ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 409, No. 5, pp. 717–722. © Pleiades Publishing, Inc., 2006.
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GEOLOGY

Stages of Geodynamic Rearrangements of the Eastern Margin of the Eurasian Continent in the Cenozoic: The Amur River–Sea of the Okhotsk Region

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Presented by Academician V.E. Khain October 17, 2005

Received October 24, 2005

DOI: 10.1134/S1028334X06050084

It is widely believed in literature that the convergent boundary between the Pacific Plate and the eastern margin of the Eurasian continent permanently existed through the Late Mesozoic and Cenozoic. However, new data in combination with recent publications on the Sikhote Alin–Sakhalin [1–5] and the East China–Japan [6–8] regions testify to geodynamic and tectonic instability of the eastern margin of the Eurasian Plate during this time interval, when the convergent boundary repeatedly gave way to the transform boundary. The information obtained makes it possible to trace a character of interaction of the Eurasian continent, including the Amur Microplate (Fig. 1) with the oceanic plates and the Sea of Okhotsk Microplate (hereafter, Okhotsk Microplate).

The Mid-Cretaceous and Cenomanian–Paleocene stages were the most important in the evolution of the Sikhote Alin–East China–Japan sector of the continental margin. These stages also predetermined its subsequent evolution in the Cenozoic. The first (late Hauterivian–early Cenomanian) stage (130–95 Ma) was characterized by origination of the Okhotsk Microplate and proceeded against the background of the abrupt increase in velocity of oceanic plate motion (up to 30 cm/yr) combined with a northwestern to near-meridional change in direction in the western Pacific [10]. This caused the development of the transform boundary at the eastern margin of Eurasia [4, 7, 8], which was accompanied by a wide zone of sinistral strike-slip faults that segmented the margin into numerous blocks of the ancient continental crust with sandwiched fragments of island arcs of different ages, accretionary prisms, and backarc basins. While moving northward under conditions of transpression and oblique convergence, these blocks made up a Mid-Cretaceous orogenic belt on the Eurasian continent in the east. The continental Okhotsk Microplate, detached along strike-slip faults, was situated to the east. It was rimmed by segments of the oceanic lithosphere along strike-slip faults and intraplate boundaries.

Subsequently (95–65 Ma ago), the eastern transform boundary of the Eurasian Plate became a convergent boundary as a result of change in direction of the oceanic plate motion from the submeridional to the northwestern one and the twofold reduction of its velocity [10]. It was a stage of the absorption of the oceanic rim of the Okhotsk Microplate with the formation of the Okhotsk–Chukotka Belt in the north and a similar East Sikhote Alin Belt above the subduction zone in the west (Fig. 2).

The complete absorption of the West Pacific crust in the subduction zone 65–58 Ma ago resulted in the sinistral strike-slip faulting and oblique collision of the Okhotsk Microplate with the eastern margin of the Eurasian continent. This led to the waning of the East Sikhote Alin Belt and the exhumation and retrograde metamorphism of amphibolites and eclogites of the deep-seated portions of slab and their westward thrusting over the Cretaceous and Paleocene rocks of the former forearc trough [1]. Still earlier (~70 Ma ago), the Okhotsk Microplate completed its northward drift and wedged up the subduction zone of the Okhotsk–Chukotka Belt. A vast continental mass that combined the eastern Eurasian Plate and the jammed Okhotsk Microplate, including the western Kamchatka in the east [11], was formed at the Cretaceous–Paleogene boundary. Although this continental-margin massif was divided into blocks [6], the Eurasia–Sea of Okhotsk sector of the continental margin was developing in similar geodynamic regimes during Eocene–Pliocene, resulting in the formation of similar structural features. This interval comprises the Eocene–early Miocene

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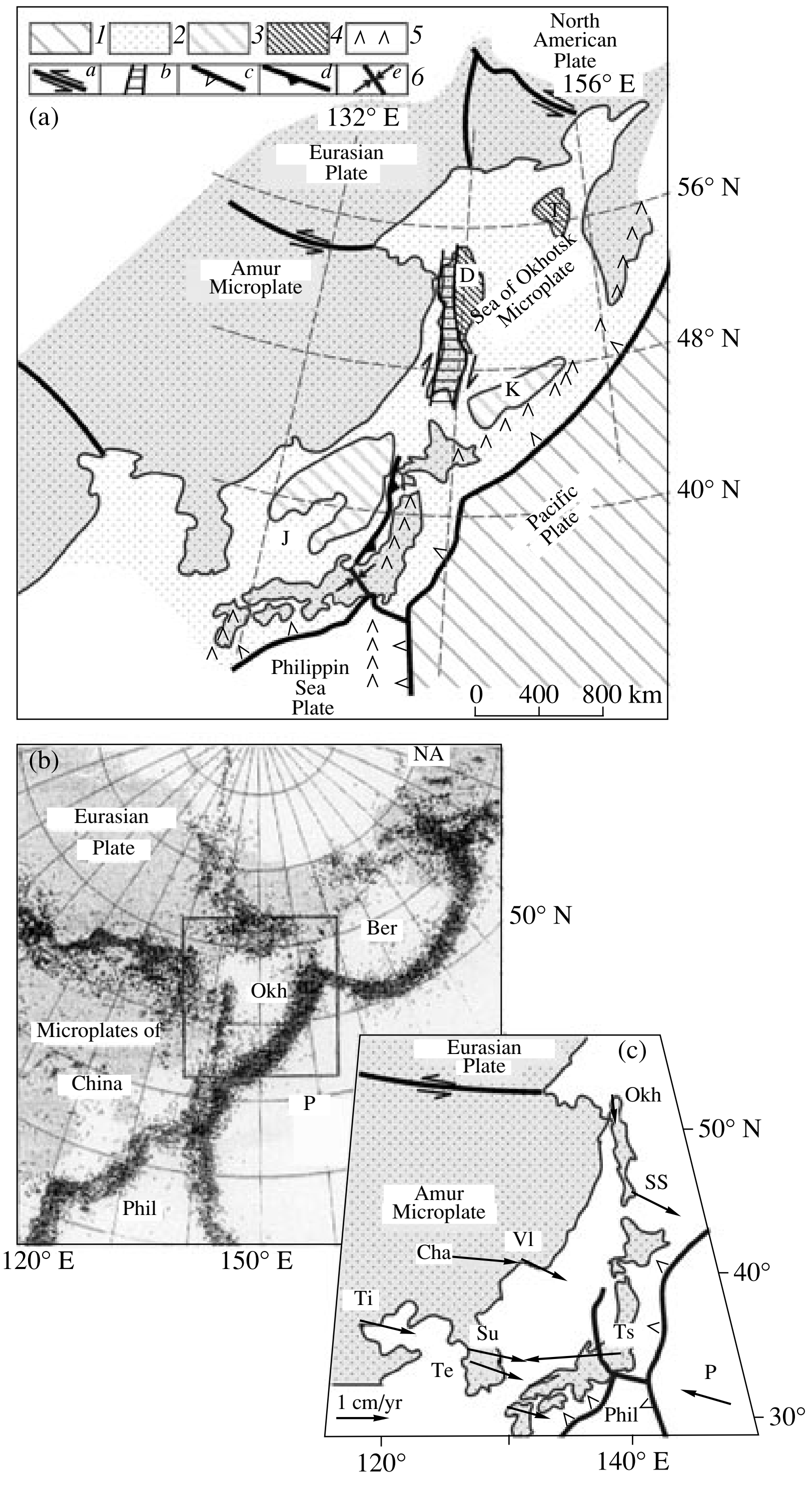

Fig. 1. (a) Boundary of the Amur and Okhotsk microplates as deduced from seismic and satellite geodetic data [3, 9] in the context of the present-day structure of the eastern Asian margin and the adjacent territories [2, 9]. (*1*) Oceanic crust; (*2*) continental crust; (*3*) extensional continental-margin basins with continental-margin crust: (J) Sea of Japan, (K) South Kuril Basin; (*4*) extensional continental-margin basins with transitional continental-margin and stretched continental crust: (D) Deryugin Basin, (T) Tinro Basin; (*5*) Kuril island arc; (*6*) plate boundaries: (*a*) transform, (*b*) diffuse transform, (*c*) convergent, (*d*) incipient convergent, (*e*) collisional. (b) Seismic belts of shallow earthquakes with a source depth up to 40 km. Lithospheric plates: (NA) North American, (Okh) Sea of Okhotsk, (Ber) Beringia, (Phil) Philippine Sea. (c) Direction and velocity of recent horizontal motions of the Earth's crust relative to the Eurasian Plate (GPS data) [9] at observation points: (Vl) Vladivostok, (Okh) Okha, (Su) Suwon, (Te) Taejon, (Ti) Tianjin, (Ts) Tsukuba, (Cha) Chanchuk, and (SS) South Sakhalin; plates: (P) Pacific, (Phil) Philippine Sea. The strike-slip fault along the northern boundary of the Amur Microplate and the incipient convergent boundary along the eastern coast of the Sea of Japan are also shown.

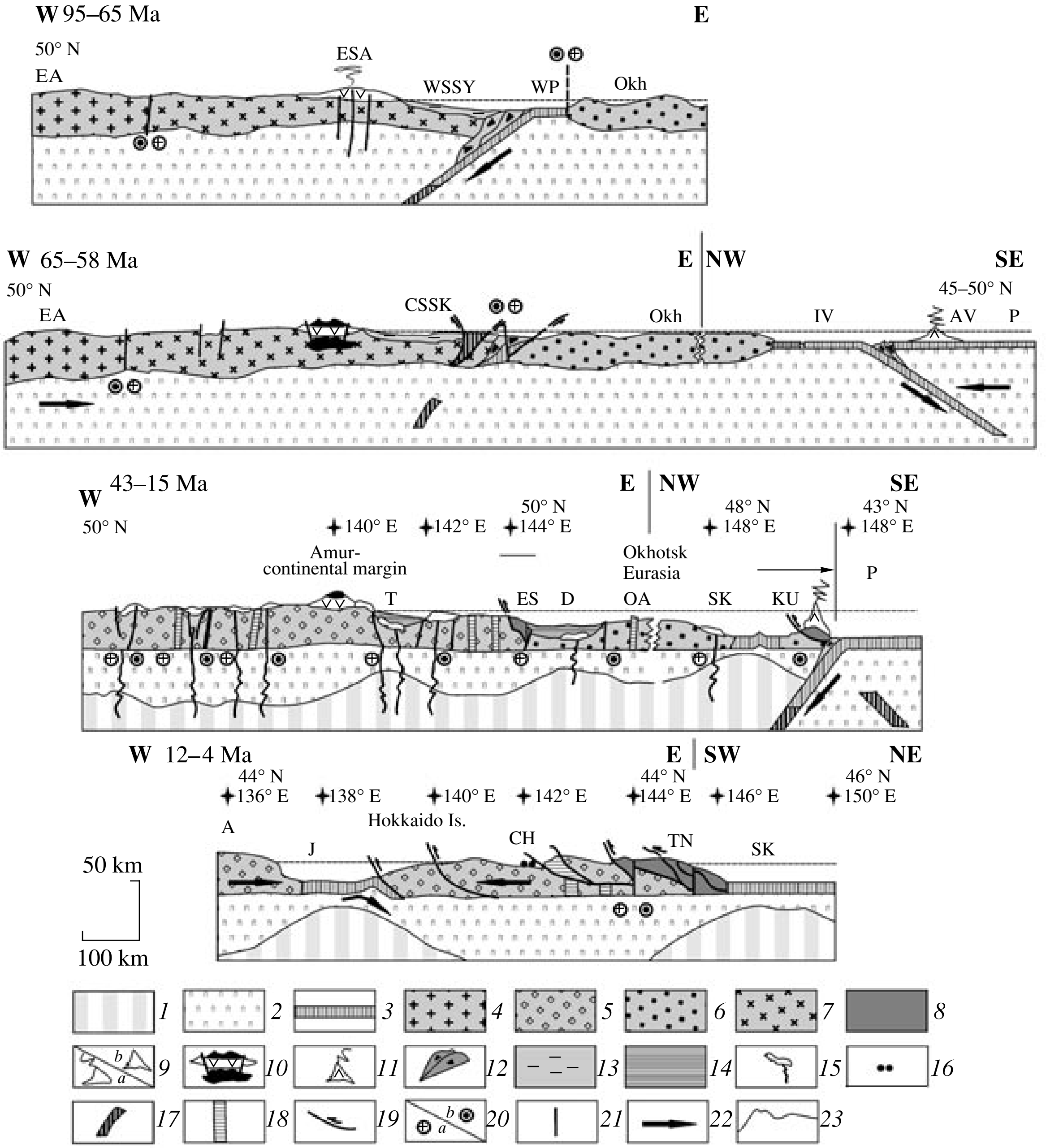

Fig. 2. A model of geodynamic evolution of the eastern margin of the Eurasian Plate in the Late Mesozoic and Cenozoic. (*1*) Asthenosphere; (*2*) lithospheric mantle; (*3*) oceanic and continental-margin crust: continental-margin basins: (J) Japan, (SK) South Kuril; (*4*) Eurasian lithospheric plate (EA); (*5, 6*) multistage continental lithospheric plates: (*5*) Amur (A), (*6*) Sea of Okhotsk (Okh); (*7*) Mid-Cretaceous orogenic belt; (*8*) middle Eocene orogenic belt zones: (ES) East Sakhalin, (TN) Tokoro–Nemuro; (*9*) East Sikhote Alin continental-margin volcanic belt (ESA): (*a*) active, (*b*) inactive; (*10*) acid volcanics at the top of volcanoes and their crustal chambers; (*11*) volcanic island arcs: (AV) Achaivayam–Valaginsky, (Ku) Kuril; (*12*) accretionary prisms; (*13*) forearc troughs: (WSSY)—West Sakhalin–Sorachi–Yezo; (*14*) sedimentary fill of basins formed during strike-slip faulting: (D) Deryugin, (T) Tatar; (*15*) strike-slip fault-related basalts, mainly of a within-plate type (not to scale) and their conduits; (*16*) strike-slip fault-line foredeeps; (*17*) moderate- and high-pressure metamorphism of oceanic slabs exhumed in oblique thrust fault zones: (CSSK) Central Sakhalin–Susunai–Kamuikotan); (*18*) strike-slip fault-related amphibolite-facies metamorphism and granitization: (CH) Central Hokkaido HT–LP metamorphic belt exhumed along a thrust fault; (*19*) thrust faults; (*20*) strike-slip faults and direction of displacement: (*a*) to the observer and (*b*) from the observer; (*21*) other faults; (*22*) direction of motion of plates and blocks. Other designations: (OA) Okeanologiya and Akademiya Nauk uplifts, (P) Pacific Plate, (WP) West Pacific Microplate, (IV) Irunei–Vatyn Basin.

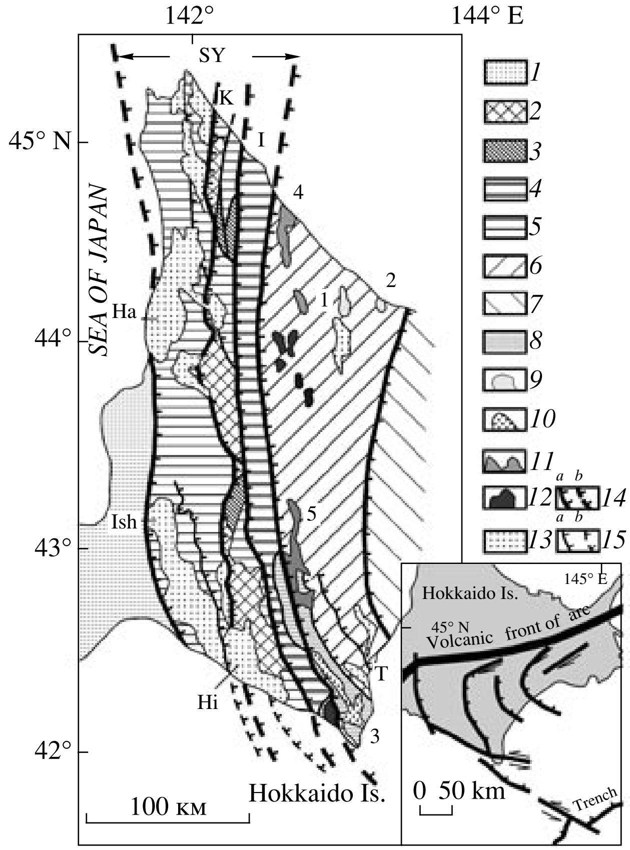

Fig. 3. Tectonic structure of central Hokkaido Island, modified after [15]. (*1*) Tuffaceous terrigenous rocks of the Jurassic–Lower Cretaceous accretionary prism (Oshima zone); (*2, 3*) Jurassic–Lower Cretaceous ophiolites of the Kamuikotan zone (K) metamorphosed under conditions of (*2*) greenschist and amphibolite facies and (*3*) glaucophane and eclogite facies; (*4*) tectonic melange consisting of ophiolites, HP metamorphic rocks, jasper, limestone, and turbidites (Idonnappu zone, I); (*5, 6*) Cenomanian–Paleocene tuffaceous terrigenous rocks related to the formation of the East Sikhote Alin suprasubduction volcanic belt: (*5*) turbidites of forearc trough: (SY) Sorachi–Yezo tectonic belt, (Ish) Ishikari zone), (*6*) terrigenous–olistostrome rocks of accretionary prism in the inner part of trench (Hidaka zone); (*7*) Campanian–Paleocene terrigenous and volcanomictic turbidites of forearc trough (Tokoro zone); (*8–15*) Cenozoic rocks of central Hokkaido: (*8*) HT–LP metamorphic rocks of the Hidaka metamorphic belt; (*9–12*) Cenozoic anatectic granites: (*9*) middle Eocene (1) Uttsudake and (2) Monbetsu plutons, (*10)* late Eocene–early Oligocene (3) Saruru–Oshirabetsu plutons, (*11*) early Miocene (4) Otchube–Ichinohashi and (5) Nisso plutons, (*12*) presumably early Miocene; (*13*) middle and late Miocene basins formed in front of thrust faults: (Ha) Haboro, (Ish) Ishikari, (Hi) Hidaka, (T) Tokachi; (*14*) middle Miocene thrust faults transformed from Eocene–early Miocene dextral strike-slip faults: (*a*) traced on land and (*b*) inferred on seabed; (*15*) other thrust faults. Inset demonstrates the Pliocene–Holocene thrust fault system on southern Hokkaido Island [13]. See Figs. 1 and 2 for legend.

stage of the dominating extension and the late Miocene–Pliocene stage of intense compression.

The Indo-Eurasian collision was the main factor that controlled kinematics and structure formation in the Eurasia–Sea of Okhotsk continental massif 43–16 Ma ago. The change in the direction of the Pacific Plate motion to the west-northwest ~43 Ma ago [10] led to the collision of the East Sakhalin–Tokoro–Nemuro island arc with the Asian continent in the middle Eocene. The collision probably took place in a southern area located far away from the present-day location of these segments.

The Indo-Eurasian collision provoked the fragmentation of the eastern Eurasian continent into a mosaic of microplates (including the Amur Microplate), as was first established by L.P. Zonenshain and confirmed subsequently by [2, 4, 6, 9]. As a result of the collision, in the Eocene the Amur Microplate drifted to the north and had a transform boundary with the Sea of Okhotsk and Pacific plates [7]. This boundary was accompanied by a wide system of closely spaced near-meridional dextral strike-slip faults in the eastern Amur Microplate (including the Tan-Lu strike-slip fault zone) and the Okhotsk Microplate. The transtensional regime gave rise to the Eocene rifting and formation of pull-apart basins in the Primorye–China–Japan region [7, 12] and the Okhotsk Microplate area [3] (Fig. 2). A similar geodynamic setting in the Eocene and Miocene over the vast territory of the two merged continental microplates is confirmed by synchronous development of pull-apart basins with three clearly distinguished and correlated (irrespective of degree of extension) stages separated by structural unconformities: (1) the Eocene (late Paleocene?)–Oligocene stage of the incipient rifting and molasse deposition, (2) the late Oligocene–early Miocene transgressive stage that corresponds to the peak of extension, and (3) the late Miocene–Pliocene regressive (postrift) stage. The strike-slip fault-line basins differed in degree of extension: thinning of the continental crust without its disintegration (grabens of the Tan-Lu, Kilchu–Menchong, Phohang–Yannamg, and Shimane–Akito–Yamagata zones); considerable extension of the continental crust with possible incipient dispersed spreading and formation of the crust of the continental-margin type (Deryugin and Tinro basins); and intense extension and formation of the continental-margin crust as a result of the Miocene spreading (Sea of Japan and South Kuril basins). The opening of the South Kuril Basin, often regarded as a pull-apart basin [13], slightly postdated the Sea of Japan Basin (initiated 20–16 Ma ago, completed ~10 Ma ago) [5, 8, 13]. Like the Sea of Japan Basin, the periphery of this basin incorporated riftogenic structures extending over no less than 100 km from Hokkaido Island to the northern sea area [14]. This region was characterized by the manifestation of similar magmatism in structures with various degrees of extension [5, 7, 14]. The extensional basins alternated in space with zones of greenschist- and amphibolite-facies metamorphism of the Mesozoic and Paleocene rocks under transpressional conditions. For example, the high-temperature (HT)–low pressure (LP) metamorphic belt of central Hokkaido includes abundant migmatites and stress-granites (43.4–16.0 Ma) similar to S-granites [15].

Since the middle Miocene (~13–12 Ma ago), the extensional setting in the adjacent Amur and Okhotsk microplates gave way to the regime of intense compression. This period was marked by clockwise rotation of the Amur Microplate (probably, the Okhotsk Microplate as well) and the onset of its motion to the east-southeast [7, 13], resulting in the termination of processes of spreading in continental-margin basins, extension at the Amur River–Sea of Okhotsk (hereafter, Amur–Okhotsk) continental margin of Asia, and magmatism [12]. The rocks of the Eocene–early Miocene basins were subject to folding, block motions, and imbricate thrusting. On Hokkaido Island, the Eocene–early Miocene strike-slip fault zone was transformed into a west-verging thrust fault zone as a result of compression (Fig. 3). The HT–LP metamorphic rocks of the Central Hokkaido Belt were exhumed along the thrust faults and eroded. A submeridional chain of strike-slip fault-line basins filled with middle and upper Miocene terrigenous sediments appeared in front of the thrust zone. In contrast to the Oligocene–lower Miocene rocks of the basement, they contain fragments of metamorphic rocks derived from the Central Hokkaido Belt and the Eocene–early Miocene stress-granites [15]. Thus, the episode of thrusting took place in the middle Miocene during the maximum opening stage of the South Kuril Basin, when the remnants of the Late Cretaceous–Paleocene island arcs previously accreted to the continent were displaced southward and attached to the eastern part of the Hokkaido continental block [13]. These processes fostered the formation of the main thrust fault zone of central Hokkaido and the imbricate west-verging structures in the Tokoro Zone (Fig. 2).

Concerning the Holocene stage, the attempts to define the Okhotsk and Amur microplates have met great difficulties and have led to various versions of the depiction of their boundary in maps [2, 3, 11, 13] due to the absence of a continuous boundary seismic belt. According to Lander (cited in [3]), the Arctic belt of shallow earthquakes, which extends from the north, produces a wide region of scattered seismicity at the northern coast of the Sea of Okhotsk and terminates near the Okhotsk Microplate. Thus, the Arctic earthquake belt does not extend to the northern part of the seabed. The meridional seismic belt of Sakhalin is recorded only in the remote southern area after a 200-km-long gap. This dextral strike-slip fault zone [9] occupies the entire width of the island and abruptly comes to an end at the northern coast of Hokkaido Island. The new (southern) segment of the seismic belt makes up a westward-oriented echelon and coincides with the initial convergent boundary at the eastern margin of the Sea of Japan Basin (Fig. 1). This fact supports the opinion of Lander [3], who believed that it is impossible to show a continuous and unambiguous boundary between the Amur and Okhotsk microplates. GPS data also cast doubts on the autonomous state of the Okhotsk Microplate in the Holocene [9]. However, the GPS data indicate that the northeastern Japanese block (probably, together with Hokkaido Island) and the Amur Microplate converge in the south at a rate of 18 mm/yr [9]. Along the southern boundary, this block collides with the southwestern Japanese block, which moves eastward as a constituent of the Amur Microplate, and the Izu–Bonin arc of the Philippine Sea Plate. One can suggest that the northeastern Japan–Hokkaido Plate will again merge with the Asian continental margin and reach the pre-Miocene position after the complete absorption of the Japanese continental-margin crust.

Satellite geodetic and seismic data suggest that the Amur Microplate is currently closely united with the Okhotsk Microplate. However, the strike-slip displacements along the Eurasian–North American plates boundary, which started to form in the Cenozoic [2, 3], affect the southern Amur–Okhotsk continental margin. Consequently, this area is marked by the origination of a new (southward moving) Okhotsk Microplate, which is currently separated from the Amur Microplate only by the fragmentary dextral strike-slip fault zone of Sakhalin Island.

CONCLUSIONS

(1) The Cenozoic dynamics of the eastern margin of the Eurasian Plate were partly governed by the Late Mesozoic events: (i) the origination of the Okhotsk Microplate in the Mid-Cretaceous as a result of its detachment from continent along a transform boundary; (ii) convergence of this microplate with continent in the Late Cretaceous owing to the subduction of the West Pacific oceanic crust beneath its eastern margin. The resultant oblique collision with participation of sinistral strike-slip faulting in the Paleocene produced the Eurasia–Okhotsk continental margin, which further developed in similar geodynamic regimes.

(2) The Amur Microplate, which appeared in eastern Asia at the Eocene–early Miocene stage, and the Okhotsk Microplate made up a common (although block-type) continental massif. Under the influence of the Indo-Eurasian collision, this massif underwent continental rifting. Pull-apart basins of various degrees of extension were formed here as a result of transtension related to the dextral strike-slip faults.

(3) The Middle Miocene–Pliocene stage was also characterized by a common geodynamic regime. The pull-apart basins at the Amur–Okhotsk continental margin were closed and their sediments were deformed in the transtensional setting. Strike-slip faults were transformed into thrust faults.

(4) Satellite geodetic and seismic data demonstrate that a continuous boundary between the Amur and Okhotsk microplates is not currently traceable. Therefore, the autonomous nature of the boundary is doubtful. The Sakhalin fragment of dextral strike-slip faults

is probably an embryonic segment of the boundary of the future microplate, which is being driven southward due to the interaction of the Eurasian and North American plates. However, the GPS data suggests the emergence of the Northeastern Japanese–Hokkaido microplate due to a counter motion relative to the Amur Microplate.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 04-05-64025, 05-05-64917, and 05-05-65198) and the Foundation of the President of the Russian Federation for the Support of Leading Scientific Schools (project no. NSh-748.2006.5).

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