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Two Stages of Granite Formation in the Sredinny Range, Kamchatka: Tectonic and Geodynamic Setting of Granitic Rocks

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Abstract—The newly formed continental crust in southern Kamchatka was created as a result of the Eocene collision of the Cretaceous–Paleocene Achaivayam–Valagin island arc and the northeastern Asian margin. Widespread migmatization and granite formation accompanied this process in the Sredinny Range of Kamchatka. The tectonic setting and composition of granitic rocks in the Malka Uplift of the Sredinny Range are characterized in detail, and the U–Pb (SHRIMP) zircon ages are discussed. Two main stages of granite formation—Campanian (80–78 Ma ago) and Eocene (52 ± 2 Ma ago) have been established. It may be suggested that granite formation in the Campanian was related to the partial melting of the accretionary wedge due to its underplating by mafic material or to plunging of the oceanic ridge beneath the accretionary wedge. The Eocene granitic rocks were formed owing to the collision of the Achaivayam–Valagin ensimatic island arc with the Kamchatka margin of Eurasia. In southern Kamchatka (Malka Uplift of the Sredinny Range), the arc–continent collision started 55–53 Ma ago. As a result, the island-arc complexes were thrust over terrigenous sequences of the continental margin. The thickness of the allochthon was sufficient to plunge the autochthon to a considerable depth. The autochthon and the lower portion of the allochthon underwent high-grade metamorphism followed by partial melting and emplacement of granitic magma 52 ± 2 Ma ago. The anomalously rapid heating of the crust was probably caused by the ascent of asthenospheric magma initiated by slab breakoff, while the Eurasian Plate plunged beneath the Achaivayam–Valagin arc.

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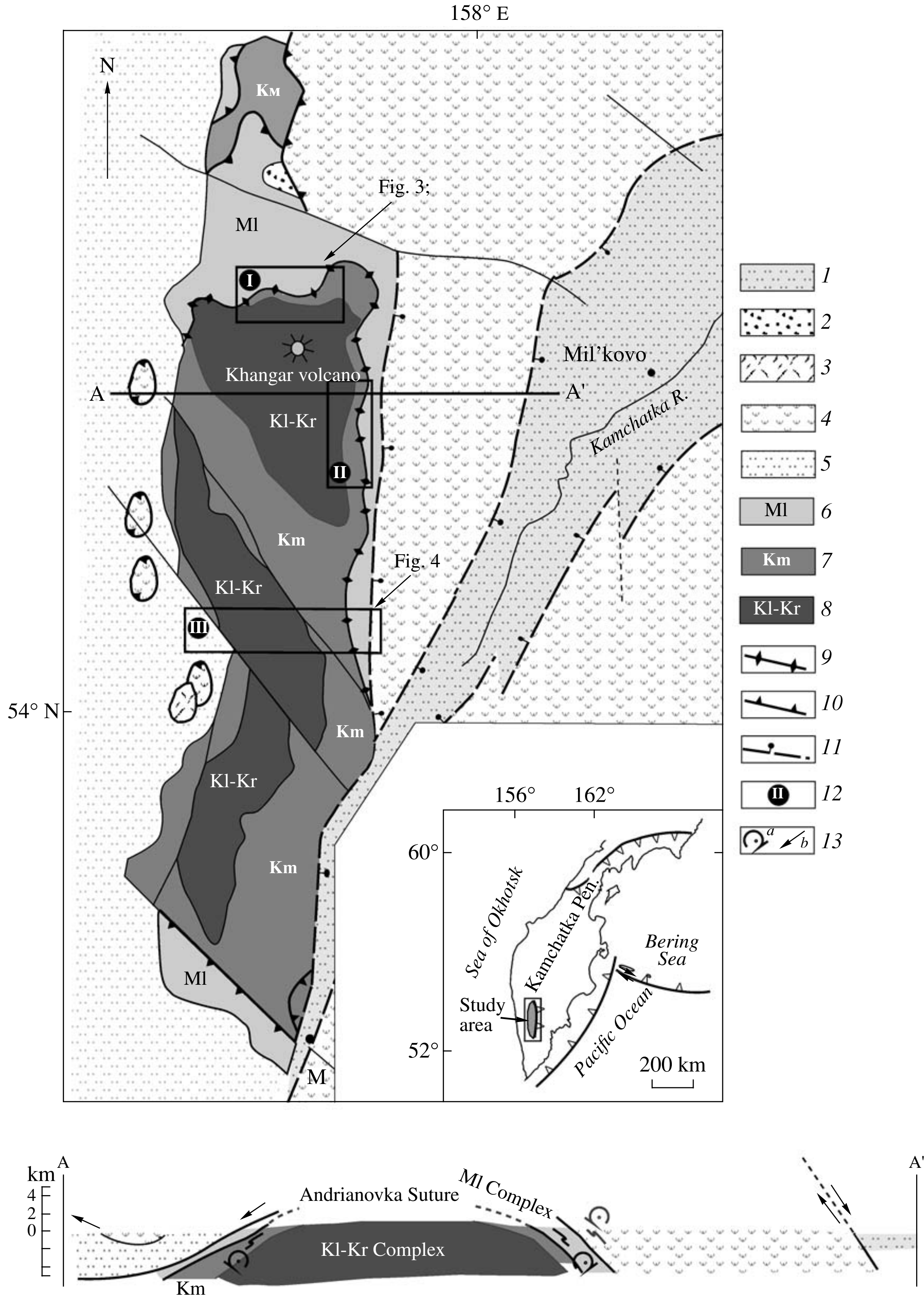
INTRODUCTION

The continental crust of Kamchatka is newly formed. The granitic–metamorphic layer was created mostly in the Late Cretaceous and Paleogene and has continued to build up until now. The origin of the continental crust of Kamchatka was largely related to the accretion of heterogeneous terranes of different ages [1, 7, 11, 12, 15, 17, 33, 43, 84]. In the course of Cenozoic accretion, two island arcs collided with the northeastern margin of the Asian continent. In the Eocene, the Cretaceous–Paleocene Achaivayam–Valagin island arc collided with the continental margin, and the Kronotsky island arc accreted to Asia in the Miocene. The tectonic models of arc–continent collision have been elaborated for the Sredinny Range of Kamchatka on the basis of detailed geological mapping, structural and paleomagnetic analysis, zircon dating with SHRIMP, fission-track dating, and physical modeling [14, 16, 17, 36, 59]. However, granite formation as an important factor in continental crust growth has remained insufficiently studied. The widespread intrusive granitic complexes of the Sredinny Range of Kamchatka are localized mainly in the metamorphic rocks of the Malka Uplift. In this paper, we consider the tectonic setting, age, and composition of two granitic complexes that mark the major stages in the tectonic evolution of the Sredinny Range and the formation of the continental crust in Kamchatka.

STRUCTURE OF THE MALKA UPLIFT IN THE SREDINNY RANGE OF KAMCHATKA

The largest outcrops of metamorphic rocks are located in the Malka Uplift of the Sredinny Range. They extend for about 200 km in the meridional direction as a tract 30–40 km wide (Fig. 1) [13]. The origin, age, structure, relationships between rock complexes, and the nature of the protolith in the Sredinny Range have been a matter of debate over the last 30 years [22, 24, 26, 34, 39, 40 and references therein]. Two structural elements—the basement and the cover that overlies the latter with conglomerate at the base—have been recognized previously [39, 40]. It was assumed in [23, 39, 40] that the Malka Group (cover) consisting of the Shikhta, Andrianovka, Kheivan, Khimka, and Alistor formations unconformably overlies the Kolpakov Group (basement) with the basal conglomerate of the Shikhta Formation. The complexly deformed poly-



metamorphic rocks of the Kolpakov Group and the Krutogorov Granite that cuts through these rocks were regarded as a basement that underlies the gently dipping rocks of the Malka Group affected by single-phase metamorphism of variable intensity.

The idea of a fold-thrust structure of the Sredinny Range was first set forth by Zhegalova [10] and developed in subsequent thematic studies [2, 25, 26]. Richter [25] established that at the headwater of the Krutogorov River, the Andrianovka Formation is thrust over both

Fig. 1. Tectonic sketch map of the southern Sredinny Range, Kamchatka, modified after [86] and sketch geological section along line A–A'. The post-Paleogene sediments on the western slope of the Malka Uplift were eliminated. (*1*) Miocene–Quaternary terrigenous rocks of the Central Kamchatka Graben; (*2, 3*) neoauthochthon: (*2*) Eocene conglomerate of the Baraba Formation, (*3*) Paleogene (?) volcanic rocks of Mount Chernaya; (*4*) unmetamorphosed allochthon: Upper Cretaceous to Paleocene cherty and volcanic rocks of the Irunei and Kirganic formations; (*5*) unmetamorphosed autochthon: Cretaceous to Paleocene terrigenous rocks of the Khozgon Formation; (*6*) metamorphosed allochthon in the Sredinny Range: Upper Cretaceous Malka Complex (Ml); (*7, 8*) metamorphosed autochthon: (*7*) Paleocene schists of the Kamchatka Group (Km); (*8*) Cretaceous gneisses of the Kolpakov Group and Krutogorov Complex of gneissic granites (Kl-Kr); (*9*) Andrianovka Suture; (*10*) thrust fault; (*11*) normal fault; (*12*) site number; (*13–*) in section: (*a*) rotation direction established from kinematic indicators [14], (*b*) direction of displacement along faults. Sites (numerals in figure): (I) headwater of the Krutogorov River (Fig. 3), (II) headwater of the Andrianovka River, (III) Kolpakov River basin (Fig. 4).

the Krutogorov Granite and the rocks of the Shikhta Formation with serpentinite melange at the base. The allochthonous attitude of the Andrianovka Formation was noted on the eastern slope of the Sredinny Range [28].

Thematic studies carried out by researchers of the Geological Institute, Russian Academy of Sciences in 2001–2006 confirmed the allochthonous nature of the Andrianovka Formation in the Krutogorov and Left Andrianovka river valleys, where it is thrust over the autochthonous Kolpakov and Kamchatka groups (Figs. 1–3). Thus, the structural grains of the contacting groups are discordant [14]. Recently, the fold–thrust structure of the Malka Uplift has been described. The Kolpakov Complex that is cut through by the Krutogorov Granite and the overlying Kamchatka Group (Shikhta Formation) make up the autochthon (Fig. 4) [45]. The unmetamorphosed rocks of the Khozgon Formation pertain to the autochthon as well. The allochthon is composed of the Andrianovka, Khimka, Irunei, and Kirganik formations.

The continental conglomerate of the Baraba Formation, which is referred to as a neoautochthon in the fold–thrust structure of the Sredinny Range, unconformably overlies both metamorphic complexes and the Cretaceous rocks of the Irunei Formation (Fig. 1) [44]. The presence of plant remains indicates the upper Campanian age of the Baraba Formation [42]. The U–Pb (SHRIMP) zircon age of the dacitic tuff from the basal unit of the Baraba Formation is 50.5 ± 1.2 Ma [36] and thus corresponds to the early Eocene.

Autochthon

According to recently obtained results [2, 26, 45], the autochthon of the Malka Uplift is composed of metamorphic rocks of the Kolpakov Group, which are cut through by gneissic granites of the Krutogorov Complex, the Kamchatka Group, and the Kheivan Formation.

The Kolpakov Group comprises sillimanite, kyanite, cordierite, cordierite–hypersthene, garnet–biotite, and biotite gneisses and plagiogneisses with sporadic interlayers and lenses of biotite–amphibole gneiss, garnet–clinopyroxene crystalline schist, amphibolite, garnet amphibolite, and metacarbonate rocks [26, 39, 40]. Gneisses are often migmatized. According to [39, 40], the rocks of the Kolpakov Group were initially metamorphosed under conditions of kyanite–sillimanite facies, locally up to garnet–cordierite–orthoclase (granulite) facies (T = 560– 800°C and P up to 7–8 kbar), and then experienced zonal metamorphism under conditions of andalusite–sillimanite facies. The protolith consisted of terrigenous, largely high-Fe pelitic rocks [39], or combined volcanic, graywacke, and clay materials [26, 37]. The bulk chemical composition of the terrigenous rocks corresponded to diorite and tonalite. The aforementioned crystalline schists and amphibolites are regarded as metamorphosed high-Ti oceanic basalts [26]. The lenticular shape of the amphibolite bodies and the occurrence of metacarbonate rocks embedded into the metaterrigenous sequence allow us to suggest that the protolith of the Kolpakov Group was comparable with the marginal continental subduction-related accretionary wedges [40].

The age of the Kolpakov Group remains controversial: 1.3 Ga by the Pb/Pb method [20]; 950 Ma by the Sm–Nd method [18]; Precambrian age by the U–Pb and Sm–Nd methods [18, 19]; two groups of dates at 100 and 60–50 Ma with single determinations at 314 and 250 Ma by the K–Ar method [84]; two groups of dates at 140–110 and 65–70 Ma by the Rb–Sr method [5, 6]; and 519 ± 23 Ma by the Rb–Sr method [3]. The U–Pb (SHRIMP) dating of zircons from gneisses of the Kolpakov Formation has yielded a wide range from the Archean to the middle Eocene [49].

The U–Pb (SHRIMP) zircon ages vary from 85.1 to 1859 Ma (see [34, 60] for a detailed description). The age of the clastic zircon grains corresponds to the age of the rocks in provenances, whereas the age of the outer rims surrounding these grains indicates the time of metamorphism. The youngest, Mid-Cretaceous ages of clastic zircon grains correspond to the age of the sedimentary protolith, and older detrital zircons were derived from the rocks eroded during the accumulation of the protolith. The age of the outer rims growing over zircons from the leucosome and melanosome in migmatites, as well as of the monazite from the gneiss, is 52 ± 2 Ma (early Eocene) and corresponds to the time of metamorphism.

The Kamchatka Group consists mainly of biotite schist and plagiogneiss with garnet, staurolite, kyanite, and sillimanite. The grade of metamorphism of the Kamchatka Group (Shikhta Formation) varies from

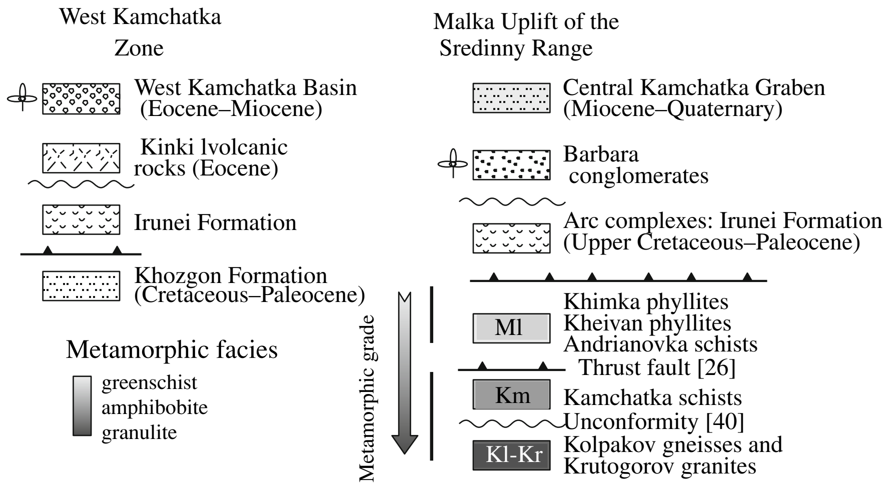


Fig. 2. Relationships of main structural units of the West Kamchatka Zone and the Malka Uplift of the Sredinny Range.

schists of the "garnet zone" to staurolite facies [25]. The metamorphic conditions correspond to $P = 3–4$ kbar and $T = 630–640°C$ [40] or $T = 550–650°C$, after [62]. The initial rock was clay with rare interlayers of polymictic and arkosic sandstones [25]. The rocks of the Kamchatka Group overlap the Krutogorov Granite that cuts through the Kolpakov Group unconformably and with basal conglomerate [26, 37, 39, 40].

The U–Pb (SHRIMP) age of zircons from metaterrigenous rocks of the Kamchatka Group ranges from 55.2 ± 3.3 to 2048 Ma [34, 60, 62]. The youngest grains constrain the Paleocene time of protolith sedimentation. The older zircons were derived from provenances.

The Kheivan Formation is composed of metasandstone, metasiltstone, and less abundant mudstone and gravelstone. During metamorphism, these rocks were transformed into phyllite of chlorite subfacies and biotite–garnet schist [25]. Devonian to Permian spores have been separated from rocks of the Kheivan Formation [29].

The U–Pb (SHRIMP) ages of zircons from the schist of the Kheivan Formation scatter from 106 to 2650 Ma [34, 60]. The peaks in the age distribution fall on the terminal Early Cretaceous and Paleoproterozoic. The youngest dates mark the time of sedimentation, so the age of the protolith can be estimated as Early Cretaceous.

Allochthon

The allochthon of the Malka Uplift in the Sredinny Range of Kamchatka includes the Andrianovka and Khimka (Alistor) formations [2, 25, 45].

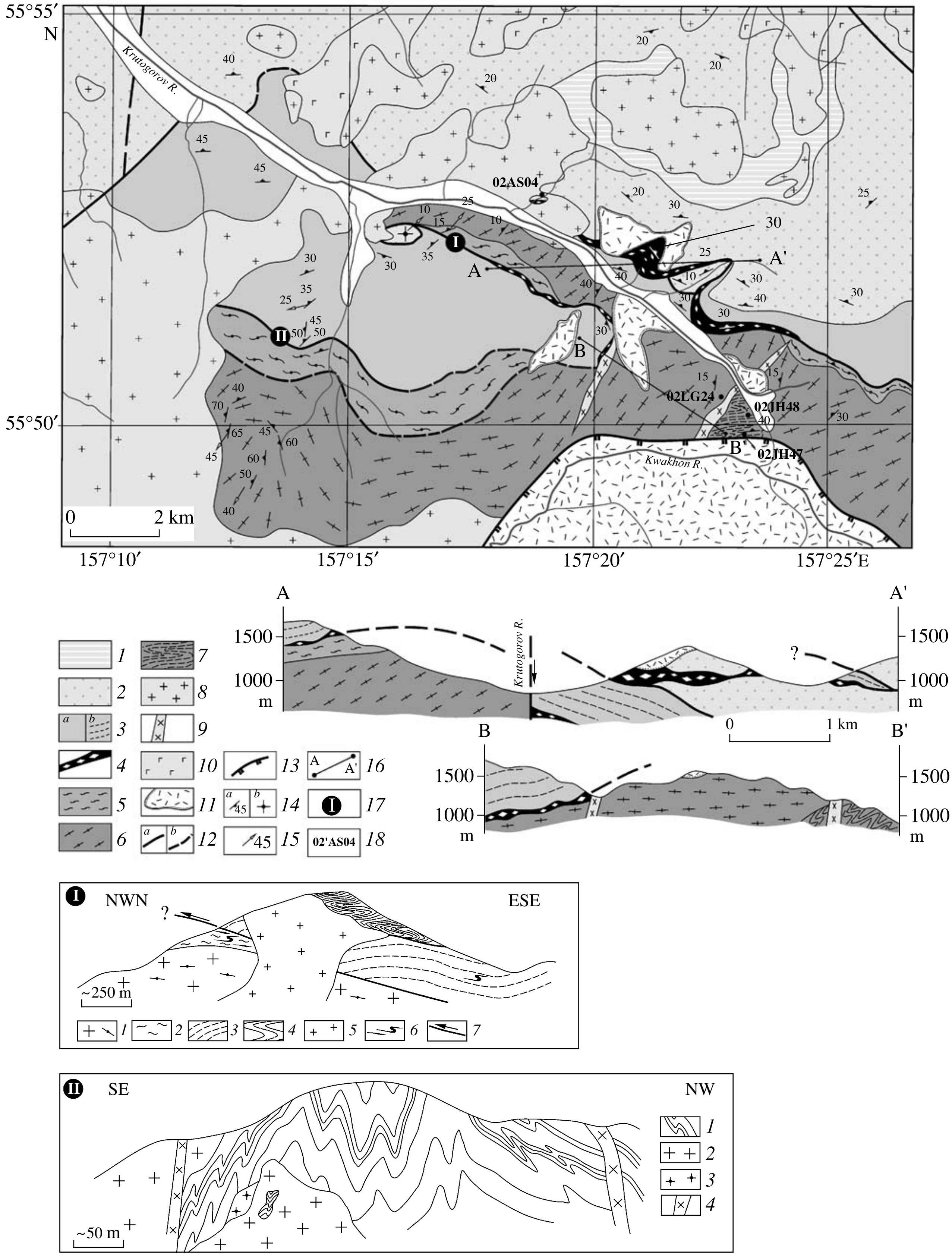
The Andrianovka Formation consists of quartz–albite–actinolite–chlorite, quartz–feldspar–amphibole, epidote–amphibole, amphibole, clinopyroxene–amphibole schists, quartzite, and amphibolite. The age of the Andrianovka Formation was previously determined as Proterozoic [9], Paleozoic [23, 40], Triassic [2], Late Cretaceous [21], or pre-Campanian [25] on the basis of relationships with under- and overlying rocks and regional stratigraphic correlation. The Sm–Nd age of whole-rock samples of amphibole schists belonging to the Andrianovka Formation is 500 Ma [18]. The cherty and volcanic rocks of marginal continental or island-arc origin were a protolith [25, 34].

The least metamorphosed chert from the Andrianovka Formation contains Santonian and early Campanian radiolarians [34]. The rocks of the Andrianovka Formation together with unmetamorphosed rocks of the Irunei Formation are cut through by Late Cretaceous pyroxenite–gabbro-syenite intrusions [41]. Thus, the new data indicate that a protolith of the Andrianovka Formation was formed in the Late Cretaceous.

The Khimka Formation overlies the Kheivan Formation and consists of albite–actinolite schist of chlorite subfacies as a product of metamorphism of tuff, tuffite, and sandstone in combination with quartzite. Some researchers have described a conformable stratigraphic contact between the Khimka and Kheivan formations [40], whereas others regard this contact as a thrust fault [45]. The Khimka Formation is a facies analog of the coeval **Alistor Formation** largely composed of amphibole schist after ultramafic and mafic volcanic rocks and likely is a facies analog of the Andrianovka Formation as well [2, 40]. No isotopic dates are available for the Khimka Formation.

RELATIONSHIPS BETWEEN GRANI TOID COMPLEXES

The granitic rocks of the **Krutogorov Complex** cutting through the metamorphic rocks of the Kolpakov Group have been studied by many authors. Khanchuk [4] considered the Krutogorov Complex as a combination of granitic plutons up to 100 km^2 in area and shee-



55°55′
N
55°50′
157°10′
157°15′
157°20′
157°25′E
Krutogorov R.
Kwakhon R.
02AS04
02LG24
02JH48
02JH47
A
A'
B
B'
0
2 km
1500
1000
m
0
1 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
02'AS04
NWN
ESE
~250 m
SE
NW
~50 m

←

Fig. 3. Geology of headwater of the Krutogorov River, modified by A.B. Kirmasov after [8, 26]. (*1–4*) Allochthon: (*1*) schist of the Khimka Formation, (*2*) schist of the Kheivan Formation, (*3*) schist and quartzite of the Andrianovka Formation (*a*, in map and *b*, in section), (*4*) metaultramafic rock; (*5–7*) autochthon: (*5*) schist of the Kamchatka Group, (*6*) gneissic granite of the Krutogorov Complex; (*7*) gneiss and migmatite of the Kolpakov Group; (*8*) equigranular granite; (*9*) diorite; (*10*) gabbro; (*11*) tuff; (*12*) faults: (*a*) proved and (*b*) inferred; (*13*) somma of the Khangar caldera; (*14, 15*) strike and dip symbols of (14) schistosity: (*a*) inclined and (*b*) near-vertical, (15) mineral lineation; (*16*) section line; (*17*) site numbers; (*18*) sample numbers corresponding to the Table. Site I. Conceptual relationships between rock complexes on the left bank of the Krutogorov River (unpublished data of A.B. Kirmasov). (*1*) Gneissic granite of the Krutogorov Complex, (*2*) staurolite–garnet–biotite schist of the Kamchatka Group, (*3*) amphibole and chlorite–amphibole schists of the Andrianovka Formation, (*4*) quartz–feldspar–biotite–muscovite schist of the Kheivan Formation, (*5*) equigranular two-mica leucogranite, (*6*) plicated quartz veins, (*7*) faults. Site II. A fragment of folded gneisses of the Kolpakov Group located at the drainage divide between the Krutogorov and the Kwakhon rivers (unpublished data of A.B. Kirmasov). (1) Biotite and biotite–garnet gneisses of the Kolpakov Group, (*2*) equigranular granite, (*3*) pegmatite, (*4*) diorite and granodiorite dikes.

tlike intrusions in the field of metamorphic rocks of the Kolpakov Group; he specially recognized the granites with oriented texture. The Krutogorov pluton has intrusive contacts with the rocks of the Kolpakov Group and is overlapped with erosion contact by the rocks of the Shikhta Formation that belongs to the Malka Group.

Khanchuk described the following varieties of the Krutogorov Granite: (1) biotite granite that grades from almost massive varieties to rocks with plane-parallel texture and (2) foliated granite with blastocataclastic microstructure. Both varieties are cut by pegmatite veins and bodies of fine-grained granite. The orientations of the lineation in the granite and the schistosity of the country gneiss coincide in the first case, while in the second case, the foliation of the granite coincides in orientation with that in the overlying rocks of the Malka Formation, crossing the contact between these rocks. In the opinion of Khanchuk [40], the structural and textural features of the granites testify to the emplacement of the Krutogorov Granite close to the time of metamorphism in the country rocks. Since the age of the Kolpakov Gneiss was previously accepted as Proterozoic (1300 ± 60 Ma, Pb/Pb method [20]), the same age was ascribed to the Krutogorov Granite [40]. According to the data reported by Richter [26], the gneissic two-mica granite of the Krutogorov Complex cuts through gneisses of the Kolpakov Group, including migmatites. The gneissic banding is expressed in the oriented arrangement of micas, plagioclase, and less frequently amphibole.

In the basin of the Krutogorov River, the gneissic granites are exposed as a sheetlike body one kilometer in apparent thickness that occupies the hinge of a large antiform trending in the near-meridional direction and in the pericline of the Khangar granite-gneiss dome as a particular structural element in the northern Malka Uplift (Fig. 3) [26]. In the opinion of Richter, it is not clear whether the Krutogorov Granite was emplaced along the spalling planes within the rocks of Kolpakov Group or is an interformational body localized between this group and an unknown overlying sequence. The granite is often blastoclastic with retrograde mineral assemblage consisting of fine-flaky biotite, muscovite, epidote, and chlorite. The orientations of the secondary schistosity in the Krutogorov Granite and the Malka Group coincide, being related to a younger tectonic and metamorphic episode [26]. In estimating the age of the Krutogorov Granite, Richter relied on the results of Rb–Sr timing, according to which metamorphism of the Kolpakov Group was dated at 127 ± 6 Ma [6]. Thus, the Krutogorov Granite should be younger than 127 Ma but older than the late Campanian, because the age of the neoautochthon that covers the fold–thrust structure of the metamorphic complexes was established on the basis of plant remains to be late Campanian–Maastrichtian [44]. In the basin of the Krutogorov River, both gneissic biotite granite and equigranular granite occur (Fig. 3). Apparently, only the gneissic granite should be referred to the Krutogorov Complex; this granite is cut through in some places by equigranular garnet-bearing two-mica granite (Fig. 3, site I). The equigranular granite cuts through the rocks of both the Kolpakov and Kamchatka groups. An important relationship was observed in a right tributary of the Krutogorov River (Fig. 3, location of sample 02AS04). The massive equigranular garnet–biotite tonalite cuts here through both a member of talc–chlorite, strongly tectonized metabasic rocks of the Andrianovka Formation, and the garnet–biotite schist of the Kheivan Formation. The intrusive contact is clearly seen, as well as hornfels and a second generation of biotite chaotically oriented in the schist as postkinematic porphyroblasts. Thus, the granitic pluton cuts through the autochthon (Kheivan Formation), the thrust fault zone composed of metabasic rocks, and the allochthon (Andrianovka Formation). Hence, the age of this granite determines the upper age limit of overthrusting.

In the area of the Right Kolpakov and Poperechnaya rivers (Fig. 4, sites I and II), the gneissic granite (Krutogorov Complex) and massive equigranular granite are distinguished as well. Two granite complexes were shown in [8] on a geological map on a scale of 1 : 200000 and designated the Early Mesozoic gneissic granite (plagiogranite) and the Late Mesozoic granite (plagiogranite). The former were mapped as fields up to 5×15 km^2 in area among schists and gneisses of the Kamchatka Group. However, during fieldwork we failed to observe such relationships. The migmatized schists of the Kamchatka Group and gneisses of the Kolpakov Group likely were included into the contour of gneissic granite.

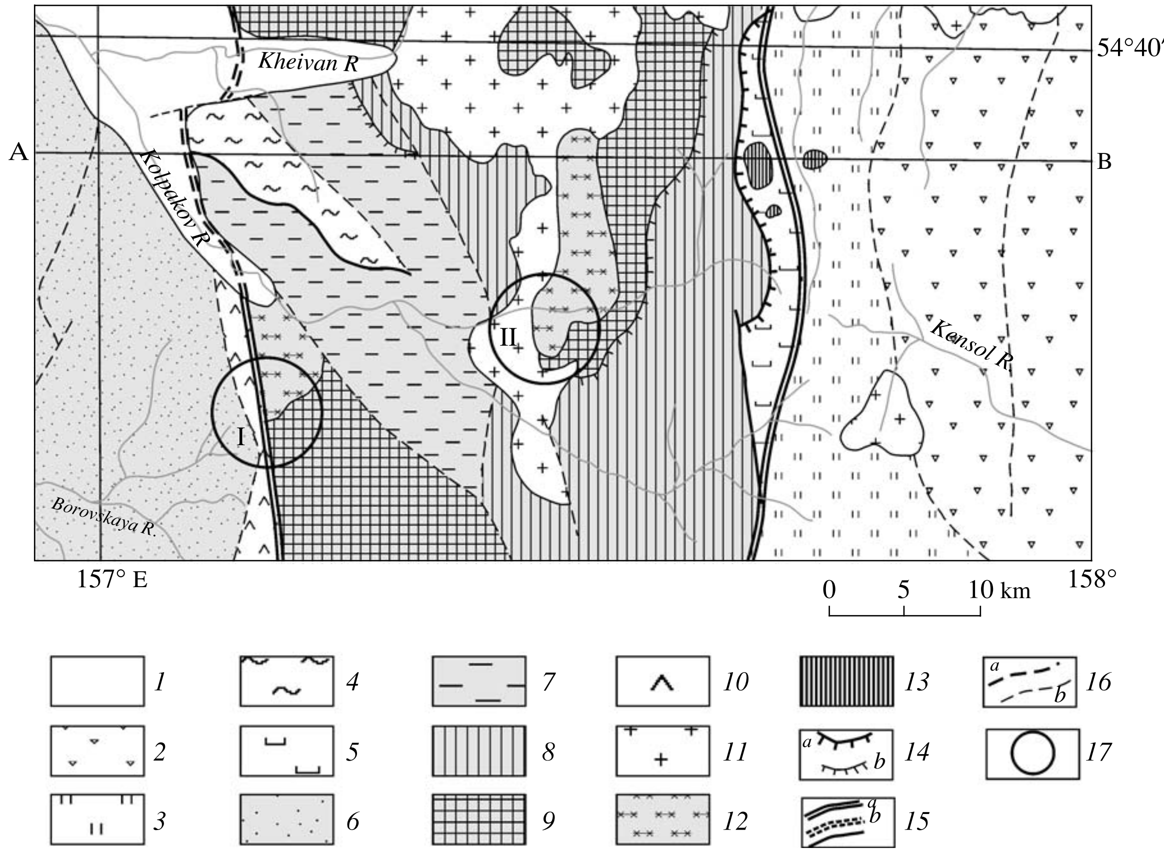


Fig. 4. Geology of the Kolpakov River basin, the Sredinny Range of Kamchatka, modified after [13, 45]. (*1*) Quaternary sediments; (*2*) volcanic and volcanosedimentary rocks of the Kirganik Formation (Maastrichtian–Paleocene); (*5*) Santonian–Campanian cherty and volcanic rocks and their metamorphosed equivalents: (*3–5*) Irunei Formation, (*6*) Khimka Formation, (*5*) Andrianovka Formation; (*6–8*) Upper Cretaceous–Paleocene terrigenous rocks and their metamorphosed equivalents: (*6*) Khozgon Formation, (*7*) Kheivan and Stopol'nikov formations, (*8*) Kamchatka Group (Shikhta Formation); (9) Lower and Upper Cretaceous metamorphic rocks of the Kolpakov Formation; (*10*) Upper Jurassic–Lower Cretaceous (?) volcanic rocks of the Kwakhon Formation; (*11*) Eocene equigranular granite; (*12*) Late Cretaceous gneissic granite and granite gneiss of the Krutogorov Complex; (*13*) Late Cretaceous (Campanian–Maastrichtian) pyroxenite–gabbro–syenite intrusions; (*14*) thrust faults: (*a*) major (boundary between autochthon and allochthon) and (*b*) auxiliary; (*15*) near-vertical faults: (*a*) major and (*b*) auxiliary; (*16*) inferred faults: (*a*) major and (*b*) auxiliary; (*17*) sites studied in detail (numerals in figure): (I) headwater of the Poperechnaya River, a right tributary of the Kolpakov River, (II) middle reaches of the Right Kolpakov River.

The gneissic granite itself is exposed as small outcrops and its contacts with metamorphic rocks are not observable. The gneissic banding is emphasized by the orientation of biotite flakes. The primary microstructure is hypidiomorphic-granular and locally poikilitic. The granite consists of quartz, plagioclase, K-feldspar, and biotite. Apatite, zircon, and titanite are accessory minerals.

The medium- to fine-grained equigranular granite occurs as plutons from 2 × 2 to 8 × 12 km^2 in area, which have intrusive contacts with metamorphic schists of the Kamchatka Group and gneisses of the Kolpakov Group and contain gneiss xenoliths. Close to the Poperechnaya River (Fig. 4, site 1), we observed injections of fine-grained muscovite and two-mica granite into the gneissic biotite granite.

The equigranular hypidiomorphic-granular granite consists of quartz, K-feldspar, and plagioclase in variable proportions. Biotite, muscovite, sporadic amphibole, and hypersthene are dark-colored minerals. Garnet occurs in variable amounts in both muscovite and two-mica varieties. Apatite, zircon, titanite, and ore mineral are present as accessories.

At an outcrop on the right bank of the Right Kolpakov River (Fig. 4, site II), the equigranular granite contains granodioritic inclusions 10–25 cm in diameter. The melanocratic inclusions consisting of plagioclase, quartz, K-feldspar, and biotite are characterized by sharp idiomorphism of the plagioclase in respect to other rock-forming minerals.

The gneissic and equigranular granites, like the country schists of the Kamchatka Group, are crossed by dikes of aplite, pegmatite, and granite porphyry.

It should be noted that the Kol tonalitic pluton was mapped in the southern portion of the Sredinny Range composed of metamorphic rocks [30–32, 37, 40]. Dif-

U–Pb (SHRIMP) dates of granitic rocks from the southern Sredinny Range, Kamchatka

Sample	Sample location, coordinates, and height	Rock and dated mineral	Average weighted age, Ma, ±2σ
02LG24	Krutogorov R. (Fig. 3), 54°50.564′ N, 157°22.754′ E, 1091 m	Gneissic granite, zircon	$^{206}Pb/^{238}U$ 78.5 ± 1.5 (n* = 9/12) MSWD = 2.1
04AS69 (M-0024/1)	Right Kolpakov R. (Fig. 4, site II), 54°29.907′ N, 157°25.994′ E, 880 m	Gneissic biotite granite, zircon	$^{206}Pb/^{238}U$ 80.2 ± 0.9 (n* = 12/13) MSWD = 1.27
04AS99	Poperechnaya R. (Fig. 4, site I), 54°23.895′ N, 157°09.081′ E, 1130 m	Mylonitized two-mica granite, zircon	$^{206}Pb/^{238}U$ 79.2 ± 1.9 (n* = 8/15) MSWD = 1.34
04AS75	Poperechnaya R. (Fig. 4, site I), 54°27.047′ N, 157°11.512′ E, 1034 m	Orthogneiss, zircon	$^{206}Pb/^{238}U$ 79.3 ± 0.9 (n* = 10/13) MSWD = 1.55
02JH47/1	Krutogorov R. (Fig. 3), 54°50.120′ N, 157°23.096′ E, 1320 m	Plagiogranitic leucosome of garnet–biotite gneiss, outer rim of zircon	$^{206}Pb/^{238}U$ 51.2 ± 0.5 (n* = 8/12) MSWD = 0.97
02AS04	Krutogorov R. (Fig. 3), 54°53.150′ N, 157°17.20′ E, 1320 m	Garnet–biotite tonalite, zircon	$^{206}Pb/^{238}U$ 51.5 ± 0.7 (n* = 13/13) MSWD = 0.27
02JH111	Left Andrianovka R. (Fig. 1, site II), 54°37.547′ N, 157°35.049′ E, 1040 m	Two-mica granite, zircon	$^{206}Pb/^{238}U$ 52.6 ± 1.2 (n* = 12/12) MSWD = 6.0
02JH111	Right Kolpakov R. (Fig. 4, site II), 54°37.547′ N, 157°35.049′ E, 1040 m	Two-mica granite, monazite	$^{208}Pb/^{232}Th$ 51.9 ± 0.7 (n* = 8/8) MSWD = 0.25
02JH117	Left Andrianovka R. (Fig. 1, site II), 54°37.017′ N, 157°34.935′ E, 1070 m	Two-mica granite, zircon	$^{206}Pb/^{238}U$ 50.1 ± 1.7 (n* = 7/9) MSWD = 8.4
02JH117	Left Andrianovka R. (Fig. 1, site II), 54°37.017′ N, 157°34.935′ E, 1070 m	Two-mica granite, monazite	$^{208}Pb/^{232}Th$ 52.1 ± 0.6 (n* = 12/12) MSWD = 0.12
04AS67	Right Kolpakov R. (Fig. 4, site II), 54°27.703′ N, 157°26.520′ E, 1693 m	Two-mica granite, zircon	$^{206}Pb/^{238}U$ 54.9 ± 0.5 (n* = 9/15) MSWD = 1.9

Notes: * n is the number of grains used for calculation of the average weighted age/total number of dated grains. The data on samples 02LG24, 02JH47/1, 02AS04, 02JH111, and 02JH117 were taken from [60].

ferent views on its age and relationships with country metamorphics of the Malka Group exist. Sinitsa and Shashkin [32] supposed that tonalite experienced metamorphism along with country rocks. Khanchuk [39, 40] contended that the Kol pluton intrudes the rocks of the Malka Group, whereas the Upper Cretaceous unmetamorphosed terrigenous rocks overlap tonalite with conglomerate at the base. Thus, Khanchuk regarded the Kol pluton as pre-Cretaceous, Late Paleozoic, or Mesozoic. The U–Pb age of magmatism is 2134 ± 325 Ma, whereas the age of metamorphism id 106 ± 31 Ma [V.K. Kuz'min et al., 2003]. We have not any new data concerning this pluton, and it is omitted in the following discussion.

U–Pb (SHRIMP) DATINGS OF GRANITES

The closure temperature of the U–Pb isotopic system in zircon is higher than 900°C [62]. It is assumed that the U–Pb zircon age corresponds to the time of emplacement of plutonic rocks and that the U–Pb system is very resistant to external effects.

About 50 zircon grains were separated from each sample. Zircons from the sample and AS57 standard [72] were placed into epoxy and polished. The zircon grains were verified for the absence of fractures and inclusions in the reflected and transmitted light at ×20 magnification. A cathodoluminescent detector mounted on a ZEOL JSM 5600 SEM was used to examine the zoning and internal structure of the polished zircons.

The isotopic measurements were performed on a SHRIMP-RG (Sensitive High-Resolution Ion Micro-Probe–Reverse Geometry) at the Microanalytical Center of the USGS in Stanford, using the standard technique [68]. A beam of oxygen anions ~30 μm in diameter was used for ionization of the analyzed matter. Each measurement consisted of five cycles. After four or five measurements of a crystal with unknown age, the AS57 standard was measured. The U and Th contents were calibrated by SL13 [85].

The ages presented in the table were corrected for ^{207}Pb with the assumption that a simple mixture of common and radiogenic lead occurs in slightly discordant zircons. The measured $^{207}Pb/^{206}Pb$ is used in correction for common lead. The age was calculated by extrapolation of the measured data on concordia along the line that corresponds to the model composition of common lead [54] at approximation for the age of particular grains.

Dating of gneissic granitic rocks. Zircons from sample 02LG24 of gneissic granite pertaining to the Krutogorov Complex and taken at the headwater of the Krutogorov River (Fig. 3) yielded an age of 78.5 ± 1.2 Ma (Table).

Gneissic biotite granite of sample 04AS69 (Fig. 4, site II) taken from the middle reaches of the Right Kolpakov River contains zonal zircons dated at 80.2 ± 0.9 Ma (Table). Sample 04AS99 of mylonitized two-mica granite was taken on the western slope of the Sredinny Range in the immediate proximity of the fault that separates the metamorphozed and unmetamorphosed rocks (Fig. 4, site I). Zircon from this sample yielded 79.2 ± 1.9 Ma. Zircons from orthogneiss sampled on the right bank of the Poperechnaya River have concordant age of 79.3 ± 0.9 Ma.

The above results show that the Krutogorov Granite crystallized 80–78 Ma ago. The four dated samples from different localities at a great distance from one another are close in age and thus indicate that a short-term episode of granite formation occurred in the Malka Uplift of the Sredinny Range in the Campanian.

Dating of equigranular granitic rocks. The zircons separated from a dike of garnet–biotite tonalite (Fig. 3, sample 02AS04), which cuts autochthonous metamorphic rocks of the Kolpakov Group; the thrust fault zone composed of metabasic rocks; and the allochthonous rocks are euhedral crystals with distinct magmatic zoning. Their age is estimated at 51.5 ± 0.7 Ma (table). This age corresponds to the upper age limit of overthrusting that happened before ~52 Ma ago.

Equigranular two-mica granites from the Left Andrianovka River basin (Fig. 1, site II, samples 02JH111 and 02JH117) and the Right Kolpakov River basin (Fig. 4, site II, sample 04AS67) contain zircons dated at 50.1 ± 1.7 to 54.9 ± 0.5 Ma (Table). The Pb–Th ages of monazite from samples 02JH111 and 02JH117 are 51.9 ± 0.7 and 52.1 ± 0.6 Ma, respectively (Table). It is noteworthy that the zircon and monazite ages of equigranular two-mica granite are very close to the age of leucosome in the migmatized garnet–biotite gneiss of the Kolpakov Group (Fig. 3, sample 02JH47/1), estimated at 51.2 ± 0.5 Ma (Table).

The U–Pb (SHRIMP) dates of zircon from the equigranular granite show that they were emplaced in the early Eocene. In addition, the ages of the outer rims of the zircon grains from the leucosome of the Kolpakov migmatite and the metamorphic monazite indicate that a peak of metamorphism and anatexis falls on the early Eocene (52 ± 2 Ma ago). This implies that the early Eocene episode of granite formation was coeval with a peak of metamorphism.

Thus, it may be stated that the Campanian (80–78 Ma) and early Eocene episodes of granite formation are established in the Malka Uplift of the Sredinny Range in Kamchatka. The granitic rocks of the first stage underwent metamorphism and acquired a gneissic appearance. These rocks should be referred to the Krutogorov Complex. The early Eocene granitic rocks were formed contemporaneously with peak metamorphism.

CHEMICAL COMPOSITION OF GRANITIC COMPLEXES

The analyzed equigranular granitic rocks correspond to granite and granodiorite in chemical composition, while the gneissic rocks and melanocratic inclusions in the equigranular granites are granodioritic [66]; both groups fall into the fields of normal alkalinity and subalkaline rocks in the TAS diagram (Fig. 5). The granitic rocks are medium- to high-potassic (Fig. 6a). The K/Na ratio varies from 0.6 to 2.45. The granitic rocks are characterized by similar saturation with aluminum relative to the Ca, Na, and K sum (ASI = 0.95–1.3) and make up a compact cluster in the field of high-alumina granite in the Al/(Na + K) versus Al/(Ca + Na + K) diagram; some samples of equigranular granites have ASI = 1.6 (Fig. 6b).

The petrochemical parameters (relationships between ASI and SiO_2, $FeO_t + MgO + TiO_2$, and SiO_2) of both equigranular and gneissic granitic rocks reveal similarity with S-granite of collisional orogens. Most of their compositions fall into the field of S-granites in the Sylvester diagram CaO/Na_2O versus Al_2O_3/TiO_2 [82] (Fig. 7).

Both the gneissic and equigranular granitic rocks are subdivided into two groups on the basis of chondrite-normalized REE patterns.

The first group of gneissic granitoids is characterized by fractionated REE patterns enriched in LREE and depleted in HREE (La_N/Yb_N = 33.07–63.56; La_N/Sm_N = 3.83–5.93); the rocks are devoid of Eu anomaly or have a small Eu maximum (Eu/Eu* = 1.01–1.85) (Fig. 8a). Granites of this group are distinguished by an elevated Sr/Y ratio within the range of 59.1 to 45.48 (Fig. 9). The second group is distinguished by higher HREE contents (La_N/Yb_N = 2.68–5.59; La_N/Sm_N = 1.47–2.44) and a distinct Eu minimum (Eu/Eu* = 0.41–0.46). The REE patterns of this group of granitic rocks are virtually identical to those of country gneisses of the Kolpakov Group (Fig. 8b).

Two similar groups are distinguished among the equigranular granites. The first group is characterized by fractionated REE patterns (La_N/Yb_N = 14.30–71.37; La_N/Sm_N = 3.04–3.96) and an elevated Sr/Y ratio (Figs. 8b, 9), but in contrast to the gneissic granites has positive (Eu/Eu* = 1.54) and slightly negative (Eu/Eu* = 0.69–0.58) Eu anomalies.

The second group of equigranular granitic rocks is enriched in HREE and reveals a distinct Eu minimum (La_N/Yb_N = 1.26–5.88; La_N/Sm_N = 1.99–2.50: Eu/Eu* = 0.16–0.44) (Fig. 8d). The equigranular granites of the second group can be subdivided into two subgroups with different total REE contents (10–20 and 80–100 chondrite units of LREE and 2–3 and 15 chondrite units of HREE, respectively). The REE patterns with a higher total REE content are similar to those of the country metaterrigenous rocks of the Kamchatka Group but differ in having a deeper Eu minimum

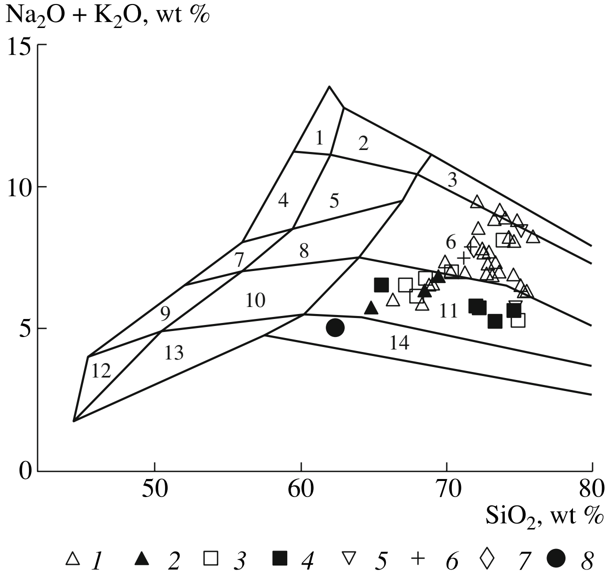


Fig. 5. Compositions of granitic rocks from the Malka Uplift, the Sredinny Range plotted on the TAS diagram [66]. (*1*) Equigranular granite, (*2*) granodiorite from inclusions in equigranular granite, (*3*) gneissic granite, (*4*) leucosome of migmatite in the Kolpakov Group, (*5*) aplite, (*6*) granite porphyry, (*7*) mylonitized two-mica granite, (*8*) late kinematic tonalite. Fields in diagram : (1) alkali syenite, (2) alkali quartz syenite, (3) alkali granite, (4) syenite; (5) quartz syenite, (6) granite, (7) monzonite, (8) quartz monzonite, (9) monzodiorite, (10) quartz monzodiorite, (11) granodiorite, (12) gabbro, (13) quartz diorite, (14) tonalite.

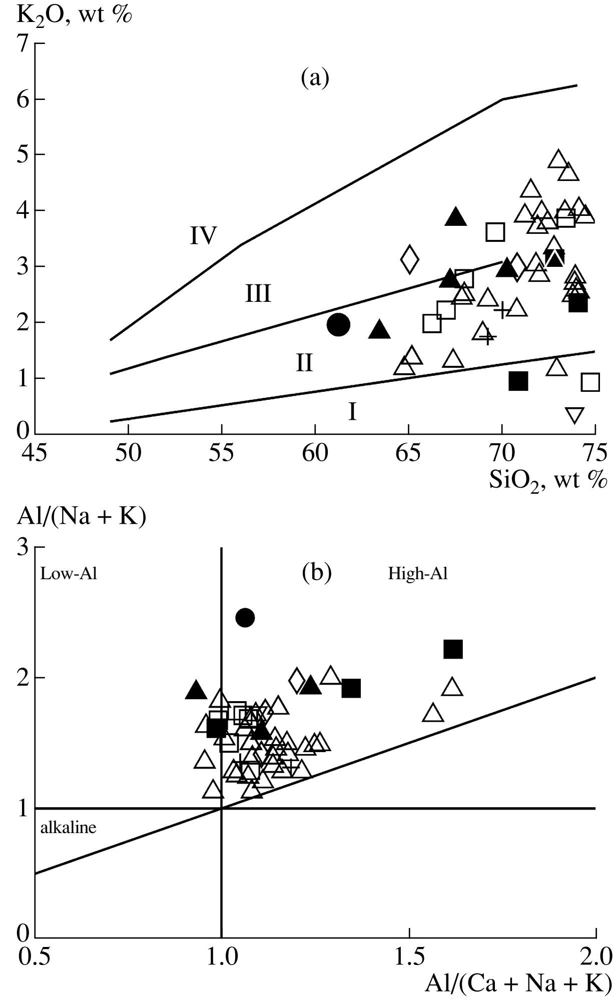


Fig. 6. Compositions of granitic rocks from the Malka Uplift, the Sredinny Range plotted on (a) K_2O–SiO_2 and (b) Al/(Na + K)–Al/(Na + K + Ca) diagrams. See Fig. 5 for legend. Fields of series in diagram (a), after [76]: (I) tholeiitic, (II) calc-alkaline, (III) high-K calc-alkaline, and (IV) shoshonitic.

(Fig. 8d). The REE pattern of the muscovite granite (sample 437/4) stands out in having flat LREE and HREE segments and the deepest Eu minimum (La_N/Yb_N = 1.26; La_N/Sm_N = 2.50: Eu/Eu* = 0.16) (Fig. 8d). Such patterns are typical of highly evolved leucogranites [15].

In general, the geochemical parameters of the first groups of both gneissic and equigranular granitic rocks (elevated La_N/Yb_N and Sr/Y ratios) bring these rocks together with adakites and high-Al tonalites, trondhjemites, and dacites (TTD). The REE patterns of the rocks belonging to second groups are similar to those of collisional granites [4] (Fig. 8d).

The spidergrams of the gneissic and equigranular granitic rocks are identical and characterized by Rb, Th, Ce, and Sm maximums and Ba, Ta, Nb, Zr, and Hf minimums, broadly resembling the syncollision granites in this respect [75] (Fig. 10).

The data points of gneissic and equigranular granites plotted on a Velikoslavinsky discriminant diagram [4] fall into the field of collisional granites (Fig. 11).

DISCUSSION

The petrography and petrochemistry of granites from the Malka Uplift of the Sredinny Range (high SiO_2 content, micas and garnet contained in rocks, and relationships between ASI and SiO_2, FeO_t + MgO + TiO_2 and SiO_2, Al_2O_3/TiO_2 and CaO/Na_2O) testify to their similarity to S-granites [50], which are commonly regarded as a result of partial melting (anatexis) of crustal metasedimentary rocks either owing to radioactive decay and heating of the anomalously thick (>50 km) crust of the collision systems or to delamination of the lithosphere and supply of the hot asthenospheric mantle to the base of the crust under postcollision conditions [27, 58, 74, 82]. The high-alumina composition of the granites in the Sredinny Range suggests that their source is metasedimentary rocks; however, the geochemical data provide for a more complex model. We realize that the comprehensive characteristic of a source of granitic magma requires the involvement of Sr and Nd isotopic data, and have undertaken efforts in this direction. In this paper, our reasoning is based on

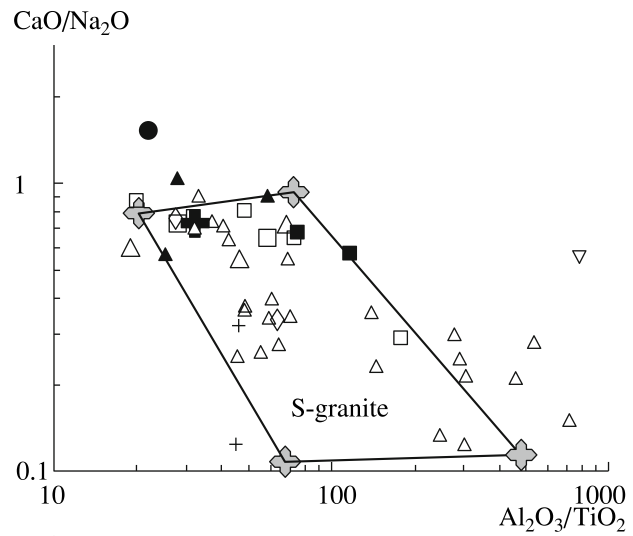


Fig. 7. Compositions of granitic rocks from the Malka Uplift, the Sredinny Range plotted on the CaO/Na_2O–Al_2O_2/TiO_2 diagram. See Fig. 5 for legend. The field of S-granites and its boundary types are given after [82].

the REE partition between granitic and country metamorphic rocks.

Geodynamic Types of Granites and Composition of Source Involved in Melting

The two groups of gneissic granites distinguished in their REE patterns (see above) could have been formed due to the partial melting of different sources.

The Campanian gneissic granites (Krutogorov Complex) of the first group with fractionated REE patterns characterized by depletion in HREE, high La_N/Yb_N ratio, and elevated Sr/Y ratio are typical of high-alumina TTD and adakites. Their origin is identified with the partial melting of mafic rocks, when garnet and/or amphibole are retained as restitic phases. The geodynamic setting of this process may be different [38, 52, 56, 65, 67 and references therein]. Similarly fractionated REE patterns are inherent to granites genetically related to the partial melting of graywackes

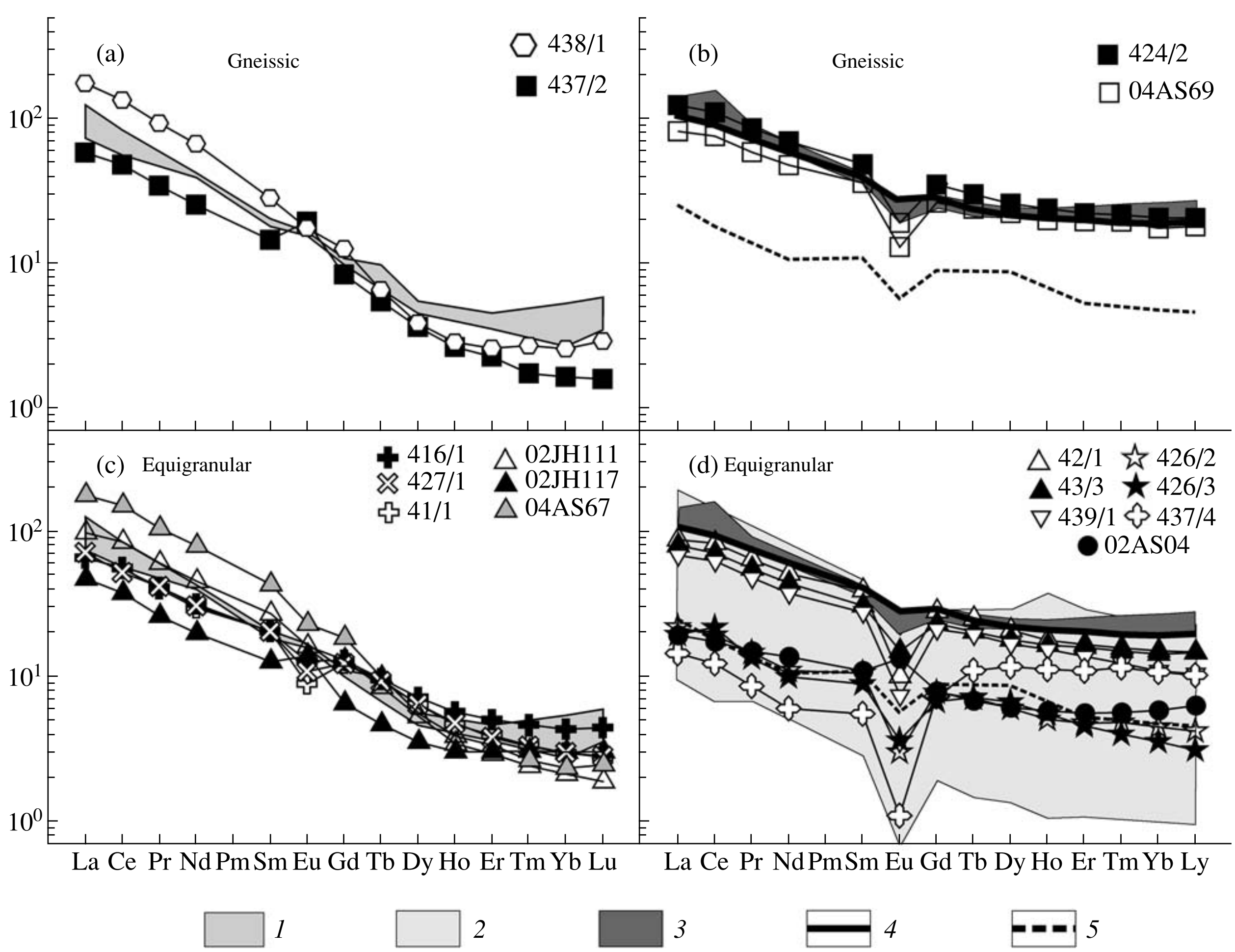


Fig. 8. Chondrite-normalized REE patterns: (a, b) gneissic and (c, d) equigranular granitic rocks of the Malka Uplift, the Sredinny Range. The chondrite composition was taken from [81]. (*1*) Archean high-alumina TTD and Cenozoic adakites, after [56]; (*2*) collision granites, after [4]; (*3*) metasedimentary rocks of the Kolpakov Group; (*4*) metasedimentary rocks of the Kamchatka Group; (*5*) Miocene Manaslu leucogranite, the Himalayas [53].

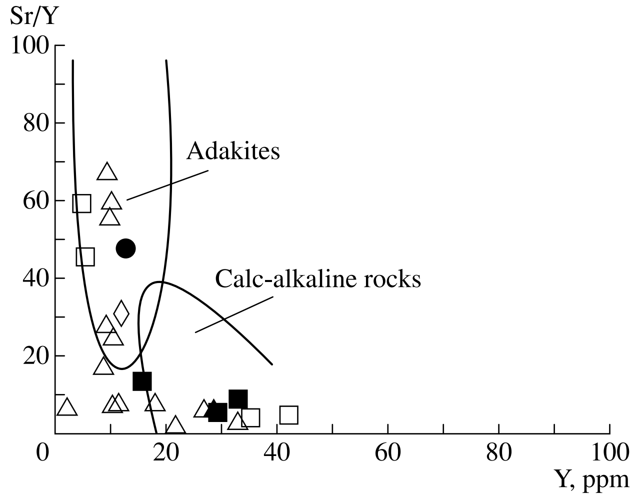


Fig. 9. Compositions of granitic rocks from the Malka Uplift, the Sredinny Range plotted on the Sr/Y–Y diagram, after [56].

in equilibrium with eclogitic restite, e.g., as suggested for the Late Cretaceous garnet-bearing two-mica low- to medium-Al granites of the Whipple Mountains Complex of the metamorphic cores in southeastern California [47].

Thus, it may be supposed that a source of gneissic granites of the first group was composed of mafic igneous rocks or graywackes metamorphosed under conditions of amphibolite to granulite facies. In the process of partial melting, garnet and/or amphibole must have been retained as restitic phases. This suggestion does not contradict the occurrence of graywackes and amphibolites (high-Ti oceanic metabasalts) in the Kolpakov Group [26] cut through by granites.

The REE patterns of gneissic granites pertaining to the second group (with low La_N/Yb_N ratio and pronounced Eu minimum) are comparable to the REE patterns of collisional S-granites derived from metapelitic sources, in particular, to the REE pattern of the Miocene syncollision Manaslu Leucogranite in the Himalayas [53]. However, the variations of the Rb/Ba and Rb/Sr ratios in the granites of this group indicate that their source may have been poor in the metapelitic component. The data points of the granites plotted on the Rb/Ba versus Rb/Sr diagram [82] are localized between the mean compositions of graywacke, shale, and the melt derived from melting of a psammitic source (Fig. 12). The metasedimentary composition of this source is confirmed by similar REE patterns of granitic rocks and country gneisses of the Kolpakov Group (Fig. 8).

The early Eocene equigranular granites are also subdivided into two groups with high and low La_N/Yb_N and Sr/Y ratios and a distinct Eu minimum. Like gneissic granites of the first group, the equigranular granites with the above-mentioned characteristics are compared with high-alumina TTD and adakites (Fig. 8). This similarity indicates that mafic rocks occurred in their source, and garnet and amphibole were restitic phases in the process of partial melting. The equigranular granites of the second group are distinguished by a wide range of total REE contents (Fig. 8), and their REE patterns do not go beyond the field of collisional granites in the Velikoslavinsky discriminant diagram. The granites of this group with high total REE contents are probably products of the partial melting of a metapelitic source, as supported by the similar REE patterns of granites and country metaterrigenous rocks pertaining to the Kamchatka Group. According to [37], a protolith of these metamorphic rocks was composed of clay with sporadic interbeds of polymictic and arkosic sandstones. The variations of the Rb/Ba and Rb/Sr ratios in most equigranular granites of the second group admit the presence of both metapelitic and metapsammitic components in the metasedimentary source (Fig. 12).

Thus, two types of sources, containing both mafic metavolcanic and metasedimentary rocks with variable contribution of metapelitic components were involved in melting during the formation of gneissic granites in the Late Cretaceous (80–78 Ma ago) and equigranular granites in the early Eocene (52 ± 2 Ma).

Geodynamic Settings of Granite Formation

The Campanian stage. Khanchuk [40] regarded the rocks of the Kolpakov Group as a metamorphosed material of an accretionary wedge. Our observations confirm this opinion. The isotopic timing of the terrigenous protolith indicates its Cretaceous age [34, 60]. Thus, the first stage of the granitic magmatism of the Sredinny Range—formation of gneissic granites 80–78 Ma in age—most likely was related to the accretionary setting at the Kamchatka margin of Eurasia. The cause of the occurrence of granitoid magmatism in the accretionary wedge of Kamchatka and other territories of the Pacific margin has remained poorly understood until now. The Miocene calc-alkaline granitic rocks known from the Shimanto accretionary wedge are peraluminous, whereas in the north they are metaluminous and contain inclusions of metamorphic rocks [78–80]. Shinjoe [78] explained the generation of accretionary granitoids by the partial melting of the sedimentary material of the accretionary wedge heated by high-temperature andesitic magma, which was a product of partial melting of hydrous peridotite in the forearc region. In the course of this process, the andesitic and granitic melts mixed, and afterward the mixed melt underwent fractionation. In terms of the model proposed in [79], the mafic melts supplied from the hot enriched mantle due to the plunging of the ocean ridge into the subduction zone were a source of heat necessary for melting of the Shimanto accretionary wedge and generation of granitic magma. Finally, as suggested

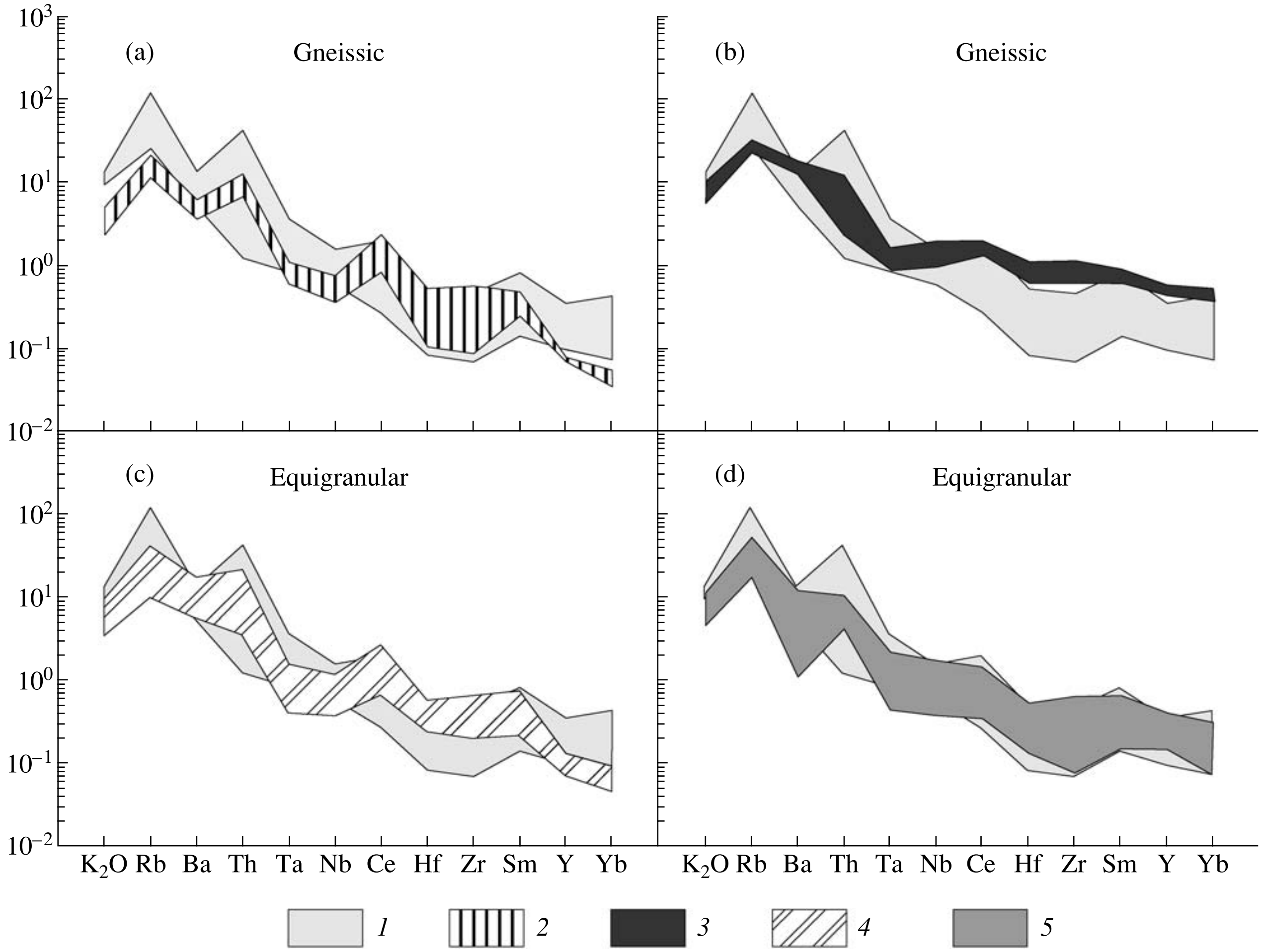


Fig. 10. Spidergrams of granitic rocks from the Malka Uplift, the Sredinny Range: (a, b) gneissic and (c, d) equigranular granitic rocks. Chemical element contents are normalized to the composition of a hypothetical oceanic granite, after [75].
(*1*) Syncollision granites, after [75]; (*2, 3*) groups of gneissic granites with (*2*) first and (*3*) second types of REE patterns; (*4, 5*) groups of equigranular granites with (*4*) first and (*5*) second types of REE patterns.

in [51], granitoids of the Shimanto accretionary wedge are postcollision and were emplaced approximately 2 Ma after collision of the North Philippine Block and Southwest Japan.

The formation of the Late Cretaceous–early Paleocene Hidaka accretionary wedge was also accompanied by granitoid magmatism, largely by tonalites. Maeda and Kagami [64] connect this phenomenon with the subduction of the Kula–Pacific oceanic ridge in the late Paleocene or early Eocene. These authors supposed that magma of the N-MORB type, having been separated from the emerging asthenospheric mantle along the Kula–Pacific Ridge, migrated into the base of the accretionary wedge and served as a source of heat. The accreted sedimentary material was metamorphosed up to the conditions of granulite facies and partly underwent anatexis with the formation of granitic magma [64]. In the special issue of the Journal of the Geological Society of Japan published in November 2006 and devoted to the Hidaka accretionary wedge, it was noted that in the main anatectic zone IV of the Hidaka Belt, both pelitic and mafic granulites were involved in partial melting. Various leucosomes are products of dehydration partial melting of biotite and amphibole, respectively. The melts generated in the main anatectic zone, while migrating, are transformed into tonalitic magma that crystallizes in form of plutons that bear attributes of both high-alumina S-type and low-alumina I-type granites [71].

In the case of the Late Cretaceous gneissic granites of the Sredinny Range in Kamchatka, the question arises of what sort of thermal event gave rise to the generation of granitic melt. The first alternative suggests underplating of the base of the accretionary wedge by mafic material as a result of partial melting of the mantle wedge above the subduction zone, although no mafic igneous rocks are observed in association with granites. By analogy with the Shimanto and Hidaka accretionary wedges [64, 79, 80], the second alternative supposes plunging of the oceanic ridge beneath the

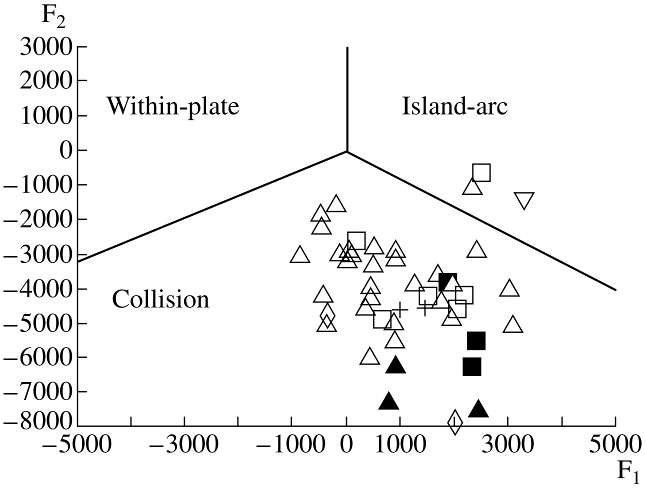


Fig. 11. Compositions of granitic rocks from the Malka Uplift, the Sredinny Range plotted on the Velikoslavinsky discriminant diagram [4] that classifies rocks by geodynamic settings. Discriminant functions F_1 and F_2 are calculated taking into account major and minor elements, including REE. See Fig. 5 for legend.

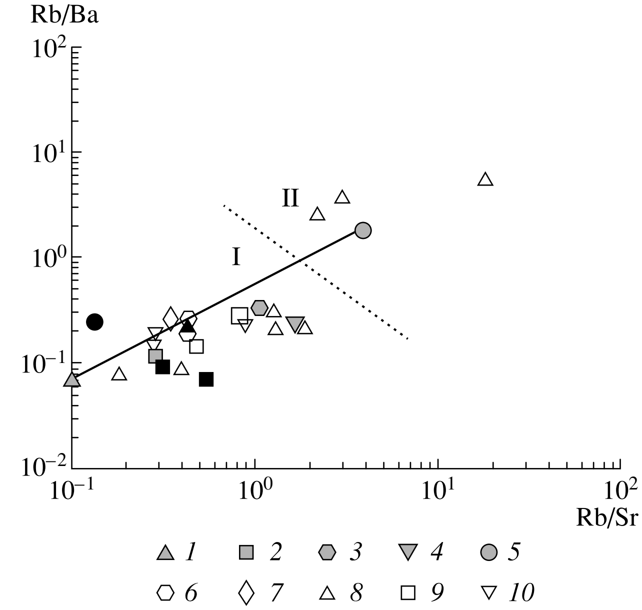


Fig. 12. Compositions of granitic rocks from the Malka Uplift, the Sredinny Range plotted on the Rb/Ba–Rb/Sr diagram. The compositions of granitoids presumably derived from metasedimentary sources are plotted. The calculated compositions: (*1*) basalt, (*2*) graywacke, (*3*) shale; (*4, 5*) melts derived from (*4*) psammitic and (*5*) pelitic sources; (*6, 7*) metasedimentary rocks of (*6*) Kolpakov and (*7*) Kamchatka groups; see Fig. 5 for other symbols. The dashed line separates the sources poor (I) and rich (II) in clay component.

Kamchatka margin, formation of a mantle window, heating of the base of the accretionary wedge, and generation of granitic melt. The occurrence of both metabasic and metasedimentary rocks in the source of the gneissic granites must be taken into account. The material of the accretionary wedge may be regarded as a metasedimentary source, whereas fragments of oceanic crust (its upper basaltic layer) incorporated into the wedge may have been a mafic source. To generate a granitic melt, the degree of partial melting of the mafic source must be not great (5–7%). A higher rate of melting results in the formation of tonalitic and trondhjemitic melts [77].

The early Eocene stage. The second stage of granitic magmatism—formation of equigranular granite—is coeval with the collision of the Achaivayam–Valagin ensimatic island arc with the Kamchatka margin of Eurasia. The dates of zircons from the equigranular granite, the leucosome of migmatite in the gneisses of the Kolpakov Group, the synkinematic garnet–biotite tonalite from the dike that cuts the Kolpakpvo Group (autochthon), the thrust fault zone composed of metabasic rocks, and the allochthonous rocks are very close to one another (52 ± 2 Ma). This implies that granite generation occurred at a peak of metamorphism. This process could not have been related to the thermal relaxation of anomalously thick crust because the time span between the peak metamorphism, emplacement of equigranular granite, and exhumation of metamorphic and granitic rocks was no longer than 2 Ma [34, 45]. The thermal and petrological models proposed by England and Thompson [57] and Patino Douce et al. [74] have shown that leucogranites are formed as a result of partial melting of metapelites in collisional systems (Himalayas, Sevier Belt in North America) 25–30 Ma after the onset of collision or 10 Ma after completion of syncollision deformation. In the collision model of granite formation in the Shimanto accretionary wedge [51], the collision is dated at 20–17 Ma and the time of granite emplacement at 15–12 Ma; i.e., the minimum estimate of the time interval between collision and granite formation is 2 Ma, as in Kamchatka. Similar estimates of the age of emplacement of granitic plutons as a result of arc–continent collision were obtained for the Jurassic–Cretaceous Peninsular Ranges Batholith in Mexico [62, 83], where collision took place 110 Ma ago [61], the age of the oldest plutons is 108 ± 1.8 Ma [62], and emplacement of granites lasted for 4.4 Ma [61].

It cannot be ruled out that equigranular granite was formed contemporaneously with the collapse of the orogen due to the decompression melting in extensional setting, as suggested by Harris and Massey [58] for the Miocene leucogranite of the Himalayas. Under this scenario, both types of sources—mafic igneous rocks and sedimentary rocks (graywackes or pelites)—should be involved in melting.

Finally, the friction heating in the course of thrust and strike-slip faulting might be a mechanism of granitic (leucogranitic) melt generation. This mechanism was used for genetic interpretation of the Neogene Moly May Leucogranite that cuts through the Coast plutonic complex in British Columbia [46]. The numerical modeling of this process was carried out in [69, 70] for the Proterozoic Harney Peak late orogenic leucogranite in South Dakota (Trans-Hudson Orogeny). It has been shown that the temperature in the thrust fault zone could have increased to 700°C or higher. As a result, small batches of leucogranitic melt can be formed as a result of dehydration melting of pelitic material, and emplaced into the crust as dikes. However, it is assumed that thrusting developed over the course of 60 Ma, i.e., much longer than collision in the Sredinny Range of Kamchatka.

Thus, a new model of the tectonic evolution of the rock complexes in the Sredinny Range was proposed on the basis of geological, structural, and new geochronological data (see [14, 34, 60] for more detailed discussion). In the Late Cretaceous (pre-Campanian), terrigenous rocks (lower units of the Khozgon Formation and its analogs) participated in the formation of the accretionary wedge [34, 40]. Afterward, these rocks served as a protolith for metamorphic rocks of the Kolpakov Group [34, 40, 60] and were cut through by gneissic granite of the Krutogorov Complex approximately 78–80 Ma ago.

About 60 Ma ago, the Achaivayam–Valagin ensimatic island arc approached the Kamchatka margin of Eurasia for a distance of a few hundred of kilometers [16, 17, 43]. Terrigenous sedimentation (upper units of the Khozgon Formation) continued for ~55 Ma in the relict basin between the margin and arc [34, 60], and the deposits of this age became the protolith for schists of the Kamchatka Group. In the process of subsequent collision, the marginal-sea and island-arc tectonic sheets were rapidly thrust over the heterogeneous continental margin. The westward-verging thrusts in the zone of the Andrianovka Suture were related to the collision [14]. As a result, the margin was rapidly buried beneath a packet of tectonic sheets. In the present-day Malka Uplift, the thrusting of the Achaivayam–Valagin arc over the terrigenous sequence of the continental margin was immediately followed by intense and fast structural rearrangement, including deep subsidence and fast (no longer than 3–5 Ma) heating of the crust, which gave rise to high-temperature (550–650°C) metamorphism of moderate pressure that embraced the lower portion of the collisional zone and resulted in the generation of granitic magma [34, 60]. This event occurred 52±2 Ma ago. According to the U–Pb (SHRIMP) zircon dates, migmatization, partial melting, and emplacement of equigranular granite proceeded synchronously.

Such heating would be impossible owing only to the conductive heat transfer from the lower crust into the terrigenous and volcanic rocks buried beneath a pile of thrust sheets. An additional powerful heat source was required. The fast heating of the crust was probably caused by destruction of the lower lithosphere and ascent of asthenospheric masses (anomalous mantle) to the lower crust (Fig. 13) [34]. As was shown recently for many examples, such an ascent is a result of slab breakoff [48, 55].

CONCLUSIONS

(1) The gneissic and equigranular granites are distinguished in the Malka Uplift of the Sredinny Range. According to the results of U–Pb (SHRIMP) dating, the former were emplaced in the Campanian (80–78 Ma ago) and the latter in the early Eocene (52 ± 2 Ma ago). The gneissic granites are correlated with the Krutogorov plutonic complex; they cut through metamorphic rocks of the Kolpakov Group and together with these rocks make up the autochthon. The equigranular granites cut through the autochthtonous Kolpakov and Kamchatka groups, allochthon, and boundary thrust fault zone in the Krutogorov River basin.

(2) The petrography and petrochemistry of the gneissic and equigranular granites, including high SiO_2 contents; the occurrence of muscovite and garnet; and the relationships between ASI and SiO_2, $FeO_t + MgO + TiO_2$ and SiO_2, and Al_2O_3/TiO_2 versus CaO/Na_2O, testify to their similarity with S-type granites. The geochemical data indicate that two types of sources—metabasic and metasedimentary (depleted and enriched in the metapelitic component)—were involved in melting to generate both gneissic and equigranular granites.

(3) The Campanian episode of granitic magmatism in the Sredinny Range—formation of gneissic granites 80–78 Ma in age—was related to accretionary setting at the Kamchatka margin of Eurasia. The cause of the outburst of magmatic activity remains ambiguous. It is suggested that granitic magma was generated by partial melting of the accretionary wedge due to underplating by mafic magma. By analogy with the granitoids of the Shimanto accretionary wedge, it is admitted that plunging of the oceanic ridge might be the cause. Both the sedimentary rocks of the accretionary wedge and the fragments of the oceanic crust (basaltic layer) incorporated therein were probably involved in melting.

(4) The early Eocene episode of granitic magmatism—formation of equigranular granites—was coeval with the collision of the Achaivayam–Valagin ensimatic island arc and the Kamchatka margin of Eurasia 52 Ma ago. The time interval that embraced peak metamorphism, emplacement of equigranular granites, and exhumation of metamorphic and granitic rocks was no longer than 2 Ma, i.e., granites were formed on a peak of metamorphism. The anomalously rapid heating of the crust was probably related to the ascent of asthenospheric masses as a result of slab breakoff, while it plunged beneath the Achaivayam–Valagin arc.

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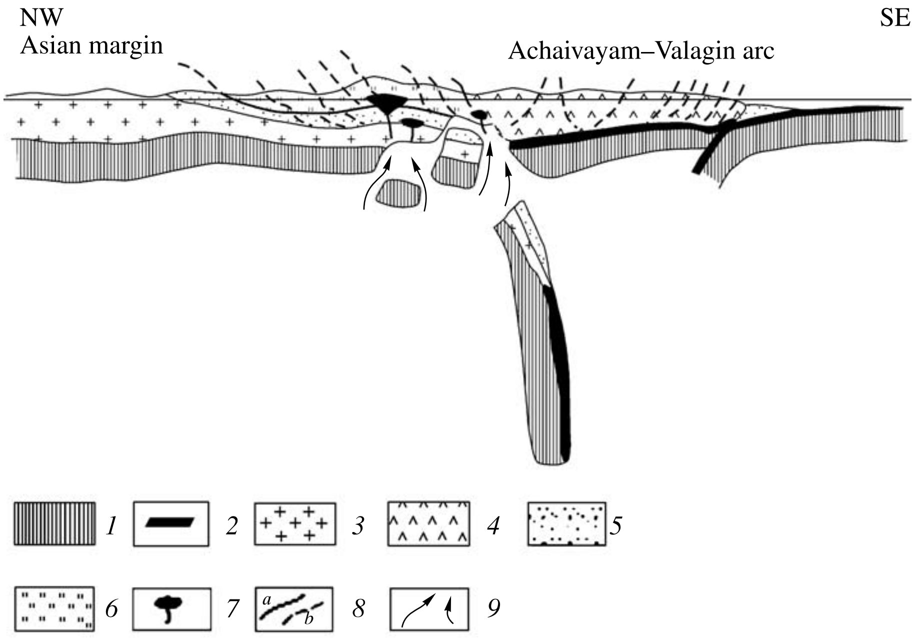

Fig. 13. A conceptual geodynamic scheme of granite formation in the zone of collision between the southern segment of the Achaivayam–Valangin island arc and the northeastern Asian margin about 52 Ma ago. See text for explanation. (*1*) Lithospheric mantle, (*2*) oceanic crust, (*3*) continental crust, (*4*) crust of ensimatic island arc, (*5*) terrigenous rocks, (*6*) volcanic rocks, (*7*) syncollision anatectic magma chambers, (*8*) faults: (*a*) major and (*b*) auxiliary; (9) ascending mantle flows.

work. Zircons and monazites were separated from granitic rocks by N.Ya. Shcherbacheva and I.S. Ipat'eva at the Laboratory of Mineralogical and Fission-Track Analysis of the Geological Institute, Russian Academy of Sciences. We are grateful to reviewers for their constructive criticism. This study was supported by the Russian Foundation for Basic Research (project nos. 04-05-65132, 05-05-64066, and 07-05-00255), the Council for Grants of the President of the Russian Federation for Support of Leading Scientific Schools (grant no. NSh-9664.2006.5), and the Division of Earth Sciences, Russian Academy of Sciences (programs of fundamental research nos. 6, 8, and 14).

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