GEOLOGICAL NOTES

Archean Xenocrysts in Modern Volcanic Rocks from Kamchatka: Insight into the Basement and Paleodrainage

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ABSTRACT

We report U-Pb zircon ages and in situ $\delta^{18}O$ values for crystals of zircon, rutile, and corundum erupted in the course of a March 2009 phreatomagmatic explosion of Koryaksky volcano, Eastern Volcanic Front, Kamchatka, Russia. Zircon crystals display a wide spectrum of crystallization ages ranging from Cenozoic to Archean, including single grains and grain-age clusters, ca. 1.7, 11, 37–56, 89–99, 152, 1461, 1946, 2584–2734, and 3314 Ma. The older end of this spectrum represents the oldest known zircon ages from Kamchatka. Oxygen isotopic values span from normal to low $\delta^{18}O$ in zircon (3.3‰ to 5.5‰), corundum (4.3‰ to 5.5‰), and rutile (2‰ to −2.8‰). As Koryaksky volcano is built over Cretaceous-Eocene and younger crust, the presence of older zircon crystals requires that these accessory minerals with their diverse ages and $\delta^{18}O$ values were derived from heterogeneous detrital components in sediment that contaminated the magma shortly before or during the phreatomagmatic eruption. We also present a compilation of published U-Pb zircon ages in Kamchatka for detrital and metamorphic grains for comparison purposes. We propose that sediment was delivered from the metamorphic Ganal and Sredinny Massifs along the Petropavlovsk fracture zone via a paleodrainage system whose remnants are now covered by the modern edifices of the Eastern Volcanic Front volcanoes. The termination of this paleodrainage system connecting to the modern north-flowing Kamchatka River postdates 1.7 Ma, on the basis of the age of the youngest detrital zircon present.

Online enhancements: appendix figures, supplemental tables.

Introduction

Zircon is a refractory mineral that can preserve inherited cores with distinct isotopic signatures of age, oxygen, and Hf isotopes as well as trace element ratios characteristic of its crystallization source (e.g., Cherniak and Watson 2003; LaMaskin 2012; Bindeman and Simakin 2014; many others). When found in the products of volcanic eruptions, such xenocrystic zircon can provide insights into the basement structure underneath a volcano. The winter and spring 2009 eruptions of Koryaksky volcano (Eastern Volcanic Front, Kamchatka; fig. 1) comprised a sequence of phreatomagmatic explosions lasting several months and deposited several centimeters of ash around the volcano (fig. 1*c*; Girina et al. 2010). Gray ash of the 2009 eruptions is <0.063 mm in size and consists of vesicular glassy shards and rock fragments that are typical for disintegrated calc-alkaline andesite from Koryaksky volcano. Much of this basaltic-andesitic ash was deposited on snow, and because tephra was collected immediately after the eruption (fig. 1), we exclude the possibility of a wind-blown or reworked origin for the samples. Mineral separation in heavy liquids revealed the presence of igneous plagioclase, ortho- and clinopyroxene, magnetite, and altered volcanic glass. In addition, minerals of hydrothermal

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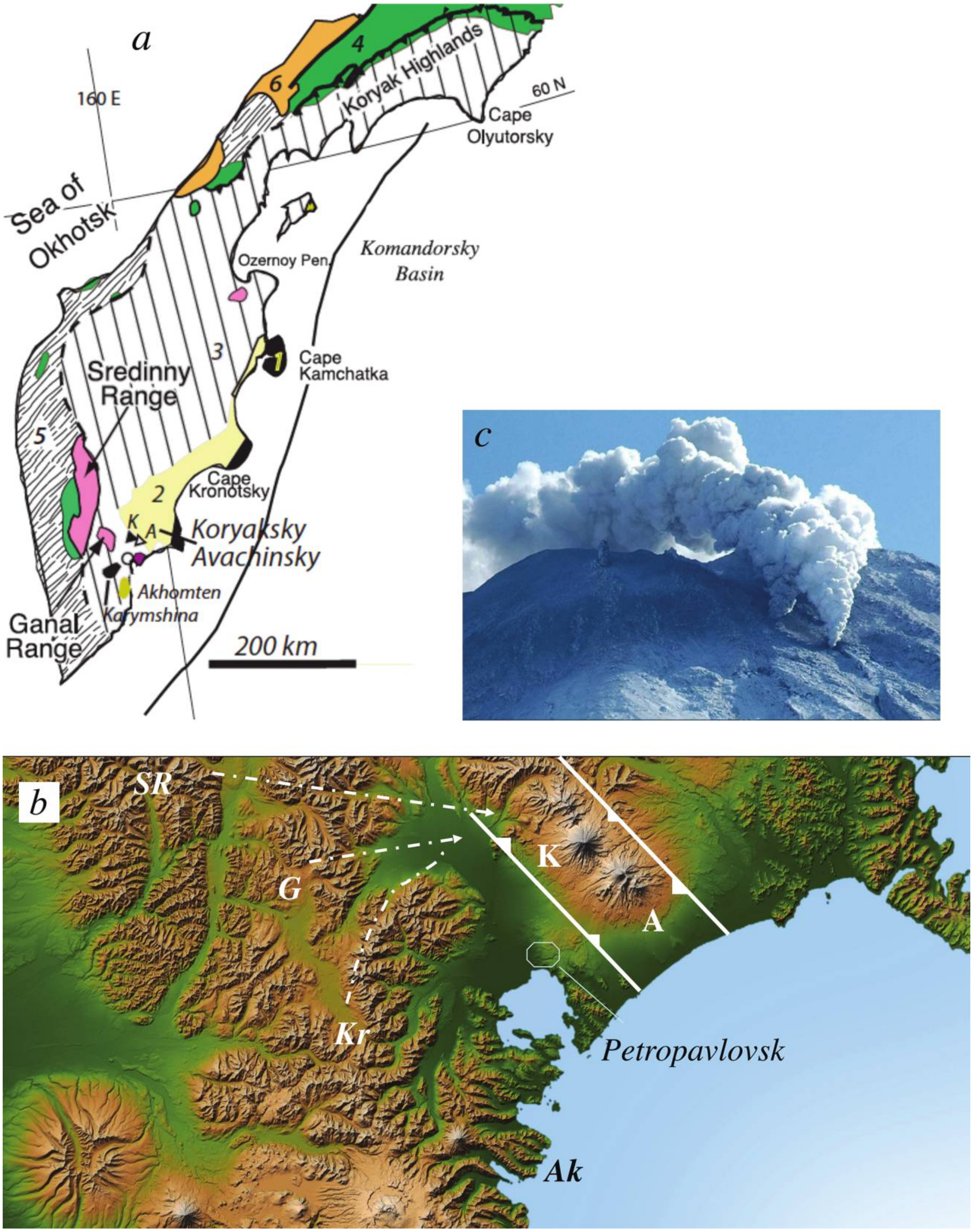

Figure 1. *a*, Tectonic map of Kamchatka and position of Koryaksky and Avachinsky volcanoes relative to zircon sources mentioned in the text, including the Ganal and Sredinny Massifs, the Akhomten intrusion, and the Karymshina caldera. Geotectonic elements shown are simplified after Hourigan et al. (2009); numbers refer to the

origin are present, including gypsum, barite, pyrite, sulfur, potassium feldspar, quartz, and amorphous silica. Accessory minerals include zircon, rutile, ilmenite, blue corundum, and pyrrhotite. This accessory mineral assemblage was the focus of the study whose results are detailed below. It should be noted that one of the authors (L.P.A.) has previously identified similar mineral assemblages, plus sphalerite, garnet, red corundum, sulfur, copper, and antimony, in the phreatomagmatic products of the 1991 Avachinsky eruption near Koryaksky, but material from that study was not retained.

Methods

Heavy mineral fractions were separated at the Institute of Volcanology and Seismology, Petropavlovsk-Kamchatsky, using crushing, sieving, magnetic, and heavy liquid techniques. Extraction from ~200 g of ash yielded 150 grains of zircon and tens of grains of rutile and corundum (fig. 2). The extracted minerals were pressed into a 2.54-cm diameter round brass holder with indium metal inserts, alongside zircon standard (KIM5; 5.09‰) and in-house rutile and corundum standards to correct for instrumental mass fractionation. The indium grain mount was lightly polished to achieve flatness, with several microns removed from the surface. Zircons were dated in a polished indium mount on a CAMECA IMS 1270 instrument at the University of California, Los Angeles (UCLA), largely following the methods in Schmitt et al. (2003), and in polished epoxy mount on SHRIMP II ion microprobes at Stanford University (see tables S1, S2, available online). An O-primary ion beam was used for dating; oxygen isotopic compositions of zircon, rutile, and corundum were determined during a separate analytical session at UCLA using a Cs^+ beam. The oxygen isotopic values were corrected for instrumental mass fractionation by using compositionally matching reference minerals whose results were reproduced with a precision of ±0.36‰ (1 SD; table S1). Rutile and corundum standards were analyzed for oxygen isotope composition by laser fluorination at the University of Oregon Stable Isotope Laboratory.

Results

Ages and Isotope Analyses of Accessory Phases. Koryaksky zircons exhibit a wide age spectrum (fig. 3*c*, 3*d*); most have Th/U ratios (0.2–1.2) typical for magmatic zircon, and several have metamorphic (<0.1) values (tables S1, S2). In the supplemental tables, we also present a compilation of published U-Pb zircon ages from Kamchatka for detrital and metamorphic grains for comparison purposes, new U-Pb ages for selected xenocrysts in other recent eruptions of Kamchatka, and a new age for the granite Akhomten Massif in the coastal ranges (fig. 1). Zircon ages fall into several groups (fig. 3) that correspond to well-established tectonomagmatic episodes in Kamchatka represented in the exposed metamorphic crust of the Sredinny and Ganal Massifs (fig. 1) and younger sources.

1. Late Eocene ages (36.8–45 Ma) correspond to Ganal amphibolites and associated intrusions. Notably, no equivalent 36–45 Ma zircon ages have been documented for the Sredinny Range (Hourigan et al. 2009, table A1).

2. Early Eocene (50–56 Ma) zircons coincide with abundant collision-related zircons in the 49–53 Ma age range (Bindeman et al. 2002; Hourigan et al. 2009; Kuzmin 2014).

3. A wide range of detrital zircon cores ranging from Cretaceous (93 Ma) to early Archean (3.3 Ga) in age derived from sources in either the Sredinny Range or Ganal amphibolites and gneisses.

4. A single 11.4 Ma zircon is too young to be derived from either Sredinny or Ganal rocks but is identical in age to the coastal granitoids, such as the Akhomten Massif near the Pacific shore (fig. 1; table S1; Seligman et al. 2014). The youngest zircons of 1.67 and 1.78 Ma correspond to Karymshina caldera magmatism in age and $\delta^{18}O$ values (Bindeman et al. 2010; Bindeman and Simakin 2014).

Here, we report the discovery of the oldest zircon age in Kamchatka—the early Archean zircon with a concordant age of 3314 ± 3 Ma ($^{207}Pb/^{206}Pb$). Another Archean zircon with a magmatic 2.73 Ga core and a metamorphic 2.58 Ga rim (Th/U = 0.03) is also present, and these add to the four previously reported 2.5–2.75 Ga zircons in the Kolpakova suite

following tectonic elements: 1 = Peninsulas terranes, mid-Cretaceous–late Eocene; 2 = Vetlovsky subduction complex, early Tertiary; 3 = Olyutorsky terrane, Cretaceous oceanic arc; 4 = mid-Cretaceous foreland basin, flysch; 5 = pre–Late Cretceous terrains; 6 = continental arc, mid-Cretaceous–Early Tertiary. *b*, Digital elevation map showing position of Koryaksky and Avachinsky volcanoes, Malka-Avachinsky graben. A = Avachinsky volcano; Ak = Akhomten; SR = Sredinny Range; G = Ganal Range; K = Koryaksky volcano; Kr = Karymshina. Potential riverine and/or glacial drainage areas from southwest to northeast into the Avacha Bay toward a low altitude of Koryaksky basement are shown by dashed lines. *c*, Field shot of the March 2009 phreatomagmatic eruption and dark ash on snow with detrital material studied in this work.

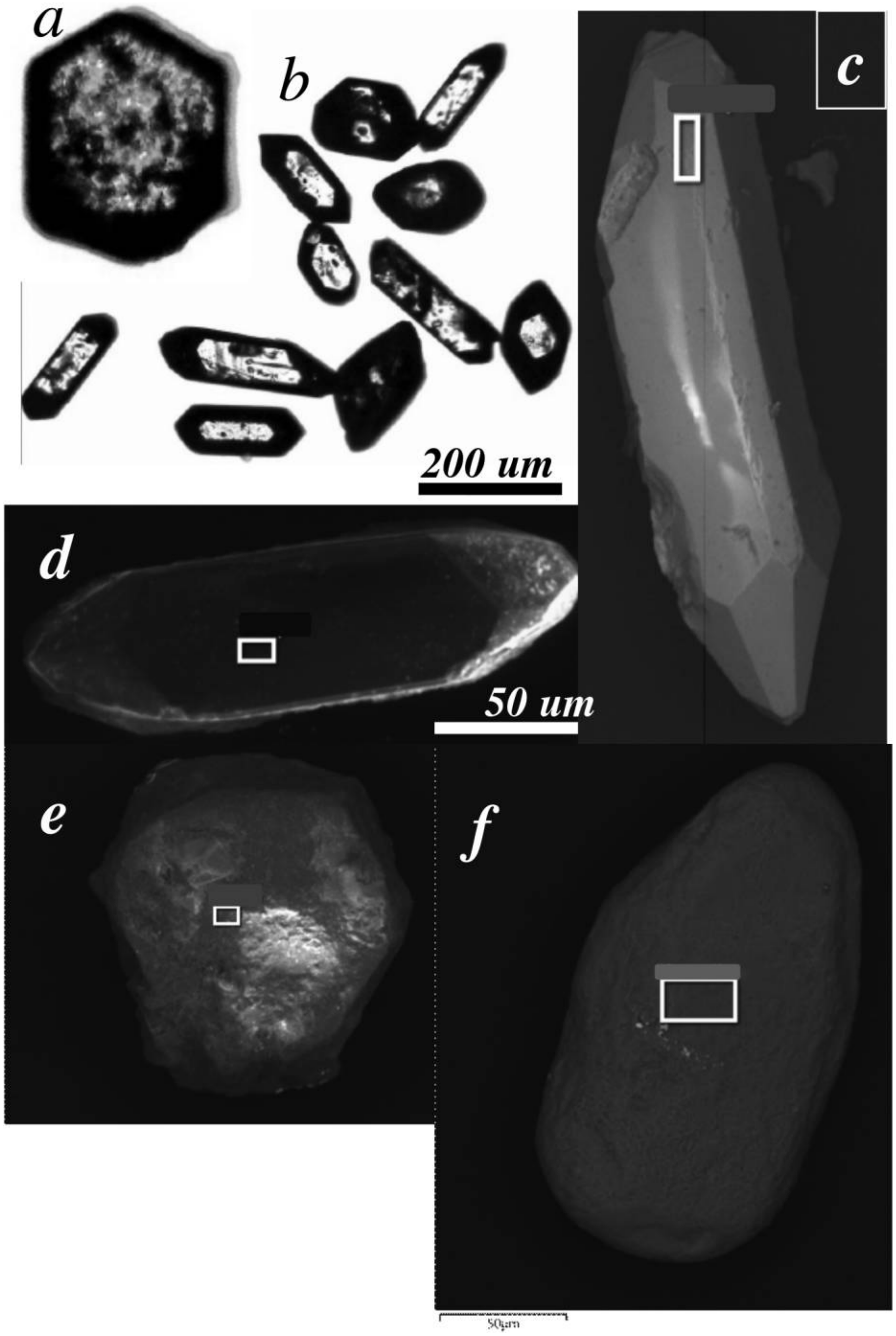

Figure 2. Optical (*a*, *b*) and scanning electron microscope (*c*–*f*) images of analyzed grains of zircon (*b*–*d*), corundum (*a*, *e*), and rutile (*f*). Note the abraded shape, likely indicative of detrital transport. Rectangles in *d*–*f* denote areas of analysis. See figure A3 for cathodoluminescence images with ion microprobe spot location.

of the Sredinny Massif (Bindeman et al. 2002; fig. 3; tables S1, S2). These 3.3–2.5 Ga zircons are likely ultimately sourced from the Siberian Craton, where such old rocks are known to occur (Poller et al. 2005), and further support a tectonic origin of Kamchatka and Okhotomorsk massif as being expelled from the hearts of Asia (e.g., Bindeman et al. 2002).

The $\delta^{18}O$ values of the analyzed zircon crystals (tables S1, S2) range from normal mantle-like values (5.2‰–5.5‰) to submantle values, which reflect crystallization from low-$\delta^{18}O$ magmas. Oxygen isotopic values of corundum are within the normal $\delta^{18}O$ range (4.4‰–5.4‰), but rutile crystals, on the other hand, display a large range of $\delta^{18}O$ values (+2‰

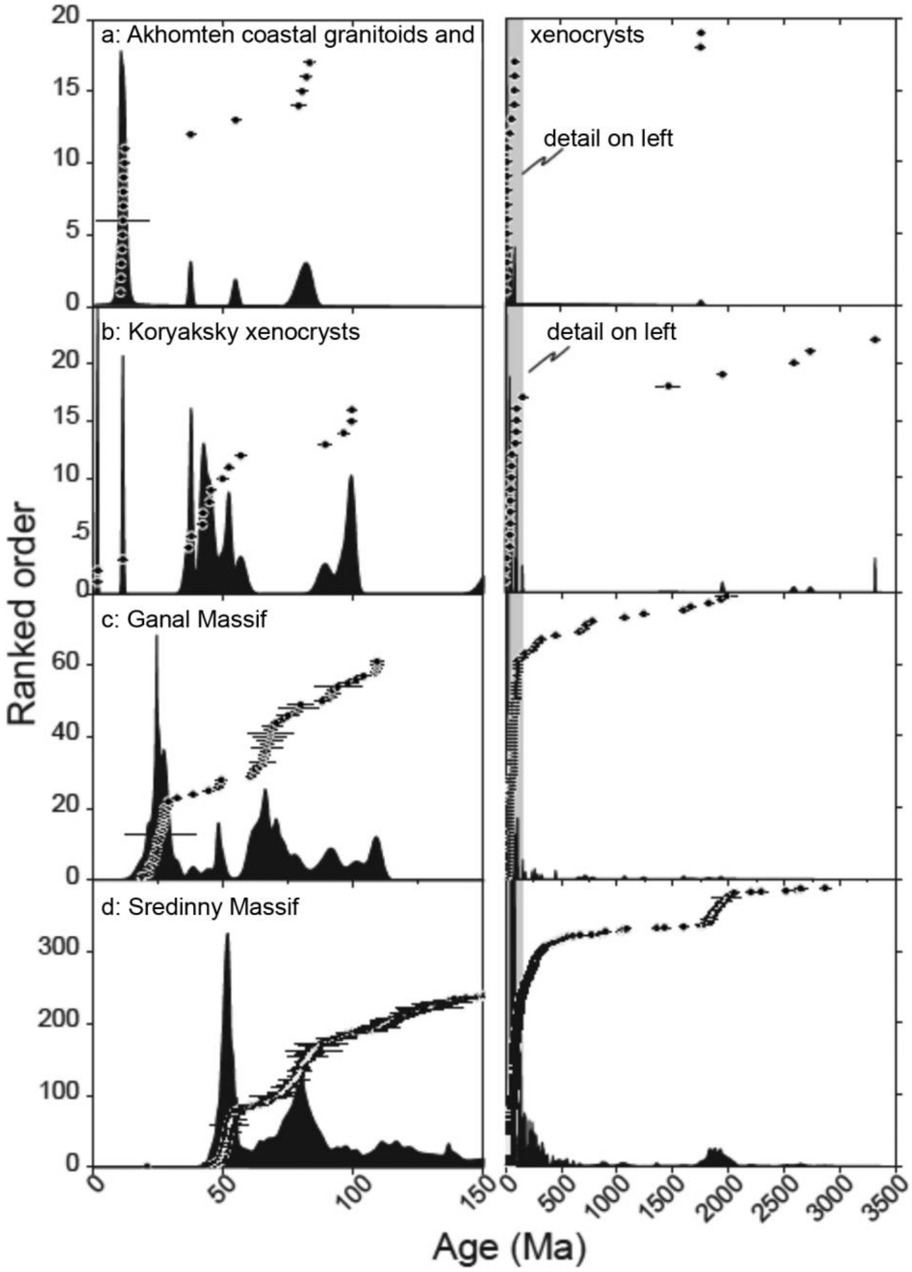

Figure 3. New data (*a*, *b*) and a compilation of ~472 published analyses of zircons (*c*, *d*) from Kamchatka plotted as probability and cumulative density distributions. Zircons from Koryaksky volcano span most of the Kamchatka Range, consistent with detrital delivery from a wide drainage area sampling the Sredinny and Ganal Massifs, and include the oldest zircon in Kamchatka (3314 ± 3 Ma) and the youngest (1.7 Ma), from Karymshina caldera. See tables S1 and S2 (available online) for data and figure 1 for locations and proposed paleodrainage. Data compilation is from Bindeman et al. (2002), Soloviov et al. (2004), Osipenko et al. (2007), Hourigan et al. (2009), Luchitskaya et al. (2008), Badredinov et al. (2012), and Kuzmin and Rodionov (2011).

to −3‰), which is below typical igneous ranges, reflecting crystallization from low-$\delta^{18}O$ hydrothermally altered protoliths. Thus, $\delta^{18}O$ values of zircon, rutile, and corundum crystals fingerprint diverse $\delta^{18}O$ sources. As rutile and zircon are inert to exchange of oxygen during weathering and lower to midgrade metamorphism due to extremely sluggish oxygen diffusion at low temperatures (e.g., Cherniak and Watson 2003), the presence of low $\delta^{18}O$ values in some rutile and zircon crystals indicates that their protolith was hydrothermally altered before the metamorphism and crystallization of these minerals. The abraded tips and ridges and rounded shape of some zircons, rutiles, and corundum (figs. 2, A2; figs. A1–A3 are available online) and the disaggregated form in which they were found indicate sediment origin and detrital transport.

Discussion

Archean and Proterozoic zircons were previously found in the Sredinny and Ganal Massifs (fig. 3) but not in the Eastern Volcanic Front, which is underlain by Createaceous-Eocene arc rocks (fig. 1). We thus suggest that the zircon, rutile, and corundum crystals with heterogeneous ages and $\delta^{18}O$ values under Koryaksky and Avachinsy volcanoes represent a sediment-derived detrital component from a variety of sources to the west (fig. 1), sampled by a shallow-rooted phreatomagmatic eruption. As the minerals do not contain volcanic glass adherent to grains, they were not incorporated into the magma in the course of phreatomagmatism. The coexistence of zircon with rutile and corundum suggests that they were derived either from S-type granitoids oversaturated with alumina and titanium oxide or from metasedimentary metamorphic protoliths; such rocks are abundant in Sredinny Range (Luchitskaya et al. 2008).

The absence of any lithic components comprising gneiss or granulite in the products of the 2009 eruptions further supports the interpretation that the analyzed refractory minerals are directly derived from either alluvial or glacial sediment delivered from the west and southwest (fig. 1). The onset of Pleisticene glaciations (2.6 Ma–11 ka) in Kamchatka is older than the youngest zircon that we found. This youngest detrital core of Karymshina age (1.78 Ma) may not be the youngest sediment age for the bottom of the volcanic edifi. Current geochronology of volcanic edifi of the Avachinsky (2741 m) and Koryaksky (3456 m) volcanoes puts them at much younger—mid- to late Pleistocene—age (Fedotov and Masurenkov 1991). Geotectonic reconstructions have long demonstrated the existence of a sublatitudinal Avacha-Malka fault or graben zone under these volcanoes (fig. 1*b*), where geophysical investigation further reveals sediment-filled depression of the crystalline basement, and electric conductivity studies also find evidence of hydrothermal circulation (Moroz and Gontovaya 2003). The low inferred paleoaltitude of the basement will be consistent with river or glacial sediment deposition to the graben. Furthermore, due to the abundance of ground and hydrothermal waters filling this depression, rising magmas may undergo frequent phreatomagmatic interactions, as is evidenced by the abundant hydrothermal minerals in products of the 1991 Avachinsky and 2009 Koryaksky explosions.

Finally, basalts and andesites from Koryaksky and Avachinsky volcanoes are characterized by high $\delta^{18}O$ values of ~7‰–8‰ and a moderate $^{87}Sr/^{86}Sr$ of 0.7034 (Bindeman et al. 2010). These values are higher in $\delta^{18}O$ than the mantle-derived magmas by ~1‰–1.3‰ and thus are related to either a higher $\delta^{18}O$ mantle or lower crustal rocks (Portnyagin et al. 2007). The analyzed xenocrystic accessory minerals, which are isotopically diverse but largely normal to low in $\delta^{18}O$, would not support shallow assimilation of their host sediments as a source for the unusually high-$\delta^{18}O$ magmas at these volcanoes. The quest for identifying surviving accessory minerals in Koryaksky, Avachinsky, and other volcanoes in Kamchatka and worldwide in magmas in which they should normally not occur serves as a probe into basement structure and paleodrainage patterns.

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