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GEOLOGY

Heavy Clastic Minerals as a Criterion for the Identification of Island-Arc Environments in Paleobasins of Orogenic Zones in the Russian Far East

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Island-arc environments in ancient basins, including forearc and backarc basins, are usually identified on the basis of the paleogeological position, structure, and composition of rock sequences, as well as the petrochemistry of volcanic and terrigenous rocks. We attempted to establish certain environments only based on heavy clastic minerals from sedimentary rocks of different (in structure and age) basins. The analysis of heavy mineral associations is a well-tested method for the establishment of provenances of clastic rocks [1, 7]. Recent studies of Cenozoic sediments in present-day oceans and marginal seas have shown that heavy clastic minerals are also indicators of tectonic and geodynamic settings in sedimentation systems [8, 9].

We examined Eocene–Quaternary sediments of the Vanuatu Trench, as well as Early Cretaceous and Early Cretaceous–Cenozoic island-arc rocks known in paleobasins of the Kiselevka–Manoma and Kema terranes (Sikhote Alin) and the Olyutorka terrane (eastern Kamchatka) (Fig. 1).

Figure 2 demonstrates the ratio of heavy minerals in sediments of these structures. The minerals form sialic (granitic–metamorphic) and mafic (volcanic) associations.

The **Vanuatu Trench** is located in the southwestern part of the Pacific Ocean and extends 2500 km along the western slope of the Vanuatu volcanic island arc. The trench formed due to the eastward motion of the Indian–Australian oceanic lithospheric plate [2, 10].

We studied sediments ranging from the Middle Eocene to the Pleistocene–Holocene. They are represented by poorly lithified pelites and silts with pyroclastics. The position of the trench in the Middle Eocene–Holocene time was favorable for the accumulation of products of synsedimentary volcanism and subsequent washout of the island arc. Therefore, the bulk of heavy minerals in sediments of the region are represented by the mafic association (mainly, clinopyroxenes, orthopyroxenes, and magnetite). Hornblende, olivine, and epidote are subordinate. Sialic minerals are represented only by sphene, ilmenite, leucoxene, apatite, and corundum. Their total content does not exceed 2.5% of the total amount of heavy minerals.

The **Udyl island-arc fragment of the Kiselevka–Manoma terrane** is located in the lower reaches of the Amur River near Lake Udyl. Valanginian–Cenomanian sediments of this area accumulated in forearc and backarc basins related to the Early Cretaceous epicontinental island-arc system [6]. These sediments are subdivided into the following lithological complexes accumulated in different facies environments.

The *cherty complex*, a fragment of the oceanic arc basement, is composed of cherts, their clayey varieties, and less common alkaline basalts and limestones. Volcanic clinopyroxenes, orthopyroxenes, magnetite, and hornblende are the major minerals. Sialic minerals (zircon, garnet, and apatite) are subordinate.

The *volcaniclastic complex* consists of tuffs, tephroids, volcanomictic sandstones, mixtites, tuffaceous silicites, clayey and clayey–cherty rocks, and rare basalts. Almost all heavy minerals of the complex are volcanic clinopyroxenes, orthopyroxenes, magnetite, and hornblende. The upper part of the complex also includes epidote, garnet, chromite, zircon, apatite, sphene, and rutile. Hence, sediments of the complex accumulated in the forearc basin. First, the synsedimentary volcanic material accumulated. The later volcaniclastic material is composed of products of the destruction of the accretion prism, which included fragments of the epioceanic volcanic arc, oceanic islands, and ophiolites.

The *graywacke complex* is composed of sandstones, clayey rocks and less common tuffs, mixtites, and tur-

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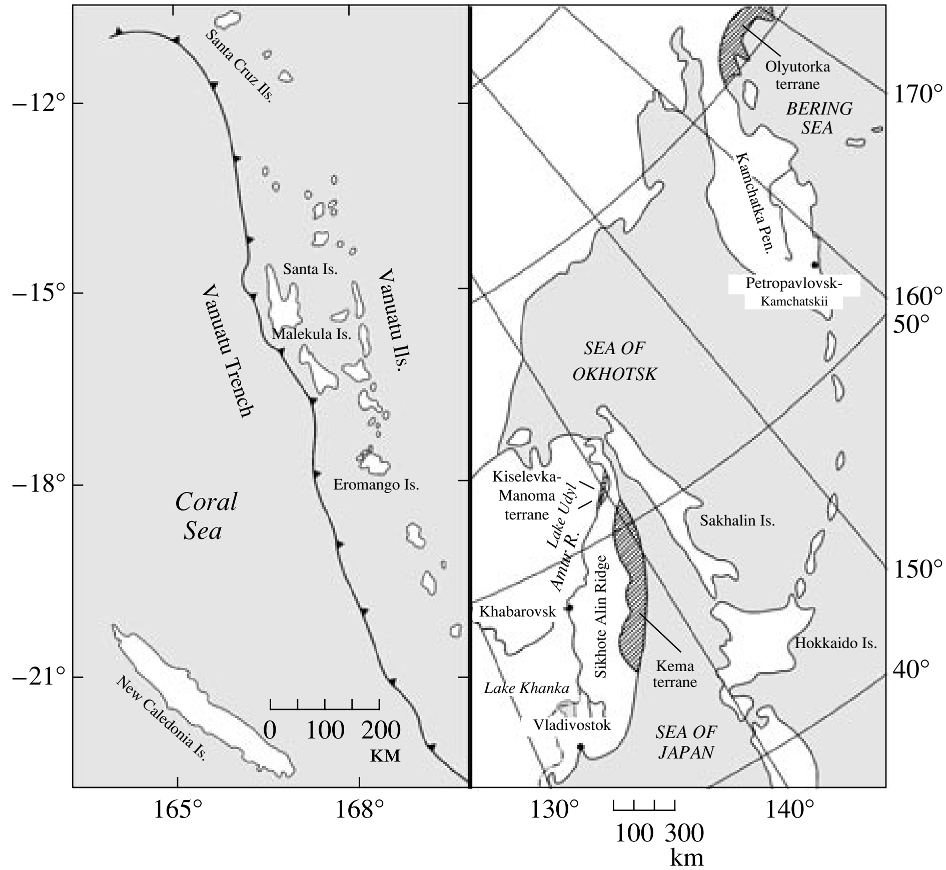

Fig. 1. Location of the studied objects.

bidites. The ratio of heavy minerals varies in different parts of the complex from a sharp prevalence of chromite (up to 50–94%) associated with pyroxenes (up to 37%) to a considerable content of zircon (up to 34%) and garnet (up to 20%). The complex probably accumulated in the backarc basin. The provenance was most likely represented by the accretion prism composed of fragments of oceanic, island-arc, and continental origin.

The *Olyutorka terrane* and paleobasin are constituents of the Mesozoic–Cenozoic Sakhalin–Kamchatka orogenic belt. The Olyutorka terrane located in the southern Koryak Upland extends 500 km along the Bering Sea coast (Fig. 1). Early Cretaceous–Neogene island-arc rocks of the terrane accumulated in the forearc basin of the Vatyna epioceanic arc [3]. They are subdivided into lithological complexes formed in different environments and, probably, at a considerable distance from their present-day position [3].

The *volcanogenic–cherty complex* consists of basalts, lava breccias, tuffs, cherts, and their clayey varieties. Clayey rocks, sandstones, and limestones are less common.

The *volcaniclastic complex* is composed of basalts, tuffs, volcaniclastic sandstones, cherts, clayey and cherty–clayey rocks, gritstones, and conglomerates.

The *turbidite complex* includes thick turbidite sequences interrupted by horizons of siltstone, sandstone, gritstone, tuff, and mixtite.

The *molasse complex* consists of sandstone, gritstone, conglomerate, clayey rocks, tuffs, and coals.

Two heavy mineral provinces are distinguished in the Olyutorka terrane. The *northern province* mainly includes island-arc clinopyroxenes (40–100%), magnetite (15–55%), hornblende (2–30%), and orthopyroxenes (1–7%). These minerals account for up to 90% of heavy minerals. The sharp prevalence of mafic minerals indicates a considerable influence of synchronous volcanism and washout of volcanic rocks on sedimentation. The role of island-arc mafic association is also significant in the *southern province*. Like in the northern province, clinopyroxene is the major mineral here, although its share is substantially lower (24–40%). This province is also characterized by high contents of magnetite (10–35%) and chromite (6–14%). Hornblende and orthopyroxene make up only 3–5%. At the same time, the content of sialic minerals is higher in this province: zircon up to 73%, apatite up to 22%, garnet up to 13%, and rutile up to 5%. Tourmaline, sphene, corundum, vesuvian, anatase, orthite, brookite, sillimanite, staurolite, andalusite, disthene, and fluorite are found only in the

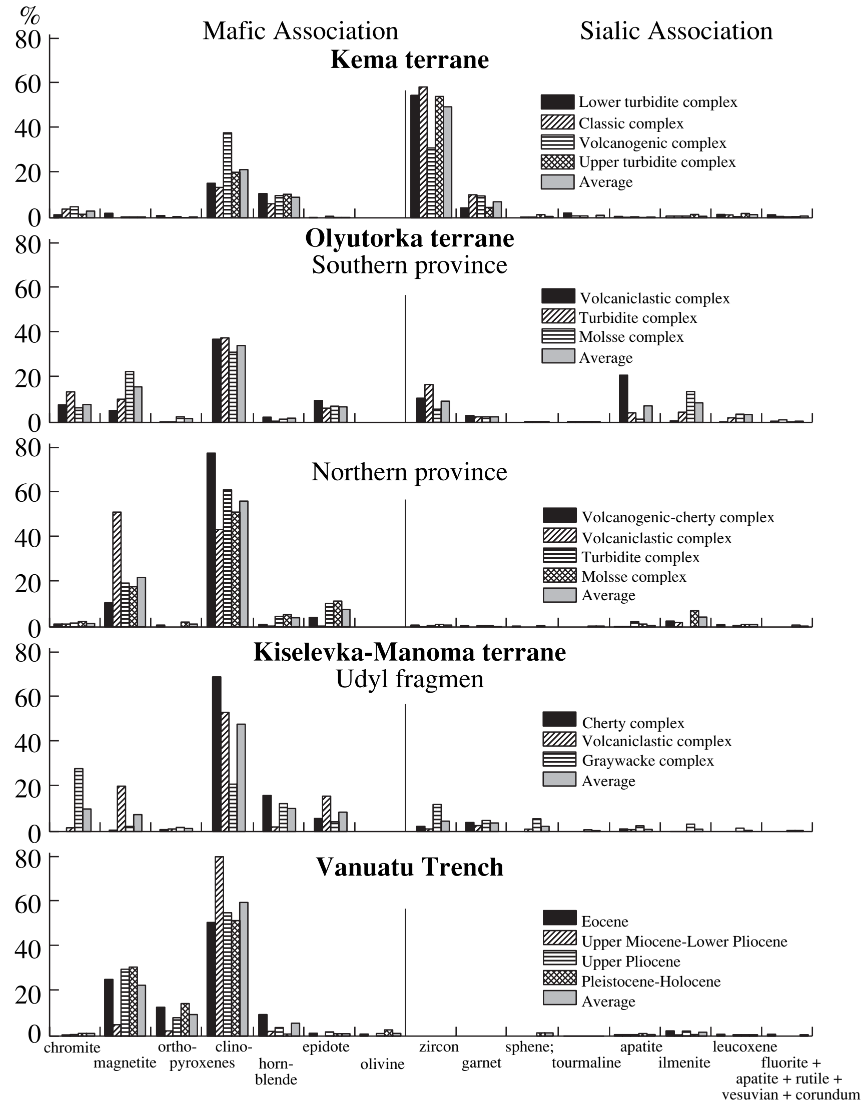

Fig. 2. Distribution of heavy clastic minerals in sediments of studied objects.

southern province. The mature continental crust could be the source of these minerals.

The composition and ratio of heavy clastic minerals suggest two sources for the basins in both provinces of the Olyutorka terrane. The principal source was the Cretaceous–Paleogene ensimatic volcanic island-arc and its oceanic basement, as well as synsedimentary volcanism. The role of another synchronous source was far less significant in general, but very important for the southern province. Judging from a great diversity of sialic heavy minerals, sedimentation in this area was strongly influenced not only by the island-arc source but also by the sialic continental blocks, probably, located in the area of the present-day Bering Sea.

The *Kema terrane* is located in the eastern part of Sikhote Alin and extends 800 km along the Sea of Japan. Barremian–Albian rocks of this area accumulated in the backarc basin of the epicontinental Moneron–Samarga volcanic island-arc system [4]. These rocks are subdivided into the following lithostructural complexes. The *lower and upper turbidite complexes* are composed of thick turbidite masses with horizons of siltstones, sandstones, gritstones, and subaqueous slumps. The *clastic complex* consists of conglomerates, gritstones, sandstones, and various mixtites. The *volcanogenic complex* includes basalts, tuffs, volcaniclastic sandstones, turbidites, and mixtites.

The Kema terrane is mainly composed of a sialic mineral association: zircon (up to 80%), garnet (up to 11%), apatite (up to 5%), and tourmaline (up to 3%). Sphene, rutile, vesuvian, anatase, and corundum make up 3% in total. The subordinate mafic association includes the following minerals: clinopyroxene (up to 40%), hornblende (up to 12%), orthopyroxene (up to 5%), chromite (up to 6%), and magnetite (up to 21%). The heavy mineral association of the Kema island-arc

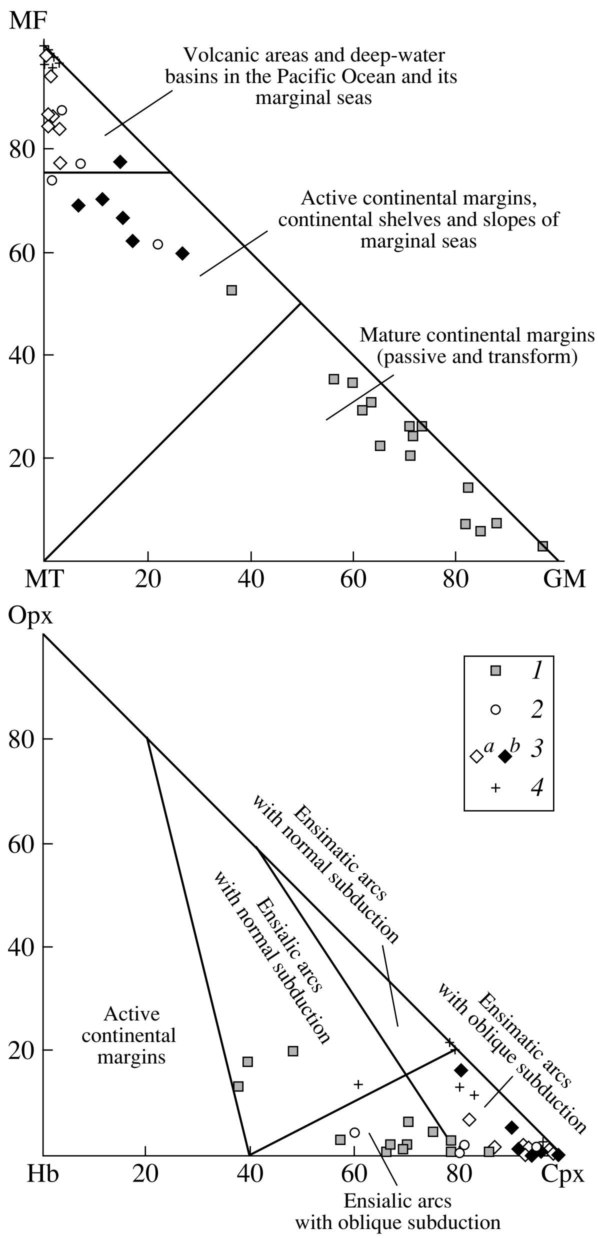

Fig. 3. Comparison of the ratio between heavy clastic minerals from sandstones of the studied objects and present-day sediments from different geodynamic environments [6]. Total content: (MF) olivine, pyroxene, and green hornblende; (MT) epidote, garnet, and blue-green amphiboles; (GM) zircon, tourmaline, staurolite, disthene, sillimanite, and andalusite. (Opx) orthopyroxene, (Hb) hornblende, (Cpx) clinopyroxene. (*1*) Kema terrane; (*2*) Kiselevka–Manoma terrane (Udyl fragment); (*3*) Olyutorka terrane: (*a*) Northern, (*b*) Southern provinces; (*4*) Vanuatu Trench.

basin is derived from two sources of the clastic material: subalkaline and calc-alkaline basalts of the island arc and its basement composed of fragments of the sialic continental crust [5].

The differences between basins related to island arcs developed on the oceanic (or continental) basement, on the one hand, and fore- and backarc basins, on the other hand, are best demonstrated by an analysis of heavy mineral associations in MF–MT–GM and Opx–Hb–Cpx diagrams (Fig. 3). In the MF–MT–GM diagram, all data points of the Vanuatu Trench, as well as sedimentation basins of the Olyutorka and Kiselevka–Manoma terranes, tend to the MF corner. They are consistent with sediments of deep-water basins and marginal seas of the Pacific Ocean, where the island-arc volcaniclastic material with some admixture of the continental sialic material was the basic source for clastics. The Opx–Hb–Cpx ratio allows separation of the material formed during the destruction of arcs with the ensialic or ensimatic basement. In the studied sediments, this ratio corresponds to the value for ensimatic island arcs at small angles of plate convergence. This is indicated by low contents of orthopyroxene and hornblende. Heavy mineral associations from the Kema terrane show their relation to two main provenances. The first, mafic provenance was represented by the ensialic island arc related to oblique subduction. Sediments accumulated in the backarc basin mainly due to washout of island-arc volcanics. The second, sialic provenance was represented by the ocean-facing fragment of the continental crust, which made up the arc basement [5].

Thus, data based only on heavy minerals are sufficient for the reliable identification of forearc basins of ensimatic arcs (e.g., the Vanuatu Trench based on the sharp prevalence of the mafic association) and backarc basins of ensialic arcs (e.g., the Kema terrane based on the prevalence of the sialic association). In the remaining cases, other data should be invoked. The origin of volcanic arcs is well identified.

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