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Geology, magmatism, metallogeny, and geodynamics of the South Kuril islands

Vadim G. Khomich[a,b,*], Natalia G. Boriskina[a,b], Sergei A. Kasatkin[a]

[a] Far East Geological Institute, Far East Branch of Russian Academy of Sciences, 159 Prospect 100 let Vladivostoku, Vladivostok 690022, Russia
[b] School of Engineering, Far Eastern Federal University, 8 Suhanova St., Vladivostok 690950, Russia

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ABSTRACT

Intense fluid thermal fluxes in the continental lithosphere and crust from sub- and supra-subduction asthenospheric zones were the root cause of the formation of magmatic chambers and the development of volcanism and multimetal ores. We demonstrate this phenomenon using the example of the South Kuril.

The southern chain (including the large Kunashir, Iturup, and Urup islands) of the Greater Kuril Ridge of the "island arc-trench" system is confined to the northwestern Pacific subduction megazone. Inherited transform faults (Nosappu, Iturup, and Urup) occur in the oceanward part of the SSE segment of the Kuril-Kamchatka trench. Repeated movements of the oceanic region sandwiched between the fault zones were accompanied by earthquakes and low-volume petit-spot-type submarine eruptions of highly alkaline basaltic rocks. The latter were sourced from an asthenospheric mantle beneath the oceanic slab. Recurrent manifestations of compressional to extensional stresses in the subduction zone during the Oligocene-Neogene and Pleistocene-Holocene were accompanied by under and overthrusting and earthquakes.

1. Introduction

Several island-arc systems spatially associated with deep-water trenches, seismofocal zones, and active volcanic centres exist near the Asian margin. It was recently found that some of these island-arc systems contain numerous bedrock deposits of not only traditional but also peculiar minerals. In particular, the PGE, rare-metal, and REE endogenous occurrences were revealed in the southern Kuril island-arc system (KIS) situated in the northwestern circum-Pacific region (Znamenskii et al., 1993; Kovalenker et al., 1993; Korzhinskii et al., 1993; Danchenko, 1999; Razin, 2011). A new type of submarine volcanism called a "petit-spot" was discovered in the vicinity of the southeastern flank of the KIS and the Kuril trench (Hirano et al., 2001; Ogawa and Hirano, 2003; Hirano et al., 2006; Fujiwara et al., 2006; Junji et al., 2009).

The presence of rather unusual magmatic rocks and mineralization allowed us to distinguish the South Kuril as a particular phenomenon that merits special attention. Comprehensive geological-geophysical, seismological, geochemical-petrological, and metallogenic data are synthesized in this paper to discuss the possible role of deep geodynamics in the formation of the specific ore-magmatic systems in this part of the Greater Kuril Range (GKR).

2. Brief Geophysical-Geological characteristics

The 1175 km-long KIS consists of two subparallel island ridges: the Greater (volcanic, internal, rear-arc, Okhotsk region) and the Lesser (nonvolcanic, external, frontal zone, Pacific region) Kurils separated by the Middle Kuril trough (Fig. 1A). The KIS system is bounded by the trapezoidal Kuril-Kamchatka trench (8–9 to 10.5 km deep, 5–10 km wide at the base and approximately 100 km wide near the water surface) in the east and by the Sea of Okhotsk and its deep-water (Kuril, South Okhotsk) basin in the west. The Bussol Strait and its eponymous canyon-like deep-water trough divide the GKR into the approximately equal southern Kunashir-Urup (length 575 km, strike 55°) and northern Simushir-Paramushir segments (length 600 km, strike 40°). The strike of these segments changes near the southern termination of Simushir Island (Fig. 1B).

Among the more than 200 volcanoes known in KIS, only 105 are subaerial (Pushcharovskii, 1992; Avdeiko et al., 2006). More than half of the subaerial volcanoes are restricted to the Kunashir-Urup segment (Fig. 2).

Complex regional geophysical studies have provided insight into the structure of the system (Zlobin and Zlobina, 1991). The thickness of its crust varies within 25–40 km with an average Moho depth of over

* Corresponding author at: Far East Geological Institute, Far East Branch of Russian Academy of Sciences, 159 Prospect 100 let Vladivostoku, Vladivostok 690022, Russia.
E-mail address: khomich79@mail.ru (V.G. Khomich).

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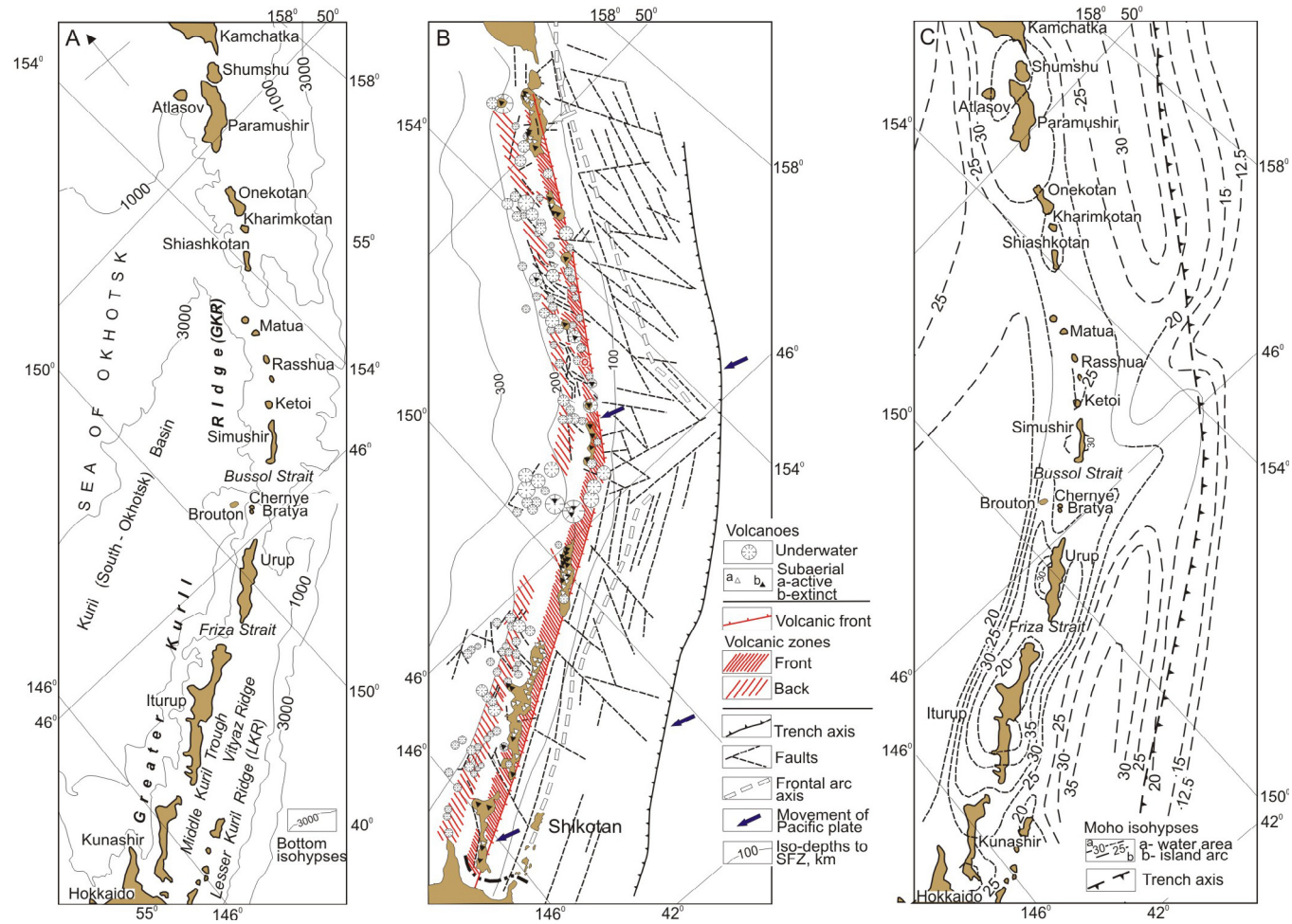

Fig. 1. Geographical (A), geological (B) and geophysical (C) maps of the Greater Kuril island-arc system. After Pushcharovskii (1992), and Zlobin and Zlobina (1991) with some modifications.

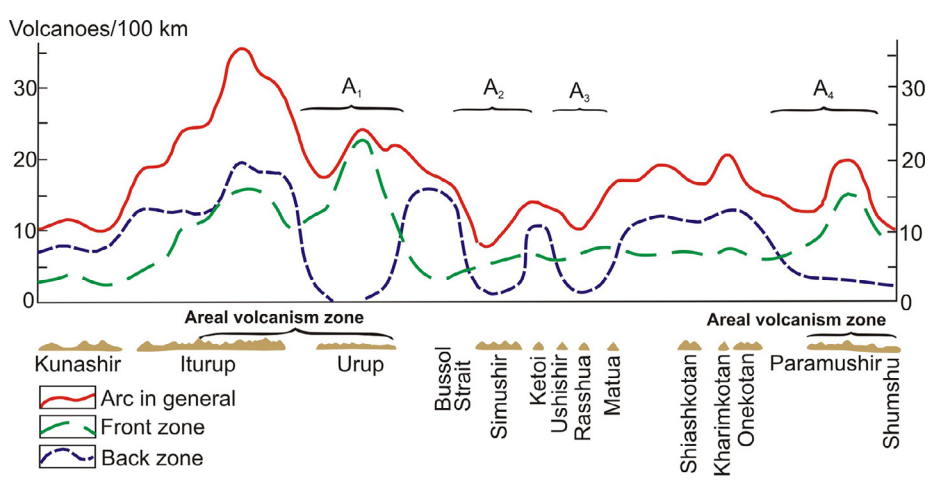

Fig. 2. Linear accumulation of volcanic centers in the Kuril island-arc. After Pushcharovskii (1992), and Avdeiko et al. (2006).

25 km (Fig. 1C). The continental crust beneath the GKR islands is 35–40 km thick, decreasing to 30–35 km beneath the island slope of the deep-water trench and Lesser Kuril Ridge (LKR). In both the cases, the upper crust occupies no more than one third of the crustal volume, whereas the mafic crust comprises two thirds. The 30-km Moho contour line is closed beneath the southern group of the GKR islands. The thickness of the crust eastward of the deep-water trench and beneath the South Okhotsk (Kuril) basin is no more than 15–20 km (Zlobin and Zlobina, 1991).

The magnetic field of the KIS and its framing is characterised by several features (Pushcharovskii, 1992; Sergeev and Krasnyi, 1987). The volcanic arc and the Kuril deep-water arc are characterised by the general negative background complicated by the local fields of subaerial and submarine volcanic edifices, whereas the Pacific Plate adjoining the Kuril-Kamchatka trench to the east defines a heterogeneous field. The normally and reversely magnetized anomaly zones of the

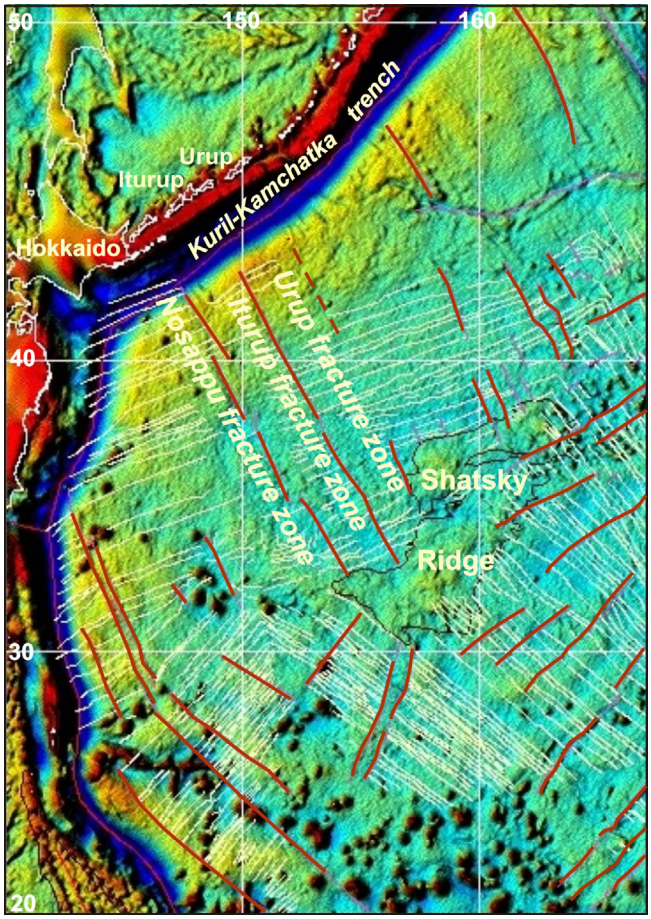

Fig. 3. Free air gravity map of the northern Pacific. After Norton (2007). Thin magenta lines show fracture zones and thin yellow lines are identified magnetic lineations. Mercator projection; scale bar is for approximately the latitude of the Hess Rise.

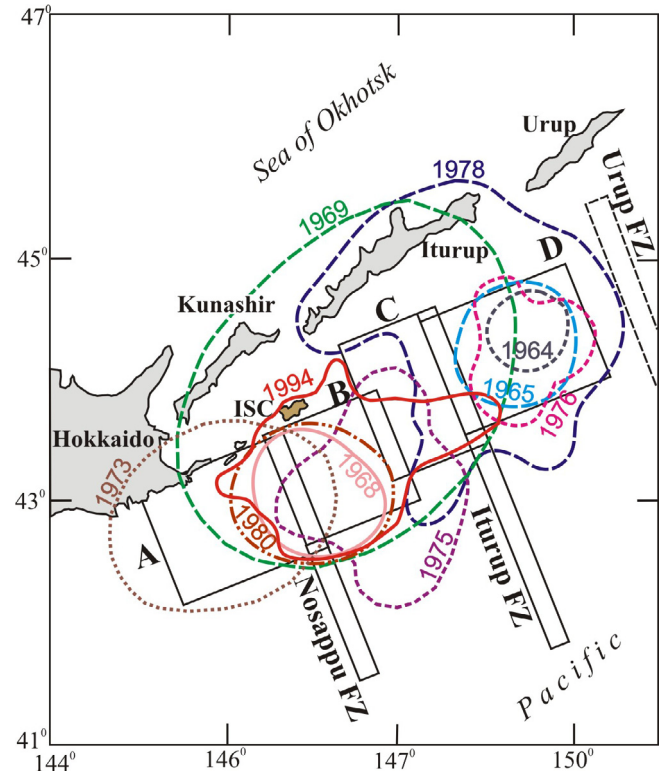

Fig. 4. Main earthquake and its aftershocks for several large earthquake sequences. ISC (Island Shikotan Center) hypocentre data are used. Four seismic blocks (A–D) and three seismic boundaries (the Nosappu FZ, the Iturup FZ and the Urup FZ) are proposed. After Kasahara et al. (1997) with modifications and additions.

second layer of oceanic crust are distinguished near the South Kuril. Such NE-trending anomalies are also recorded on the oceanic slope of the trench up to its island slope. The southern segment of the trench axis is oriented conformably with the strike of the local negatively magnetized anomaly (Fig. 3). The junction of different KIS segments corresponds to a sublatitudinal negative magnetic anomaly. A narrow transverse zone (deviating towards the trench) with low gravity values is restricted to this KIS fragment. Several transform faults were identified on the oceanic plate near the South Kuril. They are expressed by the NW-trending linear positive magnetic anomalies, which cut across the magnetic quiet zone and sign-variable banded magnetic field.

The entire trench, nonvolcanic (external) arc and Vityaz Ridge are characterised by a minimum heat flow and maximum seismic activity (Pushcharovskii, 1992; Kasahara et al., 1997) (Fig. 4). In contrast, the maximum heat flow and minimum seismicity are typical of GKR. Contrasting heat flow values were found in the southern Okhotsk basin (Sergeev and Krasnyi, 1987). In general, the KIS shows temperature inversion caused by thrusting of the cold Pacific Plate under the continental plate.

The KIS structure consists of pre-Oligocene (late Cretaceous-Early Paleogene) basement and unconformably overlying Oligocene-Neogene-Quaternary island-arc complexes (Piskunov, 1987; Fedorchenko et al, 1989; Govorov, 2002). The pre-Oligocene complexes are mainly developed on the LKR islands (Shikotan, Zelenyi, Anuchin, Tanfil'eva) as well as on the underwater Vityaz Ridge. Their stratigraphic division is debatable. They are composed of volcanomictic breccias, gravelstones, sandstones, and siltstones intercalated with pillow lavas and sills of pyroxene-plagioclase basalts and basaltic andesites. The geochronological (whole rock K-Ar) age of the lavas and sills varies from 105 ± 10 to 76 ± 5 Ma (Govorov et al., 1983). A younger paleontological and geochronological Campanian (80–70 Ma) age was determined for the sequence of amygdaloidal basaltic andesites with numerous quartz, carbonate, zeolite, and chlorite amygdules and flysch-like rhythmically interbedded psammitic-siltstones with lenses of massive fine-grained limestones and marls (Fedorchenko et al., 1989). These sequences comprise shoshonitic sills 20–250 m thick, or more rarely, flows and dikes. The K-Ar age of the shoshonites (65 Ma) corresponds to the Cretaceous-Paleogene boundary (Govorov et al., 1983).

The Danian-Paleocene-Eocene volcanic-pyroclastic sequence is characterised by numerous uniform flows of lavas, lava breccias, basalts, and basaltic andesites up to 15–20 m thick with coarse-clastic unsorted pyroclastic units. Some lava varieties contain abundant opal, quartz, carbonate, and zeolite amygdules (Fedorchenko et al, 1989). Large gabbroic intrusions cutting across Late Cretaceous (Campanian-Maastrichtian) rocks and bodies of alkaline rocks occur in the basement. The gabbros are dated at 62 ± 6 and 55 ± 5 Ma (K-Ar method, Govorov et al., 1983).

Geological bodies of the younger Oligocene-Neogene-Quaternary "island-arc" magmatism with complex structures and heterogeneous compositions are developed on GKR. Based on long-term detailed lithological-structural studies, these rocks are subdivided into green tuff, volcanogenic-siliceous-diatomite (pumice-ignimbrite), basaltic, and andesitic complexes (Table 1, Piskunov, 1975, 1987). In the southern GKR, the green tuff complex comprises a rock series from basalts and basaltic andesites to andesites, dacites, and rhyolites. The lower parts of the complex are dominated by coarse-clastic molasse, while the upper parts are mainly composed of volcanic varieties. The latter are locally overlain by a volcanogenic-flysch sequence consisting of tuffs, tuffites, sandstones, less common siltstones, and tuff diatomite interbeds.

Table 1
Comparison scheme of Cenozoic volcanic complexes of island arcs in the northwest Pacific. After Piskunov (1987) with simplifications.

System/Period			Northeast Honshu	Kuril islands
Quaternary			Andesite	Andesite
Neogene	Pliocene		Volcanogenic-molasse	Basaltoid-aquatic
	Miocene	Upper	Volcanogenic-flyschoid	Volcanogenic-siliceous-diatomaceous
		Middle		"Green Tuffs"
		Lower	"Green Tuffs"	
Paleogene	Oligocene			

Numerous dikes and stratiform and cross-cutting bodies of mafic, intermediate, and felsic composition occur among the stratified sequences. There are also hypabyssal gabbro-plagiogranite intrusions. The volcanogenic-siliceous-diatomite (pumice-ignimbrite) complex is unconformably overlain by green tuffs. Its lower and upper parts are dominated by coarse-clastic molasse, while the middle part consists of a laminated sequence of andesitic and dacitic tuffs intercalated with felsic lavas, welded tuffs, ignimbrites, fine-grained pumice breccia, gravelstones, sandstones, tuff diatomites, siltstones, and cherts.

The basaltic and andesitic complexes consisting of volcanic breccias and flows of pillow, fragmented-pillow lavas, and lava-pyroclastic rocks of intermediate-mafic composition finalize the island-arc sequence. The basaltic complex includes not only Quaternary volcanic rocks but also Pleistocene subaerial rocks that are essentially lava varieties (Fedorchenko et al., 1989). Based on petrological-geochemical studies (Martynov and Martynov, 2017), this complex was united with the andesitic complex into a single complex. Each of its units shows mafic to felsic magmatic evolution, with an increase in the amount of mafic rocks and a decrease of intermediate felsic and felsic volcanics in the younger rocks.

The GKR islands have horst-anticlinal structure with a periclinal dip (with dip of up to 30–40°) of stratified rocks and planation surfaces near the sea coasts. The structure is complicated in the peripheral parts of separate volcanic structures and in the large fault zones, which, as with many dikes, strike WNW (290–330°) and NE (40–55°).

3. Magmatism

The volcanogenic rocks of the different GKR complexes are usually ascribed to Pacific-type rocks. They are low-Ti, high-Mg rocks with a high Fe oxidation state, elevated CaO and Al_2O_3 contents, and moderate to low alkalinity (at $Na_2O > K_2O$) (Piskunov, 1987; Fedorchenko et al., 1989; Martynov et al., 2010). The volcanic rocks of the LKR have similar characteristics, but sometimes show slightly higher alkalinity, which is especially typical of the residual glasses (up to 7–9% K_2O) and layered shoshonite sills (Govorov et al., 1983; Govorov, 2002). Based on the greater distance (250 km against 200 km) of the South Kuril volcanoes to seismic focal zone (SFZ) relative to that of the North Kuril volcanoes, the conditions for magma formation beneath the South Kuril are more favourable (Pushcharovskii, 1992).

Large (up to 60–70 km^2), relatively equant gabbro-plagiogranite intrusive massifs (Valentinovsky and Prasolovsky) confined to the long-term multichannel paleovolcanoes among the green-tuff complex show significant facies variability, which is mainly typical of the intrusive rocks of the southern chain of the GKR. Its massifs have a leucocratic appearance, porphyritic textures, and low contents of quartz, feldspar, and biotite.

The shallow-water highly siliceous sediments (with significant diatomite contribution) among the subaerial pumice-ignimbrite complex are dominated by felsic clastics. Hypabyssal subvolcanic bodies (up to 4–7 km^2) on the Kunashir-Urup island chain are mainly moderately felsic in composition. In the zones of a wide distribution of pyroclastic rocks and large subvolcanic extrusive bodies, they clearly show expressed columnar jointing. The SiO_2 contents are usually no more than 63–64 wt%. The most felsic varieties are significantly enriched in alkalis. The Pliocene volcanic rocks of the complex are represented by massive pillow lavas with clastic-pillow lava breccias, hyaloclastites, and tuffs among the psephitic tuffites. In general, they are characterised by a steady composition with a predominance of calc basalts and basaltic andesites with SiO_2 = 53–54 wt%. The subvolcanic bodies are frequently represented by dikes of relatively well-crystallised diorite porphyrites (Piskunov, 1987; Fedorchenko et al., 1989). On the Kunashir, Iturup, and Urup islands, small dacitic and rhyolitic extrusions (unrelated to the central stratovolcanoes) are widespread among Pliocene sequences. These intrusions conjugated with lava flows are 200–300 m^2 in size (Fedorchenko et al., 1989).

The Pleistocene-Holocene volcanoes are similar to monogenetic volcanoes. The products of their eruptions form lava-pyroclastic fields (up to 60% of the island area) and comprise all rock varieties from basalts to dacites and rhyolites, with a predominance of two-pyroxene basaltic andesites and andesites (up to 70–80 vol% of the fields). The caldera volcanoes show bimodal compositions and consist of early basaltic andesites and late hybrid (dacitic) pyroclastics (Fedorchenko et al., 1989).

In general, the Quaternary volcanoes of the South Kuril are classified according to the stage of post-caldera evolution (Fedorchenko et al., 1989). Some volcanoes have only one dome (for instance, Golovnin Volcano, Kunashir Island), while others additionally have younger intracaldera cones (for instance, Medvezhii Volcano, Iturup Island).

Detailed petrological-geochemical studies of volcanic rocks of different ages have been carried out on the South Kuril since the end of the 20th century (Bailey et al., 1989; Syvorotkin and Rusinova, 1989). The main results are reported in papers by J.C. Bailey (1996) and Martynov and Martynov (2017). The main subjects in these publications are the Miocene-Holocene volcanic rocks of Kunashir Island, which is the reference island of the entire South Kuril chain due to its easy accessibility and its best geological study.

The rocks have high Al_2O_3 (up to 18–20 wt%) and low TiO_2 (up to 1–1.5 wt%) contents, which according to (Martynov et al., 2010) indicate that the island-arc volcanic rocks are ascribed to the supra-subduction type, with no traces of crustal contamination (Martynov et al., 2010). This is confirmed by the incompatible trace-element patterns, including elevated LILE (Cs, Ba, Rb), negative HFSE anomalies (Nb, Ta), and well expressed positive Pb and Sr anomalies. Their subhorizontal REE distribution pattern indicates their derivation from slightly depleted magmas. This also follows from the high LREE/HREE ratio, which however does not exclude the possible contribution of an enriched mantle source in their genesis. The negative Hf anomaly suggests the involvement of marine sediments. The Kunashir volcanic rocks in the $^{143}Nd/^{144}Nd$-$^{206}Pb/^{204}Pb$ diagram fall in the PREMA field (Martynov et al., 2015; Martynov and Martynov, 2017).

4. Metallogeny

Numerous pre-Quaternary occurrences of noble (Au, Ag), nonferrous (Cu, Zn, Pb, Sn), and trace (Mo, Bi) metals and metalloids (As, Sb, Se, Te), in addition to thermal springs with sublimated sulfur, molybdenite-sulfur deposits, have been known on some volcanoes of the southern chain of the GKR for over two centuries (Danchenko, 2003). Many of them are of economic grade and can be classed as deposits (Fig. 5). It is noteworthy that all ore fields, deposits, and occurrences of the Kunashir-Urup chain are most frequently intersected by faults of the Kuril-type (NE 55°) and orthogonal (NW 290–330°) directions.

In recent decades, the aforementioned occurrences were supplemented by atypical-for-KIS occurrences of PGE and such trace metals as Cd, In, Ge, and Re (Znamenskii et al., 1993; Kovalenker et al., 1993; Korzhinskii et al., 1993, 1994, 1996; Chil-Sup et al., 1995; Danchenko,

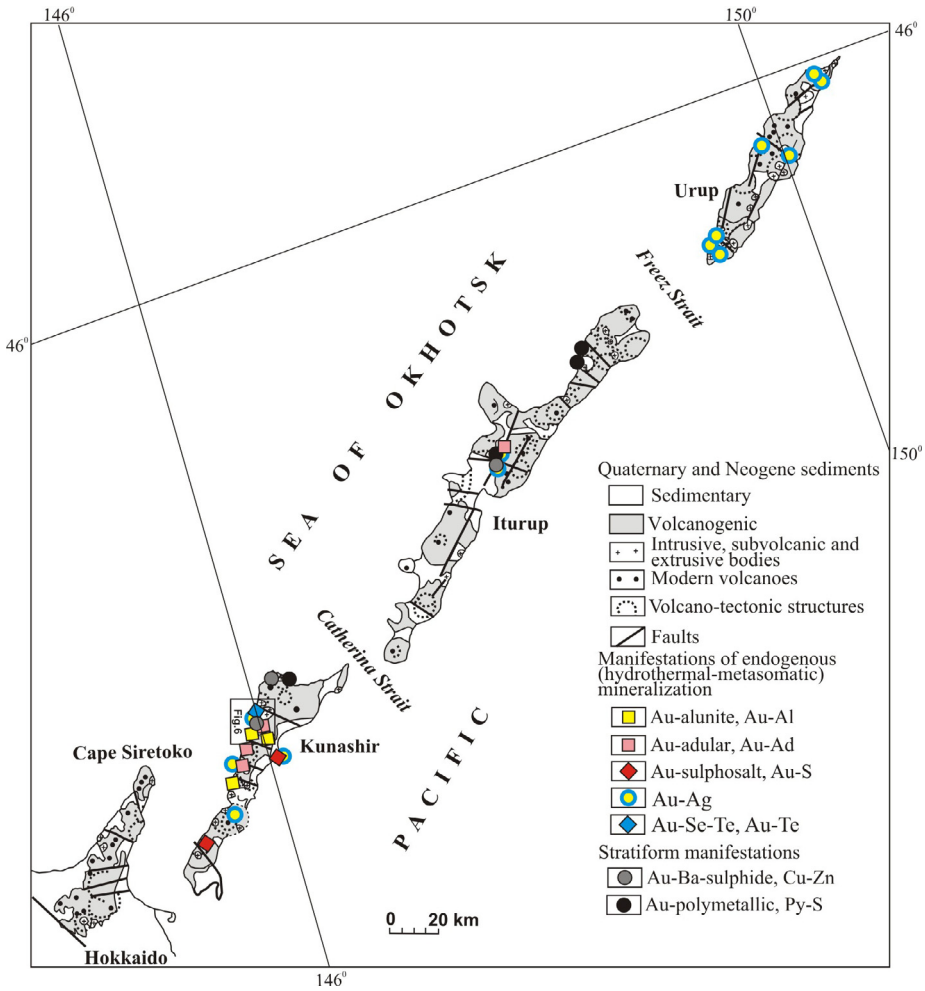

Fig. 5. The scheme of endogenous minerageny of the southern islands in the Greater Kuril Range. After Danchenko (2003), and Danchenko (1999) with modifications.

1999, 2003; Danchenko et al., 1991; Razin, 2011).

The intrusive-voclanogenic complexes of the South Kuril (SK) islands have a definite metallogenic specialisation. The volcanic-pyroclastic rocks of the green tuff complex contain stratiform exhalation-sedimentary sequences and veined hydrothermal-metasomatic bodies of the Kuroko-type sulfide-base metal ores. The main commodity of these deposits is Zn, with subordinate Pb and Cu. Such occurrences are usually associated with base metal and tin-base metal deposits (Danchenko, 1991b, 2003). The gabbroplagiogranites revealed among the green tuff complex host Au-Ag-Se-Te deposits (Kovalenker et al., 1993; Kemkina and Kemkin, 2007; Kirillov and Goroshko, 2008).

The extrusive, subvolcanic, and intrusive bodies of moderately felsic and felsic composition and aureoles of their intense metasomatic transformations among pyroclastic rocks of the pumice-ignimbrite complex are also associated with numerous gold-silver and gold-tin occurrences (Danchenko, 1991b) (Fig. 6).

Let us consider the distribution of endogenic mineralization in the relatively well studied ore clusters and fields of the SK.

The latter can be exemplified by the Prasolovsky cluster (Fig. 6), which is located on the Okhotsk coast of Kunashir Island. The cluster contains the Prasolovskoe and Severyankinskoe ore fields. The former coincides with the intrusive-dome rise (IDR), while the latter is associated with volcanotectonic sagging on the southwestern IDR flank, which is mainly composed of subvolcanic bodies and volcanic-pyroclasic rocks. The rocks of the gabbro-diorite-plagiogranite massif were dated at 33 ± 8–30 ± 2 Ma (whole rock K-Ar) and 31 ± 1 Ma (U-Pb zircon) (Rybin and Danchenko, 1994; Danchenko, 1991a; Grave et al., 2016). The basalt-andesite-dacite-rhyolite dikes revealed in the intrusive massif and its framing are Miocene-Pliocene in age. The mafic to felsic magmatic evolution of this period is confirmed by K-Ar dating of dikes of gabbros (16 ± 3 Ma), quartz diorites (11–10.5 Ma), and quartz porphyries (6 Ma) (Danchenko, 1991a; Rybin and Danchenko, 1994). Both ore fields contain copper-zinc-sulfide, sulfide-base metal, and noble metal mineralization of different types (Danchenko, 1991b, 2003; Kemkina and Kemkin, 2007). It is associated with the large subvolcanic bodies and dikes of different compositions and is accompanied by aureoles of hydromica-sericite-quartz, argillically altered rocks, and other hydrothermal-metasomatic transformations. The vein-stringer zones contain Au-cassiterite-quartz, Au-polysulfide-quartz, Au-selenide-telluride-quartz, and Au-adularia-carbonate-quartz mineralization (Danchenko, 1991b; Kemkina and Kemkin, 2007).

In the Severyankovskoe ore field, the barite-sulfide-base metal, Au-alunite(goethite)-quartz, and Au-adularia(carbonate)-quartz manifestations were discovered among subvolcanic and extrusive bodies of dacite-rhyolite composition, Late Miocene-Pliocene volcanic-pyroclastic rocks, and corresponding metasomatic aureoles. They are dated with the K-Ar method at 4–7 Ma (Miocene-Pliocene) (Danchenko, 1991a). It should be noted that the Late Pliocene basaltic andesites also contain veinlet Au, Ag-sulfosalt-quartz mineralization.

The duration of the formation of the Prasolovsky ore cluster is confirmed not only by geochronological studies but also by direct observations of cross-cutting relations between the early (Cu-Zn-sulfide, barite-sulfide-base metal) and late (Au-Se-Te-quartz, Au-adularia-quartz veins) ores, as well as by the overlapping of some ore bodies by

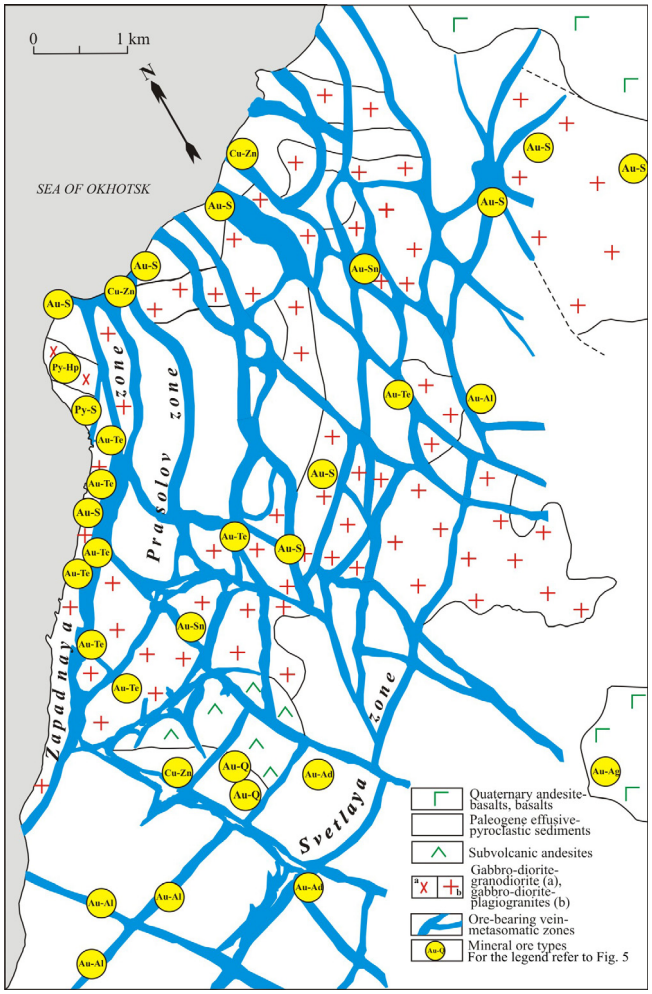

Fig. 6. Schematic map of the Prasolovsky gold node (northeast Kunashir). After Danchenko (1991b), Kemkina and Kemkin, 2007 with some simplifications.

Late Pliocene basaltic lava flows (Danchenko, 1991b). The underlying secondary quartzites with Au-alunite(goethite)-quartz mineralization contain disseminated native sulfur, Fe, Cu, and Ag sulphides, as well as later marcasite veinlets with cinnabar and sometimes orpiment and realgar.

The occurrences and deposits of the Prasolovsky cluster are characterised by a common sequence of mineral precipitation from oxide minerals to sulfides, telluride-selenides, native and intermetallic minerals, and lastly sulfate-hydroxide minerals (Danchenko, 1991b). This sequence is marked by not only temporal but also sequential spatial (from sea level to a horizon of +400 m) change of gold-cassiterite-quartz, gold-polysulfide-quartz, gold-selenide-telluride-quartz, gold-adularia(carbonate)-quartz, and gold-alunite(goethite)-quartz mineralization. This zoning is emphasised by the association of the three former types of mineralization with intrusive, subvoclanic bodies and dikes, while the two latter types are associated with extrusive and vent facies. This change is also clearly expressed in a change of mineral Sn species from oxides (cassiterite, SnO_2) to sulfides (stannite, Cu_2FeSnS_4 and kësterite, $Cu_2(Zn, Fe)\ SnS_4$) (Danchenko, 1991b).

Multiple gabbro-diorite-tonalite-plagiogranite intrusive massifs (up to 10–30 km^2 in area) and subvolcanic bodies of complex composition from dolerites, basaltic andesites, and quartz diorite porphyrites to rhyodacites are developed among stratified geological complexes (from green tuffs to basaltic and andesitic complexes) on Urup (Fig. 7) and other islands of the South Kuril group of the GKR (Piskunov, 1987; Danchenko, 1991a; Udodov and Panchin, 2002; Kovtunovich et al., 2004). Felsic magmatic rocks of different ages (7.8 ± 1.5–4.2 ± 0.9; 6.6–4.7 Ma, K-Ar) are thought to be specialised for noble metals (Kirillov and Goroshko, 2008). Five potential ore fields with quartz-sulfide, base metal (with Au), sulfosalt-sulfide, sulfide-sulfoarsenide, and low-grade sulfide gold-silver mineralization are distinguished in this area (Kirillov and Goroshko, 2008). Mineralization in the outer contacts of subvolcanic bodies and dikes of felsic composition is related to the aureoles of hydromica-sericite-quartz, hydromica-chlorite-quartz secondary quartzites rimmed by zones of kaolinite-quartz metasomatites and argillically altered rocks. The hydrothermal-metasomatic rocks yield a K-Ar age of 10.6–4.0 Ma (Kirillov and Goroshko, 2008). Updip, the secondary quartzites contain Au-bearing quartz-veined bodies. Higher in the section, they contain goethite, alunite, gypsum, and native sulfur.

Two productive mineral assemblages are distinguished at the epithermal low-sulfide gold-silver Kupol deposit (Urup Island): gold-chalcopyrite-tennantite and gold-telluride (with hessite and altaite). The first mineral assemblage contains molybdenum, bismuth, and germanium (up to 10 ppm) (Danchenko, 2003). The Otlivnoe ore field associated with the Pleistocene-Holocene multiphase subvolcanic bodies of andesite-granodiorite porphyries is especially noteworthy on Urup Island. The high-sulfide (up to 30–50% ore minerals) base metal-sulfosalt-orpiment-realgar mineralization with barite and low-sulfide gold-silver mineralization is associated with active hot chloride-sodium springs. The base-metal ores of the Otlivnoe deposit are dominated by Zn (7.5%), Cu (3.05–5.0%), and As (up to 1.9%). Sulfides contain (in ppm) Au (1,3), Ag (2 0 0), Sn (4 2 7), In (1 0 0), Hg (2 3 7), Cd (1000), Bi (8000), Mo (1 1 8), Ti (1 0 0), and Ge, Sb (3 0 0) (Kirillov and Goroshko, 2008). In the beach zone, orpiment-realgar mineralization cements modern sediments.

Atypical mineralization was found in the Kunashir-Urup chain in addition to the traditional island-arc endogenic occurrences. In 1975–1978, a rather unusual complex of raw minerals for noble metals (PGE and Au) was discovered among derivatives of the modern products of the subaerial Mendeleev and Golovnin andesite-basaltic volcanoes on Kunashir Island by V.I. Fedorchenko, A.I. Zbruev, and L.V. Razin (Razin, 2011) (Fig. 8). The elevated content of noble metals was determined using special hydro- and ore-geochemical studies of several fumarole fields along the volcano periphery, which comprises numerous hydrosolfataras (with native sulfur), vapor hydrothermal vents of different powers, bottom fumaroles, and mud pots with hot water subjected to the impact of volcanic gases, as well as large sulfide lodes (Table 2). Mentioned volcanic derivatives are promising for raw minerals of a new type (Razin, 2011).

Rhenium mineralization was discovered in the stationary gas jets of Kudryavy Volcano (Iturup Island) by geologists from the Russian Academy of Sciences (Korzhinskii et al., 1993; Znamenskii et al., 1993). High-temperature (up to 940 °C) jets have operated there in the Medvezhiya caldera for over 100 years (Tkachenko et al., 1992). Occurrences of Re (In, Ge, Tl, Cd, Se, Mo, Au, Pt, Pd, Sn, W) mineralization have some features in common with the molybdenite-sulfur occurrences of the caldera crater-lacustrine sediments (Fig. 9). A sharp (up to 10^3 times) enrichment in In, Cd, Zn, and Cu, and the presence of native Au, Pt, $Pt(OH_2)$, and $PtCl_2[P(C_4H_9)_3]_2$ was found in the altered basalts around fluid conduits of Kudryavy Volcano (Yudovskaya et al., 2006; Distler et al., 2008). Subvolcanic bodies and extrusions of rhyodacites (4.9 ± 0.3 Ma, K-Ar) and basalt-andesites (1.25 ± 0.15 Ma, K-Ar) overlain by pumice, lavas, and agglomerates of basalt-andesites with gabbro-plagiogranite xenoliths were revealed at the base of the Medvezhiya caldera (Danchenko, 1999; Ermakov and Semakin, 1996). The xenoliths presumably belong to the local buried IDR.

Subsequent revision of many Neogene-Quaternary ore-magmatic systems of the GKR confirmed that similar (Re-bearing) mineralization occurs in the epithermal Au-Ag, Cu, and Cu-Zn-Pb (± As, Sb) objects, mainly on the Urup, Iturup, and Kunashir islands (Danchenko, 1999). The high correlation coefficients of Re with Cd and In (± 0,80; ± 0,83,

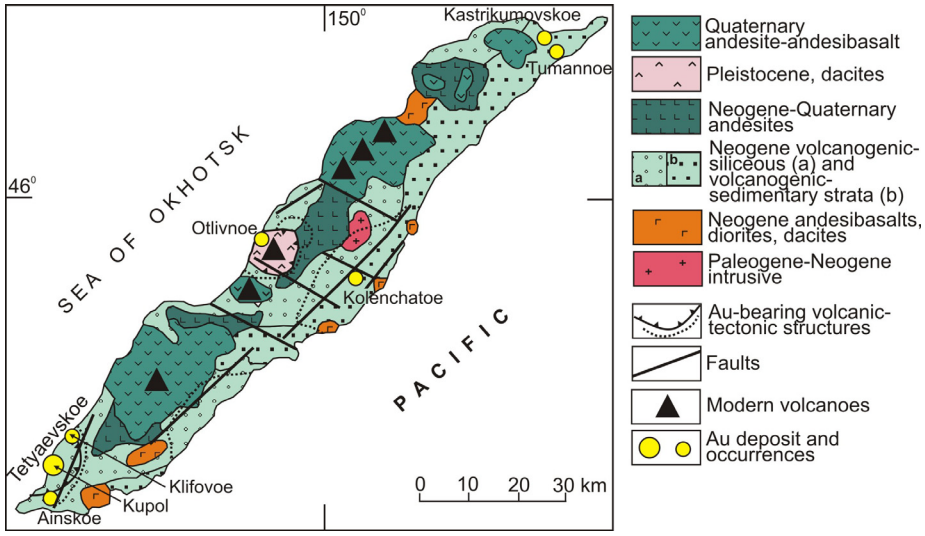

Fig. 7. The layout of ore-magmatic complexes on Urup Island. After Kirillov and Goroshko (2008) with some modifications.

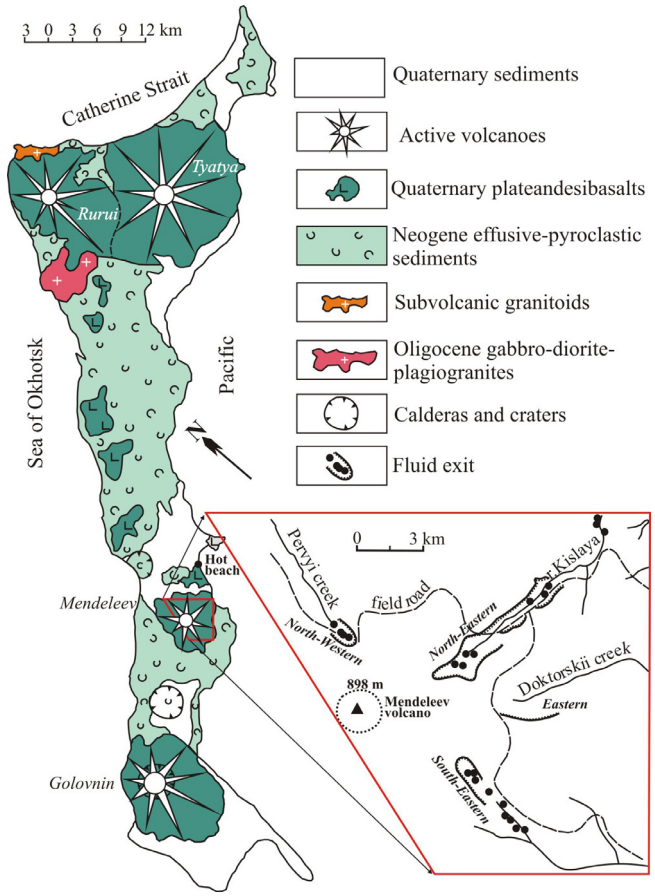

Fig. 8. Schematic geological map of Kunashir Island with fumarolic fields (in the insert) along the extrusive dome of the Mendeleev volcano. After Fedorchenko et al. (1989), Kovtunovich et al. (2002), Razin (2011), and Grave et al. (2016).

respectively) are confirmed by the wide distribution of these elements at the aforementioned islands of the South Kuril chain of GKR (Kovalenker et al., 1993).

The study of the sulfide-selenide-telluride mineralization of the Prasolovskoe epithermal Au-Ag deposit (Kunashir Island) showed that the ore bodies contain not only high-In (up to 1,5% In) sphalerite but also supergene roquesite ($CuInS_2$) in association with fahlores of the tennantite-tetrahedrite-goldfieldite series (Kovalenker et al., 1993). Rare-metal mineralization enriched in In and Cd has been forming in South Kuril since at least the late Miocene.

5. Geodynamics

More than 700 earthquakes with hypocenters deeper than 50 km have been recorded in the Kuril-Kamchatka focal zone during an almost 50-year (since 1973) distant record of seismic events. They frequently reach depths of 600–700 km (USGS site). The seismofocal zone (SFZ) with a seismically active layer at approximately 75 km thick (Pushcharovskii, 1992) has a listric fault geometry with an average dip angle of 45°. The northern Simushir-Paramushir segment extends NW 40^0 and dips more steeply (50°) than the southern Kunashir-Urup segment that strikes NE 55° and dips 38° (Fedorchenko et al., 1989).

The significant geodynamic difference between the South and North Kuril consists in their different orientations with respect to the motion vector (290°) of the Pacific Plate. The plate approaches the trench almost orthogonally (at > 70°) in the northern part of the island arc and at approximately 55° near South Kuril. This provides an oblique interaction of oceanic and continental plates with an increase of the strike-slip component on the southern flank of the GKR (Fig. 10), which cardinally changes the stress distribution on the Kunashir-Urup arc segment.

The focal mechanism solutions of the strongest earthquakes (M ≥ 5) include, foremost, the orientation of the main nodal fracture planes with respect to the direction (type) of displacements, as well as the spatial positions of the compression-extension axes and the average deformation axis in the earthquake's source. Analysis of almost 700 such solutions within the depth range of 50–700 km showed that the SFZ is dominated by reverse faults, NNE-trending updip-strike slip faults, and (rarer) low-angle variably oriented normal faults (Kasatkin, 2012). The study of the distribution of strike-slip sources with high-angle (40–90°) dips of the average deformation axis and low-angle (0–30°) dips of sinistral and dextral displacements in the fault plane showed that the dextral strike slips are developed primarily to a depth of 200 km. Their predominant strike along the GKR (NE 50–60°, Fig. 10, diagr. A) is caused by the aforementioned oblique interaction of the Pacific and continental plates in the southern part of the arc.

Most of the sinistral strike-slips are confined to the southern GKR. They are traced in the WNW direction along the subduction zone to a depth of 680 km, i.e., factually to the lower boundary of the transit mantle zone (Fig. 11). We believe that the anomalous manifestation of

Table 2
Precious metals contents (g/t) in sulfide-bed and hydrothermal vents of Mendeleev volcano according to data from the chemical-spectral kinetic (Ir-Os) analysis of dry water residues. After Razin (2011) with some simplifications.

Tested object		Rh	Pt	Au	Ir	Pd	Os	Ru	PGE + Au
Sulfide-bed		0,0053	0,17	0,065	0.6	0,57	0,3	0,1	1,858
Hydrothermal vents	No 6	0,035	н.о.	0,02	0,24	н.о.	0,075	0,21	0,58
	No 3	н.о.	н.о.	0,018	0,18	н.о.	0,09	0,054	0,342
Holle No 5, Goryachii Plyazh deposit		0,067	0,25	0,04	0,34	0,3	0,014	0,11	1,121

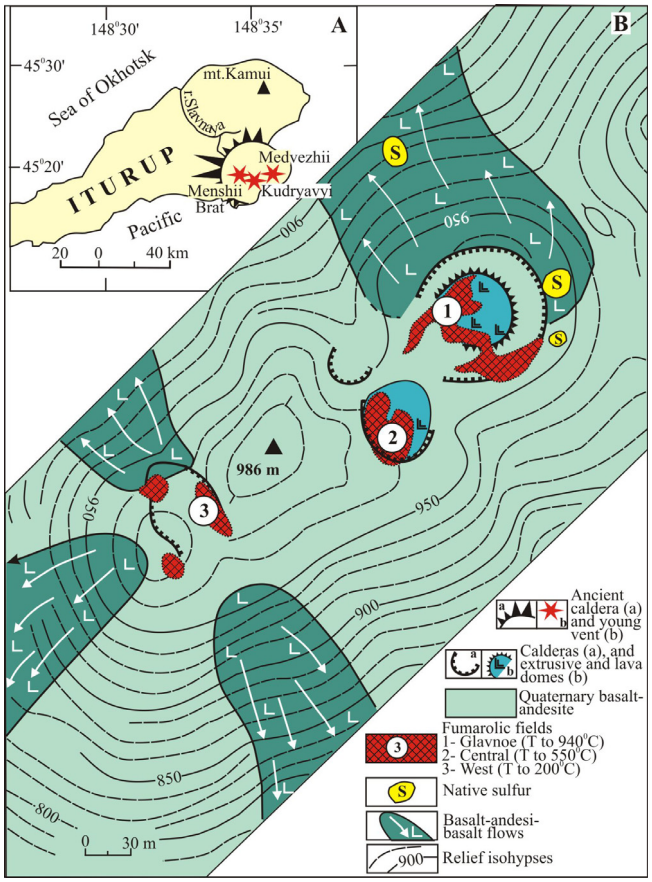

Fig. 9. A schematic structure of ancient somma (A) and the area surrounding the crater of Kudryavy volcano on Iturup Island (B). After Znamenskii et al. (1993) and Danchenko (2003) with modifications.

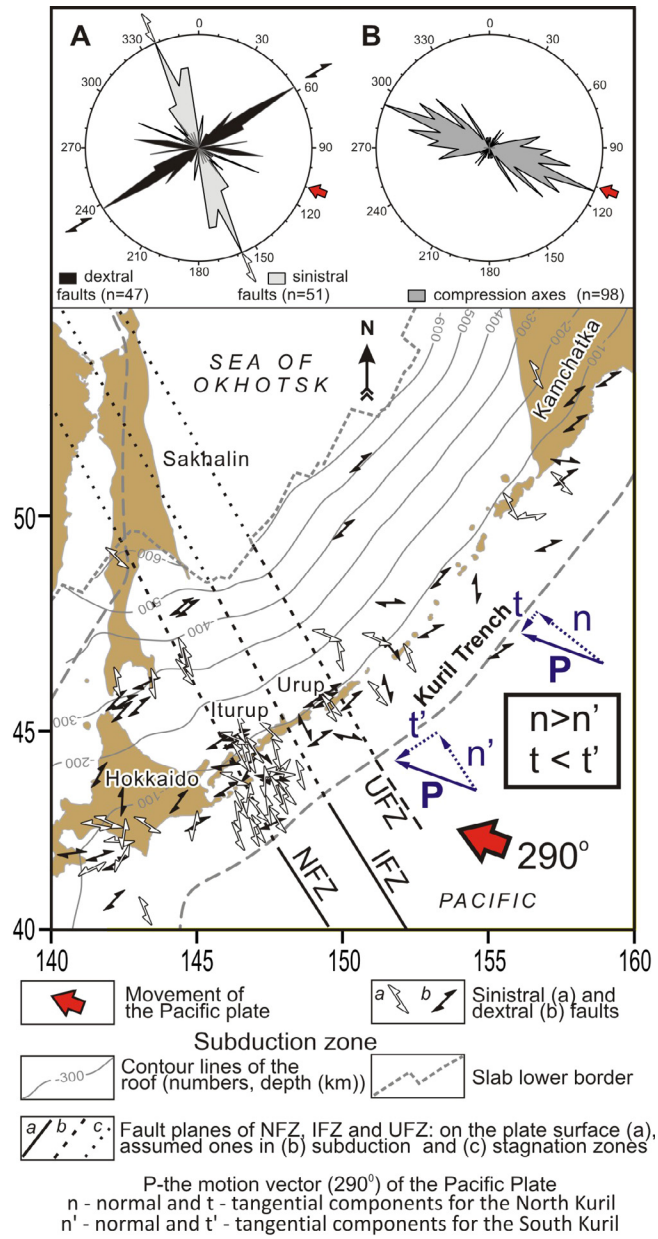

Fig. 10. Distribution of strike-slip fault earthquakes (1977–2010) within the subduction zone of the Pacific Plate (40°–55° N, 140°–160° E) with corresponding rose-diagrams of strikes for sinistral and dextral faults (A) and compression axes (B). After Kasatkin (2012) with modifications and additions.

the sinistral strike-slips is predetermined by the existence of NW-trending transform faults in the subsiding part of the Pacific Plate (Fig. 3). These subparallel fault zones (FZ) termed by Japanese scientists as Nosappu, Iturup, and less expressed Urup faults adjoin the southeastern flank of the Kuril trench (Fig. 12). The total amplitude of the sinistral displacements only along the Nosappu FZ is approximately 150 km (Nakanishi et al, 1989; Ogawa and Hirano, 2003). The aforementioned fault zones are traced in the NW direction from the Shatsky Rise margin to the Kuril trench for a distance of over 1000 km (Nakanishi et al., 1989; Nakanishi, 1993; Kasahara et al., 1997). As transform faults (ridge-ridge type), they were formed in the Late Jurassic-Early Cretaceous. Tectonic movements dominated by NW-trending (330–340°) sinstral strike slips proceed at present along particular fault planes as well as bands of sign-variable magnetization. This is best expressed in the slab bending near the ocean margin of the deep-water trench and the lower boundary of the transit mantle zone. A series of recent (1964–1980) near-Shikotan earthquakes (Kasahara et al., 1997) was recorded in the south Kuril part of the trench.

Specific (petit-spot) volcanic edifices (each up to 1 km^3 in volume) made up of highly alkaline basalts with Ar/Ar dates within 0.05–1.0, 1.8, 4.2, 6.0, and 8.5 Ma were found on the Pacific Plate segments between the Nosappu, Iturup, and Urup FZs adjoining the Kuril trench (Hirano et al., 2001; Hirano et al., 2006; Fujiwara et al., 2006). Manifestation of the peculiar within-plate highly alkaline (shoshonite) volcanism near the SFZ and trench is not accidental. The petit-spot

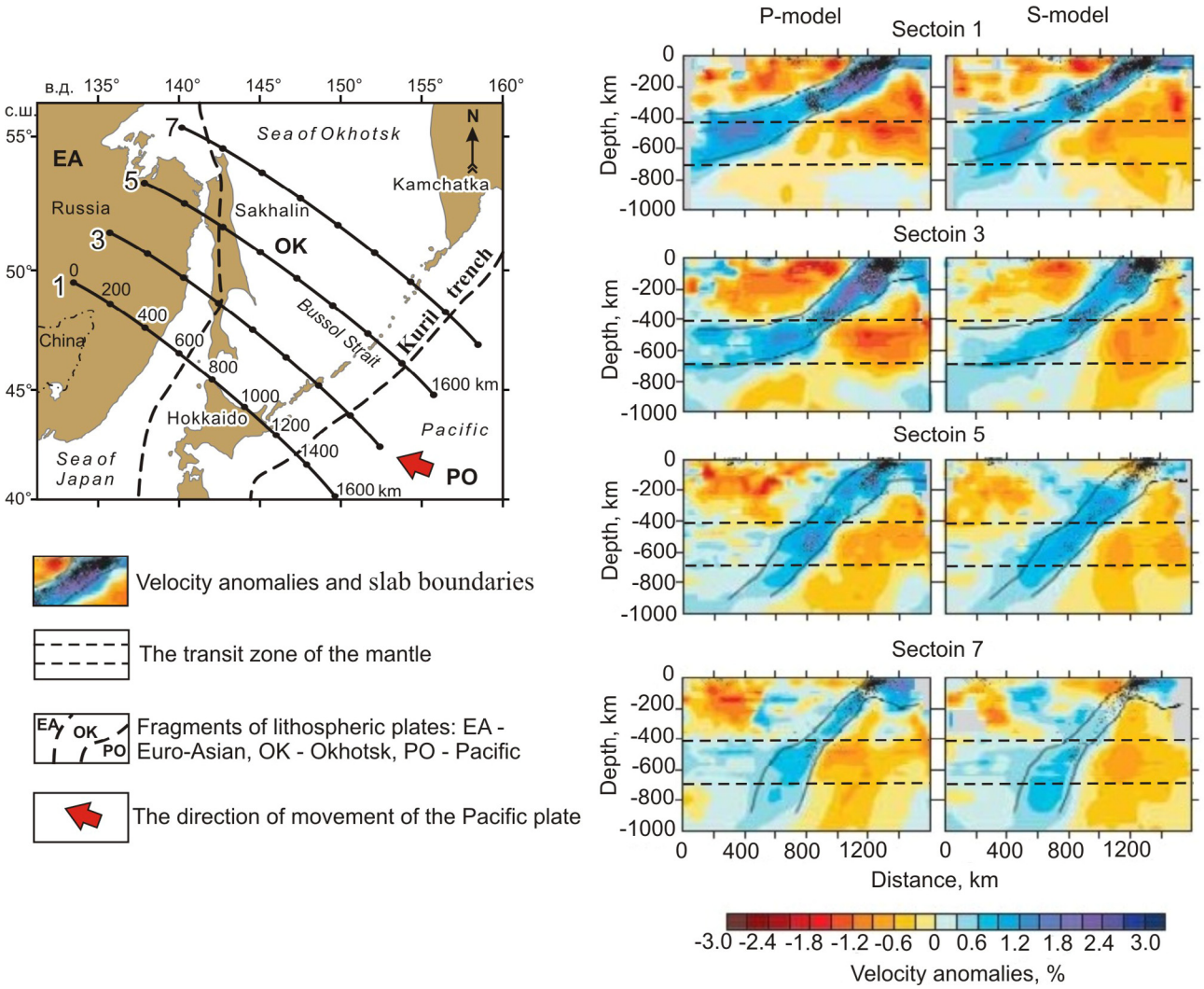

Fig. 11. Result of real-data inversion and P- and S-velocity anomalies in vertical sections across the strike of the Kurile arc. Lines show the upper and lower slab boundaries. Dots are earthquake hypocenters along a strip no more than 50 km from the profile. The position of the sections is shown in the upper left-hand corner of the map. After Koulakov et al. (2011) with minor modifications.

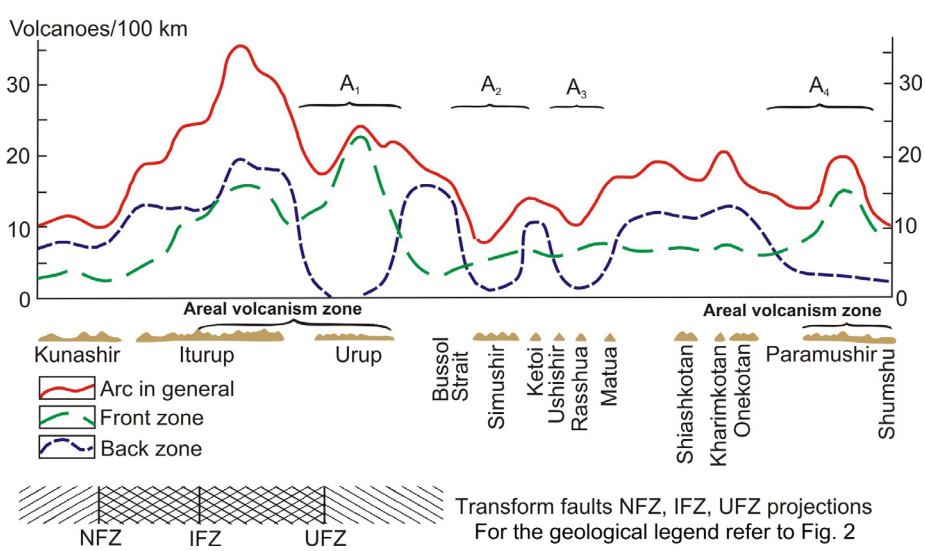

Fig. 12. Spatial relationships between linear accumulation of volcanoes in the Kuril island-arc and transform faults of the subducting Pacific plate.

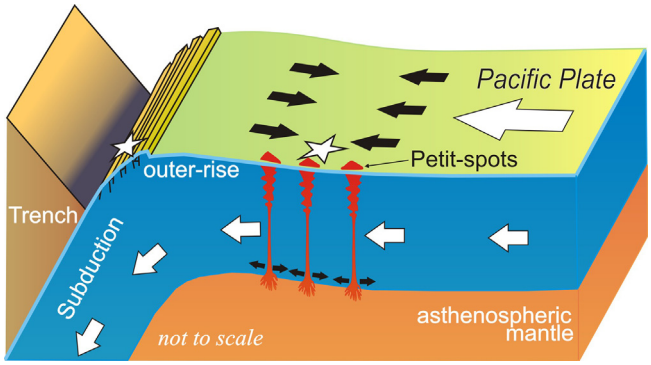

Fig. 13. Model of the formation of petit-spot volcanoes. Modified after Hirano (2011) and Hirano et al. (2006).

volcanoes are thought to be related to the deformation of ocean slab fragments near the trench margin and deep-seated (asthenospheric) sources (Fig. 13). Since the earthquakes near the South Kuril part of the trench are related to the tensile stresses of the local subduction zone, the paleotectonic structures (horst-graben type and mentioned FZs) of the oceanic slab serve as the permeable zones (Kasahara et al., 1997). The permeability is likely preserved in the gently dipping segments of the SFZ down to the oceanic slab bottom, which is in contact with sub-subduction asthenosphere.

6. Discussion

The development of the sulfide-base metal, gold-silver mineralization, PGE and rare metal mineralization at the Kunashir-Urup chain of the KIS is likely predetermined by deep geodynamics. This interpretation of the South Kuril phenomenon is supported by the presence of the large long-lived Nosappu, Iturup, and Urup transform fault zones and conjugate petite-spot type centers of alkaline volcanism. These centers are made up of flows of moderately to very porous (20–60%) pillow lavas subsequently underlain by less porous (0–20%) and massive varieties and sills of shoshonites and basanites with xenoliths (up to 100 mm) of dolerites, olivine gabbros, and peridotites (Hirano, 2006). Similar volcanic structures with alternation of amygdaloidal and massive flows and sills of shoshonites occur among the Late Cretaceous-Early Paleogene rocks on the LKR islands (Govorov et al., 1983; Govorov, 2002). It is suggested that these rocks also occur in the basement of the Oligocene-Neogene-Quaternary complexes of the GKR. The high porosity of the lavas (and amygdaloidal structures of volcanic rocks on the LKR islands) is caused by the presence of H_2O, CO_2, H_2S and other gases (CH_4, H_2, HCl, and HF (Tkachenko et al., 1992)) in small portions of asthenosphere-derived initial melts (Hirano, 2011). The $^{21}Ne/^{22}Ne$ and $^{40}Ar/^{36}Ar$ isotopic ratios indicate that magma was supplied into a petit-spot from a depleted MORB-type mantle source (Hirano, 2011). The existence of young (1.8–8.5 Ma and less Ar-Ar dates) peculiar centers of submarine volcanism near the external uplifted margin (southeastern flank) of the Kuril trench on old (135 Ma K-Ar date) cold hummocky (with a height amplitude of 100–400 m) segments of the Pacific Plate indicates the presence of permeable zones ("windows") in the oceanic lithosphere, which reach the upper mantle and asthenosphere (Hirano et al., 2001, 2006). It is likely that they influence the increased saturation of South Kuril volcanoes (Fig. 12).

The Br/I ratio (0.4–0.5) established in the condensates of gas jets of the Kudryavy Volcano can be taken as an argument in support of the contribution from I-rich marine sediments to oceanic slab melting in the SFZ during subduction (Korzhinskii et al., 1993).

The probable contribution of hotter magma, not only in the

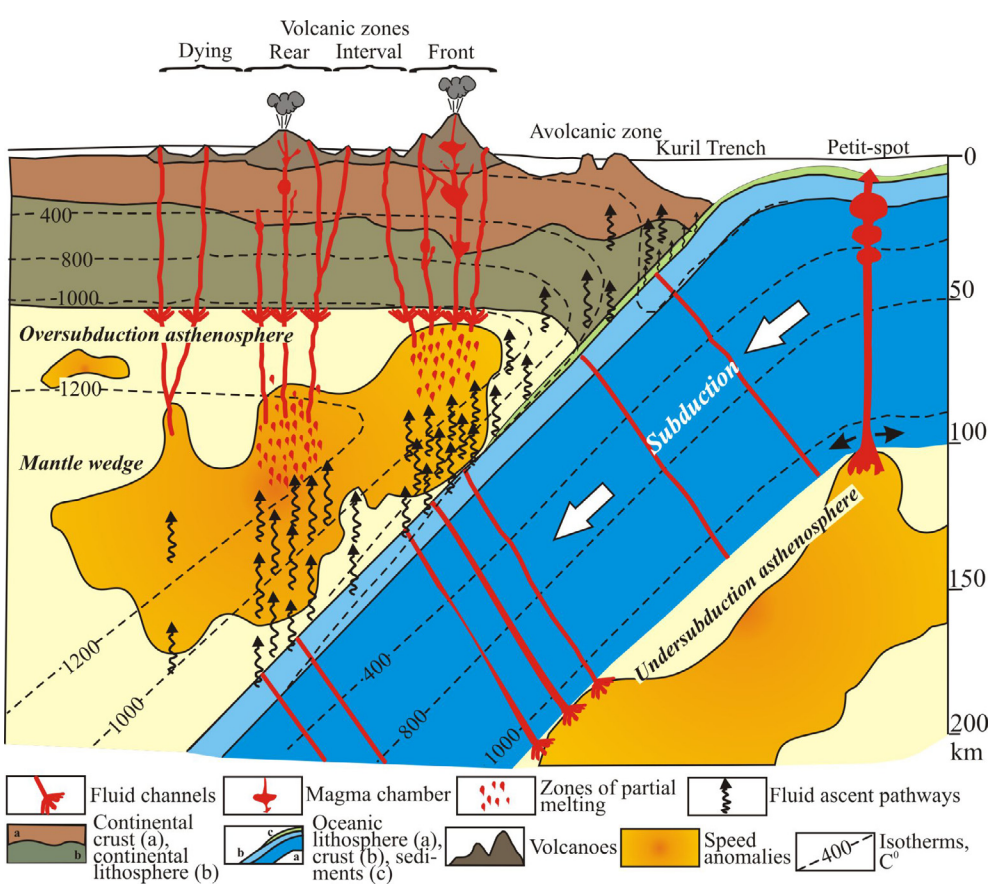

Fig. 14. Improved formation model for ore-magmatic systems of southern islands of the Greater Kuril island-arc. After Avdeiko et al. (2006) with additions.

formation of petit-spot magmatic rocks but also in the partial melting of basalts and sediments of oceanic crust of the underthrusted plate suggests a new scenario for the formation of the ore-magmatic systems of the South Kuril. Primary fluids from sub-subduction asthenosphere were likely supplied for the generation of magmatic sources in the continental lithosphere and crust and for the subsequent volcanism and ore formation from the sub-subduction asthenosphere. In this scenario, the serpentine and talc dehydration in the oceanic asthenosphere (Avdeiko et al., 2006) could be a "trigger" and primary source of water, as well as PGE, Re, In, Cd, Ag, Au, and other elements. Fluid energy flows, which were generated in the sub-subduction asthenosphere, penetrated through oceanic lithosphere and could be enriched during ascent with the aforementioned components derived from oceanic sediments in the SFZ, mantle wedge, and suprasubduction (subcontinental) asthenosphere.

The 10^1–10^4 enrichment in a wide spectrum of base, trace, and noble metals typical of high-temperature (605–940 °C) gas jets emphasises a unique diversity of metals that were supplied with fluid energy fluxes from both sub- and supra-subduction asthenospheres. The known geochemical similarity of Re (No. 75), Os (No. 76), Ir (No. 77), Pt (No. 78), and other PGE, which have similar values of ionic and atomic radii and ionization potentials (Solodov and Semenov, 1997), indicates that their occurrence on the Kunashir-Urup islands of the GKR is not accidental but was predetermined by natural conditions. With allowance for differences in the stress dynamics (extension-compression) between the southern and northern chains of KIS, respectively (Christensen and Ruff, 1988), this scenario is consistent with factual materials reported in the previous sections and can be represented as a modified, but in fact new island-arc model of OMS (Fig. 14). Therefore, special hydro- and ore-geochemical studies should be carried out near the Kamchatkan active volcanic centers in the eastern region of the peninsula to detect possible rhenium and PGM mineralization, because large PGE-bearing placer clusters, such as Seinav-Gal'moenan and others, are known in Kamchatka (Sidorov and Tolstykh, 2011). Prospecting-appraisal work should be carried out in South Kuril to reveal the Cu-Mo porphyry ores associated with Au-Ag mineralization, as in the Amur region, Primorye, Philippines, Taiwan, and Kamchatka (Khomich, 1995; Hedenquist et al., 1998; Sillitoe, 1989, 2010, Plechov et al., 2017). This assumption is supported by the presence of the Ozernovskoe (eastern Kamchatka) and Prasolovskoe and Kupol (South Kuril) Au-Se-Te quartz deposits (Kovalenker et al., 1989; Kirillov and Goroshko, 2008).

7. Conclusion

The "anomalous" metallogeny of the South Kuril is determined by deep geodynamics, which provided the impact of fluid energy fluxes from sub-subduction and supra-subduction asthenospheric zones. For this reason, more careful attention should be focused on the structure of the tectonosphere and mantle beneath other IDR of the Pacific ore belt where the existence of staged asthenospheric zones is possible.

Acknowledgements

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