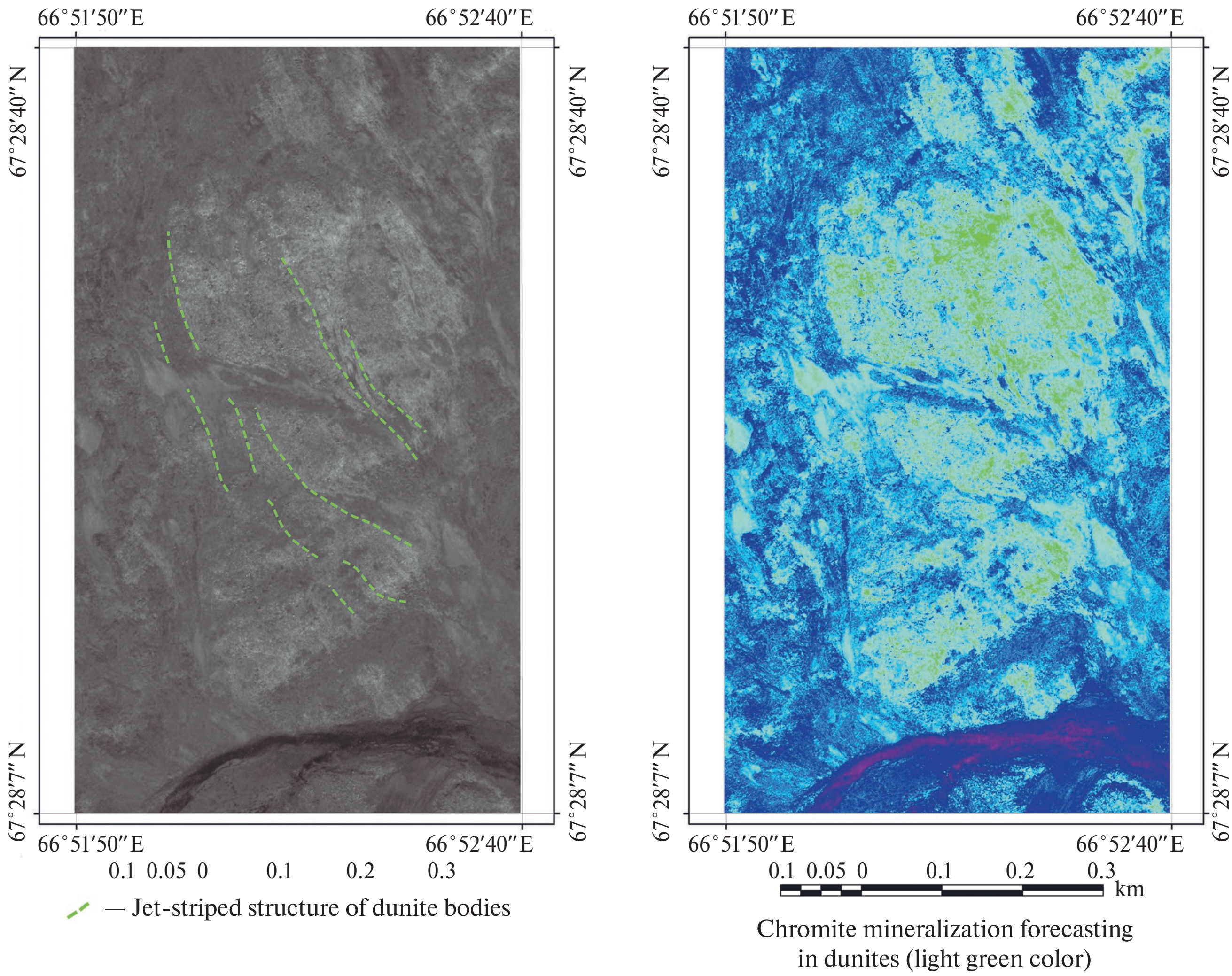


Fig. 9. Khadatinsky detailing section. Resource-P route No. 2960_1.

area, divided into three fragments by northeast-oriented disjunctives (Fig. 10).

CONCLUSION

On the basis of computer processing of infrared satellite imagery of the Hakharempe area, disjunctives controlling the location of molybdenite-nasturanic mineralization and areas of development of hydrothermally altered rocks (berezites, sericite-hydrosludic-quartz metasomatites) have been identified. The predominant development is dominated by northwestern strike-slip faults, which are complicated by shallow shear deformations of predominantly northeastern strike. Analysis of multizone space imagery, including high-resolution Resurs-P imagery, has shown that a wide range of prospecting attributes can be used to predict molybdenite-nasturanic mineralization on a scale for both ore fields and individual prospective areas (deposits), including structural factor (linear, arc, ring structures of various grades), lithological factor (delineation of lava-pyroclastic and subvolcanic formations boundaries by phototone) and hydrothermal alteration factor (detection of metasomatites of various compositions preceding and accompanying ore deposition process).

The use of high-resolution space imagery within the Khadata area of the Syum-Keu massif allowed us to determine the structural position of chromite-bearing zones and clarify the boundaries of ore-bearing dunites by phototone. As a result of interpretation of the space imagery of Canopus-PSS and Resurs-P, the discontinuous nature of the ore-bearing zone was established, which is caused by displacements along northeastern strike-slip faults, and the contours of dunite bodies within the hyperbasite field were determined. The processing of the Resurs-P space imagery allowed us to clarify the boundaries of the jet-strip structure of mineralization within the dunite bodies.

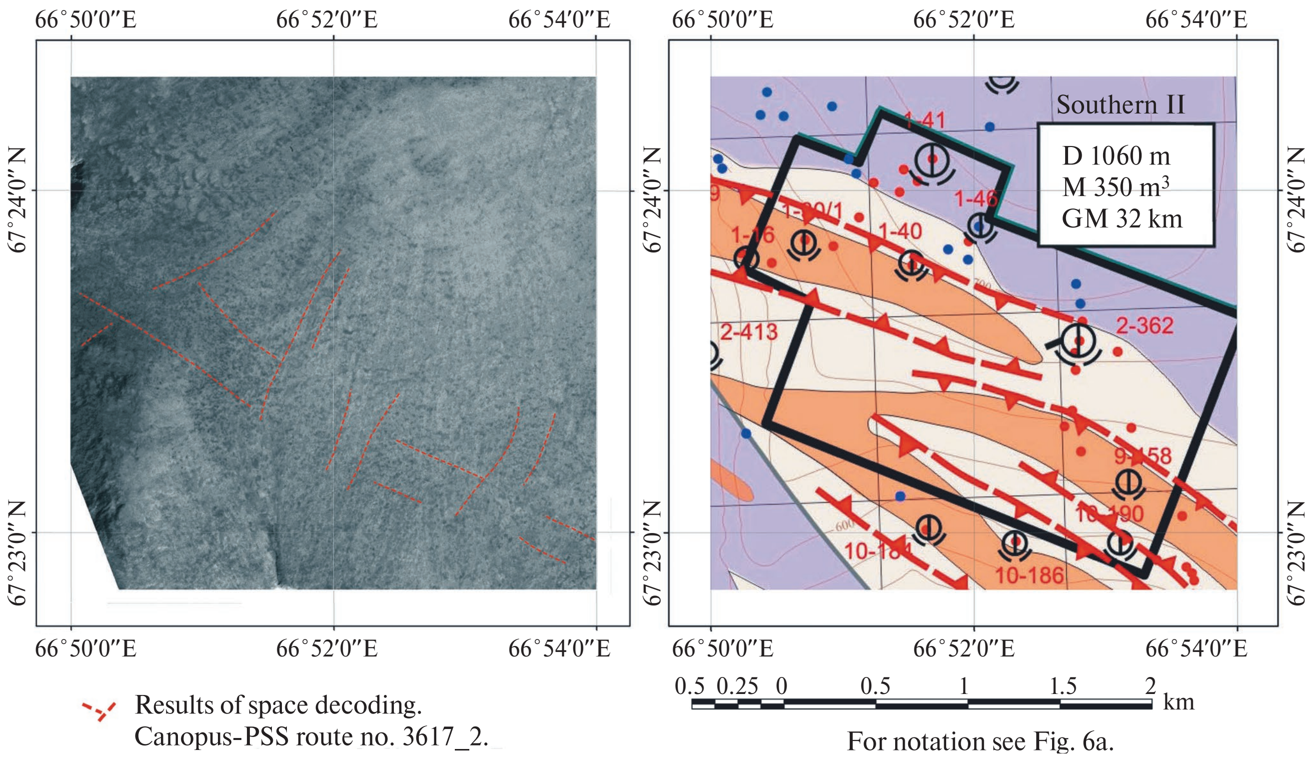


Fig. 10. Yuzhno-Khadatinsky detailing site.

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