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GEOLOGY

Magmatism of the Hadean Geon in Earth Differentiation

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Essential problems of the oldest geological stage in the Earth's history (Hadean Geon) marked by formation of geospheres and their transformation during initial interaction remain highly debatable still today because of insufficient knowledge of the chemical characteristics and chronology of the early crust and mantle. The age estimates available for this stage (~4.0–4.4 Ga) were obtained only for the Archean crust based on detrital and captured (xenogenic) zircons [1–5 and others]. Today, such zircons have been found in the metasedimentary rocks and granitoids of three terranes in Western Australia [1–4 and others] and in Acasta granitoids of western Canada [5]. This fact certainly indicates a wide regional distribution of oldest zircons and their possible occurrence in other Precambrian domains. It is clear that elucidation of the genesis of detrital and captured zircons can provide new insights into the early geological history of our planet. Genesis of zircons can only be judged from their isotopic and geochemical parameters (Th, U, $\delta^{18}O$, Pb, Hf, REE, Sr, Ba, Nb, P, and other elements). During the last decade, several works were devoted to the distribution of some of these elements and $\delta^{18}O$ in zircons, but problems related to the genesis of Hadean zircons were not scrutinized by researchers. Speculations on lithology of their host rocks are presented in [1–4, 6]. At the same time, a comparison of systemic data on Hadean zircons and analogous information on their well-studied counterparts from different younger rocks makes it possible to define relationships between geochemical features in the distribution of individual elements and isotopes in zircons. These features are controlled by petrological diversity of mantle and crustal processes and structural constraints of zircons. Thus, the comparative analysis can allow us to identify sources of detrital and captured zircons of different ages, including the Hadean varieties.

Preliminary results of the analysis of Th distribution in different-age zircons revealed that the detrital and captured zircons can be divided into two groups (Fig. 1). The first dominant group is characterized by relatively low Th concentrations (<850–900 ppm), which are comparable to those in Proterozoic and Archean detrital and captured zircons [2–5, 7, and others] and in zircons of Archean tonalite–trondhjemite–granodiorite (TTG) domes and volcanics of greenstone belts [3–5 and others]. In Th/U–Th diagrams (Figs. 2, 3), zircons of the first group (regardless of their age) mainly fall into zone II of magmatic zircons from TTG, volcanics, and igneous rocks of greenstone belts. The data points are located within the Th/U ratio interval of 0.21 to 2.1. Only some detrital zircons are confined to zone I of Archean–Phanerozoic rocks [3–5, 8, and others] subjected to metamorphism of the amphibolite and granulite facies and migmatization (Th/U < 0.21). This indicates extensive magmatic reworking of the early Hadean crust by petrological processes typical of the Archean crust. Thus, one can assume that the majority of rock associations and processes of their formation and transformation of the protocrust in the dated Hadean interval were substantially similar to those in Archean granite–greenstone terranes. Hence, there are no grounds to consider that such zircons are genetically different from their Archean counterparts. This conclusion is consistent with inferences derived from the data on $\delta^{18}O$ variations (from +5.4 to +7.9‰) in Archean and Proterozoic rocks from granite–greenstone domains [2, 6, 9, 10, and others]. The $\delta^{18}O$ value in zircons is 1–2‰ lower. This is probably related to the directed change in the mineral composition of initial rocks from melanocratic varieties to quartz-rich varieties (the SiO_2 increases from 46 to 77%). In some cases, both rocks and zircons demonstrate $\delta^{18}O$ deviations toward lower values (1.5–4.0‰) due to the hydrothermal impact or, toward higher values (up to +8 and, less commonly, 12–15‰) due to the contamination of

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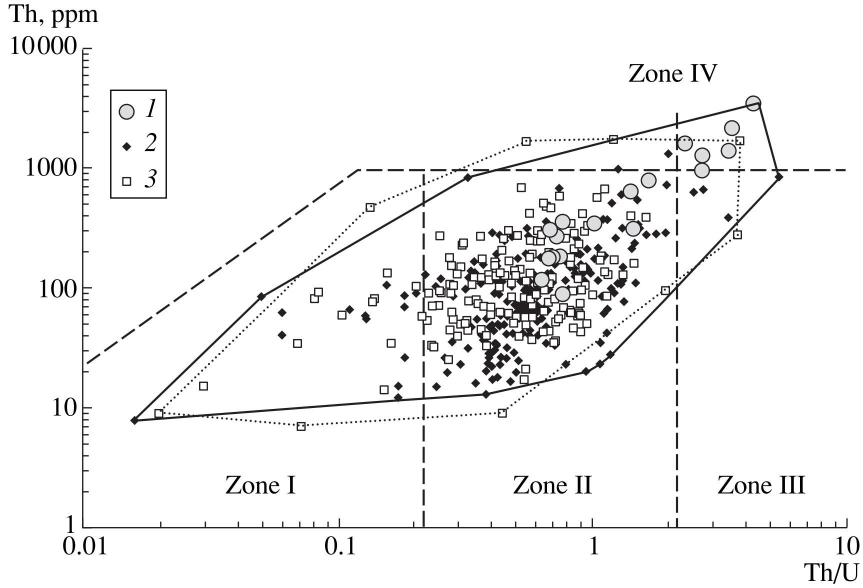

Fig. 1. Distribution of detrital and captured zircons and variations of their Th–U parameters. (*1, 2*) Western Australia; (*3*) Baltic Shield. (*1*) The oldest Hadean zircon (4276–4363 Ma) [1, 2]; (*2*) other detrital and captured Archean and Hadean zircons [1–5 and others]; (*3*) Archean and Proterozoic zircons [7 and others]. Zones I–IV are defined based on variations of Th–U parameters of zircons from Archean–Phanerozoic rocks: (I) granitoids metamorphosed to the amphibolite and granulite facies and migmatites, (II) magmatic zircon from different-age granitoids and acid volcanics of greenstone belts and island-arc formations, (III) detrital zircons with the elevated Th/U value, (IV) detrital zircons with the high Th content (>900 ppm).

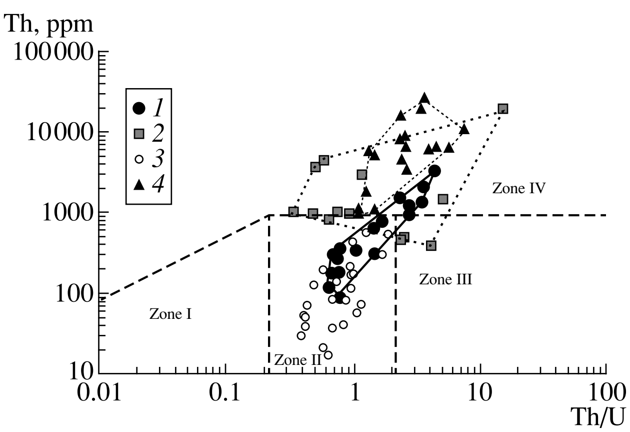

Fig. 2. Th/U parameters of oldest Hadean detrital zircon (*1*) and (*2–4*) magmatic zircons from mantle-related rocks: (*2*) alkali basalts, syenites, and carbonatites, (*3*) mafic volcanics, gabbro, and ultramafic rocks of greenstone belts, (*4*) dike dolerites from Western Australia. Zones I–IV are as in Fig. 1.

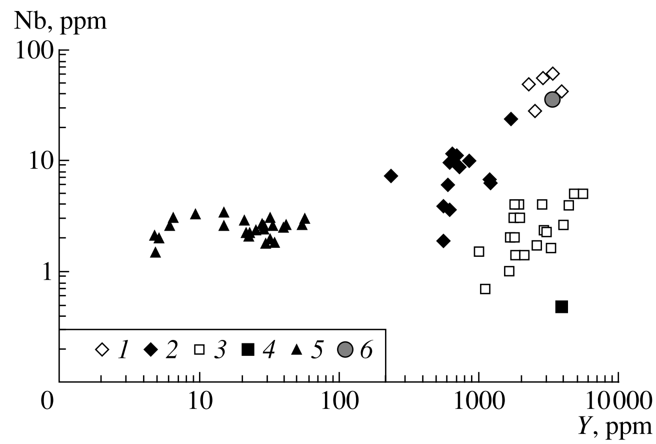

Fig. 3. Distribution of Y and Nb in genetically different zircons. (*1*) Concordant and discordant varieties of the oldest (Early Hadean) detrital zircons [2]; (*2*) Archean and Late Hadean detrital zircons [2]; (*3*) zircons from granitoids [8]; (*4*) zircon from ophiolitic eclogites; (*5*) zircon from kimberlites [12]; (*6*) zircon from alkali basalts [11].

magma sources with sedimentary material. The $\delta^{18}O$ value of 5.3 ± 0.3‰ is considered average for mantle zircons [2, 6, 10]. In general, $\delta^{18}O$ values in Hadean and Archean detrital zircons range from +4.5 to 8.1‰ and, less commonly, from +9 to +15‰ [1, 2, 6, 10]. This is consistent with the above-mentioned data on zircons from the parental Proterozoic and Archean rocks.

The Th-rich zircons of the Hadean group have been found only in the oldest fragment of detrital zircon in Western Australia [1, 2] (Figs. 1–3), where the zircons represent a part of the dated zone. Sometimes, detrital zircons with similar geochemical parameters occur also in the Archean (Fig. 2). In order to specify their genesis, let us scrutinize chronological, isotopic, and geochemical criteria of the Hadean zircon. First, let us note that the disposition of most data points make it possible to identify two age intervals. The first interval (4319–4363 Ma, based on 9 points, average 4351 ± 12 Ma) fringes the zone with the mantle $\delta^{18}O$ value (+5.0 ± 0.7‰). The second interval (4267–4288 Ma, based on

4 points, average 4286 ± 12 Ma) is associated with the crustal $\delta^{18}O$ value (+7.4 ± 0.7 ‰). In both cases, the age estimates are younger than the oldest (initial) age value of 4404 ± 8 Ma. Therefore, they suggest secondary alterations or overgrowth of marginal zones of the detrital zircon fragment if the association of the elevated $\delta^{18}O$ value with the initial age of 4404 Ma is ruled out. In both cases, the integral U–Th–Pb isotope data record distinct transitions from concordant or subconcordant values to discordant ones (Fig. 1). Moreover, the minimal Th content and Th/U ratio for discordant varieties in both cases are several times higher relative to the oldest part of the zircon fragment under consideration. Concordant points are confined to zone II of the TTG and volcanics from greenstone belts and partly to the Th–U region of alkali rocks, while discordant points are successively displaced toward zone IV of alkali rocks with substantially elevated Th contents and Th/U values (Figs. 2, 3).

Thus, the detrital zircon data can by interpreted in two ways. First, the elevated Th content and Th/U values for both superimposed processes can be explained by the presence of discordant varieties, which are usually attributed to later (up to recent) changes in geochemical parameters of zircons. However, discordant zircons from Archean and Proterozoic rocks include varieties characterized by high and/or low Th contents or a lack of notable changes in the Th concentration. Second, anomalous changes in Th–U parameters are largely related to initial crystallization or superimposed alteration of zircons by mantle magmas of elevated alkalinity. Consequently, an unambiguous interpretation of data based on Th–U parameters is impossible and additional geochemical information is needed. It appeared that the studied zircons differ from other varieties in the elevated Nb and Y concentrations [2], which is consistent with typically higher contents of these elements in alkali rocks as compared with other mantle and crustal rocks [8, 11, 12, and others]. This corresponds to the mantle $\delta^{18}O$ value determined for the age of 4351 Ma in the oldest detrital zircon fragment. In this connection, let us remember that, proceeding from the data on evolution of $\varepsilon_{Nd}(T)$ values in crustal and mantle rocks, we forecasted that an early impulse of alkali mantle magmatism was needed to transfer a significant share of incoherent elements into the Earth's oldest crust and to form the complementary depleted mantle reservoir in the upper mantle proper [13, 14]. We calculated a tentative age of this stage (4396 ± 98 Ma) that corresponds to early intense geochemical differentiation in upper shells of the Earth. Moreover, the age of the next stage (moderate geochemical fractionation of the mantle and crust) was estimated at 4281 ± 17 Ma.

It is obvious that these estimates are sufficiently consistent with recent data on geochemical anomalies and their timing based on the oldest (Hadean) detrital zircon data indicating close age of crustal–mantle endogenic events. It should be emphasized that the oldest lunar KREEP basalts with anomalously high concentrations of incoherent elements also formed approximately 4.3–4.4 Ga ago. In addition, the existence of the Hadean Geon with an age of 4286 Ma and the $\delta^{18}O$ value corresponding to crustal parameters of zircons does not contradict the contribution of an older magmatic protocrust enriched in SiO_2 owing to the admixture of sedimentary material. At the same time, the presence of inclusions with high contents of K (up to 4.3%), Al_2O_3 (up to 13.8%), and quartz in the oldest detrital zircon [1, 2] indicate a combination of mantle and crustal components in the parental melt if the inclusions are primary. If they are secondary inclusions, the above features indicate a later recrystallization of zircon in the crust and the low-temperature hydrothermal alteration is also not ruled out. We believe that the appearance of water denotes a commencement and intense development of hypergene alteration of all rock types at the Earth's surface. This corresponds, in essence, to a rapid formation of the sedimentary cover and its participation in processes of crust transformation (and intense generation of the ocean's salt composition). In such interpretation of the Hadean zircon data, the elevated (crustal) $\delta^{18}O$ value and K_2O content are most likely explained by an admixture of sedimentary material in the source. Summing up the available information, we can conclude that the oldest Hadean zircons record chronologically close superimposed processes of two (mantle and crustal) types. The crustal process should include the preliminary supergene transformation of the early crust with participation of water. This conclusion indirectly indicates the origination of surface water prior to the oldest estimate of 4404 Ma and is more consistent with the concept of stabilization of the Earth's atmosphere at 4450 ± 20 Ma [15].

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