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The Age of the Baraba Formation Inferred from the U/Pb (SHRIMP) Dating (Sredinnyi Range, Kamchatka): Geological Consequences

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Abstract—The Baraba Formation exposed in the Sredinnyi Range (Kamchatka), where it is composed of terrestrial conglomerates, was considered for a long time as the late Campanian–lower Maastrichtian in age based on the fossil flora evidence. Zircons from the tuff layer in the lower part of the formation are dated at 50.5 ± 1.2 Ma using the U/Pb (SHRIMP) method, i.e., the accumulation of their host deposits commenced in the terminal early Eocene. The Baraba Formation overlies unconformably schists and phyllites of the Malka Group, which were metamorphosed during the pre-middle Eocene time, and the Irunei marginal-sea sediments thrust over metamorphic complexes and thus suggesting the pre-middle Eocene thrusting stage.

Key words: Eocene, zircon, U/Pb SHRIMP, Baraba Formation, Sredinnyi Range, Kamchatka.

INTRODUCTION

The present-day structure of the Kamchatka Peninsula was formed in the course of accretionary–collision processes that occurred in the terminal Mesozoic–Cenozoic in the northwestern margin of Eurasia (Bogdanov and Chekhovich, 2002; Konstantinovskaya, 2002). One of the most important events in the Cenozoic regional history was collision of the Cretaceous island arc with Eurasia (Konstantinovskaya, 2000; Soloviev *et al.*, 2002). The northern segment of the arc was thrust over the continental margin (the Lesnaya suture) in the middle Eocene (Soloviev *et al.*, 2002). Its southern (Valaginskii) segment is trust along over metamorphic rocks (the Andrianovka suture) of the Kamchatka Sredinnyi Range that are considered as the exhumed part of the Okhotsk continental block (Khanchuk, 1985; Konstantinovskaya, 2000) or the uplift of the West Kamchatka microplate basement (Bogdanov and Chekhovich, 2002). From the east, metamorphites of the Sredinnyi Range are overridden by the Cretaceous–Paleogene rock complexes that were formed within the Valaginskii island arc and marginal sea separating the arc from the Eurasian margin (Zinkevich *et al.*, 1994; Konstantinovskaya, 2002).

The Baraba Formation exposed in the Sredinnyi Range of Kamchatka and composed of terrestrial conglomerates was considered for a long time as an oldest neoautochthon because it overlies unconformably both the metamorphic rocks and Cretaceous marginal-sea sediments (Shapiro *et al.*, 1986). Based on the floral remains (determination by A.I. Chelebaeva), the Baraba Formation is dated back to the late Campanian–early Maastrichtian (Shapiro *et al.*, 1986). Data on the formation age, its structural position and composition have been used to construct geodynamic models of the southern Kamchatka evolution (Shapiro *et al.*, 1986; Zinkevich *et al.*, 1994; Rikhter, 1995; Konstantinovskaya, 2000). In this work, we consider new data on the U/Pb (SHRIMP) age of zircons from basal layers of the Baraba Formation and some geological consequences inferable from dating results.

THE SREDINNYI RANGE STRUCTURE

Metamorphic rocks exposed in the southern part of the Sredinnyi Range occur within a belt approximately 200 km long and 30–40 km wide, extending in the meridional direction (Fig. 1). They are subdivided into three structural complexes. The lower one corresponds to the *Kolpakova Group* (highly metamorphosed migmatized gneisses, gneisses, crystalline schists) intruded by two-mica granites of the *Krutogorova Complex.* This structural stage was considered as a nucleus (or basement) of the Kamchatka median mass (Khanchuk, 1985; Rikhter, 1995). The age interpretation of the Kolpakova metamorphites and Krutogorova granites is ambiguous (*Explanatory Notes…*, 2000). The Kolpakova and Krutogorova complexes are unconformably overlain, locally with basal conglomerates, by metamorphosed terrigenous rocks of the *Shikhta Formation* (Khanchuk, 1985; Rikhter, 1995). The latter is composed of garnet–biotite–staurolite schists, staurolite–

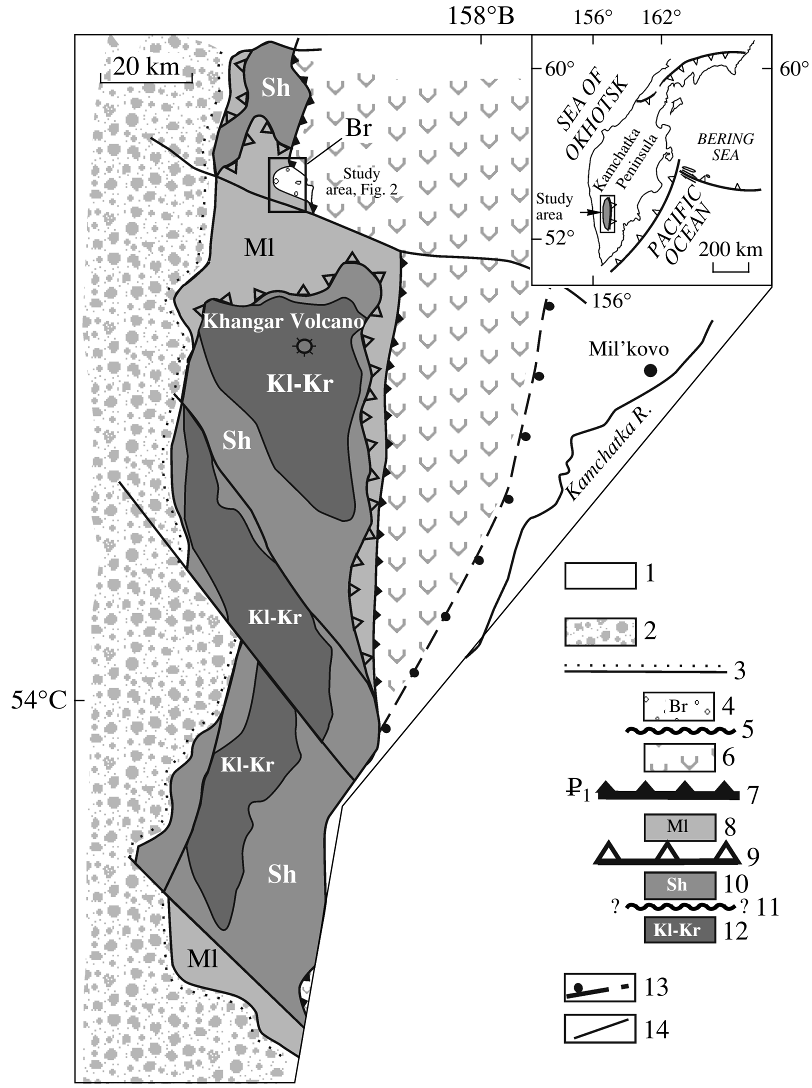

Fig. 1. Simplified tectonic map of the Sredinnyi Range, Kamchatka (Zinkevich *et al.*, 1998, with modifications) and schematic relationships between principal structural units: (1) Miocene–Quaternary sediments of the Central Kamchatka graben; (2) Eocene–Quaternary sediments of the West Kamchatka basin; (3) transgressive overlapping; (4) neoautochthon (Baraba Formation (Br), 50 Ma; (5) unconformity of the base of the Baraba Formation (Shapiro *et al.*, 1986); (6) Upper Cretaceous rocks of the island-arc terrane; (7) Andrianovka nappe; (8) Malka complex (Ml); (9) thrust fault (Rikhter, 1995); (10) Shikhta (Kamchatka) complex (Sh); (11) unconformity of the base of the Shikhta Complex (Khanchuk, 1985; Rikhter, 1995); (12) Kolpakova and Krutogorova complexes (Kl+Kr); (13) normal faults; (14) subsidiary faults.

sillimanite and biotite–muscovite plagiogneisses, and migmatites (Khanchuk, 1985; Rikhter, 1995). The *Malka Complex* that includes the Andrianovka, Kheivan, and Khimka formations is thrust over the Shikhta Formation (Rikhter, 1995). The Andrianovka Formation of amphibole, epidote–amphibole, and clinopyroxene–amphibole crystalline schists and amphibolites was regarded as correlative with the Alistor Formation (Bondarenko, 1997) and conformably overlain by the metamorphosed terrigenous Kheivan Formation, which is replaced higher in the section by the metamorphosed volcanics of the Khimka Formation. Rocks of the Malka Group are metamorphosed in the greenschist to amphibolite facies (Khanchuk, 1985).

In the western slope of the Sredinnyi Range, the unmetamorphosed Upper Cretaceous Khozgon Formation is composed of flyschoid quartz–feldspar sediments (Shapiro *et al.*, 1986) and has tectonic contacts with metamorphic complexes.

The Upper Cretaceous Irunei and Kirgakin formations of the Irunei nappe are thrust (the Andrianovka suture) over both the metamorphic complexes and the Khozgon Formation. The Irunei Formation (Santonian?–Maastrichtian) consists of terrigenous–siliceous–volcanogenic sediments accumulated in the marginal-sea basin and on the island-arc slope. The Kirgakin Formation (upper Campanian?–Maastrichtian) is composed of rudaceous tuffaceous rocks and

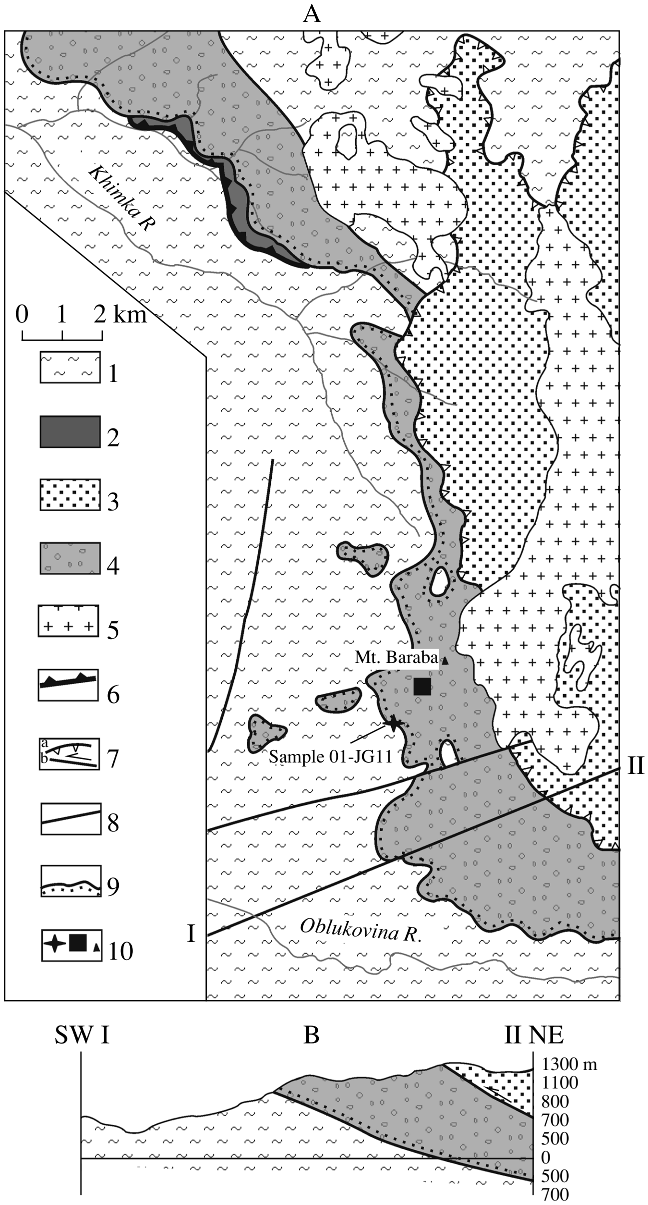

Fig. 2. Schematic geological structure of the Mt. Baraba area (Sredinnyi Range, Kamchatka) (A) and schematic cross section along line I–II (B) (Slyadnev *et al.*, 1997, modified based on materials from Shapiro *et al.* (1986) and Zinkevich *et al.* (1994)): (1) undivided metamorphic rocks of the Malka Group and Shikhta Formation of problematic age; (2) Upper Cretaceous tuffaceous–siliceous Irunei Formation; (3) Upper Cretaceous terrigenous Khozgon Formation; (4) Eocene tuffaceous–siliceous Baraba Formation; (5) Miocene granites; (6) thrust fault separating Irunei Formation from overridden metamorphic rocks; (7) thrust fault separating Khozgon Formation from overridden Baraba Formation in the map (a) and cross section (b); (8) subvertical faults; (9) unconformable boundary; (10) asterisk designates sampling sites for U/Pb dating, square shows flora locality, and triangle corresponds to Mt Baraba summit.

basic to intermediate volcanics formed in the island-arc system (Zinkevich *et al.*, 1994).

The neoautochthon above metamorphic rocks and the Irunei allochthon are represented by the Baraba Formation, the detailed description of which is given below (Fig. 2). The unconformable stratigraphic contact of the Baraba sediments with metamorphic and Irunei rocks was described by I.A. Sidorchuk and E.M. Ereshko in the course of geological mapping and thematic works (Shapiro *et al.*, 1986).

GEOLOGIC POSITION AND CHARACTERISTICS OF THE BARABA FORMATION

In its stratotype area (Mt. Baraba area, Fig. 2), the Baraba Formation is subdivided in two sequences. The lower sequence unconformably overlying schists and phyllites of the Malka Group is composed of tuffaceous and volcanic conglomerates, tuffstones, and andesitic tuffs. Pebbles of hornblende-dacite porphyrite, porphyry-like granite, basalts, acidic tuffs, tuffaceous siliciliths, jasper, cherts, and sandstones are cemented by sandy pyroclastic material similar in general composition to the pebbly material. The rock fragments are well rounded, ranging in size from sand grains to boulders. The lower sequence is approximately 150 m thick (Shapiro *et al.*, 1986; Zinkevich *et al.*, 1994).

The upper sequence conformably overlying the lower one is composed of polymictic conglomerates, breccia–conglomerate, gravelstones, sandstones, and subordinate siltstones. Cement in the rocks is sandy, sometimes aleuropelitic. Coarse clastic material is largely represented by metamorphic rocks (phyllites, schists, gneisses) and subordinate volcanics. Fragments of metamorphic rocks are subangular, unsorted, associated with better rounded granitoid, quartz, and feldspar pebbles derived from a more remote provenance (Kolodyazhnyi *et al.*, 1996). The upper sequence is approximately 800 m thick.

The stratigraphic boundary between the lower and upper sequences is sharp, probably implying a rapid change of provenances. Although there are no transitional varieties with equal proportions of volcanogenic and metamorphic material, the upper part of the lower sequence contains abundant fragments of metamorphic rocks, while basal layers of the upper sequence enclose fragments of volcanic rocks (Shapiro *et al.*, 1986).

In the right bank of the Kapitanskaya River 1.5 km of its mouth, there is exposed a tuffaceous–siliceous unmetamorphosed section 10 m thick, which we refer to the Irunei Formation. The latter overlies chlorite schists and phyllites of the Kheivana Formation.

The Baraba Formation is composed of continental facies. The fossil floral assemblage from the southwestern slope of Mt. Baraba is determined to be the late Campanian–early Maastrichtian in age (Shapiro *et al.*, 1986).

Pebbles from the Baraba Formation were studied in thin sections. Pebbles of volcanic rocks correspond in composition to rhyolites, dacites, andesites, basaltic andesites, and basalts. Pebbles of basic and intermediate volcanics could be derived from the eroded Mesozoic Irunei, Kirganik, and Kvakhona formations (Zinkevich *et al.*, 1994; Konstantinovskaya, 2002) and those of acidic and intermediate volcanics could be related in origin with the Paleocene Cherepanova Formation (Slyadnev *et al.*, 1997) and Eocene rocks of the Mt. Chernaya area (Gladenkov *et al.*, 1997). Pebbles of metamorphic rocks are identical in composition to rocks from the Shikhta Formation and Malka Group, and some of them are composed of gneisses similar to those form the Kolpakova Group. Granite pebbles could originate from the Krutogorova Complex (Khanchuk, 1985; Rikhter, 1995).

A comparison of sandstone pebbles from the Baraba conglomerate showed that they are compositionally identical to rocks of the Khozgon Formation. Radiolarites (cherts, jaspers) from pebbly fraction appeared to be similar to their counterparts from the Irunei Formation. Thus, the rocks of both the past Eurasian margin (metamorphites, granites of the Krutogorova Complex, sandstones of the Khozgon Formation) and the collided island arc (volcanics and radiolarites of the Irunei Formation) are present among pebbles of the Baraba conglomerates. The mixed pebbles derived from both the autochthon and allochthon suggest that the Baraba Formation formed after tectonic juxtaposition of two structural units.

THE BARABA FORMATION AGE

The closure temperature of U/Pb system in zircons is estimated to be over 900°C (Lee *et al.*, 1997). It is believed that the zircon age measured by U/Pb method determines the crystallization time, as the U/Pb system of this mineral is very resistant to thermal impacts.

Following the standard procedure, zircon crystals were extracted at the Institute of the Lithosphere of Marginal Seas from dacite tuff sampled from the basal layer of the Baraba Formation (Sample 01JG-11). Approximately 50 zircon grains were picked manually from the sample. Zircons from the sample and standard AS57 (Paces and Miller, 1993) were set into epoxy resin and then polished. The absence of fissures and inclusions in zircon grains was checked under magnification of 20 in the reflected and transmitted light. To study zoning and internal structure of polished zircons, we used scanning electron microscope JEOL JSM 5600 equipped with the cathode–luminescence detector (Fig. 3, A). The cathode–luminescence images revealed that zircon grains are lacking xenogenous nuclei. All the grains are prismatic and euhedral. The CL-zoning is characteristic of zircons from igneous rocks.

The isotopic ratios were measured using the Sensitive High-Resolution Ion MicroProbe–Reserve Geometry (SHRIMP-RG) equipment at the Stanford-USGS Microanalytical Center following the standard technique (Muir *et al.*, 1996). The beam of negatively charged oxygen atoms approximately 30 μm across was used for ionization of the analyzed crystals. Each measurement consisted of five cycles. After four to five runs in crystals of unknown age, we did measurements in the age standard AS57. The U and Th concentrations are calibrated relative to SL13 (Williams, 1998).

Age values presented in the table are obtained after the ^{207}Pb-correction based on assumption that insignificantly discordant zircons contain a simple mixture of common and radiogenic lead. The measured $^{207}Pb/^{206}Pb$ ratios are used to correct the common lead. By the age calculation, we extrapolated measured data to the concordia line of the model common lead (Cumming and Richards, 1975) to approximate ages determined for individual grains.

Zircons from Sample 01JG-11 are represented by small (±50–150 μm) zoned euhedral crystals (Fig. 3, A). Based on the weighted average ^{207}Pb value corrected for $^{206}Pb/^{238}U$ ages of 15 grains, the calculated age is equal to 50.5 ± 1.2 (±2σ) Ma (Fig. 3, B). The MSWD value of 0.90 shows that the data scatter does not exceed the analytical inaccuracy. A discordant age of one grain was omitted in calculations of the mean-weighted age.

Thus, the crystallization age of zircons from tuffs of the Baraba Formation is 50.5 ± 1.2 Ma. Inasmuch as tuffs formed instantly in terms of the geological time, the age of zircons is close to that characterizing the accumulation time of the Baraba Formation lower layers, and overlying conglomerates should be consequently younger than 50 Ma.

DISCUSSION

A.V. Shcherbakov was first to define the Baraba Formation prior to the World War II, although this subdivision received the official status later on (*Geology of the USSR*, 1964). Only plant remains are known to characterize sediments of the formation. During the geological survey, Yu.V. Makarov, M.I. Goryaev, and Yu.S. Voronkov sampled floral remains. Yu.V. Shtempel' and L.Yu. Budantsev who examined sampled flora referred the Baraba Formation to the Eocene (probably, Paleocene?–Eocene). B.M. Shtempel' correlated the Baraba flora with the floral assemblage from the lower layers of the Napan Formation in the Omgon Cape area (*Stratigraphy of the USSR*, 1975). Later on, M.N. Shapiro with colleagues performed additional sampling at the southwestern slopes of Mt. Baraba. A.I. Chelebaeva, who examined these remains, arrived at the conclusion that the Baraba flora is the late Campanian–early Maastrichtian in age (Shapiro *et al.*, 1986) based on the *Nilssonia* representatives present in the floral assemblage. Nevertheless, according to the private communication of M.A. Akhmet'ev (Geological Insti-

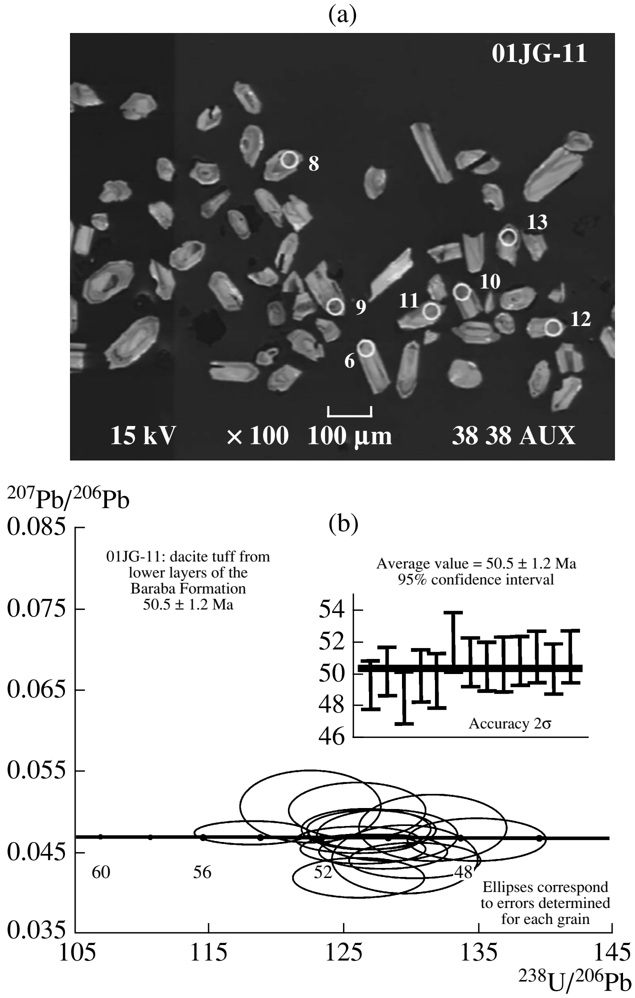

Fig. 3. (A) Cathode luminescence images of zircon crystals from Sample 01JG–11 with numbers of dated grains and white circles indicating points of SHRIMP analyses with analysis numbers shown in the table. (B) The Tera-Wasserburg plot for Sample 01JG-11, where horizontal solid line is concordia; the weighted-average age value of 50.5 ± 1.2 Ma (±2σ) is calculated based on fifteen grains and one with significant admixture of common lead (see parameters of discordance in the table) is excluded from calculations.

tute, Russian Academy of Sciences), some cycadophytes or ferns, such as *Dion* or *Cycas*, which are known from the Paleocene and Eocene sediments of Alaska, Japan, and northeastern China, can be mistaken for *Nillsonia* in case when remains are poorly preserved. In addition, the floral assemblage studied by Chelebaeva includes amentiferous forms comparable with recent Betulaceae and Fagaceae, which could hardly appear in the Campanian (personal communication of M.A. Akhmet'ev).

The new date obtained for the Baraba Formation substantially differs from the late Campanian– early Maastrichtian age inferred based on floral remains (Shapiro *et al.*, 1986). Formerly, the Baraba Formation was assumed to be of the early Paleocene (Danian) (Shapiro *et al.*, 1986) or Paleocene age (Slyadnev *et al.*, 1997), although it was substantiated indirectly. The U/Pb (SHRIMP) dating of zircons from tuffs of the lower Baraba Formation indicates that its accumulation commenced in the middle Eocene (after 50 Ma). The middle Eocene age of the Baraba Formation does not allow it to be considered as a facies analogue of the Upper Cretaceous Khozgon Formation, as it was assumed by Zinkevich *et al.* (1994).

Several facts should be noted, which indirectly evidence for the Eocene age of the Baraba Formation and are inconsistent with the late Campanian–early Maastrichtian age inferred from fossil flora. First, V.S. Vishnevskaya determined radiolarians of the Campanian–Maastrichtian age from tuffaceous siliciliths of the Irunei Formation overlain by the Baraba conglomerates at the Khimka River head (Shapiro *et al.*, 1986). The Irunei Formation accumulated in submarine deep settings, whereas the Baraba conglomerates are of terrestrial type. It is difficult to imagine such a rapid change in sedimentation settings during a short time interval. The Baraba conglomerates contain pebbles of various metamorphic rocks: gneisses of the Kolpakova Group, schists from the Shikhta Formation and Malka Group. There are new dates recently obtained for metamorphic rock from the Sredinnyi Range. For example, it was shown that Kolpakova gneisses were metamorphosed during two stages 77 and 47–53 Ma ago (Bindeman *et al.*, 2002). Second, the U/Pb (SHRIMP) dates of zircons indicate probably the Paleocene age of the Shikhta Formation protoliths (Hourigan *et al.*, 2001). Third, the assumed Cretaceous age is inconsistent with general appearance of the Baraba Formation conglomerates and their pebbles of acidic volcanics. All the unmetamorphosed Cretaceous sediments known in the Sredinnyi Range (Khozgon and Irunei formations) accumulated in deep-water settings: the Khozgon Formation at the foot of the continental slope (Shapiro *et al.*, 1986; Zinkevich *et al.*, 1994) and the lower layers of the Irunei Formation, in the marginal-sea basin (Zinkevich *et al.*, 1994; Konstantinovskaya, 2002). The Baraba conglomerates containing pebbles of acid volcanics were deposited in subcontinental settings. The Cretaceous acid volcanics have never been described in the Kamchatka region, and all Cretaceous sedimentary complexes are lacking any features suggesting influx of volcaniclastic acid material. In Kamchatka, acid and intermediate volcanics are known from the Paleocene Cherepanova Formation (Slyadnev *et al.*, 1997) and Eocene sequences of the Mt. Chernaya area (Gladenkov *et al.*, 1997), and pebbles enclosed in the Baraba conglomerates were probably derived form these rocks. Thus, many known facts are inconsistent with the late Campanian–early Maastrichtian age of the Baraba Formation, which is estimated based on floral data.

The analyzed relationships between rock complexes mentioned above and new data on the Baraba Formation age imply some geodynamic consequences. The Baraba Formation overlies unconformably schists and

The U/Pb age of zircon grains from dacite tuffs sampled from the Baraba Formation basal layers, Sredinnyi Range of Kamchatka

Grain no.	$\%^{206}Pb_c$	U, ppm	Th, ppm	Th/U	$^{206}Pb^*$, ppm	Uncorrected $^{238}U/^{206}Pb$	Uncorrected $^{207}Pb/^{206}Pb$	Age, Ma (± 1σ)
JG11-1	0.00	427	199	0.48	2.82	130.4 ± 3.1	0.0443 ± 4.1	49.4 ± 1.5
JG11-2	0.00	497	277	0.58	3.34	128.0 ± 3.1	0.0455 ± 3.8	50.3 ± 1.5
JG11-3	0.18	210	59	0.29	1.37	131.7 ± 3.4	0.0484 ± 7.0	48.7 ± 1.7
JG11-4	0.05	290	118	0.42	1.94	128.3 ± 3.3	0.0474 ± 5.4	50.0 ± 1.7
JG11-5	0.00	146	52	0.37	0.968	129.6 ± 3.4	0.0445 ± 7.7	49.7 ± 1.7
JG11-6	0.49	110	32	0.31	0.769	122.6 ± 3.5	0.0510 ± 7.1	52.1 ± 1.8
JG11-7A	0.07	937	107	0.12	6.81	118.2 ± 3.0	0.0477 ± 2.5	54.3 ± 1.6
JG11-8	0.00	377	87	0.24	2.40	134.9 ± 3.1	0.0469 ± 4.5	47.6 ± 1.5
JG11-9	0.00	647	283	0.45	4.40	126.5 ± 3.0	0.0457 ± 3.2	50.8 ± 1.5
JG11-10	0.14	394	105	0.27	2.67	126.8 ± 3.1	0.0482 ± 4.2	50.6 ± 1.6
JG11-11	0.43	197	97	0.51	1.35	126.1 ± 3.3	0.0505 ± 5.7	50.7 ± 1.7
JG11-12A	2.67	126	48	0.39	2.81	38.5 ± 3.1	0.0705 ± 3.7	##161.0 ± 5.0
JG11-13	0.00	790	163	0.21	5.38	126.1 ± 3.0	0.0469 ± 2.9	50.9 ± 1.5
JG11-14	0.00	327	93	0.29	2.23	126.2 ± 3.2	0.0422 ± 4.7	51.2 ± 1.6
JG11-15	0.14	391	112	0.30	2.65	127.1 ± 3.1	0.0481 ± 4.1	50.5 ± 1.6
JG11-16	0.44	333	93	0.29	2.29	124.9 ± 3.1	0.0505 ± 4.5	51.2 ± 1.6
Average age 50.5 ± 1.2 (95%) Ma, MSWO = 0.90, *n* = 15/16								

Note: The measurement accuracy is 1σ; (Pb_l) common lead; (Pb*) radiogenic lead. The error of standard calibration corresponded to 0.90%. Age values are calculated based on the weighted average ^{207}Pb value corrected for $^{206}Pb/^{238}U$ ages and for common Pb with an assumption that the $^{206}Pb/^{238}U$–$^{207}Pb/^{235}U$ age is concordant; (##) discordant result excluded from calculations of the weighted average age.

phyllites. Thus, it can be assumed that rocks of the Malka Group were metamorphosed prior to the middle Eocene. The Baraba rocks unconformably overly also the unmetamorphosed Irunei Formation (Shapiro *et al.*, 1986). Accordingly, it is possible to assume the pre-middle Eocene stage of marginal-sea sediments thrusting over metamorphites of the Malka Group. It should be noted also that the neoautochthon west of Mt. Baraba is overridden by the Khozgon Formation (Shapiro *et al.*, 1986; Zinkevich *et al.*, 1994; Slyadnev *et al.*, 1997). Thus, the accumulation period of the Baraba Formation was followed by additional deformation stage, when the Khozgon Formation sediments were thrust over it (Fig. 2) (Shapiro *et al.*, 1986).

CONCLUSION

(1) The crystallization age of zircons from the basal tuff layer of the Baraba Formation is 50.5 ± 1.2 Ma as determined by the U/Pb (SHRIMP) method. The accumulation of the Baraba Formation basal sediments commenced in the terminal early Eocene.

(2) The Baraba Formation overlies unconformably schists and phyllites, and, consequently, rocks of the Malka Group were metamorphosed before the middle Eocene.

(3) The Baraba Formation overlies unconformably the Irunei marginal-sea sediments thrust over metamorphic complexes, and this thrust event took place therefore in the pre-middle Eocene time.

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