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GEOLOGY

The Kema Island-Arc Terrane, Eastern Sikhote Alin: Formation Settings and Geodynamics

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The Early Cretaceous is an epoch of geologic events that predetermined in many respects the present-day appearance of structural units in the northwestern framing of the Pacific Ocean. The study of sedimentary basins genetically related to the island arcs whose fragments are known in the Far East is especially important for paleogeographic reconstructions of the evolution of the eastern margin of Asia in the Cretaceous.

The findings of island-arc volcanic rocks in Sikhote Alin and on the Sakhalin, Hokkaido, Rebun, and Moneron islands [7, 10, 11] served as grounds for recognition of the Early Cretaceous Moneron–Samarga island-arc system. In Sikhote Alin, these rocks were found in the Kema Terrane [4].

The present-day tectonic structure of Sikhote Alin is a collage of various terranes attached to the eastern margin of Asia in the Paleozoic and Mesozoic [6, 9].

The *Kema Terrane* is situated in eastern Sikhote Alin and extended along the coast of the Sea of Japan. The terrane is exposed in erosion windows among Late Cretaceous igneous rocks of the East Sikhote Alin volcanic belt (Fig. 1). The terrane is composed of the Barremian (?)–Albian turbidites that contain siltstones, sandstones, gravelstones, conglomerates, mixtites, and tuff units, and basaltic volcanic flows [4]. The Kema Terrane is thrust over the western *Zhuravlevka Terrane*, which is filled with the Lower Cretaceous turbidites and considered a continental-margin pull-apart basin [2]. The *Samarka* and *Taukhe terranes* are fragments of the Jurassic and Late Jurassic–Early Cretaceous accretionary prisms composed of tectonic sheets of turbidites and olistostromes with blocks of the Paleozoic and Lower Mesozoic limestones, cherts, basalts, gabbroids, and terrigenous rocks [1, 2]. The Early Cretaceous *Kiselevka–Manoma Terrane* is composed of tectonic sheets of the Jurassic–Lower Cretaceous cherts and associated basalts, limestones, siltstones, and turbidites [3]. We consider this terrane an accretionary prism of the Moneron–Samarga island-arc system. On the eastern side of the Kema Terrane, the Early Cretaceous complex (island-arc basalts and andesites along with volcanosedimentary rocks) occurs in the *Kamyshovy and Rebun–Kabato terranes* on the Sakhalin, Hokkaido, Moneron, and Rebun islands [7, 10, 11]. These

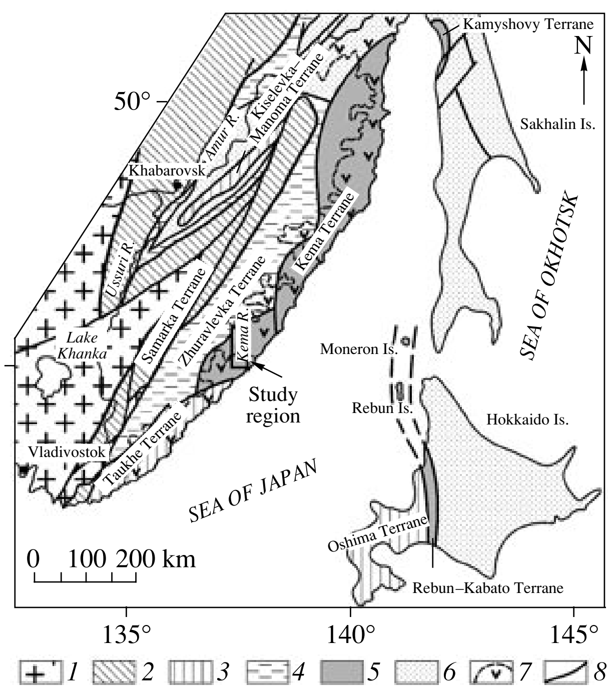

Fig. 1. Terranes in the southern Far East of Russia and the adjacent territories [4, 9]. (*1–6*) Terranes: (*1*) pre-Mesozoic, (*2*) Jurassic accretionary prism; (*3–5*) Early Cretaceous: (*3*) accretionary prism, (*4*) continental-margin pull-apart basin, (*5*) island arc; (*6*) Early–Late Cretaceous and Cenozoic; (*7*) Late Cretaceous East Sakhalin volcanic belt; (*8*) faults.

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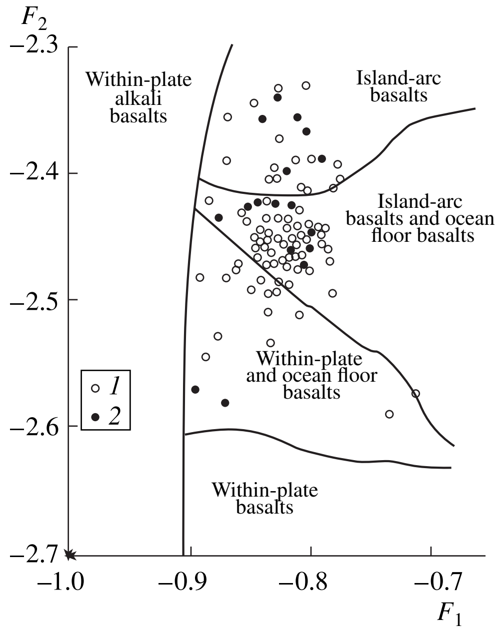

Fig. 2. Discriminant diagram for clinopyroxenes from basalts of different geodynamic settings [12]. F_1 = $-0.012SiO_2 - 0.0807TiO_2 + 0.0026Al_2O_3 - 0.0012FeO - 0.0026\ MnO + 0.0087MgO - 0.0128CaO - 0.0419Na_2O$; $F_2 = -0.0496SiO_2 - 0.0818TiO_2 - 0.02126Al_2O_3 - 0.0041FeO - 0.1435\ MnO - 0.0029MgO - 0.0085CaO + 0.0160Na_2O$. Clinopyroxenes from (*1*) sandstones and (*2*) basalts.

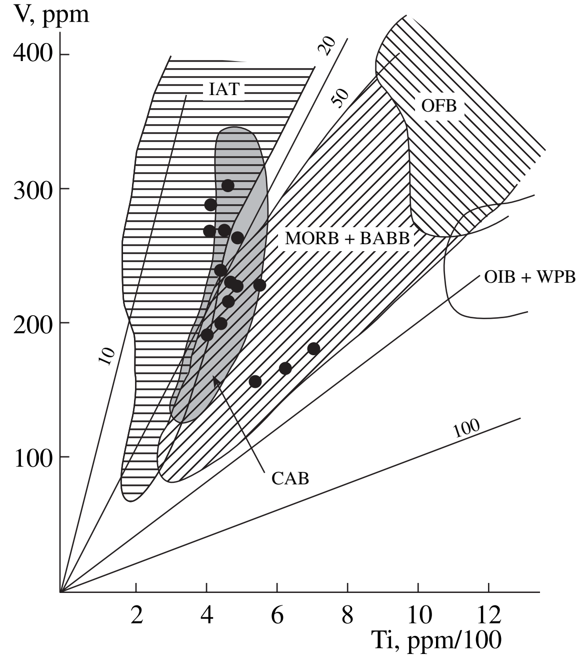

Fig. 3. Compositions of the Kema basalts plotted on the V–Ti diagram [14]. (BABB) Basalts of backarc basins, (OFB) ocean floor basalts, (OIB) ocean island basalts, (MORB) mid-ocean ridge basalts, (WPB) within-plate basalts, (IAT) island-arc tholeiites, (CAB) calc-alkaline basalts.

terranes are regarded as an axial zone of the volcanic island arc.

We studied the terrigenous rocks and lavas to determine the composition of provenance and paleodynamic setting of the Kema sedimentary basin. Based on rock-forming components, the Kema sandstones correspond to feldspar–quartz and quartz–feldspathic graywackes. Their composition indicates that the Early Cretaceous sedimentation occurred at the active continental margin in a basin related to the continental (ensialic) island arc [5]. This conclusion is supported by chemical compositions of sandstones and siltstones, as well as heavy clastic minerals that make up typical volcanic (orthopyroxene, clinopyroxene, hornblende, chromite, magnetite) and sialic (zircon, garnet, tourmaline, apatite, titanite, rutile) assemblages. Thus, analysis of associations of heavy minerals shows that they were derived from two sources. The volcanic association is related to volcanics of the ensialic island arc, whereas the sialic association is derived from a seaward protruding continental crust fragment that served as a basement of this arc [5].

The type of volcanic source may be established by chemical compositions of clinopyroxenes from the Kema sandstones and basalts. In the Nesbitt–Pearce discriminant diagram [12] (Fig. 2), these compositions mostly fall into a common field of island-arc and partly ocean floor basalts. Volcanic rocks identical to the island-arc basalts of the Kema Terrane and cherts predominate in conglomerates and gravelstones. The presence of Triassic and Jurassic radiolarians in the cherts indicate that the Jurassic–Early Cretaceous accretionary prism similar to the prisms of the Samarka and Taukhe terranes was a constituent of the basement [4, 9].

The petrology and geochemistry of the Kema basalts testify that they were related to a common magmatic source. In various discriminant diagrams, in particular, in the V–Ti plot (Fig. 3), the basalts are confidently classified as island-arc igneous rocks. In terms of the major petrologic characteristics, they belong to the high-K calc-alkaline and shoshonite series typical of backarc zones of mature island arcs [8].

The prevalence of thick turbidite units in the section is a characteristic feature of the Kema Terrane. Turbidites are often associated with mixtites, gravelstones, and conglomerates formed by high-density grain and debris flows [4]. Sporadic siltstone units with thin sandstone interbeds apparently are sediments of bottom currents. The genetic attributes show that the sediments were deposited in the lower part of the continental slope or at its rise. The Kema basalts often demonstrate a pillow structure. At their bases, the volcanic flows are enriched in siltstone inclusions oriented along the direction of flow movement. Being erupted into water, the lava flows are often cracked and split into segments divided by fissures filled with silty material that occasionally covered the lava flows. Thus, the lavas erupted

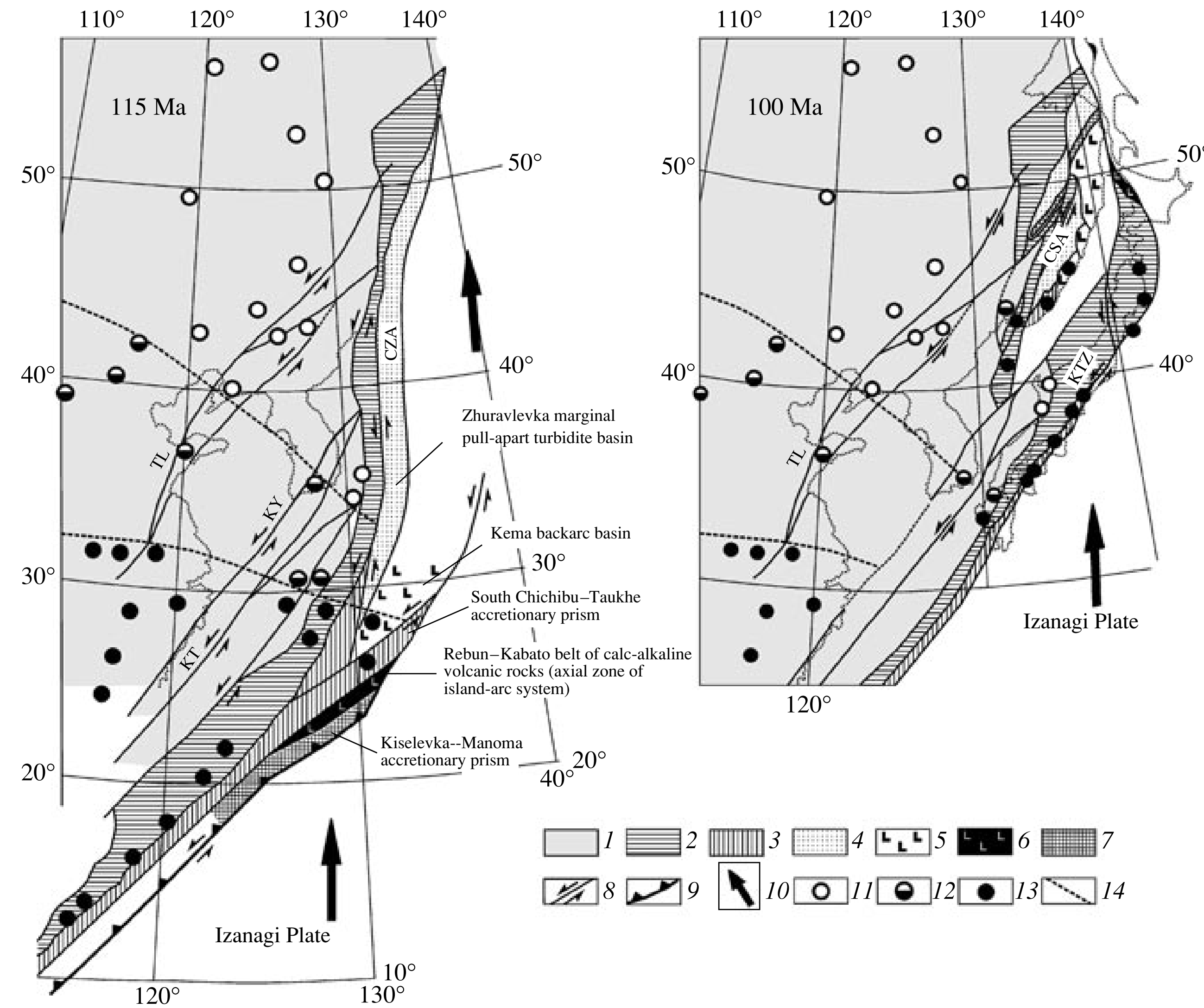

Fig. 4. Geodynamic reconstructions of the eastern Asian margin for 115 Ma ago (before main displacements along the Tan-Lu Fault System) and 100 Ma ago (before opening of the Sea of Japan. (*1*) Pre-Jurassic basement; (*2*) Jurassic terranes (fragments of accretionary prism); (*3*) Late Jurassic–Early Cretaceous terranes (fragments of accretionary prism); (*4–7*) Early Cretaceous terranes: fragments of (*4*) continental-margin pull-apart basin, (*5*) backarc basin, (*6*) axial zone of arc, and (*7*) Barremian–Albian accretionary prism; (8) sinistral strike-slip faults of the Tan-Lu system; (*9*) subduction zones; (*10*) direction of Izanagi Plate displacement; (*11–13*) floristic complexes: (*11*) Tetori, (*12*) mixed, (*13*) Ryoseki; (*14*) boundaries of paleoclimatic zones. Strike-slip faults (letters in figure): (CSA) Central Sikhote Alin, (TL) Tan-Lu, (KY) Kwangiu–Yongdong, (KT) Korea–Taiwan, (KTZ) Kurosegava tectonic zone.

on unconsolidated sediments of the marine basin [8]. The graded bedding and mainly coarse-clastic composition of tuffs indicate the explosion character of volcanic eruptions and reworking of pyroclastic material in an aqueous medium close to volcanic edifices.

Thus, the sedimentation in the Kema Terrane occurred on the slope of backarc basin contemporaneously with volcanic eruptions. Gravity flows of variable density and composition were the main transporting agents. The submarine slump dislocations at various levels of the section serve as evidence for the northeastern strike of the submarine slope and for the transport of clastic material from the southeast to the northwest [4]. Thus, the clastic material was transported not from the Asian continent in the northwest but from a continental crust salient that served as the island-arc basement and extended along a fault of the Tan-Lu system toward the ocean. This salient was sufficiently large to supply a great amount of sialic clastic material.

The coeval turbidites of the Zuravlevka Terrane, which adjoins the Kema Terrane in the west, were deposited in a quite different setting within a marginal pull-apart basin [1, 2]. The juxtaposition of two markedly distinct terranes in the Sikhote Alin may be explained by large-scale displacements along strike-slip faults of the Tan-Lu system. To restore the initial location of the island-arc paleobasin, we carried out paleogeodynamic reconstruction using the distribution of the Early Cretaceous (pre-Albian) flora. Zones of the cryophilic Tetori flora, thermophilic Ryoseki flora, and a tract of the mixed flora are distinguished along the eastern margin of Eurasia [13]. These zones are rather persistent on land where they are divided by near-latitudinal boundaries. However, the zoning is disturbed along the continent–ocean interface. In Japan, the Tetori Complex was revealed in the sedimentary cover of the Hida Massif, while the Ryoseki Complex is widespread along almost the entire length of Outer Japan, often in much more northern areas than on land. The palynoflora of the Kema Terrane is close in taxonomy to the Ryoseki Complex [4], whose northern boundary extends along 30° N; i.e., the Kema paleobasin was initially situated at this or even more southern paleolatitudes.

As shown in the paleoreconstruction (Fig. 4), the Moneron–Samarga island-arc system was located at a bend of the continental margin. The South China segment of this margin extended in the northeastern direction, while the northern continent–ocean interface was nearly meridional. Oblique subduction may be suggested as a result of the northward displacement of the Izanagi oceanic plate along the East China segment of the margin, while a segment of transform slip was situated in the northern area (turbidites of the Zhuravlevka Terrane). Precisely the bend of the continental plate was marked by the seaward protrusion of the plate fragment, which became the basement of the Moneron–Samarga island-arc system. According to the proposed reconstruction, the Kema paleobasin was located near the salient of continental crust and was subsequently replaced by the Zhuravlevka turbidite basin in the lateral direction.

Thus, the island-arc system, which existed in the Barremian–Albian time south of 30° along the eastern margin of Eurasia, comprised the backarc basin (Kema Terrane), the axial zone of the arc (Kamyshovy Terrane and Rebun–Kabato volcanic belt), and the accretionary prism (Kiselevka–Manoma Terrane). The formation of the present-day structure of the margin was completed in the late Albian–early Cenomanian, i.e., prior to the formation of volcanites in the Late Cretaceous East Sikhote Alin belt.

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