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Miocene Dislocations during the Formation of the Sea of Japan Basin: Case Study of Tsushima Island

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Abstract—Lower Miocene rocks of the Taishu Group accumulated in the Tsushima pull-apart graben, which downwarped and was filled with sediments at a particularly high rate (about 2700 m/Ma), in the background of northeastern regional shortening. A considerable part of the sedimentary prism is composed of material supplied by landslide blocks from the shallow shelf. Folding and penetration of granite intrusions on Tsushima Island occurred ca. 15 Ma ago, simultaneously with the main phase of opening of the Sea of Japan, in the field of different, northwestern shortening, which had a local character and was related to clockwise rotation of the Southwestern Japan block. These rotations in turn could have been the result of an intensive rifting episode in the Central and Honshu basins of the Sea of Japan, which are located north of Tsushima Island.

Keywords: Miocene, sedimentation, dislocations, geodynamic reconstructions, Sea of Japan, Tsushima Island

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INTRODUCTION

Tsushima Island is located in the near-axial part of the strait of the same name, at the western terminus of the Sea of Japan; it is elongated in the NNE direction, about 75 km long and 10–18 km wide (Figs. 1, 2). In a structural sense, the island is an exposed fragment of the Tsushima deep basin (graben) of Cenozoic age, which is located in the southwestern Sea of Japan and characterized by the presence of oceanic crust, in contrast to the continental blocks surrounding the basin [1]. At the latitude of the Tsushima Island, the width of the mentioned graben is about 80 km, up to 250 km in the north. The western side of the Tsushima graben is formed by the Ryongnam massif of Archean age, which is exposed at the southeastern terminus of the Korean Peninsula and its adjacent shelf and overlapped by Lower Cretaceous terrigenous deposits of the Kensan basin and Upper Cretaceous volcanic rocks [4]. The eastern side of the graben, partially exposed in the southwestern part of the Honshu Island and on Kyushu Island, is formed by terranes represented by fragments of Upper Paleozoic (?) and Mesozoic accretionary complexes overlain by Cenozoic continental coal-bearing deposits and volcanic rocks [7].

Tsushima Island is composed by Lower Miocene marine terrigenous deposits, and to a much smaller degree, by volcanogenic ones (felsic tuffs), up to 5400 m in total thickness, combined into the Taishu Group [9]. Despite the relatively young age, these deposits are characterized by a quite high degree of lithification and in this sense they do not differ much in appearance from, e.g., Early Cretaceous rocks in the Sikhote Alin region. The rocks form northeast-oriented folds and contain sills and dikes of hypabyssal igneous (felsic and, more rarely, intermediate and mafic) rocks. In the southern part of the island, sedimetary deposits are pierced by granite intrusions with a large hornfels rim; the age of intrusions is ca. 15 Ma [22]. Judging from the geophysical data, the folds of the island continue in the adjacent shelf to form an anticlinorium-like structure, whose axis gently dips north-northeast and south-southwest [7, 11] (Fig. 1). It was found that folded Lower–Middle Miocene deposits of the Taishu Group in the east-southeastern part of this anticlinorium are overlapped with erosion and an angular unconformity by the weakly disturbed cover of Late Miocene–Quaternary mostly terrigenous deposits up to 1000 m thick. The western terminus of the anticinorium is the Tsushima Fault Zone, beyond which there are Late-Miocene–Quaternary deposits of considerable thickness, exposed in the sunken block. The basin where the Taishu Group rocks accumulated could have occupied the entire Tsushima Basin, and the

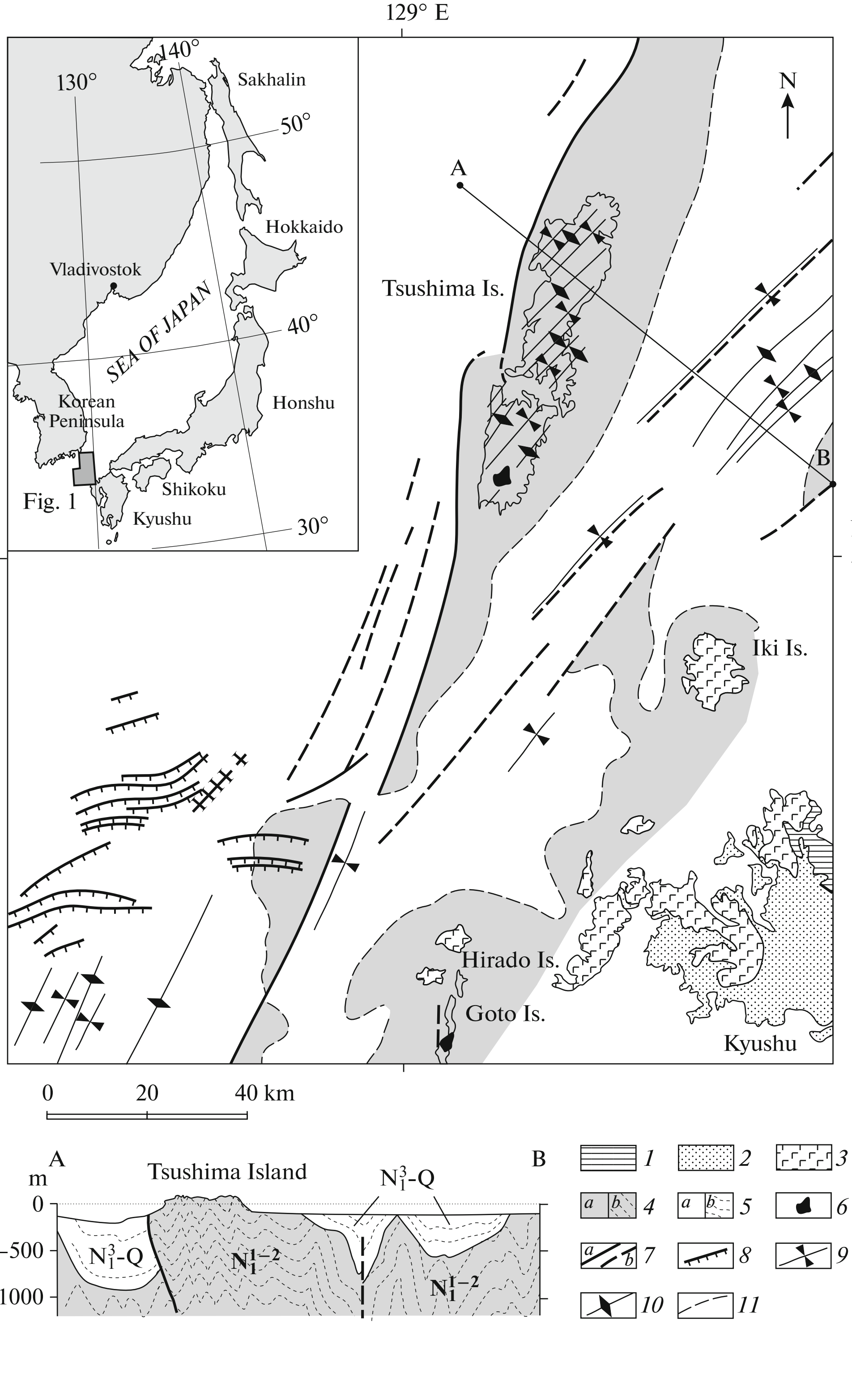

Fig. 1. Structural scheme on Tsushima Island and its surroundings, adapted after [7]. (*1*) Pre-Cenozoic basement; (*2*) Cenozoic continental deposits; (*3*) Middle Miocene–Quaternary volcanic rocks; (*4*) Lower–Middle Miocene marine deposits: (*a*) plan view, (*b*) cross section; (*5*) Middle Miocene–Quaternary marine deposits: (*a*) plan view, (*b*) cross section; (*6*) Middle Miocene (15 Ma B.P.) granite intrusions; (*7*), (*8*) faults: (*7*) established (*a*) and assumed (*b*) strike-slips, (*8*) normal faults; (*9*), (*10*) axes of syncline (*9*) and anticline (*10*) folds; (*11*) assumed boundaries of outcropping Lower–Middle Miocene deposits within water area. Inset: location of study area.

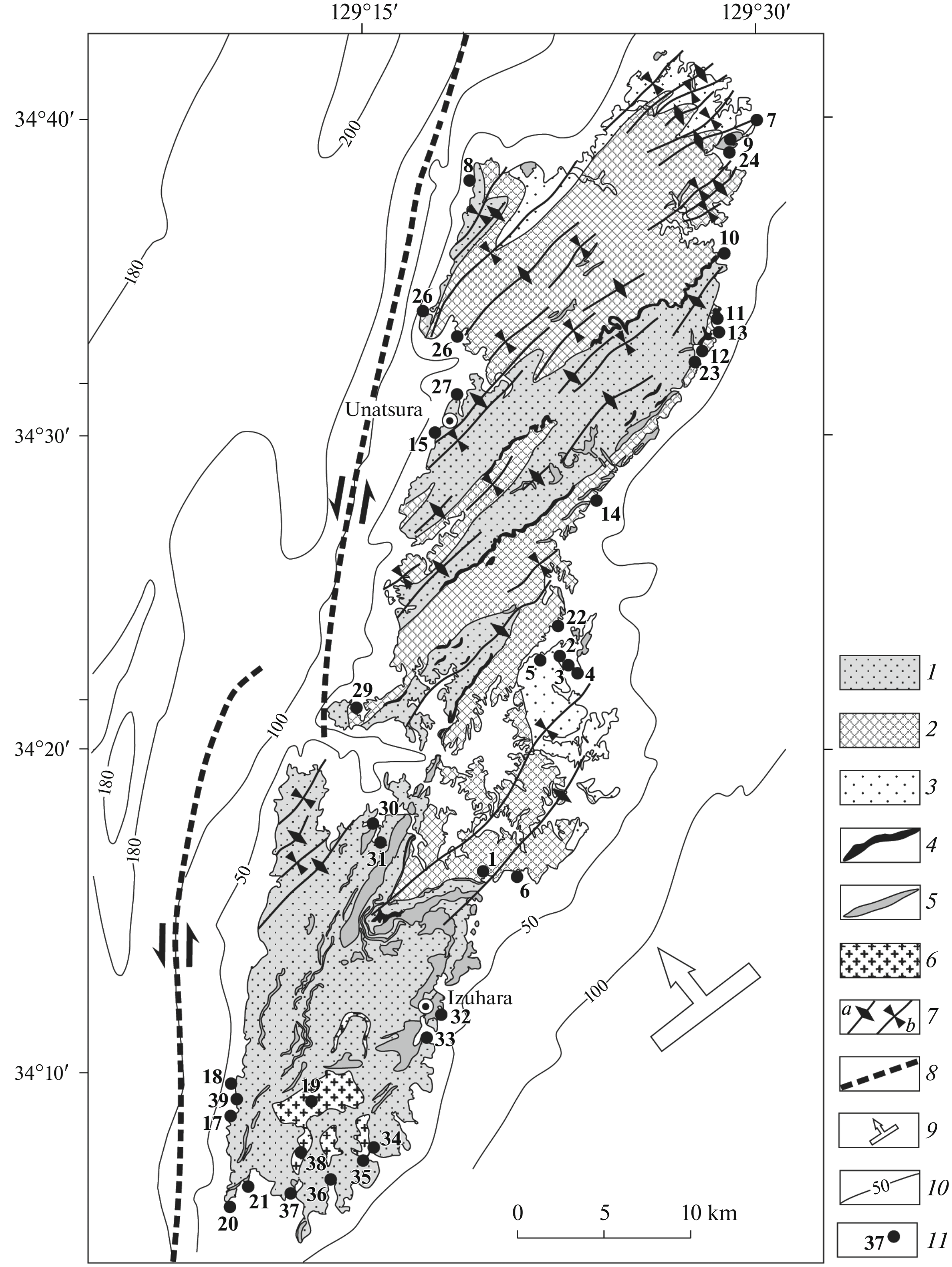

Fig. 2. Geological map of Tsushima Island, after [9] with additions. (*1*)–(*3*) Lower–Middle Miocene deposits (Taishu Group), formations: (*1*) lower, (*2*) middle, (*3*) upper; (*4*), (*5*) dikes and sills of mafic rocks: (*4*) intermediate, (*5*) felsic; (*6*) Middle Miocene (15 Ma in age) granite intrusions; (*7*) axes of anticlines (*a*) and synclines (*b*); (*8*) assumed faults (arrows denote directions of block motions); (*9*) direction of regional shortening; (*10*) isolines of seafloor depth, m; (*11*) observation points and numbers.

exposed part probably corresponds to one of its depocenters.

Tsushima Island is a unique place in a certain sense: in local outcrops, one can directly observe peculiarities of Cenozoic sedimentation and subsequent deformations of rock sequences that accumulated within the limits of deep basins filled with sediments. Logically, studies of these outcrops may shed light on how the general present-day structure of the Sea of Japan formed.

Field structural observations that became the basis of the present article were carried out in 2012–2013 under the project “Research on Earth’s Surface Processes and Biota in and near the Sea of Japan,” supported by the Government of Japan and supervised by Prof. K. Yokoyama, head of the Department of Geology and Paleontology, National Museum of Nature and Science. By the onset of our work, the available materials included a geological map of central Tsushima Island, scale 1 : 50000 [8]; a geological map of the entire island, scale 1 : 200000 [9]; and the geological excursion guide for participants of the 17th International Sedimentological Congress held in Fukuoka, Japan, in 2006 [16]. Tsushima Island is characterized by an extremely cut relief with medium-altitude mountains and crossed by automobile roads; however, it is nearly impossible to conduct geological observations along these roads because the nearby cliffs are completely covered with concrete. The studied sites (Fig. 2) are chiefly located along the well-exposed and highly cut shoreline of the island.

STRATIGRAPHY AND FACIES

The Taishu Group is quite conditionally subdivided into the lower (regressive, up to 3000 m thick), middle (transgressive, about 1400 m thick), and upper (regressive, up to 1000 m thick) formations [16, 18] (Fig. 2).

Over 70% of the Taishu Group section is represented by clay rocks (mudstones, silt-rich mudstones, and massive and fine siltstones) composing both independent members up to a few hundred meters thick and turbidite members (rhythmically interleaved sandstones, siltstones, and mudstones with interbeds of small- and fine-grained sandstones up to 20 cm thick, usually making up less than 10% of the total thickness). These clay and turbidite members accumulated under relatively deep marine conditions at the base of the continental slope. This is indicated in particular by the data on rare shelly interbeds found in these members, composed of bivalves whose skeletons are made of carbonates from cold methane seeps at depths greater than 500 m [17].

On this background, sandstone horizons and members of interleaving sandstones and siltstones (the former dominate) have been identified; these horizons demonstrate gradual transitions from fine to coarse grain in size. Notably, the mentioned transitions are observed in directions to both layer tops (regressive cycles) and bases (transgressive cycles). In the latter case, signs of erosion of underlying rocks and pockets of erosion have been reported at the bases of rhythmic deposits. The thickness of these horizons and members, which are more characteristic of the upper (regressive) formation, is from several to 30–40 m, even up to a few hundred meters in particular cases. The mentioned horizons and members sometimes contain lenticular gravelite and conglomerate interbeds up to several centimeters thick. Sandstones are feldspar-quartz in composition; in addition, they contain muscovite grains and admixtured grains of chlorite and clay shales, as well as silicious grains [16]. They are characteristic of wave ripple structures and often demonstrate clear cross-bedding and submarine landslide microfolds. Detailed investigation of these structures and orgainc remains from sandstones (among them, brackish water mollusks of Corbicula genus were found) has shown that sedimentation took place in deltaic and shallow offshore environments, under the considerable action of tidal processes [15, 16]. In addition, paleocurrents were oriented north to south along the slope of the paleobasin with NNW and NNE deviations [15]. In some cases, overlaps of sandstone bodies to predominantly clay “background” sediments were observed and interpreted as filling of erosion channels in earlier deposits with sandstones [16].

Thus, the section of the Taishu Group demonstrates a combination of deposits that accumulated in very contrasting environments: at the bottom of a deep basin and in the relatively deep bases of submarine slopes, on the one hand, and in river deltas under the considerable action of tidal processes, on the other. In this respect, it seems crucial to reconstruct the sedimentation mechanism that there be manifold evidence that the above-mentioned bodies, represented by sandstones and interleaving sandstones–siltstones (with the sandstone component being predominant), often form consedimentation landslide slabs [16, 18] with thick (several to tens of meters) dislocation zones at the bases. Manifestations of gravitational tectonics will be described below in more detail, so for now it should be noted that landslide bodies likely moved from the shelf and continental slope to fill the paleotrough along with autochthonous bottom sediments with a predominantly silt composition. The roles played by autochthonous and allochthonous materials in the section are impossible at present due to the homogeneous character of rocks. Nevertheless, it can be said that the normal stratigraphic squence is disturbed here and that aggregations of landslide bodies may reveal multiple doubling or sedimentation hiatuses.

Felsic tuff horizons are most characteristic of the middle formation base, where they are greatest in thickness (up to 50 m). At approximately the same level, terrigenous rocks contain multiple sills or, rarely, dikes of subvolcanic rocks (porphyry quartzes, plagioporphyries, and, rarely, dolerites); their thickness varies from a few to tens of meters. Horizons of analogous tuffs have been also reported at different levels of the lower formation, but they are much thinner here (up to several meters). In the upper formation, singular horizons alike have been found [18]. Zircon-based dating of a tuff interbed at the base of the Taishu

Group's visible section yielded an age of 17.9 Ma, whereas an analogous interbed at its top yielded 15.9 Ma [18]. The upper age boundary of the Taishu Group is confined by the time of granite penetration in southern Tsushima Island ca. 15 Ma B.P. [22]. Eocene and Oligocene foraminifera [21] and radiolaria [14] fossils revealed earlier had probably been redeposited [18]. Thus, we can think of a sedimentation rate close to the maximum known one: it was at least 2700 m/Ma, without diagenetic compaction of sediments being taken into account. Approximately the same rate of avalanche sedimentation (up to 3600 m/Ma) has been documented only in the pull-apart grabens of California [6].

Manifestations of Consedimentation Gravitational Tectonics

Consedimentation tectonic rocks can be found along the entire cross section of the Taishu Group; however, they are most characteristic of the upper formation; they are described as units produced by submarine landslides, boulder-hosting silt horizons, disturbed layers, etc. [15, 16, 18].

Consedimentation Landslide Bodies

Consedimentation landslide bodies can be observed in the upper formation of the Taishu Group, at its outcrop in the northeastern termination of Tsushima Island (Fig. 3). In the overall gentle southeastern dip (20°–30°), the sequence here is formed by three relatively weakly disturbed bodies, predominantly composed of sandstones 5–15 m thick; these bodies are divided by two horizons of almost the same thickness but composed of intensively schistose silt-rich mudstones with lenticular boudins of fine-grained sandstones of up to 1 m thick. The bedding in sandstone slabs is nearly parallel to the schistose zone in silt-rich mudstones, and a small azimuthal unconformity is observed only at the top of the lowest slab (Fig. 3b). This points to a prefolding, most likely consedimentation origin of these tectonites. Along with the tectonic boudinage structures, silt-rich mudstone horizons sometimes contain traces of layered slipping in the form of rotated layers with nearly horizontal rotation axes (Fig. 3c).

We also observed a series of landslide slabs consisting predominantly of sandstones and having approximately the same size in the northwestern coast of the island (Fig. 4). Here, schistozsity zones at the bases of slabs are sometimes accompanied by microfolds with complex moprphology. The base of the lowest visible slab has tectonic erosion (hewing off) signatures that seemed likely when the slab moved down the slope.

Slightly south of here, in outcrops on the eastern shore of the island, we observed a dacite tuff member of about 50 m thick (Fig. 5, point 10). This member marks the base of the middle formation and is formed by light gray rocks with well expressed bedding indicating the change of fine beds of different grain size, from lapillic to psammitic and silty tuffs. At the member top where layers dip relatively gently (20°–30°) in northwestern direction (310°–320°), a conform transition from tuffs to predominatly siltstone turbidites is seen (Fig. 5c). An olistostrome member 5–8 m thick is exposed below the base of this member: it is formed of blocks of different size, rock debris, and finer (down to sand grain size) olistolith inclusions in a siltstone matrix (Fig. 5b). Olistoliths are composed predominantly of siltstones; however, sandstones and felsic tuffs also appear. The olistostrome member is conformably underlain by a sequence of background, regularly bedded, silt-rich mudstones and predominantly silty turbidites.

In another limb of the anticline, approximately 5 km south of here, the same tuff member dips in a different, southeastern direction (125°–130°), but gently (15°–20°). Underlying siltstones here also contain olistoliths of felsic tuffs (Fig. 2, point 13).

The olistostrome member described above is an indicator of consedimentation landslide processes and probably marks the sliding zone at the base of the tuff slab that moved down the paleoslope with the sediments occurring above. This process was accompanied by destruction of the frontal part of slab, which thus provided that tuff fragments to appear in the sediments occurring below. Discovery of the olistostrome member in both limbs of the anticline indicates that the slab moved down the paleoslope at least a few tens of square kilometers in area and the extent of its movement could have been considerable.

Landslide Folds

Landslide folds are observed sporadically over the entire cross section of the Taishu Group. They usually do not appear beyond the limits of interbeds of mostly bedded sandstones. There are examples of inclined and recumbent landslide folds from 0.5 (Fig. 6a) to a few meters wide (Fig. 6b). Judging by the vergence of microfolds, sliding during accumulation of the lower formation was directed SE-NW (Fig. 6a), whereas accumulation of the upper formation was accompanied by SE-directed material transport from the northwestern side of the paleotrough (Fig. 6b).

Larger landslide folds involving turbidite members (interleaving sandstones, siltstones, and mudstones) up to several tens of meters thick can be exemplified by the structures observed on the western shore of the island, near the settlement of Unatsura (Fig. 7a, point 15). In the background northeastern (50°–60°) direction, dipping angles at this site rapidly change from gentle (10°–30°) to vertical, and the normal bedding here is combined with a overturned one. It could be initially thought that the layers were deformed under a setting of intensive lateral shortening. However, one of the objects clearly demonstrates that the

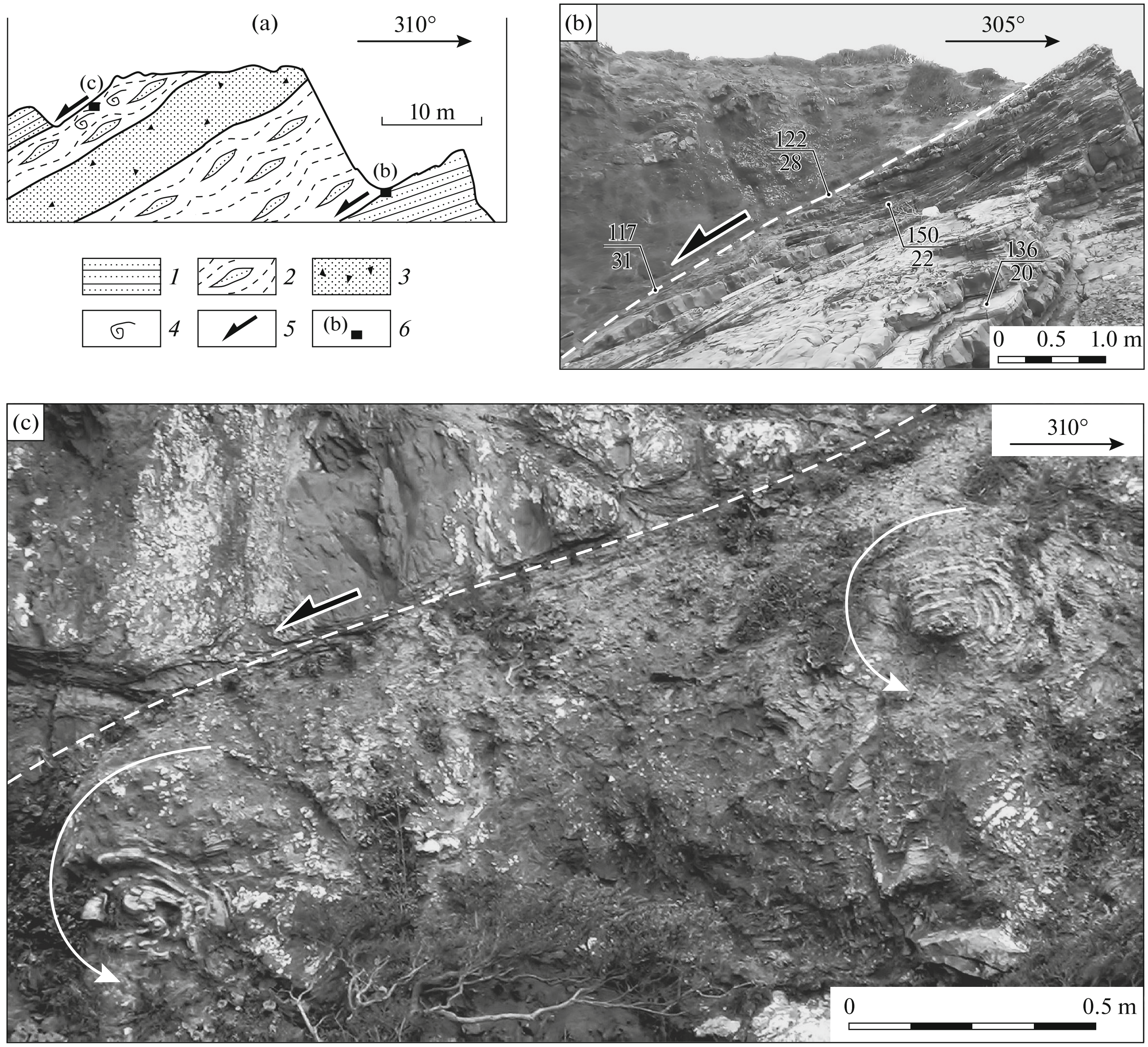

Fig. 3. Series of landslide slabs in cross section of upper formation of Taishu Group. Cape at northeastern terminus of Tsushima Island is observation point 7 (see Fig. 2). (a) Cross section: (*1*) fine- and medium-grained laminated sandstones; (*2*) schistose siltstones and silt-rich mudstones with lenticular interbeds (boudins) of fine-grained sandstones; (*3*) uneven-grained (fine- to coarse-grained) sandstones with angular inclusions of siltstones; (*4*) rolled drag folds; (*5*) direction of slab motion; (*6*) shooting viewpoints for objects shown in panels (b) and (c). (b) Boundary between slab composed of laminated sandstones and overlapping slab composed of schistose siltstones with sandstone boudins (boundary proper shown by white dashed line). Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of bedding (layers and contact zones). (c) Rolled drag folds in schistose siltstones.

core of the large overturned anticline does not penetrate the underlying sandstones that form a steeply dipping moncline (Figs. 7b, 7c). In the transition zone from the fold core to the underlying resistant sandstone, we have not identified any mechanical sliding signatures in the form of shattering zones, tectonic mud, or event slickenside surfaces with corresponding marks. All these features indicate that the mentioned structures formed at the initial stage of diagenesis of sediments, most probably resulting from large submarine landslides. Interestingly, judging by vergence of the anticline core, the supposed landslide moved in the NW-SE direction (Fig. 7c); i.e., the present-day steep NW-directed dip of its base is seemingly a secondary feature related to subsequent folding.

POSTSEDIMENTATION DISLOCATIONS

Deformations that shaped the present-day folded structure of the island lasted for less than a million

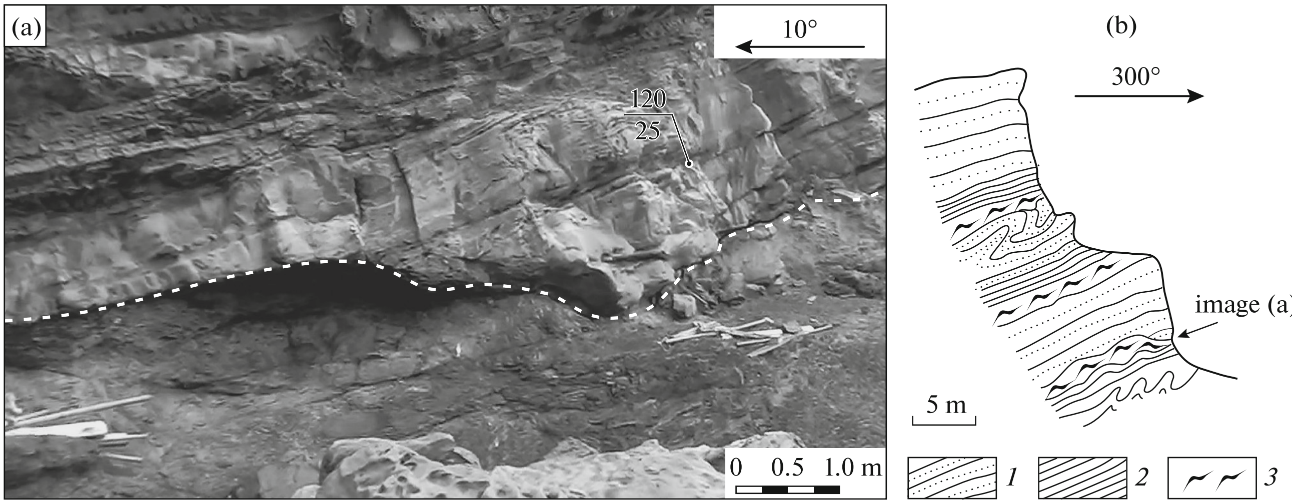

Fig. 4. Morphology of base of landslide body (a) and its position in cross section (b). Lower formation of Taishu Group, northwestern shore of Tsushima Island, observation point 8 (see Fig. 2); (a) base of lower visible landslide slab (shown by white dashed line), (b) cross section of coastal cliff. (*1*) fine- and medium-grained laminated sandstones; (*2*) schistose siltstones and silt-rich mudstones; (*3*) schistosity zones. Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of bedding.

years. This conclusion is based on zircon dates from tuffs of the upper Taishu Group (15.9 Ma [18]) and granites that pierced the already formed folds (15.0 Ma [22]). In addition to folds, the association of structural features includes fold-related faults and crack systems (tension cracks) usually filled with quartz, rarely with calcite, or even more rarely with subvolcanic and sandstone dikes.

Folded Structures

Terrigenous or, to a much smaller degree, volcanic rocks are folded to form NE-directed (40°–50°) folds (Fig. 2). A transition to domination of NNE- to meridionally directed folds can be identified only at the southwestern termination of the island. The folds are up to 15–20 km wide; their near-axial parts and limbs have superimposed folds of higher order and a few kilometers wide. Dipping angles at limbs of folds are 20°–60°, rarely more (Fig. 8). Fold hinges are nearly horizontal, with weak NE-directed dipping.

The mentioned mean direction of fold axes implies NW-directed (about 320°) shortening that in turn determines the considerable left-lateral shear component of motion along the NNE-trending Tsushima Fault Zone.

The belt of bedding orientation with the axis rotated by 30° counterclockwise compared to the main axis is less clearly distinguished in the diagram (Fig. 8); it suggests WNW-directed (about 290°) shortening. The presence of this belt indicates either variations in the direction of shortening during folding or that some sites were affected by the NNE-trending fault zone of left-lateral strike-slips.

Faults

Faults overlapping folds have, according to the geological maps [8, 9], a insignificant distribution. The cited maps contain only several meridional and NNE-trending faults in the southwestern and northwestern parts of the island. These faults are up to 5 km long, and any displacements along them are not reflected in the maps; they are generally subparallel to the Tsushima Fault Zone and likely also contain a left-lateral shear component of motion.

It should be noted that Japanese researchers obviously underestimated the role played by these faults on the island: although our field works are not comprehensive, we have repeatedly observed manifestations of shear tectonics. Most often these were steeply dipping zones of schistozed rocks, along which we identified microfolds with steeply dipping hinges. The mentioned schistosity zones have north-northeastern and northeastern directions close to those of undisturbed layers. For example, 350 m north of here (Fig. 2, point 10), a band of gently NW-dipping predominantly siltstone turbidites (dipping azimuth 320°, dipping angle 12°) is cut with a subvertical zone of intensive schistosity 5–15 m thick directed northeastwards (40°–50°) and containing fragments of microfolds with steeply dipping hinges. Within the same zone, we also observed buried fragments with subvertical rotation axes. Sometimes we observed microfolds with steeply dipping hinges showing no visible rela-

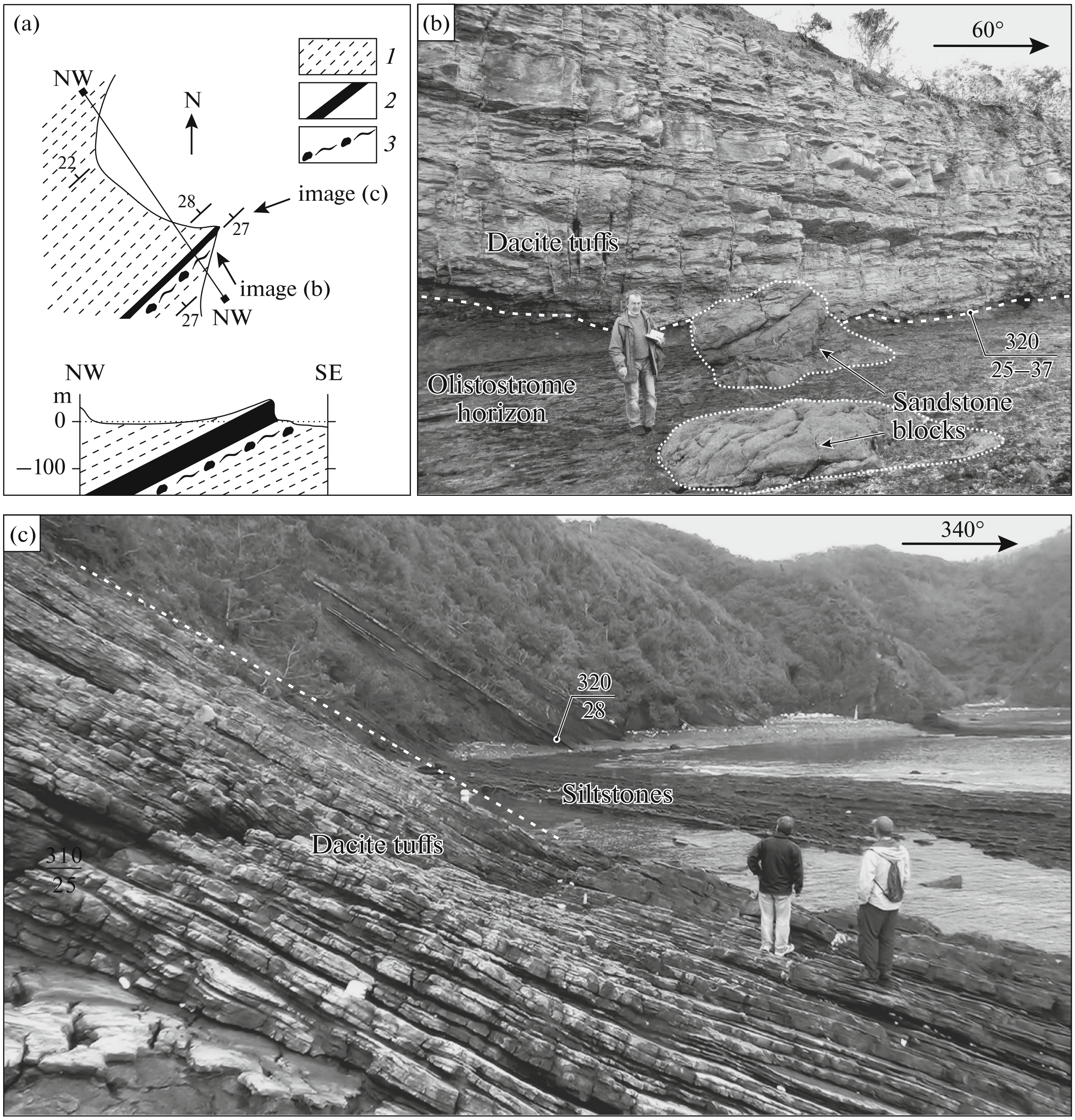

Fig. 5. Occurrence of dacite tuff horizon at base of middle formation of Taishu Group relative to underlying and overlying terrigenous deposits; eastern shore of Tsushima Island, observation point 10 (see Fig. 2). (a) Schematic plan and cross section on outcrops at observation point 10: (*1*) laminated siltstones with rare interbeds of fine-grained sandstones; (*2*) pseudopsammitic laminated dacite tuffs; (*3*) olistostrome horizon. (b) Contact between dacite tuff horizon and underlying olistostrome member. (c) Conformable transition of dacite tuffs into overlying terrigenous rocks. Contact surfaces shown by white dashed line. Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of bedding.

tionship with faults (Fig. 9). These microfolds probably formed as a result of viscoplastic lateral flow of material.

Tension Structures

Tension structures represented by veins and veinlets of quartz and calcite, as well as by rare rhyolite dikes filling ruptures, have been ubiquitously reported in outcrops of the Taishu Group. Veins and veinlets of quartz and calcite are usually up to a few centimeters thick, rarely several decimeters; dikes are up to several meters thick. With sharply dominant steep, up to vertical, dips (Fig. 10a), the directions of veins and dikes change from meridional to northwestern, oriented predominantly across the bedding, with the greatest concentration at about 310° (Fig. 10b). Quartz veinlets often group to form clearly expressed en echelon struc-

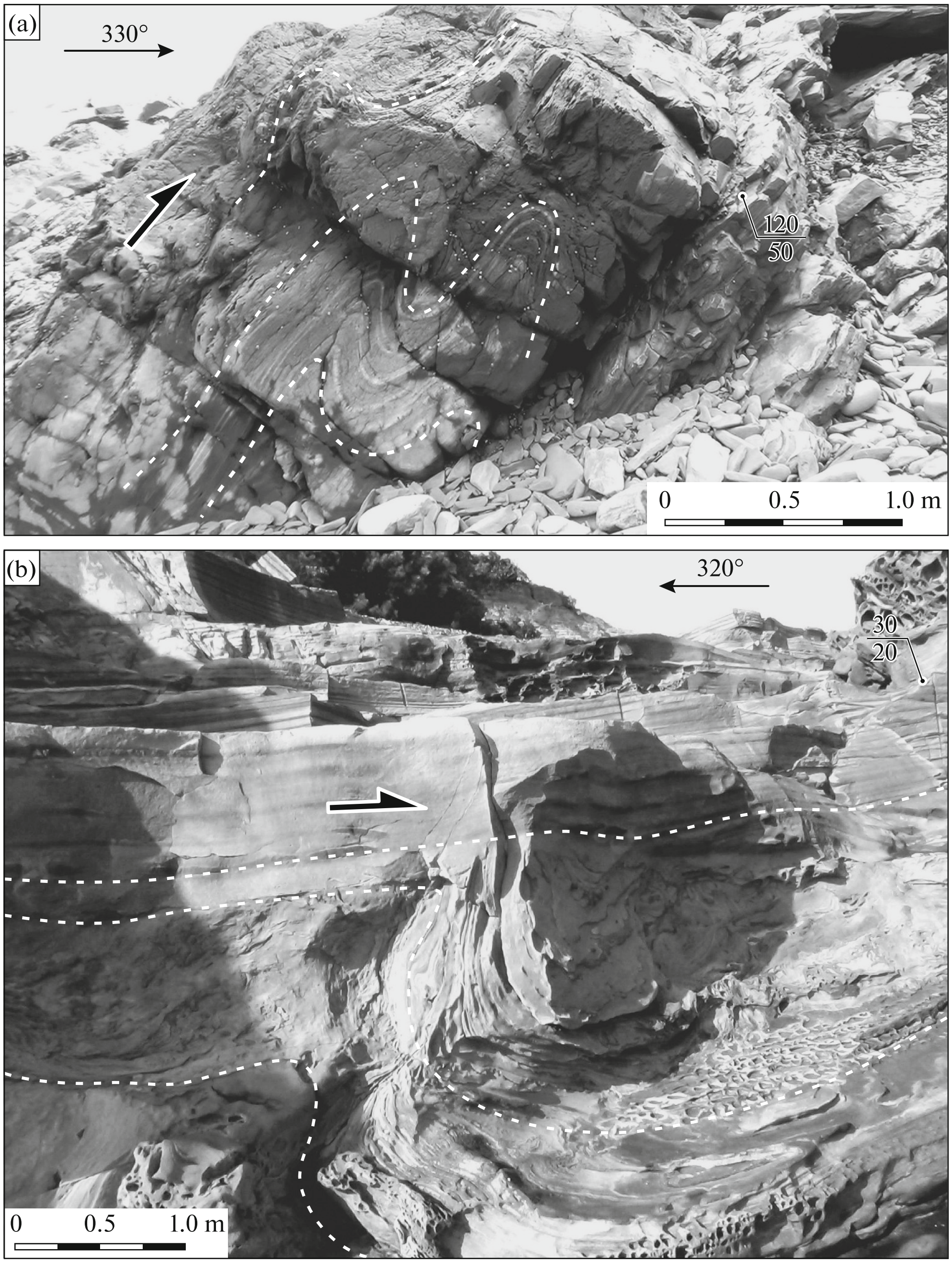

Fig. 6. Submarine landslide folds in lower (a) and upper (b) formations of Taishu Group. Arrows denote directions of material transport. Fold axes are NE-oriented (about 30°). (a) Observation point 21, (b) observation point 4 (see locations of points in Fig. 2). Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of occurrence elements.

tures, on whose basis the direction of the potential component of horizontal motion along the ruptures can be inferred. Figure 11 exemplifies a combination of en echelons of different orientations, from which it is possible to infer right- and left-lateral potential displacements and reliably identify submeridional shortening at this site. This direction of shortening is likely local, because, as mentioned above, the maximum of vein orientations has been statistically determined as northwestern (310°) and this is logically the mean direction of regional shortening. And, as was also mentioned above, the close value of 320° characterizes the direction of shortening obtained on a more represenetative sampling of bedding orientations (Fig. 8).

Sandstone Dikes

Sandstone dikes were found for the first time on Tsushima Island by us at one site on the eastern shore (Fig. 12, point 24). Here we found an exposed member

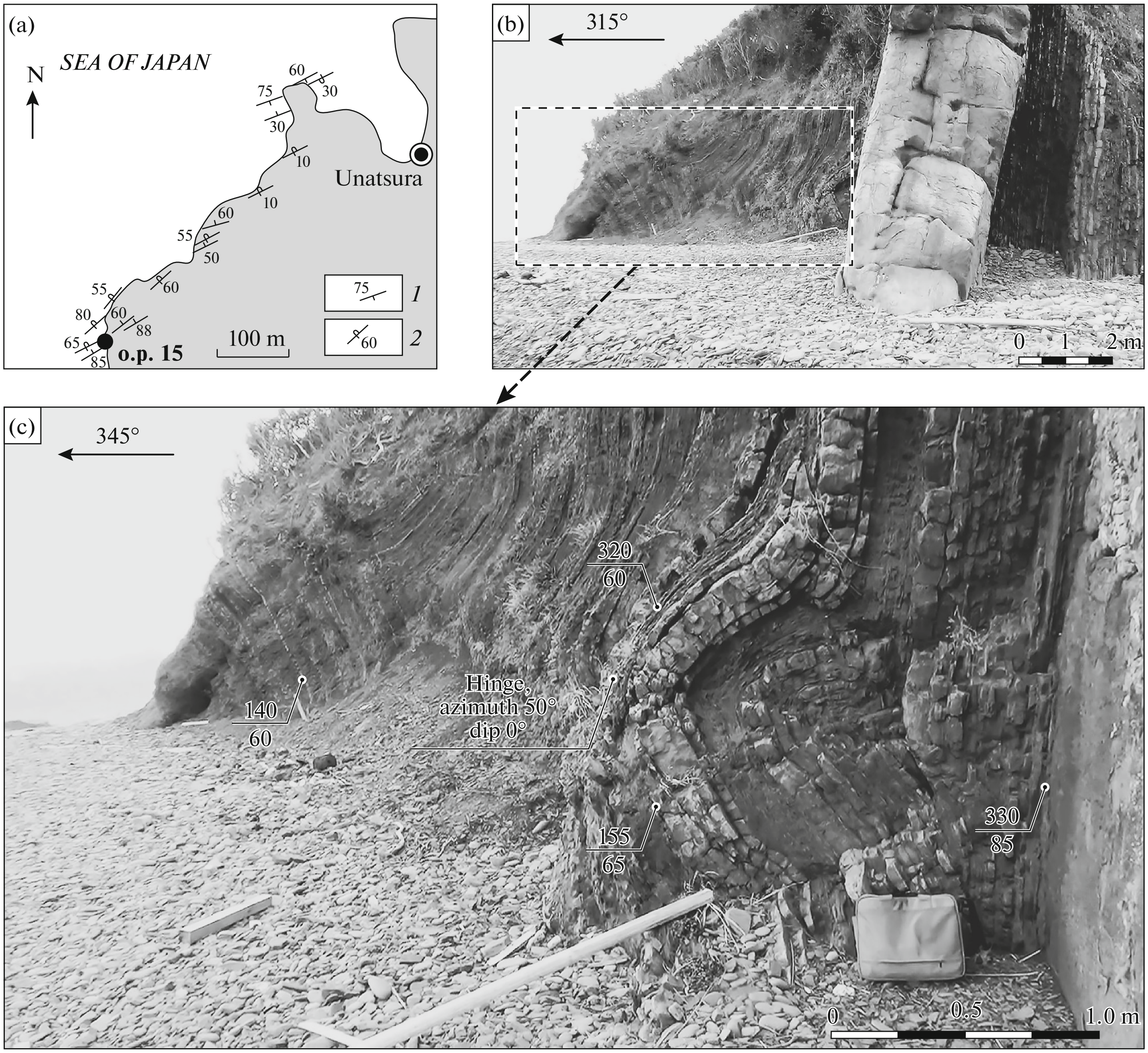

Fig. 7. Submarine landslide fold in rocks of lower formation of Taishu Group, northwestern shore of Tsushima Island, near settlement of Unatsura, observation point 15 (see Fig. 2). (a) Location of observation point 15 with bedding: (*1*) normal, (*2*) overturned; (b) general view of outcrop; (c) core of inclined fold produced by submarine landslide. Material was transported in SE–NW direction. Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of occurrence elements.

of silt-rich mudstones and siltstones containing frequent sandstone interbeds 1–5 cm thick (rarely up to 30 cm), which make up 5–10% of the total thickness. With the overall southeastern (140°–150°) dip of layers of 50°–75°, this member contains series of wave-like lenticular bodies composed of fine-grained sandstones and up to a half-meter thick. These bodies are generally elongated NNE (0°–20°, with bends to the northeast, 50°–60°), dipping westwards at 40°–70°. Sometimes, these dike chains demonstrate signs of en echelon arrangement (Fig. 12b). The fact that the discussed sandstone bodies intruded the host rocks is undoubted. It is also obvious that these dislocations involved rocks with unfinished lithification. The usually assumed source of these dikes is quicksand composed of water removed after lithification and containing suspended sand [2]. However, it is still debated at which stage the sandstone dikes penetrated. In this case, taking into consideration that the dikes penetrated already inclined clay sediments, we can quite reliably assume that penetration occurred at the stage of final folded deformations of incompletely lithified rocks. The argument for this is a relatively rapid (less than 1 Ma) transition from sedimentation to folding and

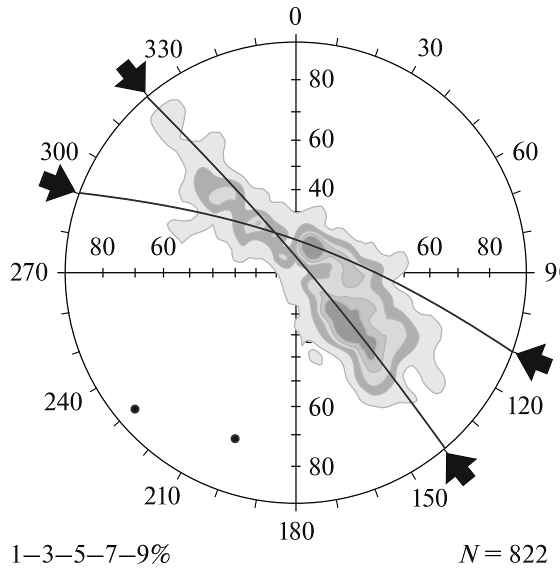

Fig. 8. Summarized diagram of bedding orientations (Taishu Group, Tsushima Island). The sampling includes orientations of layers shown in geologic map with 1 : 50000 scale of central part of island [8] and orientations of layers measured by authors during field works in 2012–2013 (Wulff grid, upper hemisphere). Shown are isolines of density (%), equators of lamination belts (arcs of great circles), and their axes (points); *N*, number of measurements. Arrows denote direction of shortening.

penetration of granites (between 15.9 and 15 Ma B.P.). This is also indicated by the predominantly NW- and NNW-directed dikes corresponding to the directions of tension structures described above.

A less probable scenario, in our opinion, is when dike-hosting rocks occurring at relatively steep angles were produced by landslide dislocation (Fig. 7); therefore, sandstone dikes could penetrate only during sedimentation, before folding had finished.

Thus, the paragenesis of postsedimentation inversion structures includes linear NE-dierсted folds, NE- and NNE-trending faults that cut folds, and NW-oriented ruptures. It is easily seen that this structural paragenesis have formed in the field of only SE–NW-directed (310°–320°) shortening. The data presented above fully confirm the earlier assumptions about this direction of shortening when during the formation of inversion structures on Tsushima Island [3, 7].

FORMATION DYNAMICS OF SEA OF JAPAN STRUCTURES

The formation of the present-day structure of the Sea of Japan can be separated into two large tectonic phases [7]: (a) the early phase associated with intensive sinking and filling of the sedimentary basin and (b) the late phase related to inversion, with folding, penetration of granite intrusions, and orogeny (Fig. 13).

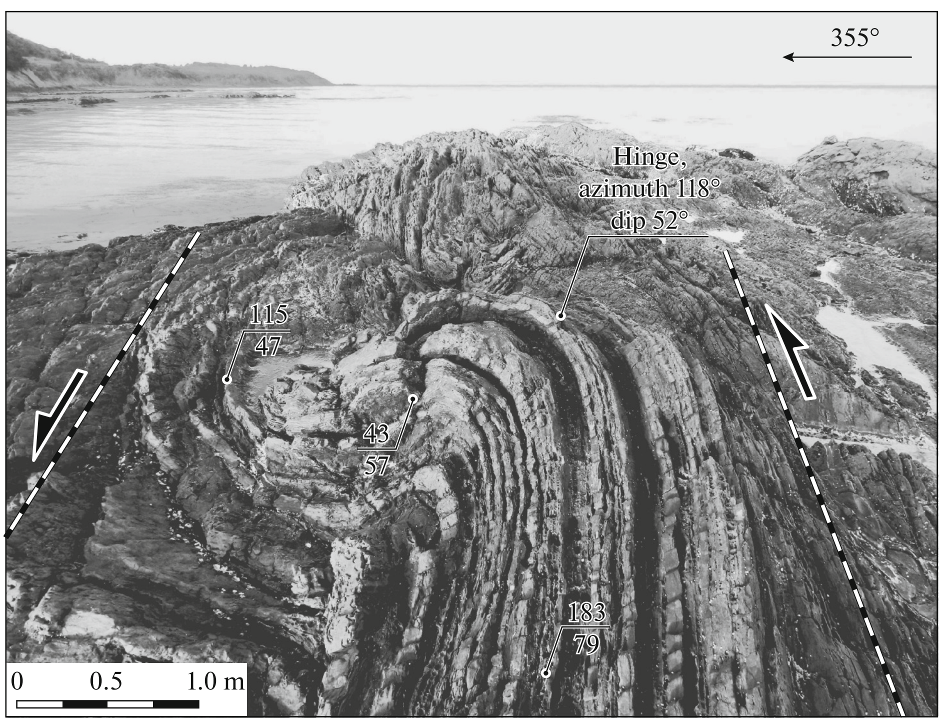

Fig. 9. Folds with steeply dipping hinges in flysch of middle formation of Taishu Group, eastern shore of Tsushima Island, observation point 24 (see Fig. 2). Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of bedding.

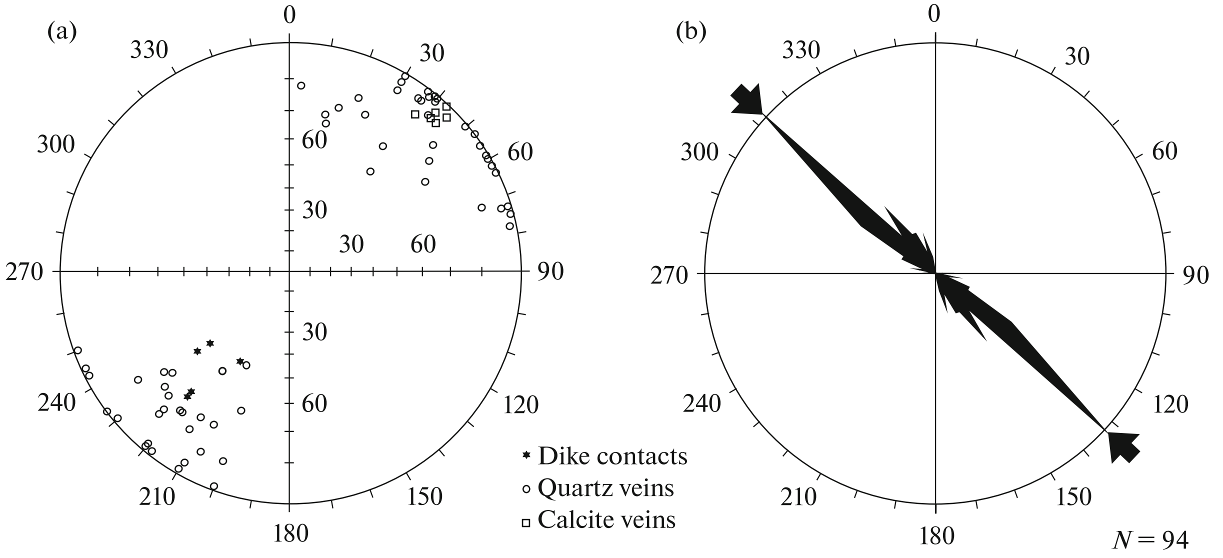

Fig. 10. Orientations of tension structures of Wulff grid, upper hemisphere (a), and rose diagram of their orientations (b). *N*, number of measurements. Arrows denote direction of shortening.

Early Phase

During the early phase, the Tsushima deep basin, like the Central and Honshu basins located northeast of it, participated in the evolution of the newly formed oceanic crust produced by passive rifting and were areas where thick sedimentary strata (and volcanic products to a smaller degree) accumulated. According to some data (e.g., [14, 21], etc.), the onset of this phase dates back to the Eocene and in this area it finished at the boundary of Lower and Middle Miocene (ca. 15 Ma ago). In contrast to the Central and Honshu basins, the Tsushima Basin was almost completely compensated with sediments probably due to the presence of a large clastic source, the supposed paleoriver mouth located slightly south of the study area [15]. The above-mentioned data on the peculiarities of the accumulation of the Taishu Group (first of all, the extremely high sedimentation rate and multiple manifestations of landslide tectonics) indicate intensive downwarping of the bottom of the paleorift and the steep slopes of this paleorift. According to the model by S. Lallemand and L. Jolivet [13], in the beginning, the basins formed during pull-apart processes in the zone where the Hokkaido–Sakhalin and Tsushima noncoaxial right-lateral strike-slip systems overlap, with NE-directed regional shortening. In later studies ([3, 12], etc.), this model was completely confirmed (Figs. 13a, 13b).

Late Phase

The late phase includes folding, left-lateral motions along the Tsushima Fault Zone, and penetration of granitoid intrusions, all of which occurred in a short period (of about a million years) in a setting of NW-directed shortening. Thus, the key date in this study—15 Ma B.P.—corresponds to an episode of simultaneous shortening, folding, and penetration of granitoid intrusions on Tsushima Island, whereas according to paleomagnetic data, this is the time of the main opening phase of the Sea of Japan [19, 20]. According to the "two doors" model by Y. Otofuji, this phase was accompanied by counterclockwise rotation of Northeastern Japan, with simultaneous clockwise rotation of Southwestern Japan [19, 20]. Thus, the dominant NW-directed shortening in the Tsushima Island region changed locally ca. 15 Ma B.P. to NW-directed due to the respective motion of the southwestern terminus of the Southwestern Japan domain during its clockwise rotation (Fig. 13c). Interestingly, left-lateral motions along the Fossa Magna Fault Zone were observed at the northeastern end of this domain; as a result of these motions, collision between the Japan and Izu-Bonin island arcs occurred and the Kanto Syntax formed [3, 23]. It is logical that the center of Southwestern Japan rotation was located closer to its central part.

The idea about the opening of the Sea of Japan in terms of passive rifting models (i.e, under a simple tension or shear-related pull-apart setting) cannot logicallly explain the clockwise rotation of Southwestern Japan : this rotation was obviously superimposed on the relatively simple pattern of the preceding long-term (about 40 Ma) passive rifting. The probable cause of structural reconstruction ca. 15 Ma B.P. was transition from the passive to the active phase of rifting; the latter was related to the formation of local sublatitudi-

Fig. 11. Coupled system of en echelon quartz veinlets formed under action of submeridional shortening, observation point 7 (see Fig. 2). Dotted lines denote boundaries of en echelon structures; small arrows, directions of shear motions; large arrow, direction of shortening.

nal tension zones, which possessed additional energy potential, in deep basins. In this case, the models demonstrating the triggering of the active rifting mechanism after the passive phase [5] are, in our opinion, quite applicable. The pressure that propagated in both directions from the tension axes was meridionally oriented; moreover, it is this pressure that caused clockwise rotation of the linearly elongated, initially NE-oriented fragment of the continetal lithosphere (at that time, Southwestern Japan) (Fig. 13c). The idea about the occurrence of the active rifting episode in the Sea of Japan during the Miocene is confirmed to a certain degree by data on (a) unusually high temperatures during melting of the depleted basaltic magmas that erupted in the Early and Middle Miocene on the surface of the bottom of the Honshu Basin and (b) the generally hot geotherm beneath this basin during the opening of the Sea of Japan [10]. The

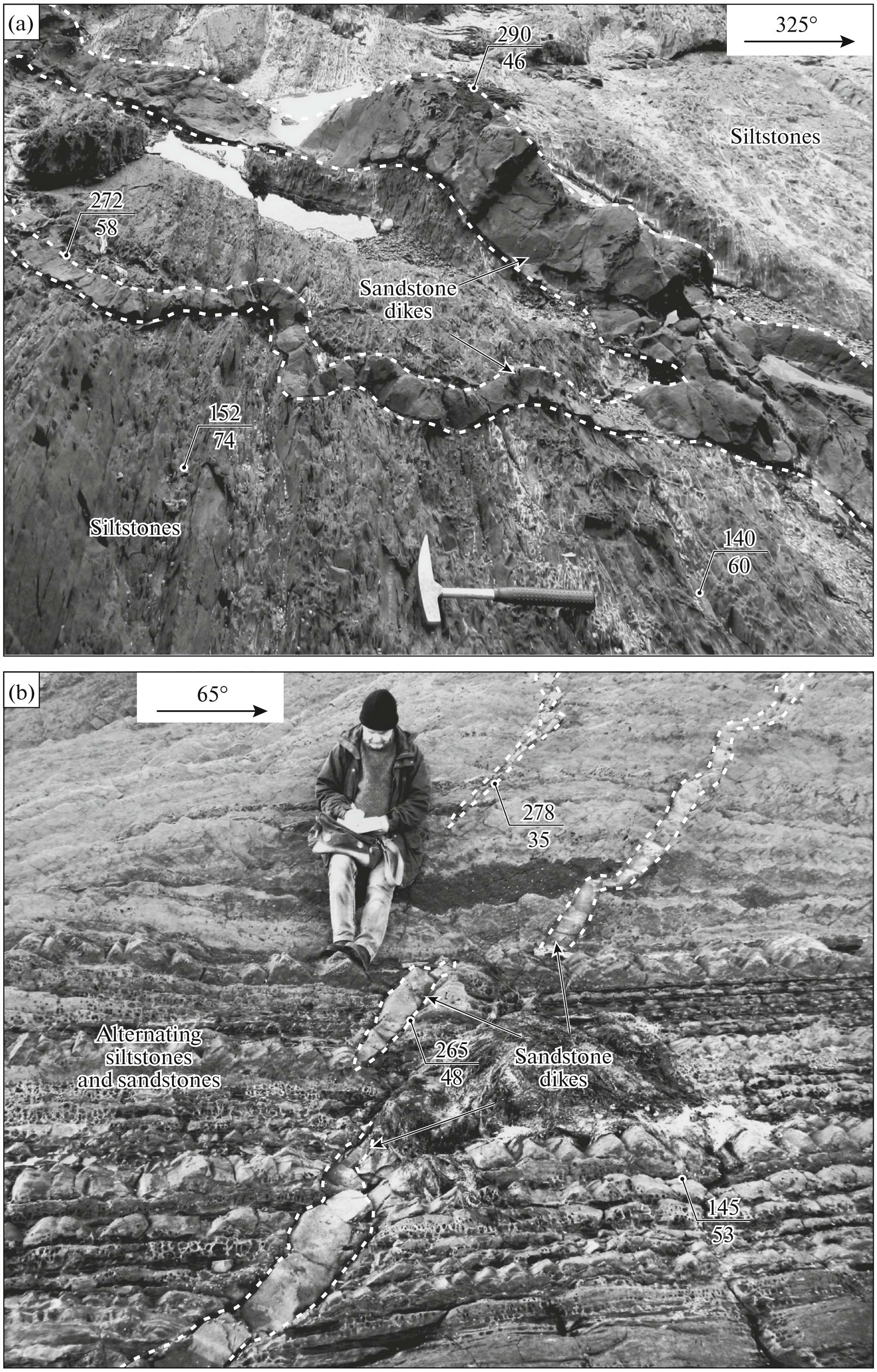

Fig. 12. Morphology of sandstone dikes penetrating steeply dipping layers of middle formation of Taishu Group, eastern shore of Tsushima Island, observation point 24 (see Fig. 2): (a) divergence of sandstone dike; (b) en echelon arrangement of sandstone dike series. Ratios indicate dipping azimuth (numerator) and dipping angle (denominator) of bedding.

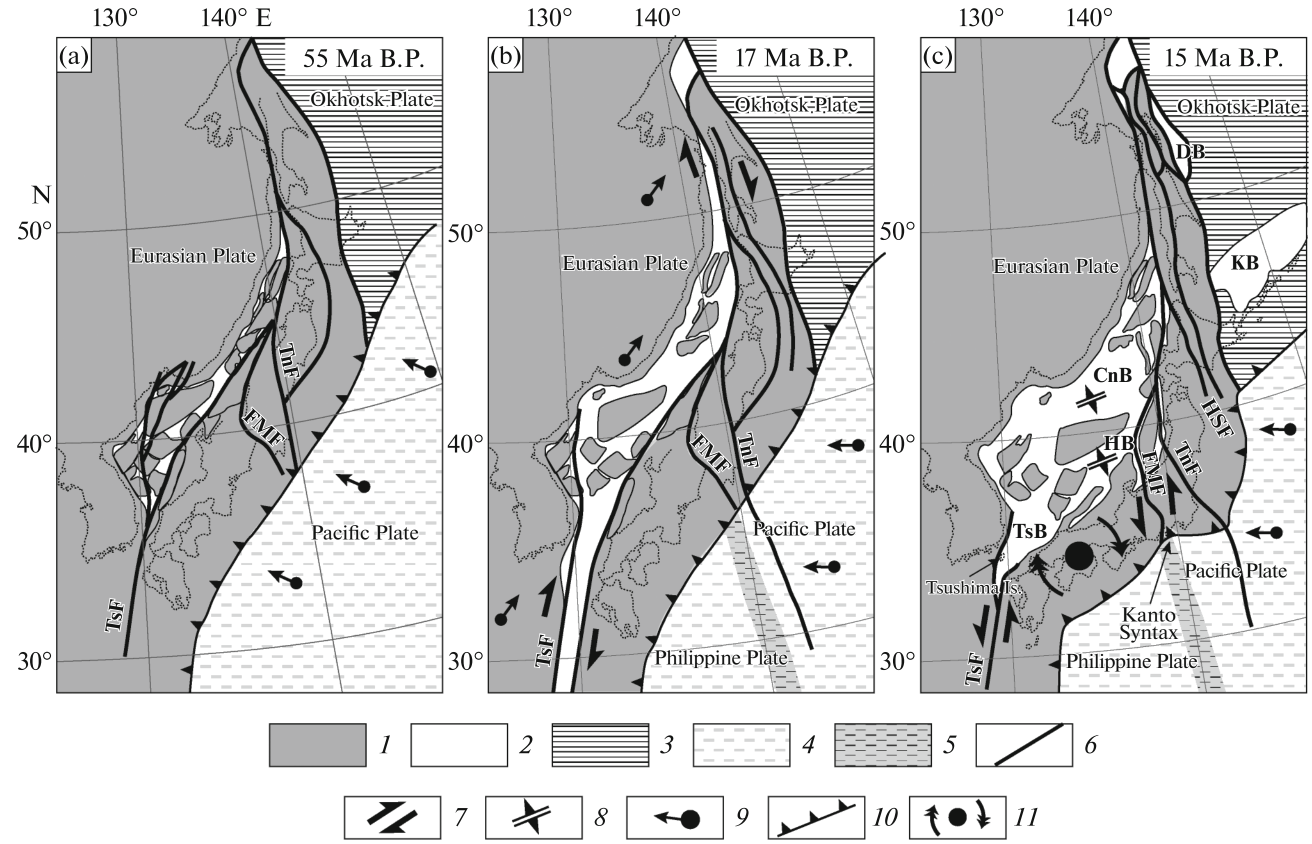

Fig. 13. Dynamics of opening of Sea of Japan, after [3] with modifications and additions. Faults and fault zones: TnF, Tanakura; FMF, Fossa Magna; TsF, Tsushima, HSF, Hokkaido-Sakhalin. Deep basins: DB, Deryugin; KB, Kuril; CnB, Central; HB, Honshu; TsB, Tsushima. (*1*) Eurasian Plate; (*2*) fragments of new-formed oceanic crust; (*3*) Okhotsk Plate; (*4*) Pacific Plate; (*5*) axial part of Izu-Bonin arc; (*6*) active faults; (*7*) directions of shear motions along faults; (*8*) active tension axes; (*9*) directions of plate motions; (*10*) subduction zones; (*11*) direction of Southwest Japan block rotation.

active rifting phase was very short, no more than a million years, and then the Sea of Japan assumed its present-day outline and the passive downwarping of deep basins continued.

CONCLUSIONS

(1) Lower Miocene rocks of the Taishu Group accumulated in the Tsushima pull-apart graben, whose downwarping and filling with sediments occurred at extremely high rates (about 2700 m/Ma) on a background of NE-directed regional shortening. Sedimentary filling is considerably composed of the material supplied from the shallow shelf with landslide bodies (slabs).

(2) Folding and penetration of granite intrusions on Tsushima Island occurred ca. 15 Ma B.P. in the field of different NE-directed shortening, which was local and related to clockwise rotation of the Southwest Japan block. This rotation could have been caused by the active rifting episode in the Central and Honshu basins located north of Tsushima Island.

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