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Episodes of Abnormally High Intensity of Tectonic Dislocations

V. V. Golozubov[a], *, M. V. Zheldak[a, b], N. N. Kruk[b], **, and S. A. Kasatkin[a]

[a]*Far East Geological Institute, Far East Branch, Russian Academy of Sciences, pr. 100 let Vladivostoku 159, Vladivostok, 690022 Russia*

[b]*Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090 Russia*

**e-mail: golozubov@fegi.ru*

***e-mail: kruk@igm.nsc.ru*

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Abstract—It is shown for the structures of the Late Permian–Early Triassic, Early–Late Cretaceous, and Early–Middle Miocene stages in the formation of the eastern margin of Asia that the evolution of the Earth's crust included periods of tectonic reconstructions, which occurred practically instantaneously from the geological viewpoint. These periods are often shorter than the resolution of both local isotope and paleontological methods of dating.

Keywords: tectonic dislocations, biostratigraphy, U–Pb dating, intrusive magmatism, volcanism, geodynamic settings, Pacific margin of Asia

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INTRODUCTION

As has long been known from studies of the dynamics of the formation of orogenic belts in time, there are situations when long periods of relatively stable development within a single geodynamic mode (e.g., in the environments of active, passive, or transform margins) alternate with epochs of folding, intrusion of huge volumes of granitoids, orogenesis, and further peneplenization. After these epochs, the evolution often proceeds in a radically different geodynamic environment with the formation of an "upper structural level," as previously stated. The dating of stages of relatively stable evolution is based on the results of the study of fossil remains of fauna and flora in the sequences of sedimentary and volcanogenic–sedimentary formations accumulated during these stages. The materials of paleontological and biostratigraphic studies are the major basis for geological maps and conclusions on the geological history of territories.

Geologists studying intrusive and effusive magmatism apply a different approach to the dating of geological events. This approach was developed with the introduction of precise radiological dating into widespread practice. In this case, we consider the periods of endogenic activity which are consistent with most of the isotope ages of magmatic, as well as metamorphic events. These periods are distinguished by the diversity of magmatism, the appearance of several magmatic associations of various types within a narrow time range, which provides evidence for strong variations in the P–T–d parameters in the crust and mantle and variability and rapid changes of magma sources. Such periods are separated from each other by stages with significantly lower endogenic activity, when magmatism, if any, is "stretched" in time and relatively uniform.

The correlation of the paleontological and geochronological data shows that the episodes of tectonic transformations, within the first approach, are in complete agreement with the "stages" of the second approach. This means that the major impulses of endogenic activity occurred in the stages of tectonic transformations, in the epochs of folding and orogenesis.

One of the key issues for understanding of the specifics of the processes occurring in the stages of tectonic transformations is the evaluation of their rate and, consequently, the duration of the corresponding geological events. In most cases, these events are instantaneous from the geological viewpoint; i.e., they are often shorter than the resolution of both local methods of isotope dating and paleontological analysis.

In our study, this regularity is considered for the structures of the Pacific margin of Asia. The paper is based on the results of our studies, as well as on the published data on the issues considered.

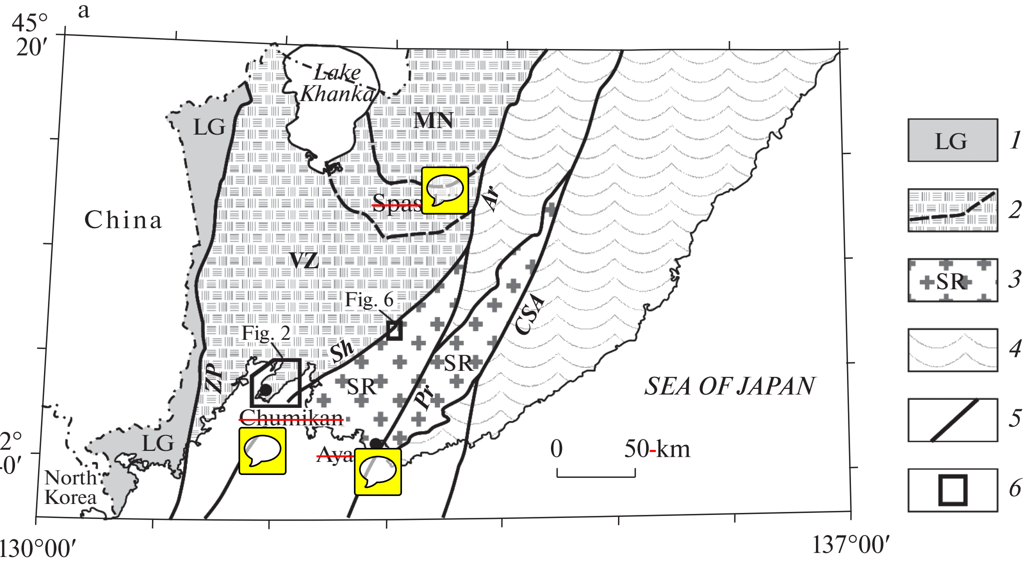


Fig. 1. Scheme of terranes in South Primor'e, after [3]. (*1*) Laoelin–Grodekovskii Terrane, the fragment of the Paleozoic active margin; (*2*) terranes of the Early Paleozoic Bureya–Khanka orogenic belt: (MN) Matveevsko-Nakhimovskii, (SP) Spasskii, (VZ) Voznesenskii, and boundaries between them (dashed lines); (*3*) Sergeevskii Terrane, the fragment of the Paleozoic and Early Mesozoic passive margin included in the structure of the Late Mesozoic Sikhote-Alin–North Sakhalin orogenic belt; (*4*) Jurassic and Early Cretaceous terranes of the Sikhote-Alin–North Sakhalin orogenic belt; (*5*) faults: (ZP) Zapadno-Primorskii, (Sh) Shkotovskii, (Ar) Arsen'evskii, (Pr) Partizanskii, (CSA) Central Sikhote-Alin; (*6*) location of the areas shown in Figs. 2 and 6.

PERMIAN–TRIASSIC BOUNDARY IN THE SOUTHERN PART OF THE EARLY PALEOZOIC VOZNESENSKII TERRANE (MURAV'EV–AMURSKII ISLAND, VLADIVOSTOK REGION, FIGS. 1 AND 2)

The Voznesenskii Terrane is composed of the Lower Cambrian sedimentary and volcanogenic formations of the passive continental margin [3] intruded by Ordovician–Silurian granitoids (the Artemovskii and Nadezhdinskii massifs, the massif of Russkii Island, and others, 420–450 Ma) [8]. The cover of the terrane in the considered region includes the local Middle–Late Devonian red continental deposits [3] and more abundant Permian deposits (Figs. 2 and 3). As is assumed, the latter were formed in the environment of transform boundaries of plates [7, 8] and include the terrigenous formation accumulated under the marine–coastal environments and on the continent (the Pospelovskaya Formation, up to 2500 m, the Kungurskii and Roudskii stages), concordantly overlain by intermediate and acid rocks, alternating with the layers of volcanogenic–sedimentary and marine–coastal sedimentary rocks (the Vladivostokskaya, Chandalazskaya, and Lyudyanzinskaya formations with the total thickness up to 2300 m, fauna of the Capitanian, Wuchiapingian, and Changhsingian stages) [26]. The Lyudyanzinskaya Formation at the top of the sequence of Permian rocks in this region is dated by the Dzhul'finskii and Dorashamskii stages (the Wuchiapingian and Changhsingian stages of the International Scale) by fossil remains; i.e., its formation finished later than 254 m.y. ago (bottom of the Changhsingian Stage) [26]. This was followed by folding and intrusion of the Sedankinskii granite complex with zircons dated as 249.7 ± 3.5 and 260.7 ± 3.1 Ma (Table 1) [23]. The bottom of the discordantly overlying Triassic marine–coastal terrigenous deposits contains a layer of basal conglomerate with pebbles and boulders of variegated volcanic and sedimentary (including limestone with foraminifera of the Chandalazskii Horizon) rocks and granitoids. Among the granitoids we registered granite with zircons with an age of 265 ± 1.8 Ma (Figs. 4a and 4b) in the outcrop on the coast of Sportivnaya Bay of Vladivostok; i.e., in the first approximation, this rock may be attributed to the Sedankinskii Complex. 50 ages (36 of them are concordant) were obtained for the detrital zircons from the layer of coarse–medium-granular sandstone in conglomerate of the same outcrop. 17 points provide an age of 269 ± 2 Ma; the others are more ancient (Figs. 4c and 4d). According to these data, we may assume that the Sedankinskii Complex includes several intrusive phases within 270–250 Ma; the first phases were most likely synchronous to volcanism of the Vladivostok age. In addition, it is not excluded that among the sources of detrital zircons with an age of 269 ± 2 Ma in the basal conglomerates are acid volcanic rocks of the Vladivostok Formation (Capitanian Stage). These conclusions do not contradict the ages of the detrital monazites (with a peak at 273.2 ± 27.1 Ma) extracted from the sandstone of the Triassic basal formation in the area of Gornostai Bay (Vladivostok) (Fig. 5) [25]. As expected, the sandstones of the Pospelovskaya Formation collected and studied together with the Triassic rocks do not contain Permian monazites [25].

Thus, we may declare with confidence that the granitoids of the Sedankinskii Complex were already exposed on the surface and eroded during the formation of the Triassic basal layers. The basal conglomerate is overlain by alternating marine–coastal sandstone, gravelstone, and conglomerate containing the key fauna of the Induan Stage of the Triassic [26], the bottom of which is dated as 252.17 Ma and the top, as 251.2 Ma [15]. The Induan deposits are overlain by a thick (~4500 m) layer of marine–coastal and continental terrigenous deposits, which were accumulated during the whole Triassic (up to the Norian Stage, inclusively, ~50 m.y.). If we accept that the folding and intrusion of the latest granitoid phases occurred almost synchronously, between 254 and 252 Ma, it turns out that the erosion of the rocks overlying the granite with a thickness of a few thousand meters and the appearance of rounded granite fragments in the overlying sediments most likely proceeded within 1 m.y. Thus, we may suggest that the relatively long (25 m.y.) period of the Middle–Upper Permian marine–coastal sedimentation accompanied by quite active volcanism of the variegated composition was very rapidly replaced by a long (~50 m.y.) period of stable marine–coastal sedimentation without any volcanism. The period of transition (1–2 m.y.) included a serious structural transformation: folding of the Permian deposits, intrusion of granite, orogenesis, and peneplenizatipon, which resulted in exposure of the granite on the Earth's surface. These data are in a good agreement with the data on the global catastrophe at the Permian–Triassic boundary, which resulted in the most intense in history extinction of biota [6].

BOUNDARY BETWEEN THE LOWER AND UPPER CRETACEOUS (SIKHOTE-ALIN OROGENIC BELT)

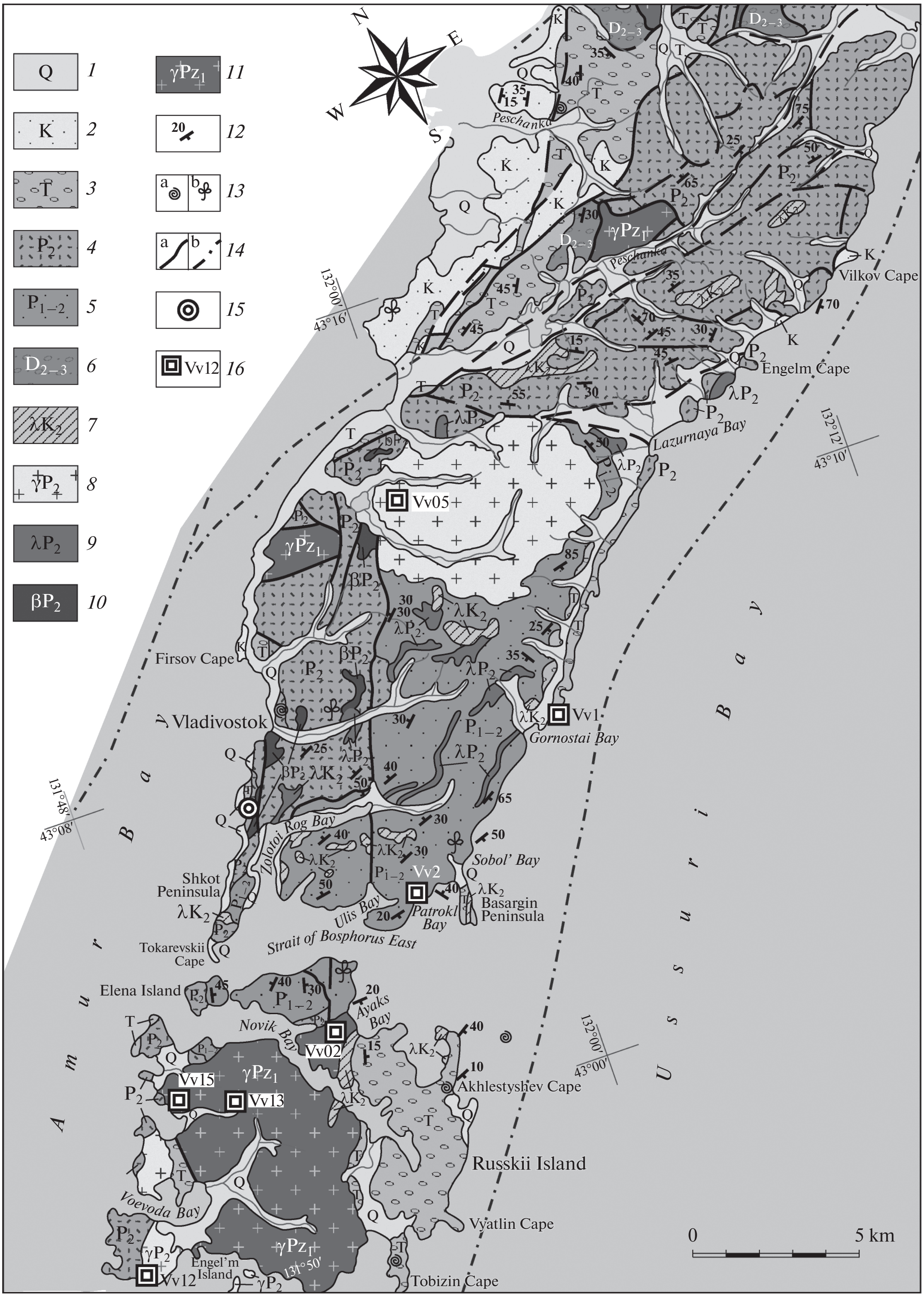
The Zhuravlevskii Terrane of the Sikhote-Alin is composed of terrigenous deposits with a total thickness of >12 000 km accumulated from the Berriasian to the Albian inclusively (~35 m.y.) under the conditions of the near-shift marginal basin along the transform plate boundaries [3, 4]. No intrabasin unconformities are registered to date; the Lower Cretaceous sequence was deformed in one structural plan. The formation of the basin and deformations of the terrigenous deposits accumulated during the whole Early Cretaceous (~40 m.y.), as well as the folding of the complexes of the Samarkinskii Terrane located to the west, which is the fragment of the Jurassic accretionary prism, occurred in the field of NW (mostly 330–350°) compression. As a result, the sediments were folded in the NE direction accompanied by the sys-

Table 1. Location of the points of sampling, rock types, and U–Pb age of accessory zircons in granitoids from the Vladivostok area, after [22]

Sample	Location of points of sampling	Rocks	Age, Ma
Vv02	43°02′08″ N 131°53′03″ E	Granite	422.2 ± 2.5
Vv05	43°12′08″ N 131°59′20″ E	Granite	260.7 ± 3.1
Vv12	42°58′55″ N 131°45′11″ E	Granite	249.7 ± 3.5
Vv13	43°01′59″ N 131°48′54″ E	Granodiorite	431.9 ± 2.7
Vv15	43°02′11″ N 131°47′45″ E	Porphyry granite	423.7 ± 3.2

tems of left shifts of the NNE orientation [4]. The completion time of these deformations can be roughly estimated by the age of the earliest granitoid intrusions consistent with folding. Within the Zhuravlevskii Terrane, these are the granitoids of the Tatibinskii Complex; the first dating of accessory zircons and monazites from them provided the ages of 100–108 Ma (Albian–Early Cenomanian) [17, 24]. In principle, this conclusion does not contradict the data that the youngest formations of Sikhote-Alin subjected to folding and left-side shifts were dated by fauna as Middle–Late Albian (Luzhkinskaya Formation) [4], whereas the intermediate and basic volcanic rocks overlying them with an angular unconformity and occurring almost horizontally (Petrozuevskaya and Sinanchinskaya formations) were dated by flora as Cenomanian [10]. These volcanic rocks start the formation of the supersubduction Eastern Sikhote-Alin volcanoplutonic belt [12]. The transition from sliding of the Izanagi oceanic plate along the Asian margin to subduction is explained by change of the direction of motion of this plate from NNW to WNW [3, 4].

Our studies in the south of Primor'e, in the zone of influence of the Shkotovskii Fault limiting the Sikhote-Alin orogenic belt from the west (Fig. 1), enabled us to specify the time for completion of this stage of dislocations. In this area, the continental terrigenous variegated deposits of the Korkinskaya Formation [4] (Figs. 6a and 6b) accumulated from the Late Albian to the Cenomanian [11] are folded into the system of complex folds of NE orientation (common for Sikhote-Alin). The Shokotovskii Fault has a steep dipping to the northwest (315@) there, and the slip hatching provides evidence for a left-side shift—overthrust char-


Q 1
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λK2 7
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20 12
a b 13
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15
Vv12 16
N
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S
W
Peschanka
Vilkov Cape
Engelm Cape
Lazurnaya Bay
132°00′
43°16′
132°12′
43°10′
Vv05
Firsov Cape
Vladivostok
Vv1
Gornostai Bay
131°48′
43°08′
Zolotoi Rog Bay
Sobol' Bay
Shkot Peninsula
Vv2
Basargin Peninsula
Patrokl Bay
Ulis Bay
Strait of Bosphorus East
Tokarevskii Cape
Elena Island
Novik Bay
Ayaks Bay
Vv02
Vv15
Vv13
Akhlestyshev Cape
132°00′
43°00′
Russkii Island
Voevoda Bay
Vyatlin Cape
Engel'm Island
131°50′
Vv12
Tobizin Cape
0
5 km
Amur Bay
Ussuri Bay

Fig. 2. Geological map of the Murav'ev–Amurskii Peninsula and Russkii Island compiled using the geological maps 1 : 50000, authors N.G. Mel'nikov et al. (1991). (*1*) Loose Quaternary deposits and marine area; (*2*) Lower Cretaceous epicontinental coal deposits (Nikanskaya Group) and Lower–Upper variegated deposits (Korkinskaya Group); (*3*) Triassic marine–coastal deposits; (*4*) Upper Permian sedimentary, volcanogenic–sedimentary, and volcanogenic deposits (Vladivostokskaya, Chandalazskaya, and Lyudyanzinskaya Formations); (*5*) Lower–Upper Permian marine–coastal and epicontinental deposits (Poselkovskaya Formation); (*6*) Middle–Upper Devonian epicontinental deposits (Lyutogorskaya Formation); (*7*) Late Cretaceous rhyolite; (*8*) Late Permian granite (Sedankinskii Complex); (*9*) Late Permian rhyolite; (*10*) Late Permian diabase and gabbro; (*11*) Early Paleozoic granitoids; (*12*) elements of rock occurrence; (*13*) points of collection of fauna (a) and flora (b) remains; (*14*) established (a) and assumed (b) faults; (*15*) points of sampling for the study of the U–Pb age of accessory and detrital zircons in Triassic basal conglomerate (see Fig. 4); (*16*) points of sampling for the study of the isotope age of zircons from granitoids (after [23]) and monazite from sandstone (after [25]) and sample nos.

acter of displacement, which suggests the submeridional (Early Cretaceous) direction of the regional compression (Fig. 6c). The volcanic rocks of the Sinanchinskaya Formation (Cenomanian [10]) and Primorskaya Group (Turonian–Campanian [10]) occurring almost horizontally are observed on the erosive surface of these folds in the same region. These volcanic rocks "seal" the zone of the large shift (Arsen'evskii Fault) over a considerable distance, which in itself indicates the termination of the active (left-shift) stage of its evolution by the beginning of the formation of the volcanic belt.

To the north of the Alchanskii Basin, the local troughs are filled with the terrigenous deposits of the Stolbovskaya Formation dated by the Late Cenomanian flora [1]. The typical sigmoid shape of these troughs and the presence of coarse-clastic facies along their margins suggest their near-shift origin in the environment of the submeridional regional compression [1, 4]. Thus, the active influence of such compression has been observed up to the Late Cenomanian inclusively.

Thus, we may conclude that very intense folding and shift deformations, intrusion of granitoids, their subsequent erosion, and the whole transition from the mode of transform sliding of the Izanagi oceanic plate to the subduction environment occurred in the Late Cenomanian. With account for the duration of the Cenomanian Stage (~6.6 m.y., between 100.5 and 93.9 Ma [14]), the duration of this period may be as short as a few millions years.

THE BOUNDARY BETWEEN THE LOWER AND MIDDLE MIOCENE (TSUSHIMA ISLAND)

Tsushima Island, in the southern part of the Japanese Sea, is composed of the Taishu Group represented by terrigenous, mostly clayey rocks with minor interlayers of rhyolite and rhyodacite tuff (Fig. 7). The total thickness of the section of this group is ~5400 m and its age has long been defined as Eocene–Oligocene–Miocene by fossil remains, mainly foraminifera and radiolaria [19, 22]. However, the results of zirconology recently performed for the tuff horizons near the base and at the top of the group show that the accumulation of the Taishu Group occurred during 2 m.y. between the ages of 17.9 ± 0.1 and 15.9 ± 0.2 Ma (the boundary between the Lower and Middle Miocene) [20]. Thus, we can assume a rate of sedimentation close to the maximal one (not less than 2700 m/m. y.), without account for sediment compaction upon diagenesis. A similar rate of avalanche sedimentation (up to 3600 m/m.y.) was registered in only one other place on Earth, namely in the Californian near-shift troughs [13]. The above-mentioned Eocene and Oligocene microfauna is most likely redeposited.

The Taishu Group is dislocated with the formation of a system of linear folds of the NE orientation and

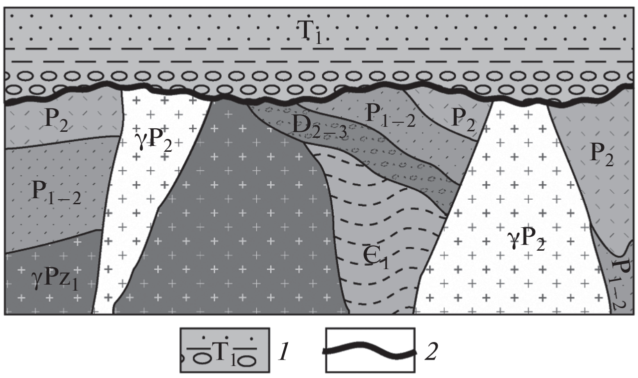

Fig. 3. Structural relationships between the Paleozoic and Lower Triassic complexes in the southern part of the Voznesenskii Terrane. See the text for explanations. The scales are not followed. (*1*) Basal conglomerate overlain by aleurolite–sandstone deposits (Induan Stage, Lower Triassic); (*2*) angular unconformity. See Fig. 2 for the legend for the pre-Triassic formations.

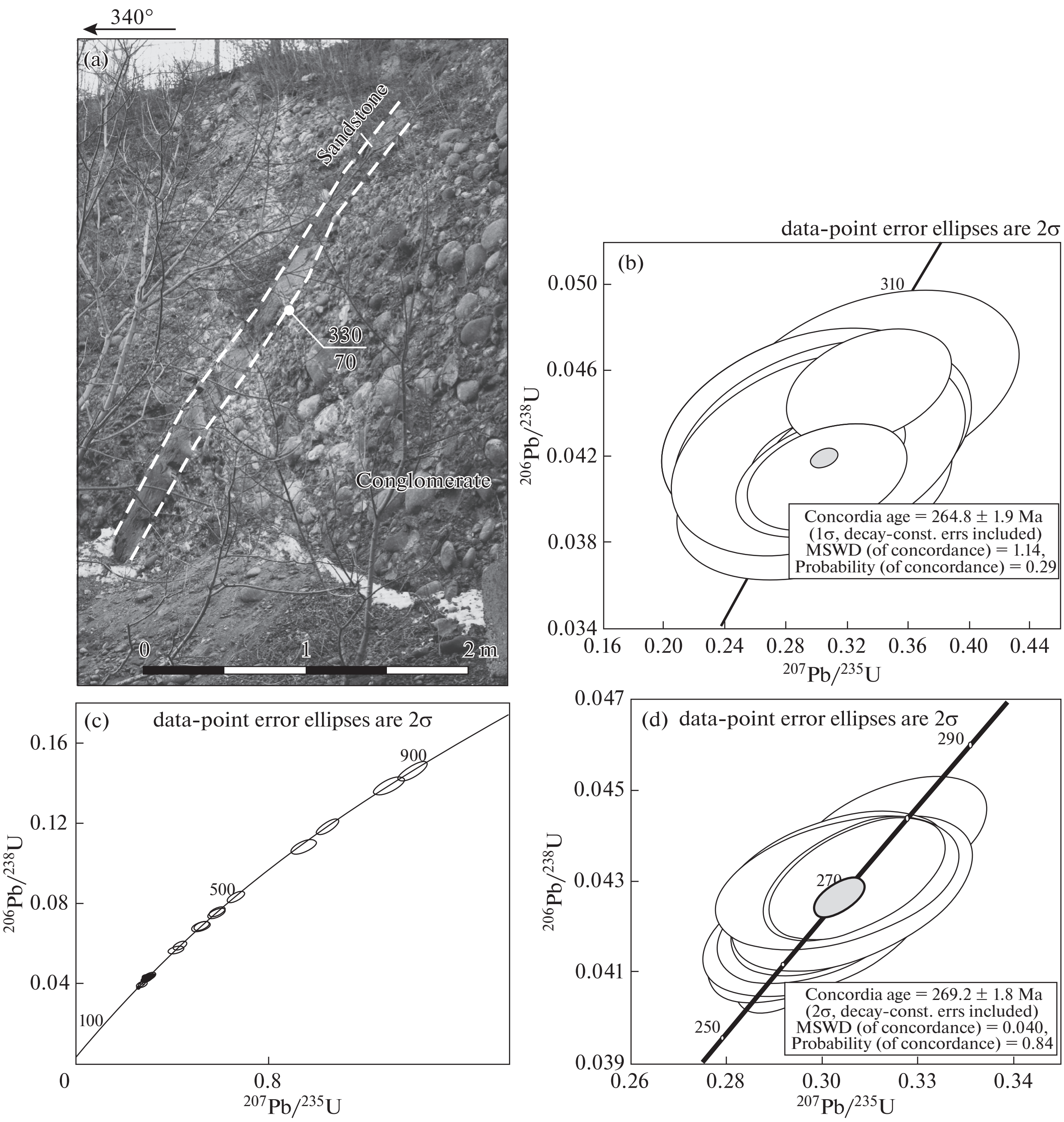

Fig. 4. Results of the U–Pb isotope studies of accessory and detrital zircons from basal conglomerate of the Induan Stage, Triassic, in the outcrop near Sportivnaya Bay (Vladivostok, see location in Fig. 2). (a) General view of the outcrop. Conglomerate with an interlayer of coarse-granular sandstone. Numerals indicate the elements of occurrence of the layering: azimuth in the numerator, dip angle in the denominator; (b) diagram with concordia for accessory zircons of granite from boulder; (c, d) diagrams with concordia for detrital zircons from the interlayer of coarse-granular sandstone in conglomerate: (c) summarized diagram, (d) its fragment for 17 grains of the Permian age. See explanations in the text. U–Pb isotope ages of accessory and detrital zircons were studied at the Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, and at the Far East Geological Institute, Far East Branch, Russian Academy of Sciences. Zircon grains were mounted into an epoxy, then cleaned in a warm ultrasonic bath: first, for removal of probable fatty pollution in a 2% solution "Citranox" (Alconox, Inc, United States); then, for removal of probable lead pollution in a 2% HNO_3 solution. This operation allows us to avoid "pre-ablation" of the studied sample. The U–Pb isotope studies were carried out using an instrumental complex including a NWR-213 ultraviolet laser (Electro Scientific Industries Inc., United States) and an Agilent 7500a mass spectrometer with inductively coupled plasma (Agilent Technologies, United States). The beam diameter was 20 μm; the ablation time was 100 s; the crater depth reached 30–40 μm. In general, the methodology of analytical studies was close to that described in [16]. The technical details of the methodology of measurement of isotope ratios are described in [2, 9]. A mass spectrum was scanned by the centers of the following weights: 206, 207, 208, 232, and 238. Since the Hg backgrounds in the mass spectrum were constantly high, the weight 204 was not measured. The U–Pb age was calculated using the software complex GLITTER [www.mq.edu.au/GEMOC]. The stability of operation of the apparatus and reproducibility were carried out by analysis of the standard zircon Temora 2 (each eighth measurement). The software Isoplot/Ex v. 3.00 [18] was applied for plotting of the diagrams with concordia and error ellipses.

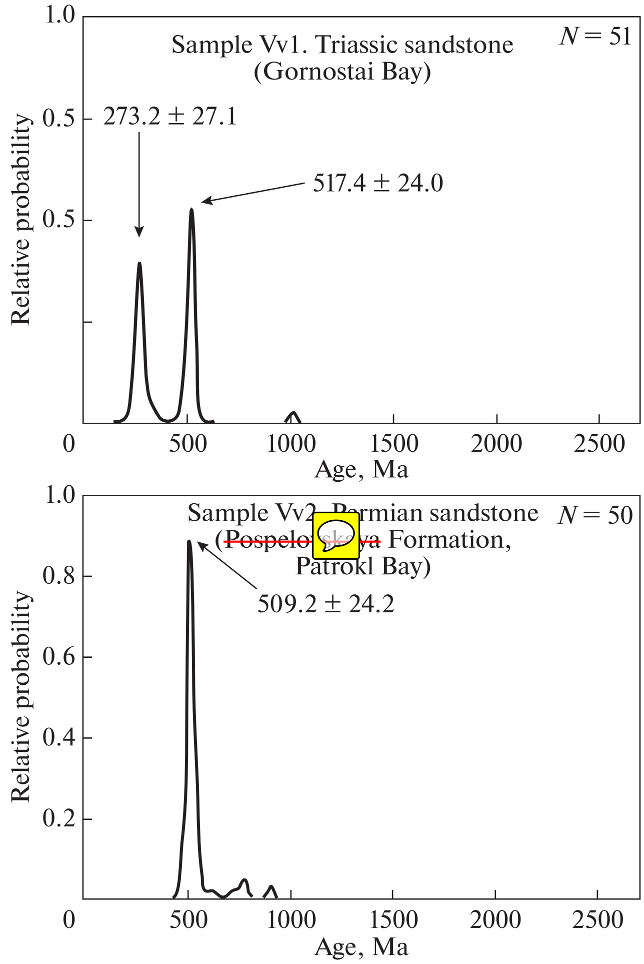

Fig. 5. Diagrams of the distribution of relative age probability for detrital monazites from sandstone of the basal layers of the Triassic and Lower–Upper Permian Pospelovskaya Formation, after [25]. Murav'ev–Amurskii Peninsula, Vladivostok. The location of sampling points is shown in Fig. 2.

intruded by the granite massif in the south of the island. The K–Ar dating of amphibole and biotite monofractions from this granite provided an age range of 13.3–17 Ma with slightly variable average ages of individually taken amphiboles (15.9 Ma, average from eight samples) and biotite (15.4 Ma, average from ten samples) [14]. A similar K–Ar age (15.4 ± 0.8 Ma) was obtained for the muscovite from the calcite–quartz–muscovite–chlorite vein at the exocontact of this granite [14]. According to these data, folding and intrusion of granite occurred almost instantly for less than 1 m.y. It is noteworthy that the major phase in the opening of the Sea of Japan corresponds to this "moment" (~15 Ma) as well [5, 21].

CONCLUSIONS

The data considered above allow us to suggest that the duration of the processes in the epoch of tectonic reconstructions (including folding, intrusion, orogenesis, and erosion) did not exceed a few millions years. Some of these processes, such as intrusion and cooling of intrusive bodies (including giant granite batholiths) and the formation of post-magmatic ore-bearing systems proceeded almost instantly in the geological sense (during <1 m.y.), rather than during tens of millions of years, as is sometimes believed [3].

The considered examples show that very short (1–2 m.y.) periods of transitions from one geodynamic setting to another are regular rather than exceptional. It is noteworthy that this tendency is the most evident for the youngest Cenozoic events. With transition to the older periods (Mesozoic and Late Paleozoic), the duration of such transitions is often lower than the resolution of the local methods of isotope dating, as well as paleontological studies, even for the most studied objects.

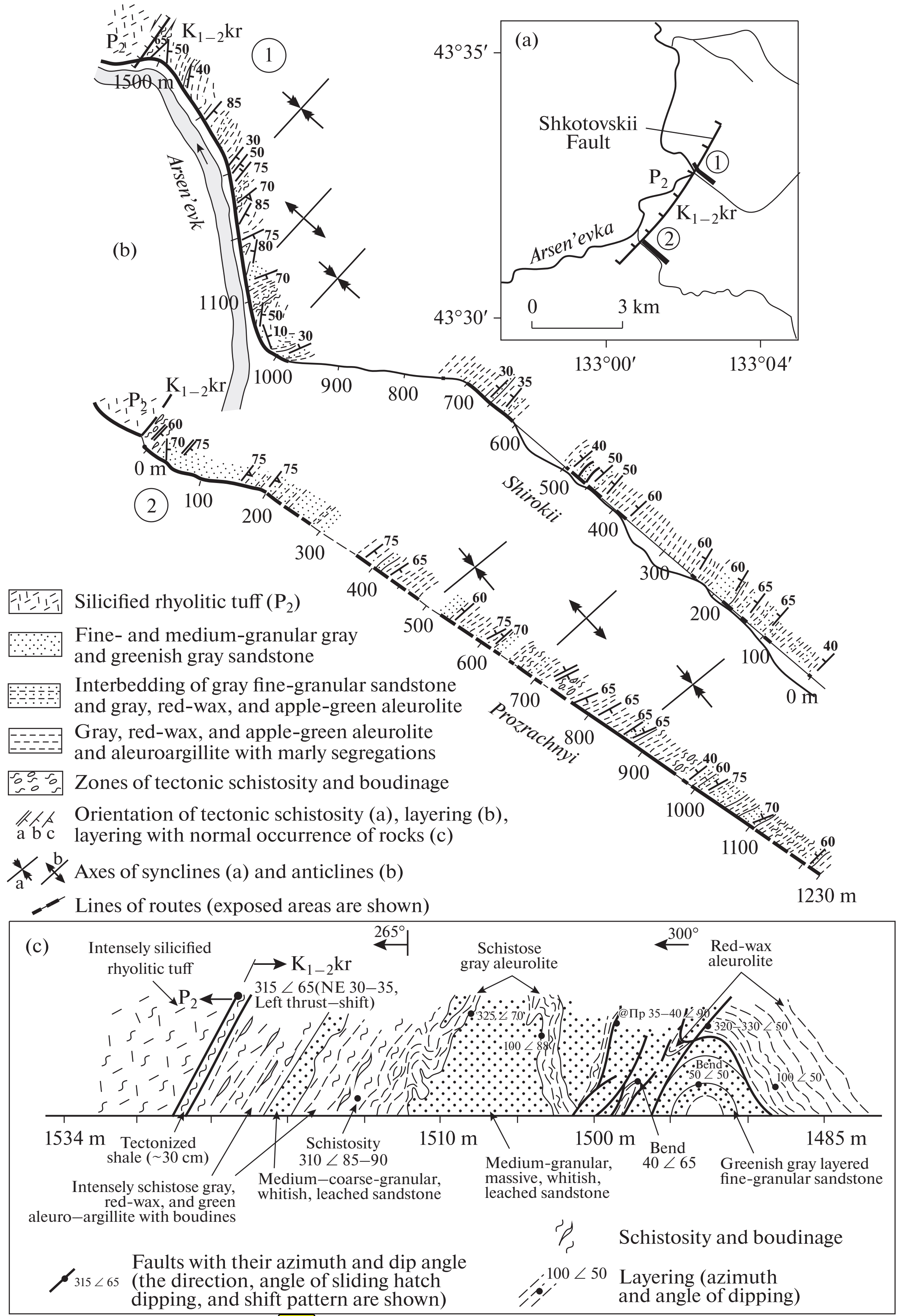

Fig. 6. Dislocations of rocks from the ~~Korkinskaya~~ Group in the upper reaches of the Arsen'evka River, after [4]. See the location in Fig. 1. (a) Scheme of the section; (b) geological plan of the basins of the Shirokii and Prozrachnyi creeks; (c) character of dislocations of rocks from the ~~Korkinskaya~~ Group in the zone of the Shkotovskii Fault. See explanations in the text.

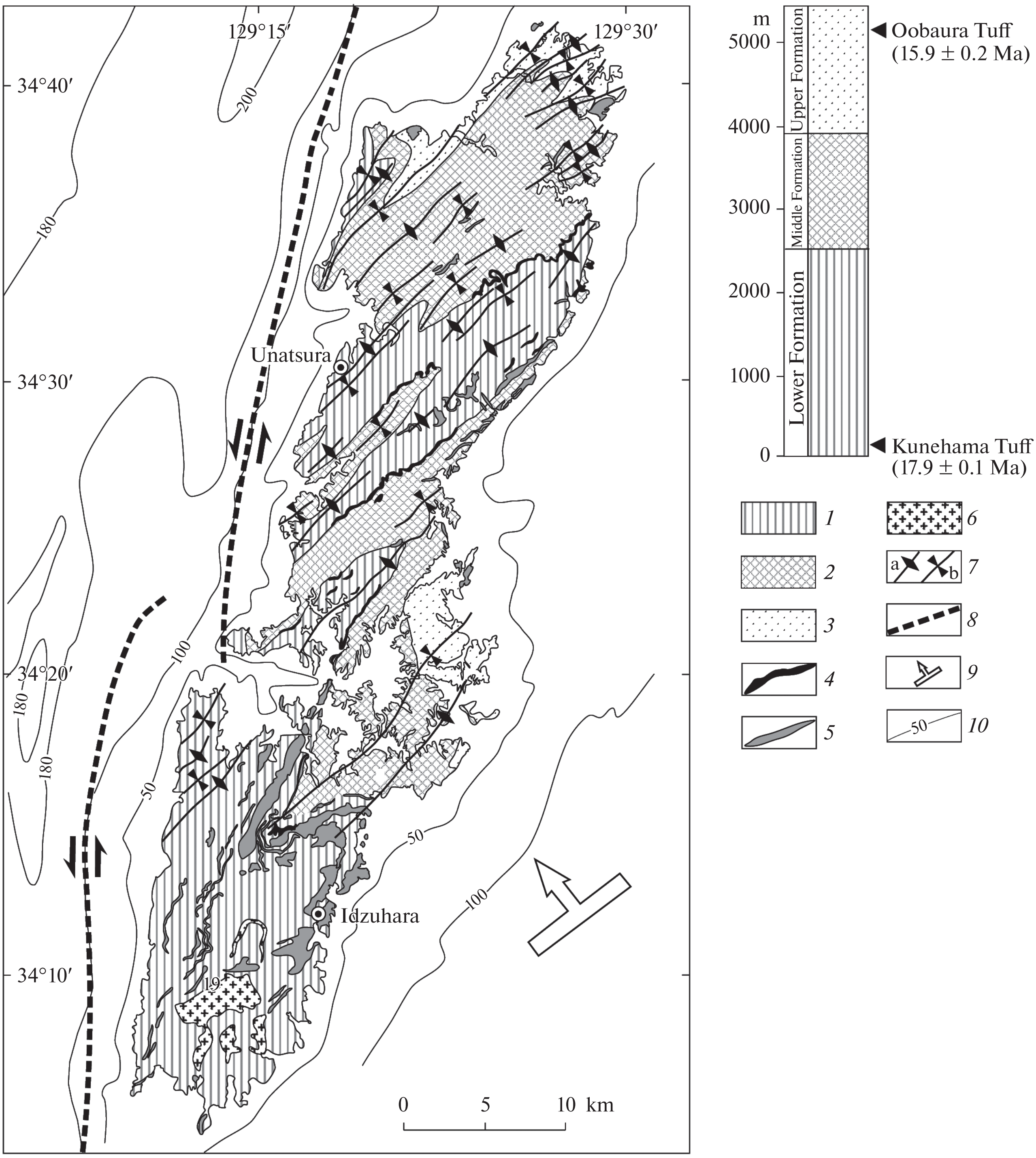

Fig. 7. Geological map of Tsushima Island, modified after [5]. (*1–3*) Lower–Middle Miocene deposits (Taishu Group): lower (*1*), middle (*2*), and upper (*3*) formations; (*4*, *5*) dykes and sills of the basic (*4*), intermediate, and acid (*5*) rocks; (*6*) Middle Miocene (15 Ma) granite intrusions; (*7*) axes of anticlines (a) and synclines (b); (*8*) assumed faults. Arrows show assumed directions of block migration; (*9*) direction of the regional compression; (*10*) isodepths of the seafloor (m).

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