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GEOLOGY

U–Pb Ages of Detrital Zircons from Modern Sediments of the Yangtze River and Stages of Orogeny in Southeast Asia

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The problem of periodicity in continental growth is important for defining global cycles of the Earth evolution. One of the methods appropriate for solving it is mass U–Pb dating of detrital zircons and monazites from sandy sediments of large world rivers that drain vast territories [1]. The distribution spectra of U–Pb ages obtained for zircons or, less commonly, monazite from sediments of modern river systems yield information on the main stages of orogeny, continent formation and composition of terranes constituting the basement of river basins and serving as sources of sedimentary material [2]. The distribution of the obtained ages is compared with that of the ages of bedrock complexes in the basin. The coincidence of peaks in age spectra obtained for zircons and rocks in drainage areas provides grounds for the conclusion on the largely juvenile character of the continental crust in the particular region [1]. On the other hand, the discrepancy between them implies crustal material recycling (i.e., reworking of previously subducted zircon-bearing crustal material) and/or substantial changes in the provenance usually due to tectonic processes. For tectonic reconstructions, spectra of ages available for zircons from modern sediments are compared with ages obtained for zircons from older sequences [2].

The previous methods used for the assessment of periodicity and rates of continental growth based on the dating of zircons from granitoid complexes have several disadvantages. Their weakest point is the double counting of crustal material recycled during subductional–collisional processes. The method used in this study is based on the dating of magmatic zircons only. It is characterized by several advantages owing to the following features: (1) even collection of zircons from both sedimentary and crystalline rocks; (2) determination of the age of juvenile crust due to high closure temperature of the U–Pb isotope system in zircons, thus avoiding the recycled material; (3) direct determination of the age continental crust formation by dating magmatic zircons only according to [1].

This paper presents data on U–Pb ages obtained for zircons from modern sand sampled at the mouth of the Yangtze River, the largest river in China. The obtained histograms and distribution spectra (relative probability curves) of the U–Pb ages were analyzed in terms of (1) determination of the main stages of crust formation in Southeast Asia [3]; (2) comparison of the age spectra with the stages obtained in the available geodynamic reconstructions [4]; (3) comparison of the zircon age spectra with those obtained on monazites from the same sediments [5] and on zircons from older sediments of the Yangtze River basin [6]; (4) establishing probable recycling of continental crust material during the formation of Southeast Asia geological pattern, in particular, the Yangtze Craton and surrounding orogenic belts.

The 6300 km long Yangtze River delivers material into the Yellow Sea from a drainage basin of ~1 807 000 km^2. The drainage area is dominated by Phanerozoic rocks of the Yangtze Craton (or South China block) and Songpan-Ganzi, South-China, and Qinling-Dabie foldbelts (Fig. 1) [4]. The outcropped rocks characterize the crystalline basement and post-orogenic complexes (definition after [4]), including sedimentary basins, and volcanic traps occupying 50, 45, and 5% of the drainage basin, respectively. The crystalline basement consists of the rocks formed during five epochs of orogenesis (ages, Ma): Zhongtiaoan (1800–2400), Yangtzeian (800–1000), Caledonian (400–500), Indosinian (200–230), and Yanshanian

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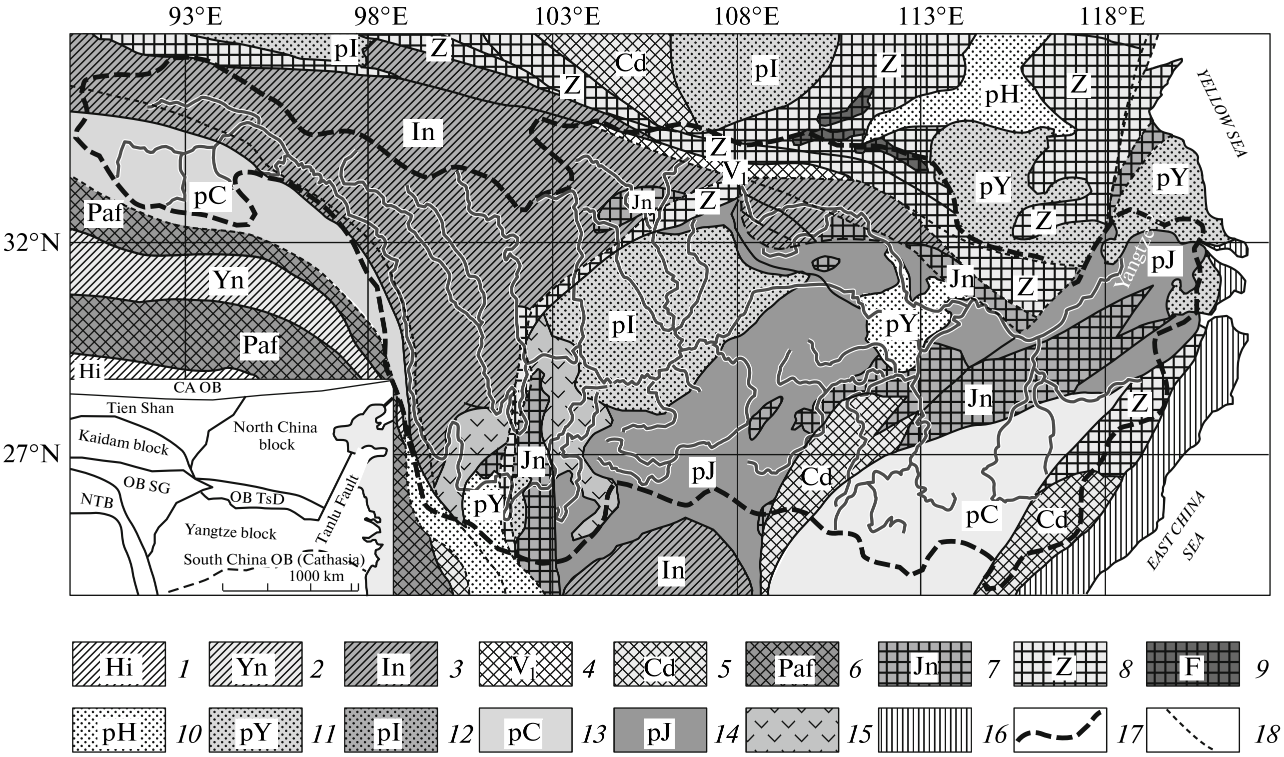

Fig. 1. The schematic tectonic structure of the Yangtze River basin and adjacent regions, after [4], modified. (*1–9*) Continental crust (orogenic epoch, Ma): (*1*) Himalayan (Pg_2–N_2), Yanshanian (J_3–K_2), (*3*) Indosinian (T_3), (*4*) Variscian (C_1), Caledonian (O–S), (*6*) Pan-African (V–$Є_1$), (*7*) Yangtzean (PR_3), (*8*) Zhongtiaoan (PR_1), (*9*) Fupingian (AR_3); (*10–12*) superimposed sedimentary basins: (*10*) post-Himalayan (<2 Ma), (*11*) post-Yanshanian (<80 Ma), (*12*) post-Indo-Sinian (<200 Ma); (*13–15*) post-orogenic complexes: (*13*) post-Caledonian (D–P), (*14*) post-Yangtzean (PZ_{2-3}), (*15*) Permian–Triassic trappes; (*16*) volcanics of the active continental margin (J_3–K_1); (*17*) contour of the Yangtze River drainage basin; (*18*) faults. Abbreviations in the inset: (NTB) North Tibet block, (OB) orogenic belts: (CA) Central Asian, (TsD) Qinling-Dabi, (SG) Songpan–Ganzi.

(100–160) [4]. The structures superimposed on the orogenic basement are represented by post-Yangtzeian (600–300 Ma) and post-Caledonian (400–250 Ma) rock complexes, post-Indosinian (<200 Ma) and post-Yanshanian (<80 Ma) sedimentary basins, and Permian–Triassic traps [4]. By considering the orogenic complexes together with the superimposed post-orogenic sedimentary covers, the drainage basin consists of the rocks of the Zhongtiaoan (Paleoproterozoic, ~8%), Yangtzeian (Neoproterozoic, ~29%), Caledonian (Early Paleozoic, ~18%), Indosinian (Early Mesozoic, ~26%), and Yanshanian (Paleogene, ~1%) orogenic epochs, post-Indosinian (Middle Mesozoic, ~1%) and post-Yanshanian (Paleogene, ~11%) sedimentary basins, and Permian–Triassic plateaubasalts (4%) (Fig. 1).

U-Pb isotopes were analyzed for about 300 zircon grains using the spot-analysis method (a ThermoElemental VG PlasmaQuad 2 LA ICP MS) which was described in detail [1, 7]. For confirming the magmatic origin of zircons, their internal structure was examined under a JEOL JSM-5310 scanning electron microscope. For this purpose, only zircon grains with characteristic oscillatory zoning and ratios $0.1 < Th/U < 4.0$, suggesting their magmatic origin [8], were selected.

Figures 2 and 3a show the results of U–Pb isotope dating of zircons. In Fig. 2 we can recognize the following tendencies in the distribution of U–Pb isotope ratios: (1) a large number of zircons are plotted along the curve and have U–Pb ages from 0.1 to 1.0 Ga; (2) the data points are scattered to form clusters at 800–900, 1800–1900, and 2500–2600 Ma; (3) the zircons which plot off the curve have U–Pb ages with a big interval. Approximately 220 zircons are plotted on the curve. We could not obtain true discordant ages for the grains plotted off the curve, because they obviously have different origin. Therefore, we calculated $^{207}Pb/^{206}Pb$ ages for the discordant U–Pb ($^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$) ages exceeding 1 Ga. The grains on the curve have the same U–Pb and Pb–Pb radiogenic ages and those plotted off the curve have minimal Pb–Pb ages. The low concordant data (<90%), i.e., points located far away from the curve, were excluded from the final datasets used for interpretation (Fig. 2).

The U–Pb age histogram includes 227 best results displays (Fig. 3a) demonstrates six main groups or peaks (Ma, *N* is the number of grains): 2500–2700

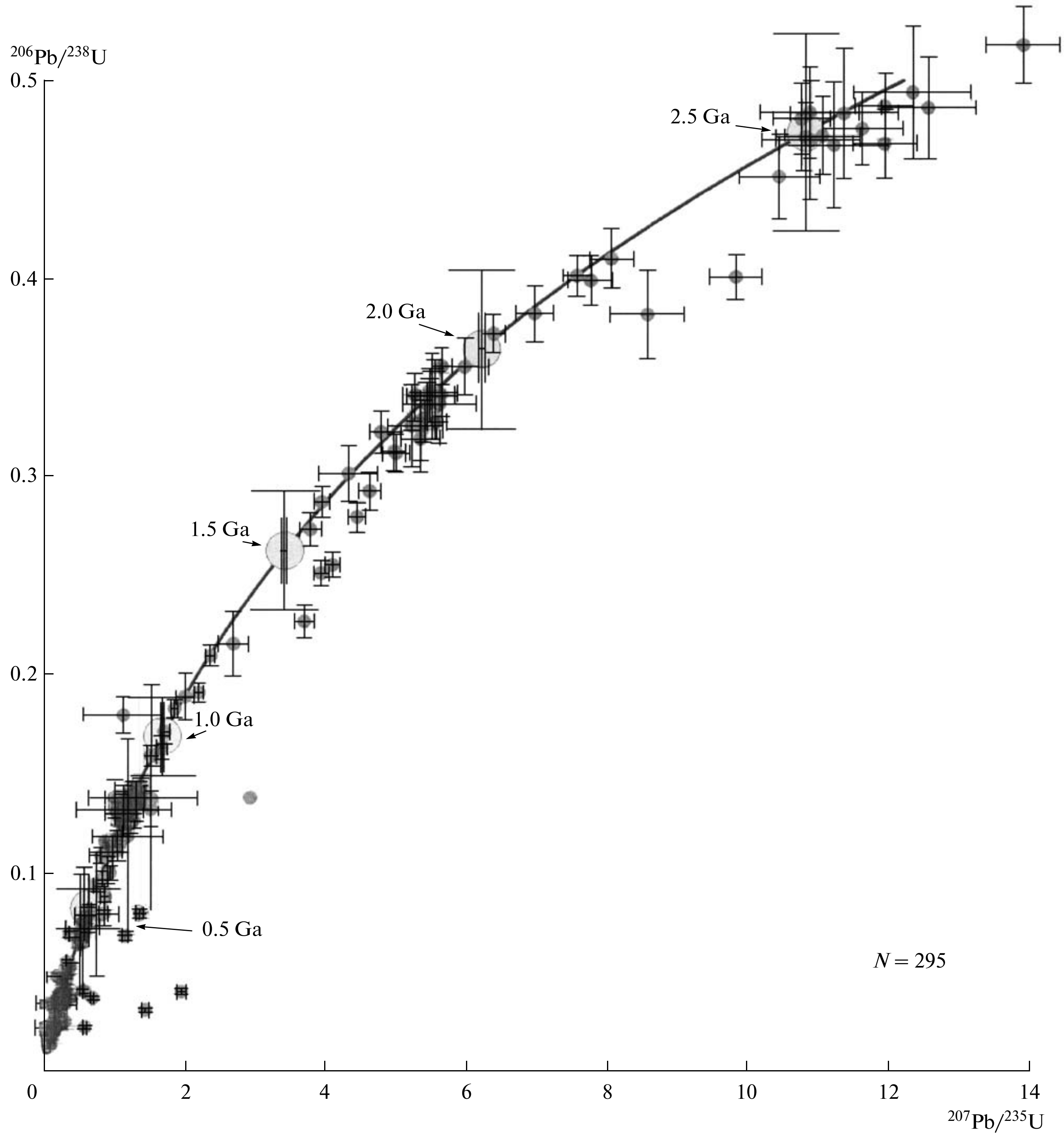

Fig. 2. The U–Pb concordia diagram in-site analyses of detrital zircons from a sand sampled at the Yangtze River mouth.

($N = 12$), 1800–2000 ($N = 25$), 700–1000 ($N = 48$), 400–500 ($N = 17$), 200–300 ($N = 38$), and 100–160 ($N = 14$). The wide range of both Phanerozoic and Precambrian ages reflects the multistage tectonic evolution of the structures of Southeast Asia. The age peaks usually coincide with the ages of the rocks composing the orogenic basement of the Yangtze River basin, but the percentage of age peaks and the areas occupied by the rocks of correspondent ages is different (Fig. 3), with Phanerozoic orogenic belts and overlying volcano-sedimentary complexes being dominant (Figs. 1, 3b).

Few, if any zircons are older than 2800 Ma thus matching the scarcity of Paleo–Mesoarchean crust (>3 Ga) in the Neoarchean Sino-Korean Craton, which preceded the formation of the Yangtze Craton in the Late Paleoproterozoic [9]. The exposed Mesoarchean crust, and the 2970 Ma Tiejiashan and the 2994 Ma Anshan granites, are present outside of the drainage basin [10].

The 2500–2700 Ma peak (5% of the dataset) likely marks the formation of the of Sino-Korean Craton crystalline basement during the Wutaian orogeny [4], which occurred during the 2.75–2.65 Ga global geodynamic event [11]. The zircons of those ages could have been delivered from the Neoarchean Kongling trondhjemites at the northern Yangtze Craton [12], however the area of their outcrops is less 1% of the total drainage area (Fig. 1).

The 1800–2000 Ma peak (11% of dataset) corresponds to the Zhongtiaoan orogeny marked by eventual cratonization of the Sino-Korean block and formation of the crystalline basement beneath the Yangtze Platform. The rocks of those ages outcrop in the western and northern frame of the craton (8% of the drainage area) [4].

The largest peak at 700–1000 Ma (21% of the dataset) marks the Yangtzeian orogeny related to the amalgamation of the Rodinia supercontinent, and consolidation of the Yangtze and Cathasia blocks [13]. The orogenic complexes related to this phase (29% of the drainage area) are exposed in the central part of the craton, which, in turn, consists of post-Yangtzeian orogenic and sedimentary rocks.

The 400–500 Ma peak (8% of the dataset) marks the beginning of the Phanerozoic orogeny related to the evolution of the northern Tethys and resulted in the formation of the South-China orogenic belt due to intracontinental collisional orogeny [14]. The rocks of these ages, i.e., Caledonian orogenic and post-orogenic complexes outcrop in the southeastern and northwestern parts of the Yangtze basin (17% of the drainage area).

The 200–300 Ma peak (17% of the dataset) corresponds to the Indosinian orogeny related to the closure of the Paleo-Tethys and amalgamation of the South China, North China, and North Tibet blocks [9], which was accompanied by intrusion of collisional granitoids, which outcrop in the South China and Songpan–Ganzi orogenic belts (26% of the drainage area).

The 100–160 Ma peak (9% of the dataset) marks the late Yanshanian orogeny related to intracontinental deformation as a result of subduction of the Pacific oceanic plate under the active continental margin of East Asia [9].

The subordinate isotope data, which form no peaks in the histogram and probability curve, are the points in the intervals of 2000–2500 ($N = 11$), 1700–1000 ($n = 20$), and <100 ($N = 6$) Ma (Fig. 3a). The data between 2000 and 2500 Ma correspond to the age of the Wutaian and early Zhongtiaoan orogenies, which outcrops are practically unknown in the drainage basin. No outcrops of 1700–1000 Ma granitoids have been reported for the area under investigation as well. The post-Yangtzeian superimposed covers probably formed evidently after the formation of the craton basement at 1800 Ma outcrop in the southwestern, northwestern, and western parts of the Yangtze Craton [4]. The orogenic structures of that age were possibly subducted during the subsequent closure of the Paleo-Tethys and Paleo-Asian oceans, south and north of the craton, respectively, and the recycled zircons were captured by Neoproterozoic orogenic granitoids (Fig. 1). The lowest peak at <100 Ma (Fig. 3a) likely marks the Himalayan orogeny related to the collision between

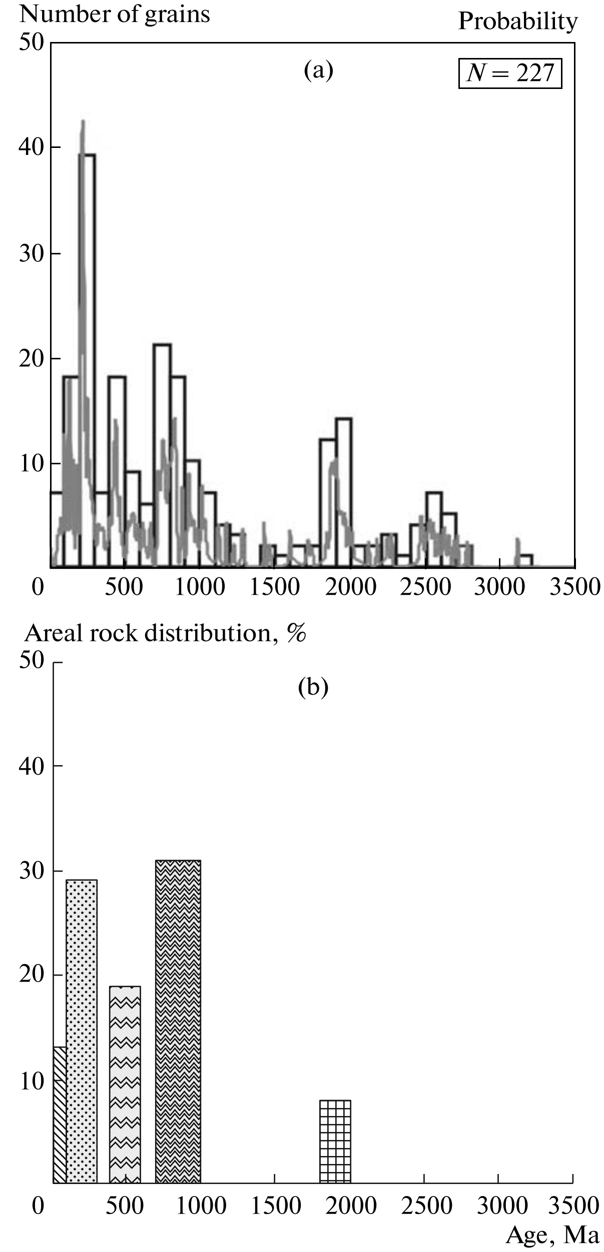

Fig. 3. (a) U–Pb (<1Ga) and Pb–Pb (>1 Ga) age histogram coupled with probability density distribution plots; (b) the areal distribution of the orogenic basement rocks complexes in the Yangtze River drainage basin, after [4].

India and Eurasia [15]. The rocks of that age are absent within the drainage basin (Fig. 1).

We compared the obtained zircon age spectra with those obtained on monazite from Neogene–Quaternary sediments of the Yangtze River mouth [5], and with the age spectra on zircons from Triassic sediments of the Songpan–Ganzi belt [6]. All the "monazite" spectra, except for the Pliocene one, show a clear peak at <25 Ma marking with the Himalayan orogeny, which is related to the India–Eurasia collision. This peak is not seen in the "zircon" spectrum (Fig. 3a). A possible explanation is that the K–Al varieties in granitoids containing mostly monazite are a major rock type in Himalayan orogenic complexes compared to the calc-alkaline varieties in older foldbelts containing zircon. Besides, the "monazite" spectra almost lack the oldest peaks at 2.5–2.7 Ga due to the scarcity of K–Al granitoids in older orogenic complexes compared to the calc-alkaline varieties, because the Archean–Early Paleozoic complexes are dominated by trondhjemites, which are modern analogues of adakites or island-arc amphibole-bearing andesites. The formation of less fertile K–Al granitoids began later, during the melting of tonalitie–trondhjemites. The other peaks and their amplitudes coincide in the "monazite" and "zircon" age spectra.

The age spectra of zircons in the Late Triassic Songpan–Ganzi sandstones are generally similar to the modern "zircon" spectrum. At the same time, the youngest spectrum (late Norian) has no Caledonian peaks (400–500 Ma). At that time, the Songpan–Ganzi turbidite basin was separated from the Caledonian South-China orogenic belt by the Paleo-Tethys bay and Longmen-Shan foreland [6].

Thus, the episodes of crust formation recognized in this study generally coincide with the stages of orogeny in Southeast Asia, which were previously estimated based on geochronological data on parental rocks. However, the origin of the 2500–2700 Ma peak remains unclear. The low distribution of the rocks of that age within the drainage basin and the presence of the distinct Neoarchean peak in the histogram, allows us to suggest the recycling of older crustal material in younger orogenic belts. This fact also may be explained by our insufficient knowledge about distant areas in South China, where old magmatic complexes may occur, or by insufficient geochronological studies of orogenic complexes, which may incorporate zircons recycled from the older continental crust.

The comparison between ages obtained for detrital monazites and zircons showed that due to the wider distribution of zircons in granitoids of all types, their age spectra provide more reliable information on the stages of crust formation, especially, for the Early Precambrian.

Study of age spectra obtained for detrital zircons from different horizons of sedimentary rocks allows us to trace the evolution of provenances and to recognize the stages of orogeny, i.e., granitoid magmatism. All this can be used for reconstruction geodynamic settings and forecasting mineral deposits, which are formed in sedimentary basins, in particular, the deposits of oil and gas, like it has been done for the Caspian region [2].

In future, the data discussed in this study can be combined with the published geochronological data on zircons from parental rocks [3, 10, 12, 13] and on detrital zircons from older sedimentary horizons [6], and to contribute more to our knowledge about the complex tectonic history of Southeast Asia, including formation and recycling of continental crust during both the Precambrian and the Phanerozoic, several stages of breakup, collision, and amalgamation of continental blocks and many cycles of anorogenic, orogenic, and post-orogenic granitoid magmatism.

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