

Structure of the Lithosphere and Its Influence on Gold Mineralisation in Southeast Kamchatka

A. G. Nurmukhamedov^a, * and M. D. Sidorov^a

^a Research Geotechnological Center, Far Eastern Branch of Russian Academy of Sciences, Petropavlovsk-Kamchatsky, 683002 Russia

*e-mail: nurmuxamedov1949@mail.ru

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From the 1980s to the present, a set of geophysical methods has been implemented in southeast Kamchatka, including the earthquake converted waves method, magnetotelluric sounding, gravimetry, magnetometry, and seismology. Based on a comprehensive interpretation of the data obtained, a geological and geophysical model of the Earth's crust and upper mantle along the Khodutka Bay—village of Nikolaevka profile was constructed. A genetic relationship has been established between dynamically active areas of the Earth's crust with gold deposits. A hypothesis has been put forward about the division of a previously single xenoblock into two separate fragments under the action of strike-slip faults along the Nachikinskaya transverse dislocation zone. The southern fragment is represented by the Pribrezhny Terrane. To the west of the terrane is a permeable zone in which modern volcanism has occurred. The intrusion of magma and high-temperature fluids enriched in noble metal solutions into the upper layers of the crust occurs through a magma conduit formed in the palaeosubduction zone.

Keywords: Palaeo-Kamchatka, Earth's crust, upper mantle, subduction, terrane, ore occurrence

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INTRODUCTION

Solving problems of the structural position of gold ore deposits in the field of modern volcanism is a priority task of Kamchatka scientists (Petrenko, 1999). Therefore, of great interest are the results of deep geological and geophysical research conducted by OJSC (PGO) Kamchatgeologiya near known gold deposits and ore occurrences in the zone of active volcanism (Nurmukhamedov et al., 2020; Nurmukhamedov and Sidorov, 2022; Nurmukhamedov and Sidorov, 2019a). Such studies are important in that they make it possible to identify the genetic relationships of deposits with the deep structural features of the lithosphere and to predict the presence of new ore-bearing areas in other parts of the region.

Kamchatka is located in northeastern Eurasia, and its territory has the characteristic features of active continental margins. The structure of the lithosphere of Southeastern Kamchatka, as well as throughout Eastern Kamchatka, is governed by subduction of the oceanic lithospheric plate under the marginal part of the continental plate. This is one of the few places where several gold deposits and ore occurrences are located directly in the zone of modern active volcanism (Petrenko, 1999).

In metallogeny in the Pacific continent–ocean transition zone, zones of interaction between the sub-

ducting oceanic and continental lithosphere are of decisive importance (Zonenshain et al., 1973; Smirnov, 1974; Petrenko, 1999). This interaction leads to intense release of endogenic energy along extended zones in the form of volcanic belts (Fig. 1). The study area pertains to the southern branch of the Central Kamchatka volcanic belt (CKVB) with superposition of structures of the Eastern Kamchatka volcanic belt (EKVB). The northern and southern branches of the CKVB, which once belonged to a single structure, under the action of left-lateral shear dislocations, are separated and spaced along the Nachikinskaya transverse dislocation zone (NTZD). On the tectonic diagram¹, a fragment of which is shown in Fig. 2, the southern branch of the CKVB and EKVB join up in the Kuril–South Kamchatka island-arc volcanic zone.

According to I.D. Petrenko (1999), the main structural elements of volcanic belts are volcanotectonic structures (VTS). All VTS are genetically related to acid magmatism, which is probably a reflection of granitisation chambers confined to long-lived crustal

¹ A.G. Nurmukhamedov Report on the results of studies on the object "Creation of a Seismotectonic Zoning Scheme for the Koryak–Kamchatka Fold Zone Based on Generalized Deep Geological and Geophysical Research." Two Books and 1 Folder. Book 2: Petropavlovsk-Kamchatsky: OJSC Kamchatgeologiya, 2013.

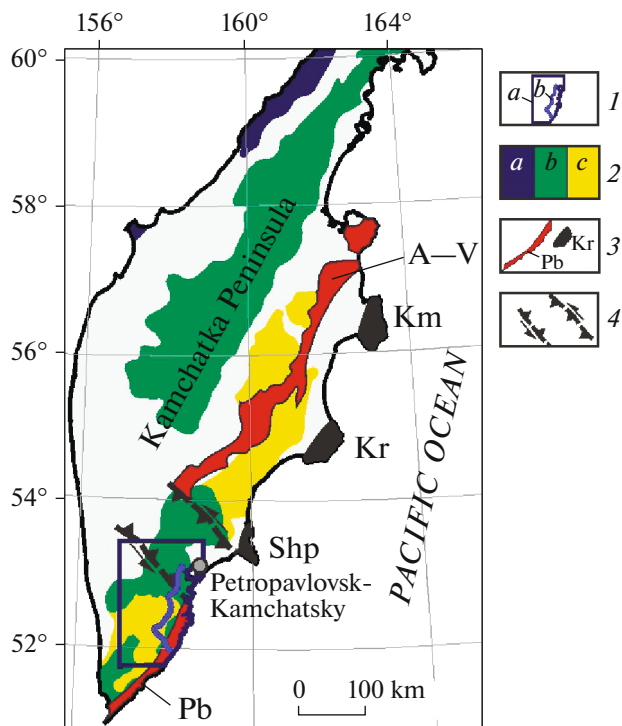


Fig. 1. Overview map. (1) Contours of study area (a) the Khodutka Bay–Nikolaevka Village geophysical profile (b); (2) volcanic belts (Petrenko, 1999): West Kamchatka–Koryak volcanic belt (a), Central Kamchatka volcanic belt (b), Eastern Kamchatka volcanic belt (c); (3) terrains and their design: Pb: Pribrezhny, A–V: Achaiyayam–Valaginsky (Shapiro and Solovyov, 2009), Shp: Shipunsky, Kr: ronotsky, Km: Kamchatsky; (4) Nachikinskaya transverse dislocation zone (arrows show direction of shear dislocation).

extension zones. VTS play a major role in the formation of ore gold deposits and their development is closely related to the existence of peripheral acid–medium–acid magma chambers at various depths, which are connected to the surface. The formation and existence of such chambers is accompanied by dehydration of magma and the formation of hydrothermal systems. The main role in such systems is played by meteoric waters. The proportion of juvenile water in most cases does not exceed 5% (Belousov, 1978; Hedenquist and Houghton, 1987), but this juvenile component carries the main load in ore-forming hydrothermal systems. Most researchers, including V.I. Belousov (1978) and I.D. Petrenko (1999), have confirmed the relationship between hydrothermal fields and acid volcanism.

Thus, we can talk about the existence of magmatic–hydrothermal systems within which gold deposits and ore occurrences form in the zone of modern volcanism (Goncharov, 1983). It has been noted (Petrenko, 1999) that at all gold deposits in Southeastern Kamchatka, the upper boundary of mineralisation is formed at a depth no greater than 100–300 m from

the palaeosurface. However, the problems of near-surface ore formation cannot be solved without studying the depth component of the mentioned systems. According to (Belousov, 1978), the thermal power of acid subvolcanic bodies is insufficient to form long-lived hydrothermal systems, such as those that exist in the zone of modern volcanism. These chambers themselves can be a source of heat for hydrothermal fluids only for a very short time, and in the absence of external heat input, they cool relatively quickly. Acid volcanism and active hydrothermal activity in such places arise under the action of a deeper process, such as basaltic magmatism. Here, energy transfer occurs via emplacement of magmatic melts and high-temperature aqueous fluid enriched in noble metals into upper crustal layers crust via zones of weakness. In such a magmatic–hydrothermal model, acid chambers are considered accumulators of heat coming from depths with basaltic magmas.

Similar models with different structural types of hydrothermal systems are also considered in the South Kamchatka ore district (Petrenko, 1999). The upper parts of these models were developed on the basis of data from geological and hydrogeological surveys of various scales, as well as geophysical studies carried out in the vicinity of gold deposits. The maximum depth of such research does not exceed a few hundred meters. Information about the deep parts of magmatic–hydrothermal systems was gleaned by I.D. Petrenko (1999) from various published sources, often unrelated to the area under study, and the information is schematic in nature. For example, the monograph (Petrenko, 1999) does not reflect the results of deep geophysical research carried out in 1980–1990 along the Opala Mountain–Vahil River and Apache–Mutnaya Bay profiles (Fig. 2). The profiles intersect the Tolmachevsky active magma chamber (TAMC), in the vicinity of which there is the Porozhistoe gold deposit and several ore occurrences of the Karymshinsky ore cluster (Fig. 2).

The aim of this article is to supplement information about the deep structure of the dynamically active region of Southeast Kamchatka and the supposed genetic relationship between gold deposits and the structural features of the lithosphere in the zone of modern volcanism. The results are based on materials from the earthquake converted wave method (ECWM), several modifications of magnetotelluric sounding (MTS), gravimetry, magnetometry, seismology, and geological data obtained in 1980–2013 by OJSC (PGO) Kamchatgeologiya. The data from geophysical research carried out along the Khodutka Bay–village of Nikolaevka profile are analyzed. The profile runs along a range of active (Khodutka, Mutnovskaya Sopka, Gorely) and extinct (Piratkovsky, Asacha, Vilyuchinskaya Sopka) volcanoes (Figs. 2–5) and intersects ore fields of the Asachinskoe, Mutnovskoe and Rodnikovoe gold deposits.

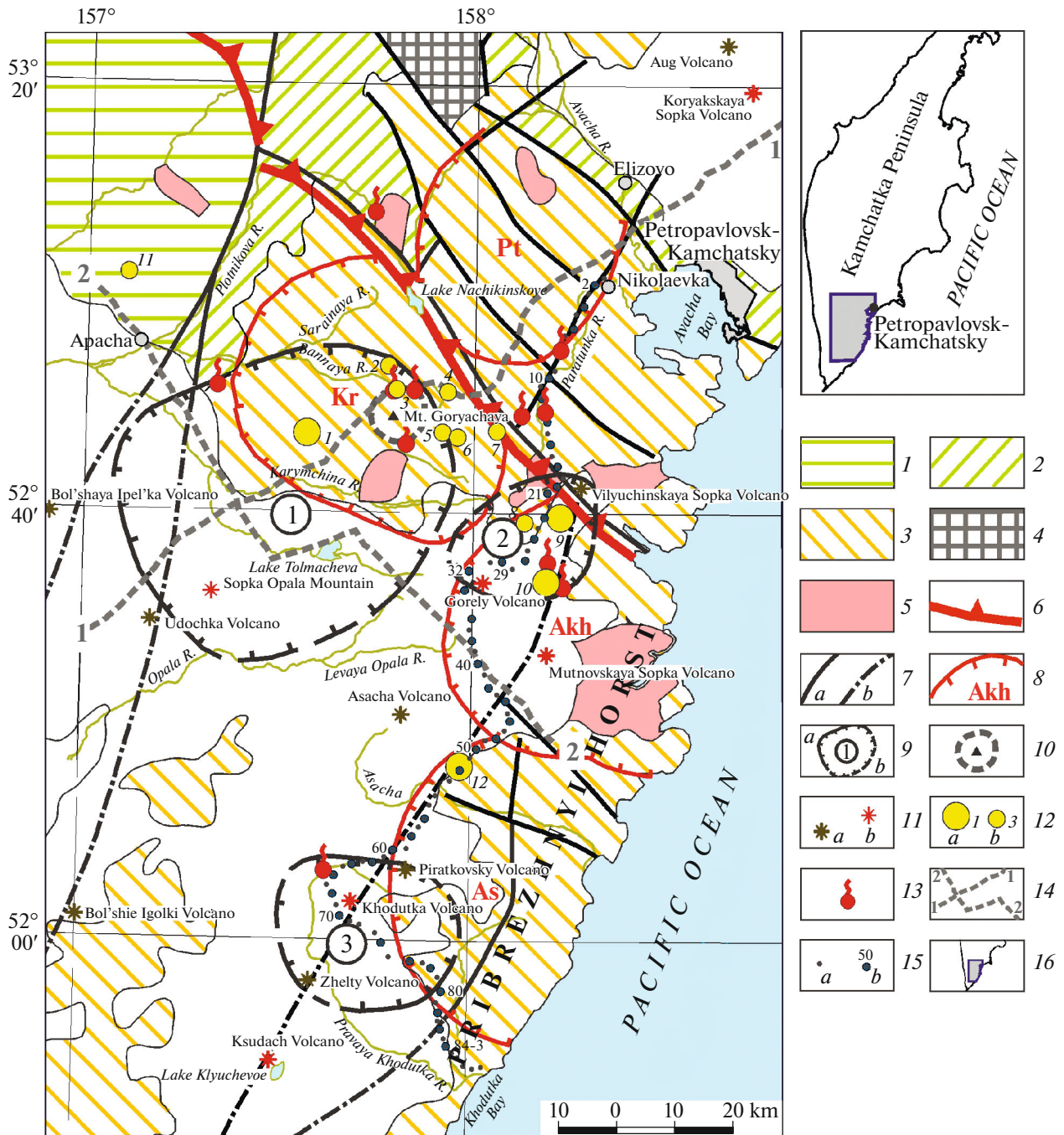


Fig. 2. Tectonic chart of the Koryak–Kamchatka folded zone (amended from Nurmukhamedov and Sidorov, 2019a; 2019b with simplifications and additions). (1) Koryak–West Kamchatka folded zone; (2) East Kamchatka subzone of the Olyutorsko–East Kamchatka folded zone; (3) Kuril–South Kamchatka island-arc volcanic zone; (4) Pre–Late Cretaceous metamorphic units; (5) Intrusive and subvolcanic bodies of predominantly medium and acid composition; (6) Southwestern boundary of the Nachikinskaya transverse dislocation zone; (7) Major faults: outcropping (a) and buried by overlying rocks (b); (8) Volcanotectonic structures (Kr: Karymshinskaya; Pt: Plotnikovskaya; Akh: Akhomtenskaya; As: Asachinskaya (also referred to as Asacha)); (9) Proven (a) and inferred (b) boundaries of crustal and mantle–crust electrical conductivity anomalies formed in zone of Tolmachevsky active magma chamber (1), in vicinity of Gorely, Mutnovsky, and Vilyuchinsky volcanoes (2), and Khodutka, Piratkovsky Peak and Zhelty volcanoes (3); (10) Contours of Goryachaya Hill palaeovolcano; (11) Extinct volcanoes (a), active volcanoes (b); (12) Deposits (a) and ore occurrences (b) of gold (1: Porozhistoye; 2: Yagodka; 3: Bannoe; 4: Verkhne–Bystrinskoe; 5: Geofizicheskoe; 6: Karymshinskoe; 7: Rogatka and Bystrinskoe; 8: Rodnikovoe; 9: Mutnovskoe; 10: Gol'tsovskoe; 11: Asachinskoe); (13) Sources and fields of thermomineral waters; (14) Lines of ECWM–MTS geophysical profiles: Opala Mountain–Vakhil River (1–1) and Apacha Village–Mutnaya Bay (2–2); (15) Observation points on the Khodutka Bay–Nikolajevka Village profile: AMTS, MTS, and GMTS (a), coinciding points of ECWM–MTS (b) and their numbers; (16) Research area.

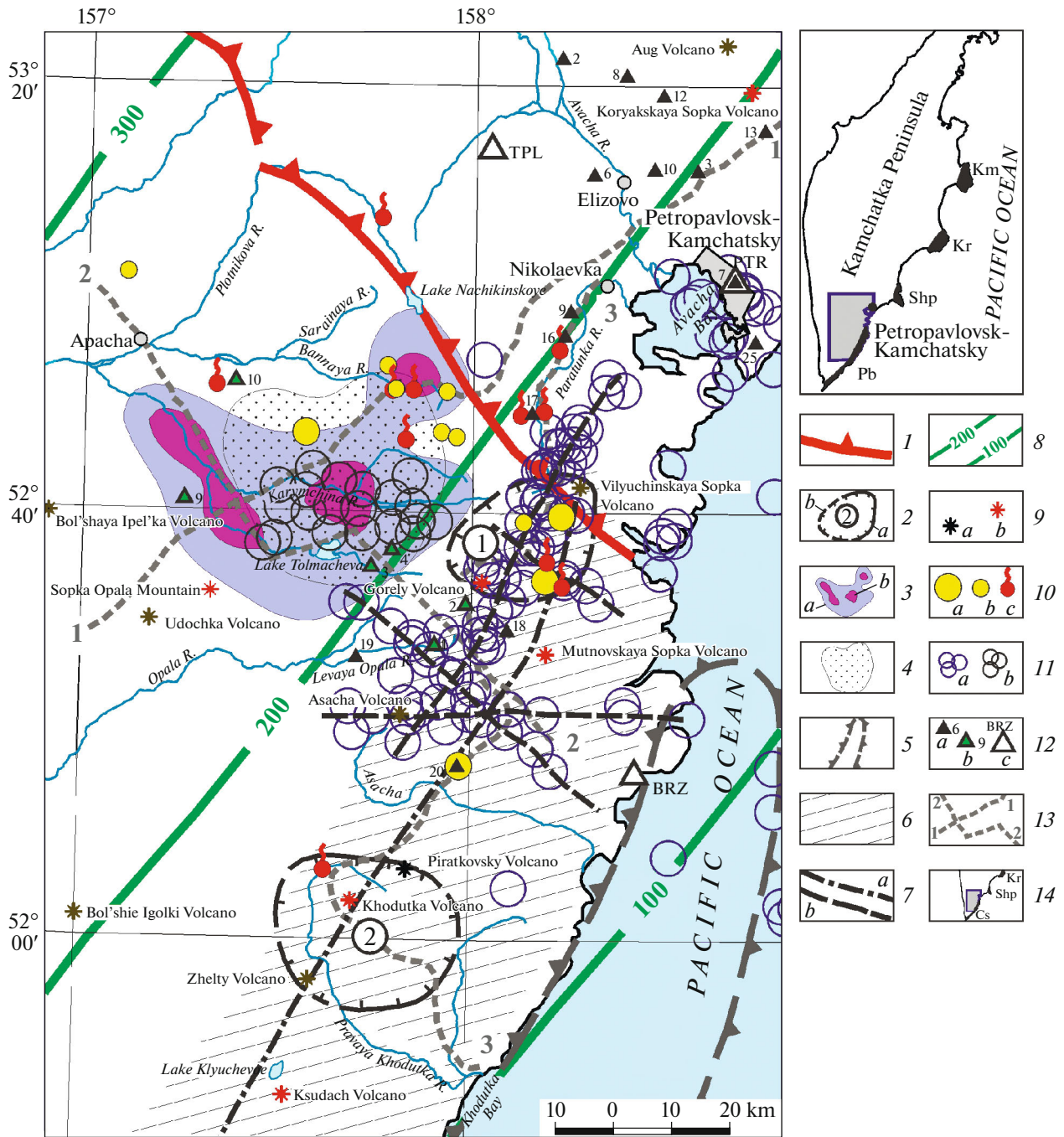


Fig. 3. Map of local earthquake epicenters recorded from 1981–1988 using “Cherepakha” (“Turtle”), ASS 6/12 (based on materials³ with additions). (1) Southwestern boundary of Nachikinskaya transverse dislocation zone; (2) confirmed (a) and inferred (b) boundaries for crustal and crust–mantle electrical conductivity anomalies formed in vicinity of Gorely, Mutnovskaya Sopka and Vilyuchinskaya Sopka volcanoes (1), and Khodutka, Piratkovsky Peak, and Zhelty volcanoes (2); (3) Contours of decompaction zone in transition layer at the depth of 40 km (a), areas of maximum decompaction in the depth interval of 35–45 km (b) (Nurmukhamedov and Sidorov, 2022); (4) Intrusive diorite–granitoid massif; (5) Gravity maximum; (6) Zone of high–gradient gravity field, the area of modern active volcanism; (7) Discontinuities identified by morphology of gravity field (a) and seismological data (b); (8) isolines of depths (km) to seismic focal zone (Tarakanov, 1987); (9) Extinct (a) and active (b) volcanoes; (10) Deposits (a) and ore occurrences (b) of gold, sources and deposits of thermal mineral waters (c); (11) Epicenters of earthquakes ($h = 0–40$ km) detected for time periods 1981–1985 (a) and 1987–1988. (b); (12) Points of installation of “Cherepakha” equipment (ASS 6/12) in 1981–1985 (a), 1987–1988 (b) and location of stationary seismic stations of Institute of Volcanology, Far Eastern Branch, USSR Academy of Sciences (c); (13) Lines of ECWM–MTS profiles: Opala Mountain–Vakhil River (1–1), Apacha–Mutnaya Bay (2–2), Khodutka Bay–Nikolaevka (3–3); (14) Research area, the position of terranes and their notations (Km: Kamchatsky; Kr: Kronotsky; Shp: Shipunsky; Pb: Pribrezhny).

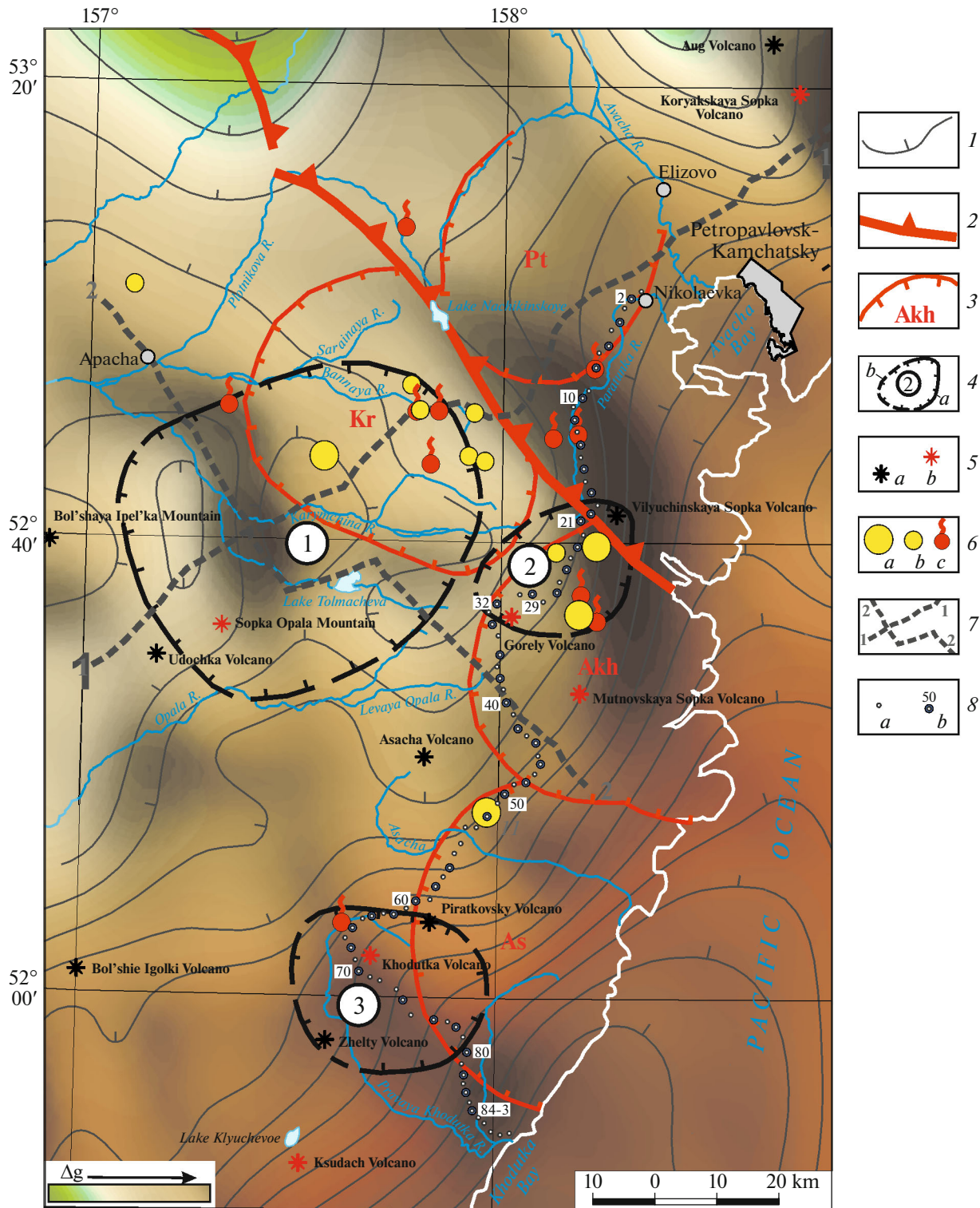


Fig. 4. Morphology of gravity anomalies in Southeast Kamchatka (shadow image of gravity field is used as colour substrate in diagram). (1) Gravity isoanomalies (bergstrichs are directed towards decrease in field intensity); (2) Boundary of the Nachikinskaya transverse dislocation zone; (3) Volcanotectonic structures: (Kr: Karymshinskaya; Pt: Plotnikovskaya; Akh: Akhomtenskaya; As: Asachinskaya); (4) confirmed (a) and inferred (b) boundaries of crustal and crust–mantle electrical conductivity anomalies formed in zone of Tolmachevsky active magma chamber (1) in vicinity of Gorely, Mutnovskaya Sopka and Vilyuchinskaya Sopka volcanoes (2), Khodutka, Piratkovsky Peak, and Zhelty volcanoes (3); (5) Extinct volcanoes (a), active volcanoes (b); (6) Deposits (a) and ore occurrences (b) of gold, sources, and fields of thermomineral waters (c); (7) ECWM–MTS geophysical profiles: Opala Mountain–Vakhil River (1–1) and Apache Village–Mutnaya Bay (2–2); (8) Observation points on the Khodutka Bay–Nikolaevka Village: AMTS, MTS, and GMTS (a), coinciding ECWM–MTS points (b) and their numbers.

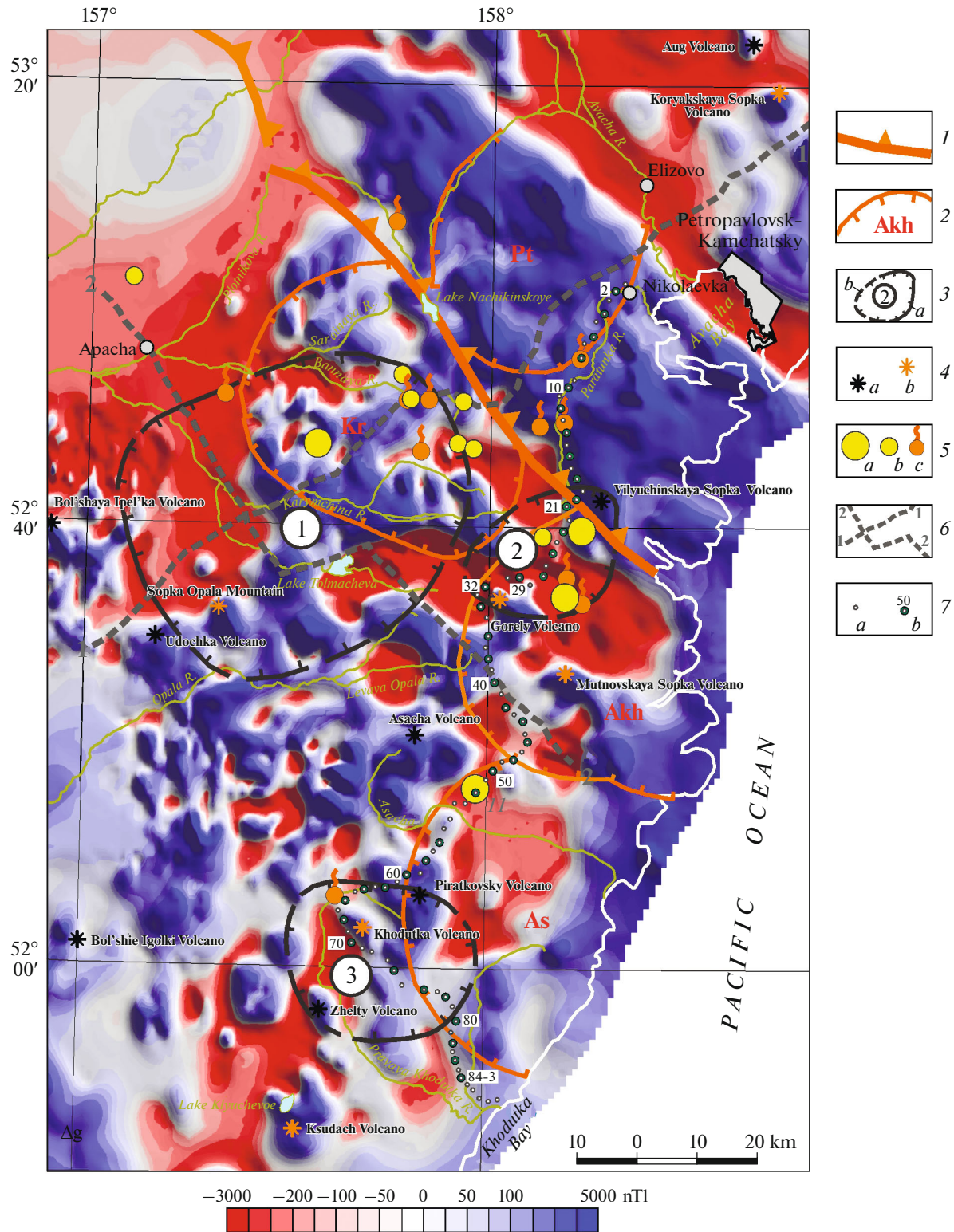


Fig. 5. Morphology of magnetic field (ΔT)_a in Southeast Kamchatka (shadow image of magnetic field is used as colour substrate in diagram). (1) Boundary of Nachikinskaya transverse dislocation zone; (2) Volcanotectonic structures: Kr: Karymshinskaya; Pt: Plotnikovskaya; Akh: Akhomtenskaya; As: Asachinskaya; (3) confirmed (a) and inferred (b) boundaries of crustal and crust-mantle electrical conductivity anomalies formed in zone of Tolmachevsky active magma chamber (1), in vicinity of Gorely, Mutnovskaya Sopka and Vilyuchinskaya Sopka volcanoes (2), Khodutka, Piratkovsky Peak, and Zhelty volcanoes (3); (4) Extinct volcanoes (a), active volcanoes (b); (5) Deposits (a) and ore occurrences (b) of gold, sources, and fields of thermomineral waters (c); (6) ECWM-MTS geophysical profiles: Opala Mountain-Vakhil River (1-1) and Apache Village-Mutnaya Bay (2-2); (7) observation points on Khodutka Bay-Nikolaevka profile: AMTS, MTS, and GMTS (a), coinciding ECWM-MTS points (b) and their numbers.

GEOLOGY

To date, a wide range of geological and geophysical studies of various scales have been carried out in the study area, a review and analysis of which is presented in (Nurmukhamedov, 2017; Nurmukhamedov and Sidorov, 2019a; 2019b). The Khodutka Bay–Nikolaevka Village profile crosses the territory where PGO Kamchatgeologiya carried out gravimetric and aeromagnetic surveys on a scale of 1 : 200 000, and in some areas, aeromagnetic surveys on a scale of 1 : 50 000. Based on the data obtained, several geological maps on different scales were compiled for the entire territory of Kamchatka, including a geological map on a scale of 1 : 1 500 000 (Geologicheskaya..., 2005).

In 2007–2010, OJSC Kamchatgeologiya, the branch of JSC VNIIGeofizika - GEON Center and LLC Severo-Zapad carried out a set of in-depth ECWM-MTS studies along the Trans-Kamchatka (1300 km) profile, the southern fragment of which is the Khodutka Bay–Nikolaevka profile² (Figs. 1, 2), ~170 km in length. The profile in the NNE direction crosses the districts of the Rodnikovoe, Mutnovskoe, and Asachinskoe gold deposits and passes east of the ore occurrences of the Karymshinsky gold ore cluster (Fig. 2). To date, gold mining is carried out only at the Asachinskoe deposit; the rest are in various stages of geological exploration. All the cited deposits and ore occurrences are attributed to gold–silver formation. The main ore mineralisation phase in the South Kamchatka ore district, which includes the cited deposits, occurred in the Pliocene–Early Pleistocene (Petrenko, 1999).

In order to study seismicity in the southeast of the peninsula, seismological studies were carried out³ (Fig. 3). The results give a general idea of the geodynamic and magmatic processes in subsoil of Southeast Kamchatka.

The study area is part of the East Kamchatka subzone of the Olyutorsko–East Kamchatka folded zone. In the north, the profile intersects structures of the NTDZ. The zone is characterized by NW-trending faults. The central part of the profile runs along the western border of the Pribrezhny Horst, and the southern fragment crosses this horst to the southeast. A positive gravity field anomaly was recorded above

the horst (Fig. 4), a significant part of which is located in the Pacific Ocean. The western boundary of the horst is expressed as a gravitational step elongated to the north-northeast. In the same place is the Mutnovsky fault (Fig. 2) with the same strike as the gravity step (Fig. 4). The fault is overlain by volcanosedimentary rock sequences. In the step zone are active and extinct volcanoes, as well as the Akhomten and Asacha VTS.

Southeast Kamchatka pertains to regions where modern geodynamic processes are actively occurring. In the Upper Pleistocene–Holocene, the territory was a site of powerful areal volcanism. The result of volcanic activity is represented by groups of low (up to 100–300 m) cinder cones of predominantly basaltic composition, distributed from the latitude of the valley of the Paratunka and Karymchina rivers in the north to Cape Lopatka in Kamchatka's extreme south (Vazheevskaya, 1980). The area is characterized by an alternating magnetic field (ΔT)_a with a mosaic arrangement of high-gradient local anomalies (Fig. 5), which is typical of zones of areal volcanism. In the northeast of the site, the distribution of such areas is bounded by the Yuzhno-Bystrinsky block (Aprelkov and Olshanskaya, 1989) of the NTDZ, where there is an intense positive magnetic field (ΔT)_a characterized by a northwestern orientation of anomalies.

It should be noted that the most recent manifestation of areal volcanism (Late Holocene) was noted in the Tolmachevsky Dol area (Vazheevskaya, 1980), in the vicinity of the eponymous lake and river (Fig. 3). Here, at the intersection of the Opala Mountain–Vahil River and Apacha River–Mutnaya Bay profiles, according to geophysical data, a transition layer with a thickness of 10 km has been identified, located between the Earth's crust and upper mantle (Nurmukhamedov et al., 2016, 2020; Nurmukhamedov and Sidorov, 2019a, 2019b). However, the results of 3D density modeling (Nurmukhamedov and Sidorov, 2022) convincingly show that this layer is contained between the Moho boundary of the marginal part of the continental lithosphere and the roof of the oceanic lithosphere that subducted in the past (palaeosubduction roof). As for the oceanic lithosphere, the density of which is 3.2–3.3 g/cm³, the transition layer is characterized by a reduced density: ≤ 3.14 g/cm³. In the layer itself, in the depth range of ~35–45 km, local maximum decompaction zones have been identified (≤ 2.8 –3.0 g/cm³), which the authors (Nurmukhamedov and Sidorov, 2022) identify with melt chambers (Fig. 3). This layer is characterized by high permeability and, as a consequence, an anomalous heat flow (HF). According to some data (Smirnov and Sugrobov, 1980), the thickness of the HF at some points reaches 126–167 mW/m² versus 67–84 mW/m² of the “background HF”; according to others (Krasny, 1987), the measured HF within the same territory is

² A.G. Nurmukhamedov, Report on the Results of Studies on the Object “Development of a Geological and Geophysical Model of the Deep Structure of the Koryak–Kamchatka Fold Zone (Regional Linking ECWM-MTS Profile Cape Lopatka–Khailino).” Four books and one folder. Book 1: Petropavlovsk-Kamchatsky: OJSC Kamchatgeologiya, 2010.

³ G. Pak, V.S. Smirnov, and S.E. Aprelkov, Results of Geophysical Research at the Petropavlovsk-Shipunsky Forecasting Site and Mutnaya Bay–Apacha Regional Geophysical Profile. Report of the Kamchatka Integrated Geophysical Party of Regional Studies Conducted in Southern Kamchatka under the Program for Predicting Earthquakes and Volcanic Eruptions in 1987–1989. Sheets N-57-XIX-XXII; N-57-XX5-XXVII; N-57-31–33. Elizovo: EGFE PGO Kamchatgeologiya, 1989.

140 mW/m². Clearly, the independent HF estimates are very close.

According to some estimates (Nurmukhamedov, 2017), the permeable zone formed over a long period of time, probably from the Late Palaeogene. Melt chambers are sources of magma, the ascent of which led to the formation in the crust of a block saturated with mafic and ultramafic intrusions (Sidorov and Nurmukhamedov, 2022). Under the influence of HFs and differentiation of incoming magma, in the depth range from 8–10 to 30 km, an intrusive massif of predominantly diorite-granitoid composition was formed (Nurmukhamedov and Sidorov, 2022) (Fig. 3). Apophyses extend from the massif into the upper layers of the crust, some of which are exposed on the surface. The area is characterized by the presence of closed hydrothermal systems with the participation of post-magmatic solutions. This explains the formation of the gold deposit and ore occurrences of the Karymshinsky ore cluster (Nurmukhamedov et al., 2020).

Due to the interaction of the oceanic lithospheric plate with the overhanging continental plate, a seismic activity zone is formed: the seismic focal zone (SFZ). In the study area, the SFZ plunges from 100 km in the southeast of the site to 300 km in the northwest (Taranov, 1987). The Khodutka Bay–Nikolaevka Village profile passes through a segment where the depth to the SFZ is 100–200 km (Fig. 3). Some seismic events are located at relatively shallow depths, from a few to several tens of kilometers, and do not pertain to the focal zone. So, in 1987–1988, in the TAMC area, in the southern frame of the intrusive massif, a swarm of weak ($M \leq 5$) earthquakes was recorded³ (Fig. 3), called the Tolmachevsky epicentral zone (TEZ). The swarm coincides with the area of maximum concentration of cinder cones. The manifestation of seismic activity is explained by the movement of magma through a zone of weakness—a periodically “revived” (Zobin, 1979) eruptive fissure with a sublatitudinal strike (Nurmukhamedov et al., 2020; Nurmukhamedov and Sidorov, 2019b). Earthquakes are classified as type 1 (volcanotectonic earthquakes), which are indirectly related to volcanic eruptions (Chubarova, 2006).

As a result of seismological studies in 1981–1985³, a linearly elongated zone (Fig. 3) of high seismic activity was recorded, which in plan view coincides with the gravity step (Fig. 4). In the region itself there are areas where epicenters are concentrated. A significant number of earthquakes here are also classified as type 1, the nature of which is due to deep-seated magmatic processes.³ The seismically active zone almost completely coincides with the axis of the increased seismicity zone (AISZ), identified¹ based on data from the updated earthquake catalog posted on the website <http://www.emsd.ru/ts/>. The AISZ can confidently

be traced in the south-south-west direction up to Cape Kambalny in southern Kamchatka.

RESEARCH METHOD

In-depth ECWM studies were carried out according to standard methods (Pomerantseva and Mozzhenko, 1977). At each ECWM point (Fig. 2, 4, 5), triaxial recording of seismic waves was carried out. The average distance between points was 4 km. Recording of seismic events is done in the “as detected” mode. The duration of one stop was at least 30 days, which yielded a standard set of data necessary for identifying the boundaries of the exchange. The methodology for field observations and interpretation of ECWM data is presented in (Nurmukhamedov et al., 2016).

Electrical survey work was carried out in three modifications: AMTS (audio MT sounding), MTS, and DMT sounding (deep MTS). The field observation methodology is described in detail in (Nurmukhamedov et al., 2018).

A comprehensive analysis of the impedance tensor shows that the MT data up to a period of 1 s throughout almost the entire profile correspond to the 1D model (in a horizontally layered medium). During long periods (from 1 s in individual areas and from 10 s throughout the entire profile), the MT data correspond to an inhomogeneous environment. In this case, the inhomogeneities are mainly two-dimensional (2D) in nature. They manifest themselves as discrepancies between the TE and TM curves and reflect the influence of the regional induction effect formed in the Pacific Ocean (Moroz and Moroz, 2011). The weak influence of 3D inhomogeneities can be traced throughout almost the entire profile in periods longer than 100 s, and in certain areas in shorter periods (1–30 s).

Analysis of the obtained materials shows that 2D inversion of MT data is possible, but taking into account the influence of 3D inhomogeneities. For this, a 3D geoelectric model was calculated for the entire territory of the Koryak–Kamchatka folded zone,² where its structure is represented as a set of geoelectric blocks with a constant resistivity value. The combination of blocks (model elements) approximates various geological structures: sedimentary basins, depressions, fault zones, deep conductive structures, etc. A detailed description of the 3D modeling methodology is presented in (Belyavsky and Aleksanova, 2014; Belyavsky and Yakovlev, 2016).

To construct the final geoelectric model, bimodal 2D inversion of normalized curves corresponding to the regional longitudinal (TE) and regional transverse (TM) directions according to the program was carried out (Rodi, Mackie, 2001). In general, the methodology for constructing a 2D geoelectric model is close to the methodology presented in (Nurmukhamedov

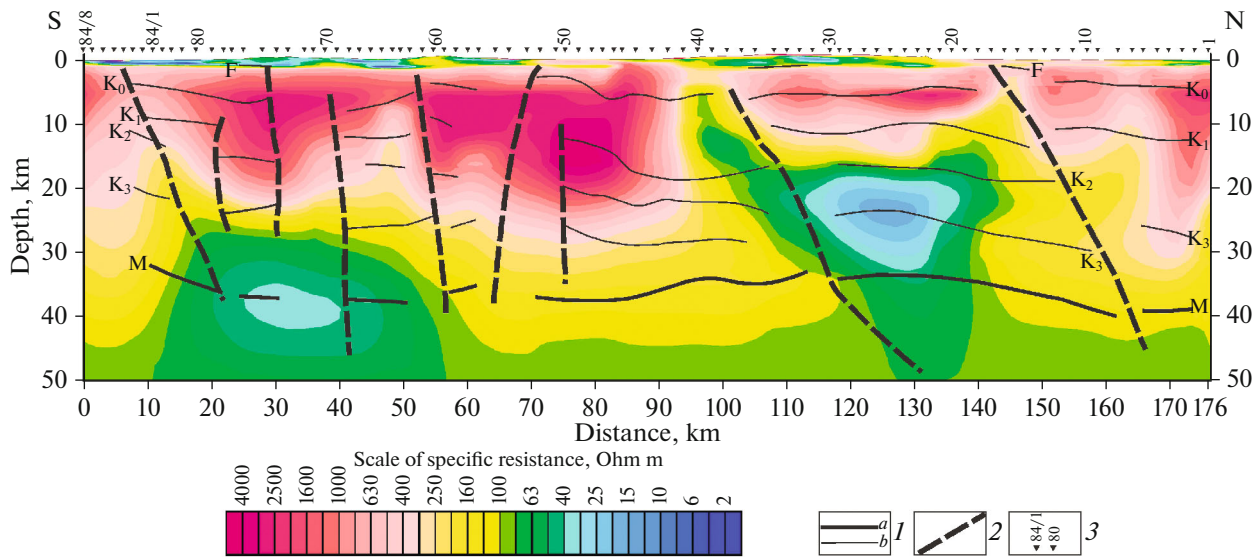


Fig. 6. Two-dimensional geoelectrical model along the Khodutka Bay–Nikolaevka Village profile. (1) Seismic boundaries identified by ECWM: Moho discontinuity (a) and other boundaries (b); (2) Faults identified by ECWM; (3) MTS points and their numbers. Position of profile is shown in Fig. 1.

et al., 2018). The starting model was created based on the results of 1D and 3D inversion of MT data. In the upper part of the section, where the data corresponds to the 1D model, the resistivity was set according to the 1D inversion results; in the lower part, according to the 3D modeling results (section of the 3D model along the line of the profile), which made it possible to take into account the influence of 3D inhomogeneities. The applied technique made it possible to obtain the most reliable geoelectric model along the Khodutka Bay–Nikolaevka Village profile (Fig. 6).

In addition to the presented geoelectric model, using the same initial data, but using a different interpretation scheme, our colleagues constructed a deep geoelectric section (Moroz and Samoilova, 2013) using 1D inversion of the TE-mode curves. Despite the qualitative convergence, there are noticeable differences in these models. For example, the configuration and depth of occurrence of high-resistivity and abnormally low-resistivity objects differ. This is especially noticeable in the depth of the lowest-resistivity part of the crust-mantle conductor in the southern half of the model, where according to the article (Moroz and Samoilova, 2013) it is 40–55 km, and in the geoelectric model (Fig. 6) 32–45 km. In the northern part of the section (Moroz and Samoilova, 2013), no branches from the crustal high-conductivity object were recorded, which is clearly seen in the geoelectric model in Fig. 6. According to the authors of this article, these differences could have arisen due to lack of consideration of the three-dimensionality of the geoelectric medium in the middle and lower parts of the section when performing 1D inversion of the MTS curves.

To study the rock density distribution in the crust and upper mantle, 2D density modeling was performed (Fig. 7) using gravimetric survey materials at a scale of 1 : 200 000, according to the method described in (Sidorov and Nurmukhamedov, 2022). The initial framework of the model was the boundaries and faults identified by the ECWM (Nurmukhamedov et al., 2016). The initial density values of the upper layers of the section were determined from rock samples outcropping on the surface. For deep layers, density values are taken from published sources. Thus, for Upper Cretaceous deposits, the density is assumed to be 2.67 g/cm³; for the granite–metamorphic (“granite”) layer, 2.64–2.8 g/cm³; for the granulite–mafic (“basalt”) layer, 2.80–3.07 g/cm³, and for the upper mantle, 3.30 g/cm³. The indicated densities are taken as primary data for iterative selection of the model. Calculations were carried out using the Geosoft Inc. software package. (GMSYS, Oasis Montaj, Grav/Mag Interpretation, 3D Euler, MAGMAP filtering).

In addition, the authors also performed 2D magnetic modeling (Fig. 7). Aeromagnetic survey materials at a scale of 1 : 200 000⁴ were used as the reference data. The simulation was carried out with a constant geometry of the selected elements in the density section. As a result, the effective magnetic parameters for the blocks of the density model were determined. On the section of the profile between the Mutnaya and

⁴ M.D. Sidorov, Report on Studies on Creating Remote, Geochemical, and Geophysical Foundations of the Third-Generation State Geological Map-1000, sheets N-(56), 57, (58); M-57 (advanced stage). Three books. Book 2: Geophysical Basis. P-Kamchatsky: KPSE, 2001.

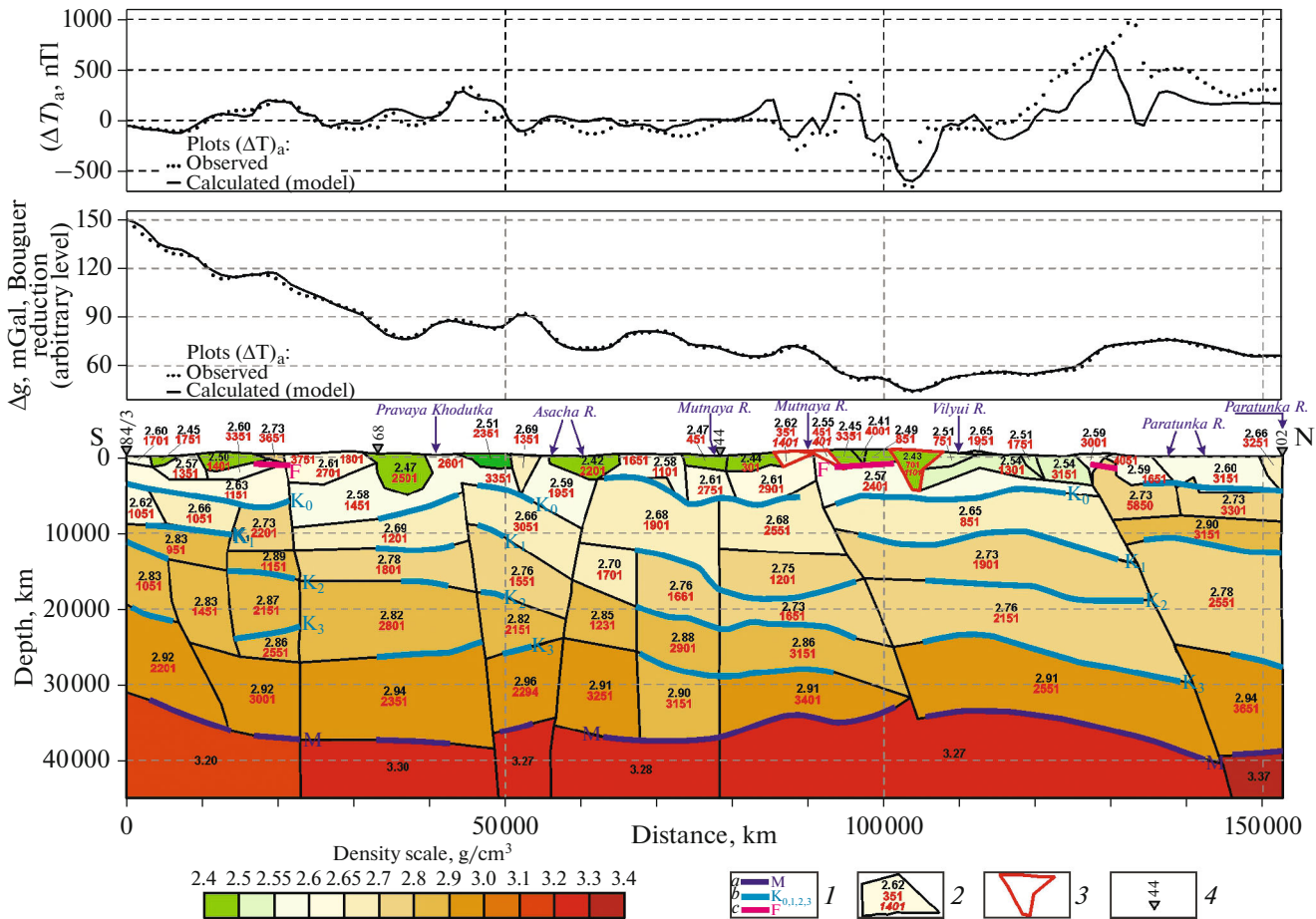
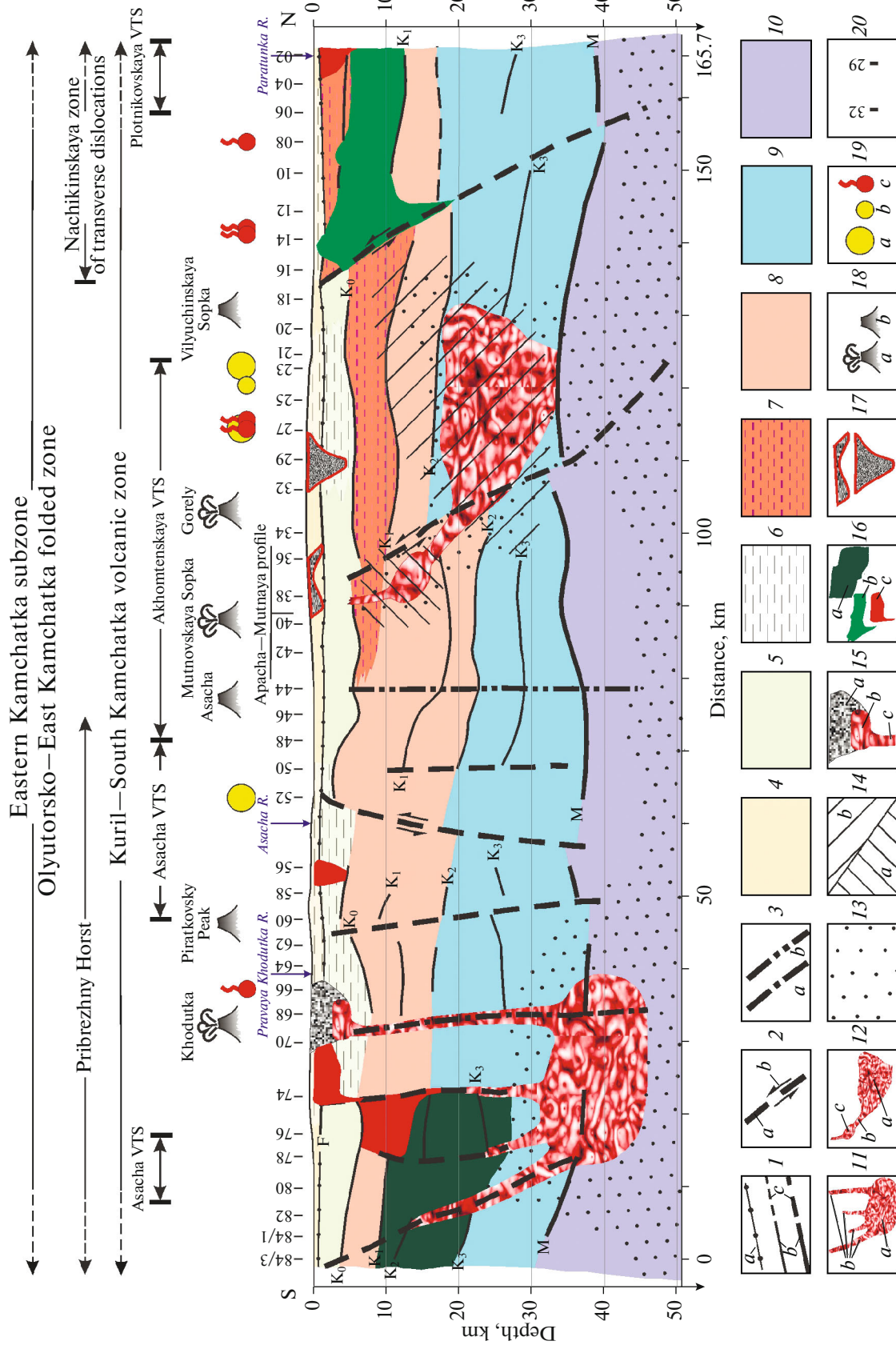


Fig. 7. Deep density model along the Khodutka Bay–Nikolaevka Village profile. (1) Seismic boundaries identified by ECWM: Moho discontinuity (a) and other seismic boundaries identified in crust (b, c); (2) Units boundaries, and (from top to bottom) their average density values (g/cm^3), magnetic susceptibility ($1.26 \times 10^{-3} \text{SI}$), and remanent magnetisation ($10^{-3} \text{A}/\text{m}$); (3) Model blocks where remanent magnetisation vector is directed to upper halfspace; (4) ECWM points and their numbers. Position of profile is shown in Fig. 1.

Vilyucha rivers in the upper part of the section, the remanent magnetisation vector is directed toward the upper halfspace, and its value exceeds the inductive one. Here, the profile intersects an ignimbrite

sequence. For these rocks, such a ratio of magnetic vectors was noted earlier during petrophysical studies accompanying geological surveys in the Sredinny Ridge and on the Kamchatka isthmus. In the remain-

Fig. 8. Deep geological–geophysical model along the Khodutka Bay–Nikolaevka Village profile. Names and boundaries of geological structures above model are given according to tectonic chart shown in Fig. 2. Position of profile is shown in Fig. 1. (1) Roof of Upper Cretaceous rock unit based on MTS data (a); boundaries identified by ECWM: confirmed (b), inferred (c), identified with roof of Upper Cretaceous rock unit (F), roof of consolidated crust (K_0), boundary between upper and lower crust (K_2), Moho discontinuity (M) and other seismic boundaries within crust (K_1 , K_3); (2) Fractures according to ECWM data (a) and shear dislocations along them (b); (3) Faults identified: (a) according to ECWM data, but not confirmed by density modeling, (b) according to results of density modeling; (4) Cenozoic volcanosedimentary rocks; (5) Mesozoic rocks; (6) Hydrothermally altered Mesozoic–Cenozoic rocks; (7) Top layer of metamorphic rocks predominantly occurring in greenschist and epidote–amphibolite facies; (8) Granite–metamorphic (granitic) layer of upper crust; (9) Granulite–mafic (basaltic) layer of lower crust; (10) Upper mantle; (11) Crustal–mantle magma chamber (a) and inferred magma and magmatic fluid pathways (b); (12) Lower-crust magma chamber (a), magma ascent conduit (b) and intermediate magma chamber (c); (13) Reduced resistivity areas ($50\text{--}100 \Omega\text{-m}$ versus $200\text{--}1000 \Omega\text{-m}$); (14) Zones of reduced P - (a) and S -wave (b) velocities (Gontovaya et al., 2010); (15) Volcanic depression (a) under Khodutka volcano, inferred peripheral magma chamber (b) and conduit (c) leading to it; (16) Crustal unit bearing numerous intrusive mafic and ultramafic bodies (a), intrusive mass of complex composition, from gabbro–gabbrodiorites to diorite–granodiorites (b), intrusive massif of granite–granodiorite composition (c); (17) Reverse magnetisation of ignimbrites; (18) Projections of active (a) and extinct (b) volcanoes closest to profile and their names; (19) Deposits (a) and ore occurrences (b) of gold, sources, and fields of thermomineral waters (c); (20) ECWM–MTS observation points and their numbers.



ing parts of the section, the total vector is directed to the lower half-space.

Seismological studies (Fig. 3) were carried out with Cherepakha equipment sets, which included SK-1P seismic receivers and ASS-6/12 recorders. Records of local earthquakes were used in processing. The epicenters, hypocenters, and other parameters of seismic events were determined by methods presented in (Pomerantseva and Mozzhenko, 1977). Processing of the obtained data consisted of processing earthquakes of the energy class $K \leq 7$ and $K \geq 7$. Processing of weak earthquakes ($K \leq 7$) was carried out using records from Cherepakha stations. Processing of earthquakes with $K \geq 7^3$ was done using the database of the Institute of Volcanology, Far Eastern Branch, USSR Academy of Sciences, obtained by the regional seismic network. As a result of processing local epicenter data, an earthquake catalog and a map of local earthquake epicenters were compiled,³ a fragment of which is shown in Fig. 3.

The authors of this article have constructed a deep geological and geophysical model along the Khodutka Bay–Nikolaevka Village profile (Fig. 8). During its creation, crustal and mantle faults constituted the framework, as well as the boundaries of the lithosphere, identified from ECWM data. The identified seismic boundaries are discontinuous, which is particularly noticeable in the southern half of the model, where the pattern of the deep structure is supplemented by the density modeling results: the boundaries not traced by the ECWM continue as boundaries of layers and blocks with different densities.

In Mesozoic–Cenozoic strata, in the active hydrothermal activity zone, there are areas of hydrothermally altered rocks. The entire rock sequence is penetrated by crustal and crustal faults, dividing the crust and upper mantle into separate blocks. The model includes anomalously low-resistivity areas (15–40 Ω m against a background of 150–2000 Ω m), interpreted as crust–mantle and lower-crustal magma chambers, the supposed feeders of active volcanoes. The model indicates the boundaries of the main geological structures intersected by the profile, projections of volcanoes, ore occurrences and gold deposits located close to the profile, as well as sources of thermal mineral waters.

ANALYSIS OF GEOLOGICAL AND GEOPHYSICAL MODEL AND DISCUSSION

As noted above, Kamchatka is located on the active continental margin as a result of subduction of oceanic lithosphere under the continental plate and collision. Along the eastern coast of Kamchatka, an area of terranes of the eastern peninsulas is distinguished (Fig. 3). Geological description and palaeogeodynamic reconstructions of the accretion of island-arc

blocks to the continental slope of Eastern Kamchatka are presented in a number of publications (Mishin, 1996, 1997; Seliverstov, 2009; Shapiro and Solov'ev, 2009, etc.). According to N.I. Seliverstov (2009), the Shipunsky (Avacha according to N.I. Seliverstov) and Kronotsky island-arc blocks became part of the accretionary complex of Eastern Kamchatka in the Late Miocene, and the northernmost—Kamchatka—at the end of the Pliocene. The authors of this article are interested in the Pribrezhny Terrane in Kamchatka's extreme southeast (Fig. 3), previously identified solely by the specific morphology of the gravity field (Mishin, 1996, 1997). A characteristic feature of the northern terranes is outcrops of mafic and ultramafic rocks (Aprelkov and Olshanskaya, 1989), but in the zone of the inferred Pribrezhny Terrane such rocks are not exposed. This can be explained by the fact that the area is covered from the surface by Quaternary and Middle Eocene–Pliocene volcanosedimentary rock strata (Geologicheskaya..., 2005). The belonging of the structure to the terrane could be confirmed (or refuted) by the presence of pre-Eocene formations here, but such rocks have not been found in this area. In addition, by the time the articles (Mishin, 1996, 1997) were published, no deep geophysical research had been carried out in the vicinity of the analyzed structure. Such studies were carried out much later, in 2009 along the Khodutka Bay–Nikolaevka Village profile. Analysis of the geological and geophysical model (Fig. 8) makes it possible to refine the specific features of the geological structure of the lithosphere and the structural position of the inferred terrane, and to identify the genetic relationships between gold deposits and deep features of the lithosphere.

The thickness of the crust varies between 30–40 km. Closer to the coastline, a tendency towards thinning of the crust is noticeable, characteristic of the entire southeastern coast of Kamchatka (Nurmukhamedov et al., 2016). The upper and lower parts of the crust are characterized by a more complex morphology. In the north of the profile, the thickness of the granite–metamorphic layer is 12–14 km. In the southern direction, the thickness of the layer gradually decreases, reaching less than 10 km in the extreme south of the profile. The thickness of the lower crust (granulite–mafic layer) varies between 16–22 km. However, in the vicinity of an inclined fault that penetrates the crust and the lithospheric mantle (ECWM points 34–38), thinning of the lower crust to 10–12 km is observed. In the same place, compensation of the thickness of the entire crust is noted due to an increase in the granite–metamorphic layer to 16–22 km. Boundary K_2 separating the upper and lower crust is discontinuous. Its disrupted continuity is particularly noticeable in the southern part of the model.

The authors of this article typified the Earth's crust using the methodology proposed by I.P. Kosminskaya (1967). The method involves analyzing the ratio of the thickness of the upper and lower crust to its total thick-

ness. Thus, in the interval of points ECWM 02–36, the thicknesses of the upper and lower crust are comparable, but with a slight excess in the thickness of the lower crust. According to formal characteristics, this corresponds to transitional suboceanic crust, characteristic of passive continental margins, but since the territory under study is attributed to the active margin, in the authors' opinion, the crust should be classified as a transitional subcontinental type. In the central part of the model (Fig. 8, points 36–50), the thicknesses of the upper and lower crust are comparable, with the upper layer slightly predominant. Given the insignificant thickness of the entire *consolidated* crust (30–35 km), this area should also be classified as transitional subcontinental.

The model identifies crustal and crustal–mantle faults that form the boundaries of the blocks. Along individual faults, displacement of the layer boundaries is observed. The most significant displacement amplitude (8–10 km) was noted along boundary K_2 along an inclined crust–mantle fault (Fig. 8, points 34–36). In this place, the geophysical profile at an acute angle intersects the crust–mantle fault, which can be traced along a linearly elongated epicentral zone (seismic lineament) with a north-northeast strike (Fig. 3).

In the northern part of the model there is an inclined deep-seated fault, which in plan view coincides with the Vilyuchinsky fault, previously identified based on geological data and which is the southwestern boundary of the NTDZ (Fig. 2). The fault plane dips to the northeast at an angle of 80° – 85° . Displacement of layers was noted along the fault.

A completely different character of the section is observed in the southern part of the model. A significant number of faults of various inclinations and configurations were noted here (Fig. 8). The division of the crust into separate relatively small blocks indicates that this area was subjected to powerful destructive impacts in the relatively recent geological past. In the density model (Fig. 7), this place is marked by a consisting of a crustal block, characterized by high densities (2.83 – 2.89 g/cm³) and magnetic susceptibility $(951$ – $2151) \times 1.26 \times 10^{-5}$ SI. The block is bounded at the top by section K_1 . Judging by the physical properties, the block consists of rocks ranging from mafic to ultramafic.

Thus, both in structure and rock composition, this section of the crust has a separate, alien character in relation to the rest of the model according to the following main features:

- a significant increase in thickness of the lower crust with considerable thinning of the upper crust is recorded in the section;

- at a depth of ≥ 10 km, a high consisting of a block of rocks with a presumably mafic–ultramafic composition, characteristic of northern terranes, was noted;

- the entire block and its frame are penetrated by numerous crustal and crustal–mantle faults.

Based on all the information obtained, the authors believe that the southern fragment of the profile intersects the flank, the most destroyed part of the Pribrezhny Terrane. The destruction of the terrane occurred as a result of its attachment to the continental slope of Kamchatka. Based on the available data, it is difficult to determine the time of the xenoblock's accretion to Palaeo-Kamchatka. However, if we consider volcanism as a geological event that developed after or during the accretion of the island-arc block to the continental margin, then the age of the rocks of the volcanic complex (VC) can be taken as a time reference, from which we can determine the *approximate* time of the terrane's entry into the accretionary complex of Southeast Kamchatka.

There are two versions of the terrane's entry:

- in accordance with the geological map (Geologicheskaya..., 2005), the age of the most ancient undivided volcanogenic rock complex (VC) dates back to the Oligocene–Miocene and it can be assumed that the attachment of the island-arc block and the formation of the Pribrezhny Terrane could have occurred no later than the Upper Oligocene;

- it is possible that the volcanogenic complex overlies older volcanic formations than the indicated ones – possibly the VC of the Lower Oligocene. In this case, the entry of the terrane into the accretionary complex of Kamchatka could have occurred no later than the Upper Eocene.

A similar viewpoint is proffered by N.I. Seliverstov (2009), who believes that accretion of the island-arc block occurred at the end of the Eocene–beginning of the Oligocene. This version presupposes the initial existence of a single xenoblock, the division of which into separate fragments occurred under the impact of shear dislocations along the NPDZ with a shear amplitude of at least 100 km. The southern fragment of this xenoblock is the Pribrezhny Terrane.

One of the events in the geological history of Kamchatka was accretion of the Achaivayam–Valaginsky island arc to Palaeo-Kamchatka. According to A.V. Solov'ev (2005), the collision occurred in the Early–Middle Eocene; according to M.V. Luchitskaya (2013), in the early Eocene. In both estimates, the age of entry into the accretionary complex of the peninsula is close to the second for the accretion of the Pribrezhny Terrane. It can be suggested that the Achaivayam–Valaginsky Terrane (Fig. 1) is a northern fragment of a once unified terrane accreted to Palaeo-Kamchatka in the Eocene. The division of the single structure occurred under the influence of a left-lateral transform fault along the NTDZ (Fig. 1).

It seems to the authors that the reason for such a powerful shear dislocation could have been the subsequent entry of the Shipunsky and Kronotsky terranes into the accretionary complex of Eastern Kamchatka

in the Late Miocene and the Kamchatka Terrane (Fig. 3) at the end of the Pliocene (Seliverstov, 2009). The accretion of the island-arc blocks blocked the subduction of the oceanic lithosphere, but at the same time, its lateral pressure on the marginal part of the continental plate continued for some time (until the subduction zone jumped to the east). The pressure led to high-amplitude shear dislocation. The stated viewpoint is consistent with the opinion of I.D. Petrenko (1999), where a large-scale shear dislocation was also noted along the Nachikinskaya (Malko-Petropavlovskaya) transverse dislocation zone, but in relation to the CKVB. It was noted “that the northern and southern branches of the CKVB belong to a single structure, broken along the Malko-Petropavlovsk transverse dislocation zone. The displacement of their axes in plan is explained by “...large-scale shear dislocations in the Miocene–Pliocene” (Petrenko, 1999, p. 12). It should be noted that the stated viewpoint is close to the conceptual model of the jump in the subduction zone in the Late Miocene (Avdeiko and Palueva, 2006) and the geodynamic evolution of the Central Kamchatka and East Kamchatka volcanic arcs (Avdeiko and Bergal-Kuvikas, 2015).

The morphology of the gravity field (Fig. 4) gives grounds to believe that the majority of the Pribrezhny Terrane is located in the ocean and stretches along the southeastern coast of the peninsula, including Cape Lopatka. To the west of the terrane is a 30–40-km-wide zone within which modern volcanism has occurred. Increased seismicity was also noted in this zone. The epicenters of local earthquakes form a narrow lineament with a length of 70 km (Fig. 3), where the hypocenters of seismic events are concentrated at relatively shallow depths, from 2–5 to 15–20 km⁵. As noted above, the seismically active lineament almost completely coincides with the AISZ and possibly continues to the south-southwest.

Upon analysis of the geoelectric model (Fig. 6), it is clear that below the Moho boundary, there is a layer with a reduced electrical resistivity level, 80–130 Ω m. The layer contains geoelectric inhomogeneities with a lower resistivity value, which above the Moho boundary transform into localized electrical conductivity anomalies. Thus, in the south of the profile, in the depth range of 30–45 km, a crust–mantle object with a resistivity level of 30–50 Ω m is distinguished. It is suggested that the low-resistivity anomaly is associated with an area saturated with magmatic melts and hydrothermal solutions (Moroz and Samoilo, 2013), and faults penetrating the Earth’s crust (Fig. 8)

⁵ Ya.B. Shvarts, Report on Detailed Prospecting Geophysical Studies at the Dachny Site, Prospecting Geophysical Studies on the Western Flanks of the Mutnovsky Steam-Hydrothermal Field, and Studies on Summarizing Geophysical Materials for the Mutnovsky Geothermal District in 1987–1990. (Second Dachnaya Expedition Party). Six books. Book 1: text of report. Elizovo: EGFE PGO Kamchatgeologiya, 1990.

serve as pathways for the ascent of magma and magmatic fluid into the upper layers of the crust.

In the northern half of the profile, in the vicinity of the Akhomten VTS, in the depth range of 18–33 km, a lower-crustal electrical conductivity anomaly (15–40 Ω m) was identified, which coincides with a zone of relative decrease (–5 to –10%) in longitudinal wave velocity (V_p) (Gontovaya et al., 2010). An apophysis extends from the anomalous object, which almost completely coincides with the inclined fault. As noted above, a high-amplitude shear dislocation is observed along the fault. The selected objects are interpreted by the authors as follows.

In the lower crust there is a magma chamber. From the source along the inclined crust–mantle fault, magma and deep fluid ascent into the zone of active volcanoes. The rise of magmatic material occurs along an extended seismically active fracture, a fragment of which in the section (Fig. 8) is an inferred inclined magma conduit. At a depth of 11–16 km from the surface, expansion of the magma conduit was noted. The formation of a kind of “bloat” can be explained by the formation of an intermediate magma chamber. This agrees well with the seismic tomography results (L.I. Gontovaya, oral communication), according to which in the vicinity of Mutnovsky volcano, in the depth range of approximately 10–20 km (Fig. 8), a zone of relative decrease (–5 to –7%) in shear wave velocity (V_s) occurs. At the same depths, a local area with anomalously high ratios of the longitudinal to shear wave velocity has been confidently identified (V_p/V_s): 1.85–1.95 or more. An anomalous decrease in V_s , and increase in V_p/V_s values speak to the presence in this place of an object with high rock plasticity—probably a magma chamber. Advancement of magma into the upper layers is accompanied by active seismic events: volcanotectonic earthquakes, the epicenters of which form an extended seismic lineament.

An increase in the electrical conductivity anomaly (Fig. 6) is also observed to the north of the lower crustal source, at MTS points 16–21, where the profile once again intersects the eruptive fissure. It is assumed that entire fracture is filled with melts, magmatic fluids, and hydrothermal solutions. The depth to the upper boundary of such a zone may vary depending on the geological conditions. The authors suggest that MTS studies have recorded only individual fragments of an extended magmatic zone (Fig. 8) in places where the geophysical profile intersects this zone. Judging from the electrical conductivity distribution pattern (Fig. 6), the identified sources have roots in the upper mantle.

It should be noted that the presence of the electrical conductivity anomaly in the analyzed part of the section, coinciding with a zone of low velocities, is not accompanied by rock decompression (Fig. 7). Similar situations are discussed in the monograph (Balesta, 1981), where the author notes that in the zone of active

volcanism, the rock density decreases with increasing temperature, but its decrease is small, a few percent. It is likely that the melting effect and increase in density with depth mutually compensate each other.

In accordance with the geoelectric model (Fig. 6), areas with resistivity levels from 800 to 4000 Ω m have been identified in the upper crust. The most significant areas in terms of scale, where the resistivity reaches maximum values (3000–4000 Ω m), are noted in the southern half of the profile. At this location, the profile crosses the western flank of the Pribrezhny Terrane at different azimuths. The high resistivity level can be explained by the manifestation of regional metamorphism, which accompanied the accretion of the xenoblock. The zone of intense heat removal, occurring predominantly via convection, extends from the Koshelevsky hydrothermal system in the southwest of the peninsula and further through the Ilyinsky, Zheltovsky, Ksudach, and Khodutka volcanoes (Fig. 2–5) to the Mutnovsky geothermal region inclusive (Smirnov and Sugrobov, 1980). According to published data (Krasny, 1987), the measured HF in the vicinity of the southern part of the profile is 70–110 mW/m²; in the central part, 90–110 mW/m²; and in the north, 60–90 mW/m². HFs, as well as active hydrothermal activity, contributed to deep metamorphic alterations in rocks with a high resistivity level.

Some of the most well-known thermal water deposits are located in close proximity to the Khodutka Bay–Nikolaevka Village profile (Figs. 2–5). To the west of the profile, at a depth of 8–10 km or more, there is an intrusive massif of acid–medium acid composition (Nurmukhamedov et al., 2020; Nurmukhamedov and Sidorov, 2019b). In the vicinity of the massif (Fig. 3) is the Karymshinsky ore cluster, in which closed systems of postmagmatic ore-bearing solutions functioned for a long time (Nurmukhamedov et al., 2020). Similar massifs along the Khodutka Bay–Nikolaevka profile were not found, but in the south (Fig. 8, points 56, 58 and 70, 74), blocks with granite–granodiorite intrusions were identified. In the same place, active hydrothermal activity was noted, where the existence of closed hydrothermal ore-forming systems is also inferred.

The Asachinskoe, Mutnovskoe, and Rodnikovoe gold deposits, as well as the Rogatka and Bystrinskoe ore occurrences, are spatially adjacent to the Mutnovsky fault (Fig. 2). According to I.D. Petrenko (1999), in surface structures, the fault is manifested as an extension zone, expressed in the form of a graben 10 km wide. Its formation occurred no later than the Middle Miocene. The fault identified along the seismic lineament (Fig. 3) runs parallel to the Mutnovsky at a distance of approximately 10–12 km. It seems to the authors that both tectonic faults belong to a single inclined fault, identified in the model in the interval of points 29–40. Indeed, the first of them was identified from geological and geophysical data (Geologich-

eskaya..., 2005); the second, from a linearly elongated zone of concentration of earthquake epicenters. The hypocenters of seismic events were recorded in the depth range from 2–5 to 15–20 km with their maximum concentration at a depth of 8–14 km. Taking into account the average distance between the mentioned faults and the depth to the areas with the maximum concentration of hypocenters, it is easy to see that the dip angle of the fault plane is approximately 45°, and the dip azimuth is 300°. Such parameters are close to modern SFZ (Seliverstov, 2009). However, the depth to the SFZ in the vicinity of the seismically active lineament is 170–180 km. Based on the available data, it can be suggested that in this place, a fragment of ancient subduction—palaeosubduction—was recorded by geophysical methods. Subduction was blocked by the Pribrezhny Terrane no later than the Upper Oligocene or at the end of the Eocene—beginning of the Oligocene, with its subsequent jump to the east into the ocean. The suggestion about the existence of a palaeosubduction zone here is confirmed by the results of volumetric density modeling of Southern Kamchatka (Nurmukhamedov and Sidorov, 2022). The model clearly distinguishes two surfaces with a density of 3.33 g/cm³, plunging west-northwest to great depths (Nurmukhamedov and Sidorov, 2022). One of them is located under the Pacific Ocean and is interpreted by the authors as a fragment of the roof of modern subduction; the second plunges under the peninsula and is identified with the palaeosubduction roof. The blocking of the latter, according to the authors, occurred in the Middle–Late Palaeogene as a result of accretion of the island-arc block to Palaeo-Kamchatka.

It is noteworthy that a significant part of the gold deposits and ore occurrences are concentrated in the region adjacent to the southwestern border of the NTDZ, the Vilyuchinsky fault. To the northeast of this boundary, neither gold deposits nor ore occurrences have been discovered to date, which indicates that the ore formation process occurs in a dynamically active zone of modern volcanism. Judging from the location of the Asacha, Akhomten, Karymshinskaya, and Plotnikovskaya VTS (Figs. 2, 4, 5), the amplitude of the shear dislocation along the fault is 50–60 km. According to M.M. Lebedeva and S.E. Aprelkova (1979), the noted dislocation occurred in the Miocene–Pliocene, and according to I.D. Petrenko (1999), in the Pliocene–Early Pleistocene. The authors of this article hew to the second viewpoint. During the same period of time, the main phase of ore mineralisation occurs. Probably, the process of ore formation occurred first, and then a left-sided dislocation carried the already formed deposits along faults. As a result, an L-shaped zone was formed, within which gold deposits and ore occurrences are located. The main ore-controlling and ore-generating role in it is played by a seismically active fault in the palaeosubduction zone, and this is one of the main features of

the architecture of the lithosphere in the study area. Essentially, the zone of seismically active lineament and the adjacent areas is a rift zone — a zone of recent extensions 30–40 km wide.

Let us briefly present the time of this sequence during which the formation of the lithosphere took place in Southeast Kamchatka. Until the Eocene inclusive, the oceanic lithosphere subsided under the overhanging continental lithosphere. At the end of the Eocene—beginning of the Oligocene, the island-arc block was accreted to the continental slope of Palaeo-Kamchatka, which led to blocking of the subduction zone and its jump to the east, into the ocean. The formation of the rift zone probably began in the Oligocene, after which, in Oligocene-Quaternary time, volcanic activity intensified. The main phase of gold mineralisation occurred in the Pliocene—Early Pleistocene.

In accordance with the proposed geological and geophysical model, the formation process of gold deposits is as follows. From the extended crust—mantle magmatic zone, magmatic melts and high-temperature fluids enriched in noble metal solutions ascend along discontinuous faults—magma conduits. The geological and geophysical model (Fig. 8) shows individual fragments of the magmatogenic zone and the inferred feeder channels. Under the influence of powerful HF and differentiation of incoming magma, magma chambers of moderately acid and acid compositions are formed in the upper layers of the crust. Examples include an intermediate chamber in the vicinity of Mutnovsky volcano and a peripheral chamber in the vicinity of Khodutka volcano. As a result of dehydration of magma, juvenile waters saturated with noble metal solutions are released. Ore-bearing solutions mixing with infiltration (meteoric) waters form high-temperature hydrothermal systems, within which active metamorphic development of rocks occurs, along with the formation of epithermal gold deposits. Thus, in the vicinity of the Asacha and Akhomten VTS, in the upper layers of the crust, areas of hydrothermally altered rocks of Mesozoic—Cenozoic age were formed (Fig. 8), in the vicinity of which are gold deposits and ore occurrences. The constant feeding of magmatic—hydrothermal systems with high-temperature fluid enriched in noble metal solutions makes the ore formation process continuous over time.

CONCLUSIONS

1. The model created based on ECWM, MTS, gravimetry, magnetometry, and other data shows the main boundaries of the lithosphere and identifies previously unknown elements of the structure of the Earth's crust. In general, the crust in Southeast Kamchatka can be classified as transitional subcontinental.

2. The authors, based on geological and geophysical data, believe that in Kamchatka's extreme south-east there is a xenoblock: the Pribrezhny Terrane. It has been suggested that this terrane is a southern fragment of what was once a single island-arc terrane, accreted to Palaeo-Kamchatka in the Eocene. Its northern fragment is the Achaivayam—Valaginsky Terrane. The separation of xenoblocks occurred under the action of a left-lateral transform dislocation along the NTDZ with a displacement amplitude of at least 100 km.

3. Most of the Pribrezhny Terrane is located in the Pacific Ocean and stretches along the southeastern coast of Kamchatka, including Cape Lopatka. To the west of the xenoblock is a zone of recent extensions 30–40 km wide, in which modern volcanism has occurred. The ascent of magma occurs along an extended eruptive fissure: a magma conduit. The intrusion of magma into the upper crustal horizons is accompanied by active seismic events—volcanotectonic earthquakes, the epicenters of which form an extended seismic lineament.

4. The eruptive fissure is inherited from the zone of maximum inflection of palaeosubduction, a slab, and this is one of the main features of the architecture of the lithosphere in the study area. The presence of palaeosubduction is confirmed by geological and geophysical data. No later than the Upper Oligocene, the subduction zone was blocked by the Pribrezhny Terrane, which led to its jump to the east, into the Pacific Ocean.

5. In the geological and geophysical model, crustal and lower-crustal magma chambers have been identified. From the chambers, along faults, magma and magmatic fluid rise into the zone of active volcanoes. In the center of the model, at a depth of 11–16 km from the surface, expansion of the magma conduit was noted. The formation of a kind of “bloat” is explained by the presence of an intermediate magma chamber. Both the crust—mantle and lower-crustal chambers are fragments of an extended crust—mantle magmatogenic zone, with its roots going into the upper mantle.

6. The gold ore formation process occurs in the dynamically active region of Southeast Kamchatka, the southern part of the EKVB. The Rodnikovoe, Mutnovskoe, and Asachinskoe deposits, as well as the Rogatka and Bystrinskoe ore occurrences, are genetically associated with an eruptive fissure, which plays the main ore-controlling and ore-generating role in the formation of deposits. Based on the results, the authors propose a model formation of gold deposits in the study area. From the extended crust-mantle zone, along deep faults-magma conduits, magmatic melts and high-temperature fluids enriched in solutions of noble metals rise. Under the action of HF and magma differentiation, intermediate and peripheral magma chambers of moderately acid and acid compositions formed in the upper layers of the crust. As a

result of dehydration of acid magma, juvenile waters saturated with noble metal solutions are released. Ore-bearing solutions, mixing with meteoric waters, form closed hydrothermal systems, where the formation of epithermal gold deposits occurs.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests to report.

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