中生代から新生代にかけてのプレート沈み込みに起因するマグマの特徴

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journal or publication title	東北アジア研究
number	9
page range	179-219
year	2005-03-28
URL	http://hdl.handle.net/10097/41105

Magmatic Expression of Plate Subduction beneath East Asia in the Mesozoic through Cenozoic

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Key words : East Asia, Mesozoic, Cenozoic, Pacific plate, subduction, magmatism

> The controversy over the issue of convective layering and depth of plume sources is likely to be resolved when the so far rather fuzzy seismic imaging of the Earth's interior becomes comparable in resolution to that achieved by geochemical mapping, so the geophysical and geochemical data can be more specifically correlated.
>
> (Hofmann, 1997)

Abstract

Mesozoic through Cenozoic magmatic evolution of East Asia was governed by oceanic plate subduction responsible for generation of a high-velocity anomaly, known as "the stagnated slab", at the mantle transition zone and the low-velocity Transbaikal mantle domain at depth of 200-350 km. Based on spatial-temporal distribution of magmatic activity, the anomalous mantle region is suggested to be a time-integrated expression of subduction processes. High- and low-velocity material could be stored firstly during closing of the Mongolia-Okhotsk Ocean finalized at ca. 140 Ma. After terrane accretion and structural reorganization at 113-107 Ma, subduction of the Kula-Izanagi plate defined the northern margin of the anomalous mantle region. Low-velocity anomalies extended from a continental margin landward over 1000 km beneath Aldan shield of the Siberian craton. The

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structural reorganization between 65 and 50 Ma took place contemporaneously with accretion of the Okhotsk Sea plate to Eurasia. Block rotation and extension at the continental margin were accompanied by formation of the oblique Sikhote-Alin slab flexure of the Pacific plate. Afterwards, the slab flexure was widening to the south due to landward growing of the directly subducted Honshu-Khingan slab fragment. The latter resulted in development of the southern margin of the anomalous mantle region. The structural reorganization between 21 and 15 Ma was coeval to accretion of the Philippine Sea plate to Eurasia with formation of the Japan-Korea oblique slab flexure, trench rolling-back effect, block rotations, and extension at the continental margin. The present-day subduction activity of the Pacific slab is focused at the oblique Japan-Korea and direct Hokkaido-Amur flexures.

1. Introduction

Mesozoic through Cenozoic evolution of East Asia was related traditionally to plate motions in Pacific Ocean and marginal seas. This approach was based on plate reconstructions derived from temporal interpretations of magnetic lineation in the ocean floor, hypothesized directions of plate motions relative fixed hotspots, geological and geochronological interpretations of accreted oceanic terranes and data on temporal evolution of magmatism (Natal'in, 1993 ; Maruyama et al., 1997 ; Yamaji and Yoshida, 1998 ; Khanchuk, 2000 ; Parfenov et al., 2003 and others). After Molnar and Tapponnier (1975) rejuvenation of the hypothesis by Argand (1924) on influence of the India-Asian collision on seismic activity and deformations in Inner Asia, numerous multi-disciplinary studies supported this point. The collisional hypothesis became dominating in explanation of tectonics not only in Inner Asia but also at the Eurasia-Pacific convergent zone (e.g. Worrall et al., 1996). In the 70-ths, hotspot activity in oceanic plates was referred by Morgan to plumes ascending from the lower mantle (core-mantle boundary). In the early 90-ths, this hypothesis was applied for explanation of intraplate volcanic activity in some areas of East and Central Asia (Nakamura et al., 1990 ; Rasskazov, 1991 and others). It was speculated also that diffused intraplate Cenozoic volcanism in this area was produced by a broad asthenospheric upwelling from a deeper level ("hot region") (Tatsumi et al., 1990) or by convective flow ascending from the core-mantle boundary (Zonenshain et al., 1991).

In oceans, magmatism is generated in deep mantle plumes as well as in shallow low-velocity mantle (Hofmann, 1997). In continents, plume activity is usually less obvious than in oceans and often doubtful. For instance, a deep plume nature of the Yellowstone hotspot, originally proposed by Morgan, was not confirmed by seismic tomography. This region is underlain only by the upper mantle low-velocity anomaly (Christensen et al., 1992). A positive exception, however, is a plume-derived magmatism in Northeast Africa advocated in numerous studies. Plume activity was expressed here geomorphologically by the Ethiopian and East African domes, tomographically by image of a low-velocity column ascending from the core-mantle boundary, and magmatically by a specific composition of plume component in terms of Sr, Nd, Pb, and He isotopes similar to the lower mantle material (component FOZO or C).

Hotspot-related high terranes are not characteristic for East and Central Asia. In the latter region, a hotspot-like activity at the moving plate similar to one in the Yellowstone hotspot was described only in East Sayan in terms of spatial-temporal shift of Late Cenozoic volcanism relative to a crescent-like high terrane. No any low-velocity columns starting from the lower mantle or plume-derived mantle composition were defined in Cenozoic volcanic rocks. The common component in Cenozoic basalts from South Siberia showed relatively unradiogenic strontium and neodymium and radiogenic lead ($^{87}Sr/^{86}Sr = 0.7040 - 0.7041$, $\varepsilon Nd \sim +3$; $^{206}Pb/^{204}Pb = 18.1 - 18.2$; $^{206}Pb/^{204}Pb = 18.1 - 18.2$; $^{206}Pb/^{204}Pb = 18.1 - 18.2$). This component is likely represent the sub-lithospheric convective upper mantle domain (Rasskazov et al., 1999). Similar sub-lithospheric common component with higher εNd was recognized also in Cenozoic mantle xenoliths-bearing basalts from East China (Zou et al., 2000). All evidences indicate deep-seated conditions of magmatism in Central and East Asia, which are apparently different from the typical plume-related conditions beneath Northeast Africa.

Development of global seismic tomography brought a new insight on the Cenozoic evolution of East Asia. The recognized high-velocity lower mantle obviously contradicted to hypotheses on hot material ascending from the core-mantle boundary. Resemblance of high-velocity lower mantle beneath the western margin of North America and the eastern margin of Eurasia was interpreted as a result of long-term Mesozoic through Cenozoic subduction of oceanic plates. Studies of the last decade show that Cenozoic rifting and magmatism in Central, Southern, and East Asia were due to combined effects of (1) generation of low-velocity sub-lithospheric mantle, (2) collisional events at plate boundaries, and (3) subduction of oceanic plates beneath the continent (e.g. Rasskazov et al., 1998).

The aim of this study is to find regularities of the Mesozoic through Cenozoic magmatism which could be indicative for formation of high-velocity and low-velocity mantle anomalies beneath East Asia. Magmatic events in the Eurasia-Pacific convergent zone are regarded with special attention to subduction history of oceanic plates. In the convergent zone, magmatic liquids were generated in various sources occurred within the slab, mantle wedge or overriding plate. Petrological and geochemical criteria, applied to erupted basalts, did not show evidence on sources from the mantle levels deeper than 150 ㎞ probably because of shallow re-equilibration of ascending magmatic melts. Hence, demonstration of deeper magmatic processes requires special approaches. Here we present a model for evolution of deep-seated processes using spatial-temporal evolution of magmatism correlated with a shape of the currently active part of the Pacific slab and low-velocity anomalies for searching these features at the previous Mesozoic through Cenozoic development of East Asia.

2. Geophysical data on mantle anomalies

The Western Pacific is dominated by steep slabs (e.g. Gorbatov and Kennett, 2003). In the early 90-ths, the improved P-wave tomography showed a high-velocity slab-like anomaly bending subhorizontally near the leading edge of the Wadati-Benioff zone beneath the South Kuril to Bonin arcs. The recognized stagnated slab fragment extended toward a continent as far as 1,000 ㎞. A high-velocity anomaly was detected also bellow 660-㎞ discontinuity. Steep slabs beneath the northern Kuril and Mariana arcs were recorded to penetrate into the lower mantle (Fukao et al., 1992). Recent high resolution seismic tomography demonstrated fragmented character of the high-velocity slab descending from the Japan Trench underneath Eurasia. The stagnated slab fragment was outlined within the transition zone between 410 and 660 ㎞. Two high-velocity fragments were recognized at the level of the lower mantle (van der Voo et al., 1999).

A possible lateral extension of the stagnated slab below China and adjacent areas at the 660-㎞ and 410-㎞ seismic discontinuities was discussed by Revenaugh and Sipkin (1994) on basis of long-period records of multiple-Sc-S reverberations from intermediate and deep-focus earthquakes. High reflectivity of the mantle was attributed to high olivine content within a basalt-depleted tectonosphere extending below the 410-㎞ discontinuity. The southern boundary between high-velocity slab and low-velocity mantle was defined approximately at latitude of 40° N and the southwestern one was indicated roughly parallel to a continental margin. At the 660-㎞ discontinuity, the southwestern boundary of the seismically fast block was shown obliquely relative to the 410-㎞ boundary (Fig. 1 A). It was registered by decreasing brightness of the reflector usually interpreted as a direct contact of a cold, dense, seismically fast slab material with the lower mantle.

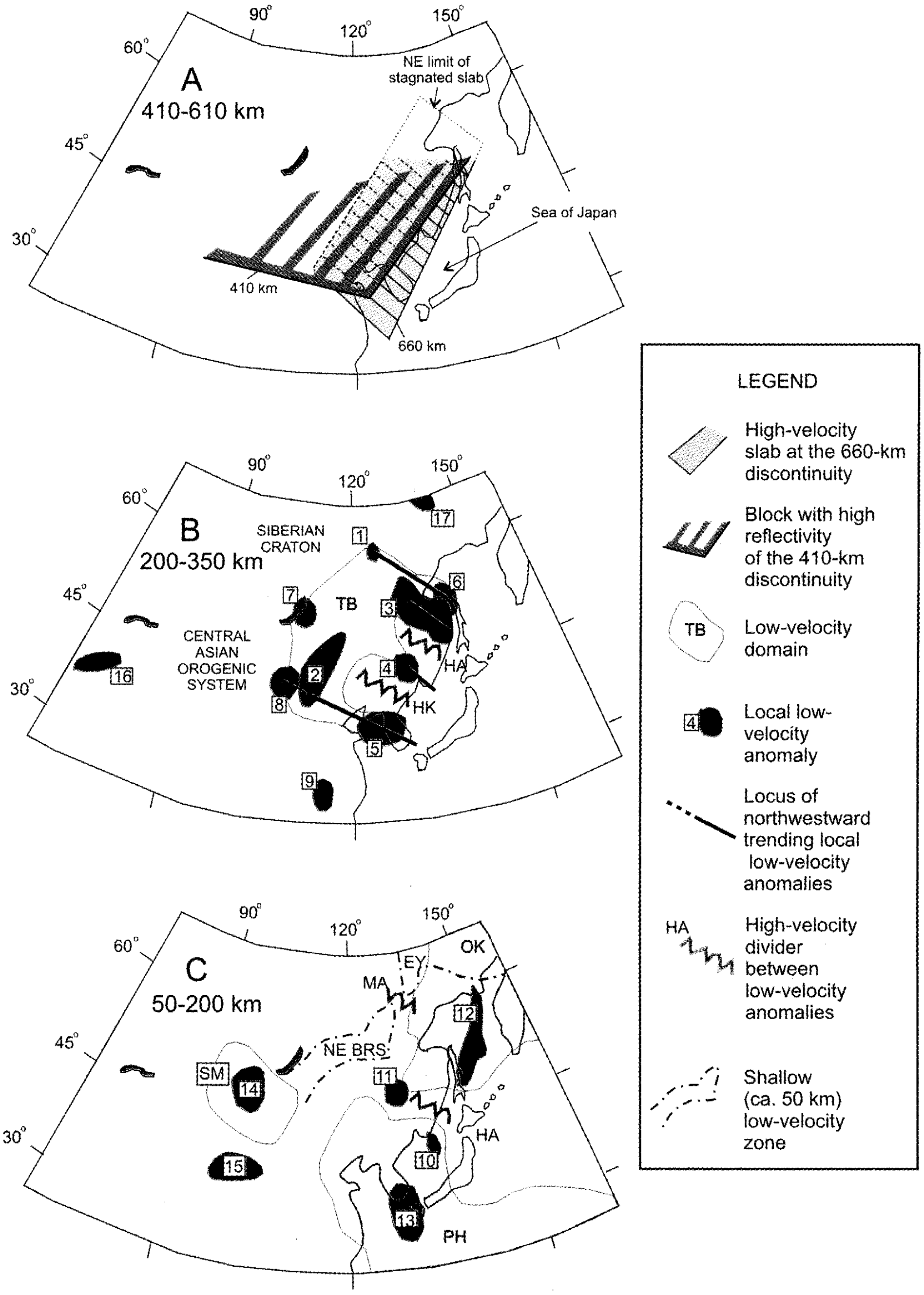


Fig. 1 : Spatial relations of slab-related high-velocity anomalies at the 660-km and 410-km discontinuities (A) and low-velocity anomalies within mantle stages of 200-350 km (B), 50-200 km (C) in East and Central Asia. Block boundaries in (A) are after Revenaugh and Sipkin (1994). The possible northeastern limit of the stagnated slab-like fragment is shown after extrapolating of high-velocity anomaly in the profile GG' of Fig. 7 by Gorbatov et al. (2000). (B) and (C) are modified after Rasskazov et al. (2003). Low-velocity domains: TB - Transbaikal, SM - Sayan-Mongolia, OS - Okhotsk Sea, PH - Philippine Sea. Local low-velocity anomalies: 1 - Lena (depth of 300-350 km), 2 - East Mongolia (250 km), 3 - Sovgavan-Uda (200-250 km), 4 - Amur (200-250 km), 5 - North Korea (200-250 km), 6 - North Sakhalin (300 km), 7 - North Baikal (250 km), 8 - South Mongolia (200 km), 9 - South China (300-350 km), 10 - South Primorye (100 km), 11 - Zeya (100 km), 12 - Sakhalin-Magadan (above the Okhotsk Sea domain), 13 - South Korea (200 km), 14 - North Mongolia (150 km), 15 - Tsaidam (100 km), 16 - Tarim (300-350 km), 17 - Elga (200 km). High-velocity dividers: HA - Hokkaido-Amur, HK - Honshu-Khingan, MA - Middle Aldan. Shallow low-velocity zones: NE BRS - Northeastern Baikal Rift System, EY - East Yakutia. Fig. B demonstrates tracks of low-velocity anomalies defined by directly subducted slab flexures above the mantle transition zone (see discussion in the text).

The expression of the slab at the 660-km discontinuity is spatially comparable with its landward extension at profiles of high resolution seismic tomography (van der Voo et al., 1999). The northeastern limit of the high-velocity fragment is exhibited by T-shape slab junction beneath the northern margin of the Okhotsk Sea (Gorbatov et al., 2000 ; Fig. 7, profile GG').

Seismic tomography shows the Philippine Sea slab fragment dipping at least up to 200 km beneath Eurasia from the Ryukyu Trench. Seismic activity of this slab exhibits the currently active subduction. High-velocity slab-like fragments in the land side of the Okhotsk Sea plate reveal no seismic activity indicating possible formation in the geological past. The high-velocity fragment extends beneath the Late Mesozoic Okhotsk-Chukotka volcano-plutonic belt up to the 660-km discontinuity. It was interpreted as a remnant slab subducted before ~55 Ma (Gorbatov and Kennett, 2003). However, no similar deep slab-like fragment was defined beneath the Late Mesozoic East Sikhote-Alin volcano-plutonic belt (Gorbatov et al., 2000).

The stagnated slab-like high-velocity fragment of the transition zone is situated next to the present-day active slab descending from the Japan Trench. The extrapolated northeastern margin of the slab at the 660-km discontinuity is apparently separated from the steep active slab downgoing from the Kuril trench. The Okhotsk Sea plate occupies a "window" between the active and stagnated slab fragments.

The tomographic models assume existence of a region with relatively low seismic velocities above the high-velocity slab fragments. Recently, an upper mantle 3D seismic model of S-waves was compiled on basis of long period records of the IRIS system with additional data from temporal digital seismic stations used in 1992-1993 in the Russian-American project "Teleseismic tomography of the Baikal Rift", and digitalized analog records of the Novosibirsk, Irkutsk, and Yuzhno-Sakhalinsk seismic stations during 1975-1987. This seismic image revealed local low-velocity anomalies at depth between 50 and 350 km. The large Transbaikal low-velocity domain was defined in a form of a lens extending between the Baikal and Sea of Japan at a range of 200-350 km. The southeastern portion of the lens was recorded above the Pacific slab fragments (Fig. 1).

3. Timing of magmatic and tectonic events

The Mesozoic through Cenozoic evolution of East Asia was suggested to be governed by successive change of tectonic situations from active continental margin (Jurassic-Berriasian) through transform continental margin (Aptian-Albian) to a continental margin with island arcs (Hauterivian-Cenomanian), and again from active continental margin (Late Cretaceous) through transform continental margin (late Maastrichtian(?)-Paleogene) to a continental margin with island arcs (Neogene). This scheme was inferred from plate reconstructions by Engebretson et al., which constrained northwestward motion of the Kula-Izanagi plate at 100-85 Ma and its westward motion at 85-74 Ma. The change in plate motion at ca. 85 Ma presumed a transition from oblique to frontal subduction of the Kula-Izanagi plate beneath Eurasia (Khanchuk et al., 1997 ; Khanchuk, 2000 ; Parfenov et al., 2003).

The available data indicate that spatial-temporal distribution of Mesozoic and Cenozoic magmatism in East Asia was strongly influenced by the Early Cenozoic structural reorganization. Here we consider, therefore, Mesozoic events, predated the main reorganization, Early Cenozoic ones exhibited the structural change itself, and the later Middle-Late Cenozoic events.

3.2. Mesozoic

3.2.1. Tectono-stratigraphic terranes

The southern part of the Russian Far East was assembled by tectono-stratigraphic terranes of Central Asia and Pacific systems. The latter terranes moved northward with lateral (transform) displacement relative to the former. The youngest sediments and lavas at the Amur suture (Kiselevka-Manoma terrane) dated back to the Hauterivian－middle Barremian (ca. 130-125 Ma) were interpreted as evidence of the final closure of oceanic structure. The northern side of the Amur River area within a corner between the Mongolia-Okhotsk and Amur sutures was considered as the Early Cretaceous Khingan-Okhotsk active continental margin occupied by a magmatic arc extended from Maly Khingan to Okhotsk Sea (Natal'in, 1993). Recent detail studies showed distribution of lithologically identical deposits in both sides of the "Amur suture". As the Michan-Fuchun extension of the Tan-Lu fault zone, this structure was interpreted as an expression of the Early Cretaceous compression due to northeastward motion of the Pre-Cambrian Alchan block (Khanchuk et al., 2004).

Volcanic rocks of high-K calc-alkaline and shoshonitic compositions intercalated with oceanic sediments dated back to the Aptian-Albian in East Sikhote-Alin and Sakhalin were considered as fragments of the Moneron-Samarga island system (Simanenko et al., 2004). The Kema terrane, which belonged to this arc system, overtrusted both the Berriasian-Albian turbidites of the Zhuravlevka terrane and the pre-middle Barremian Kiselevka-Manoma accreted wedge (Fig. 2).

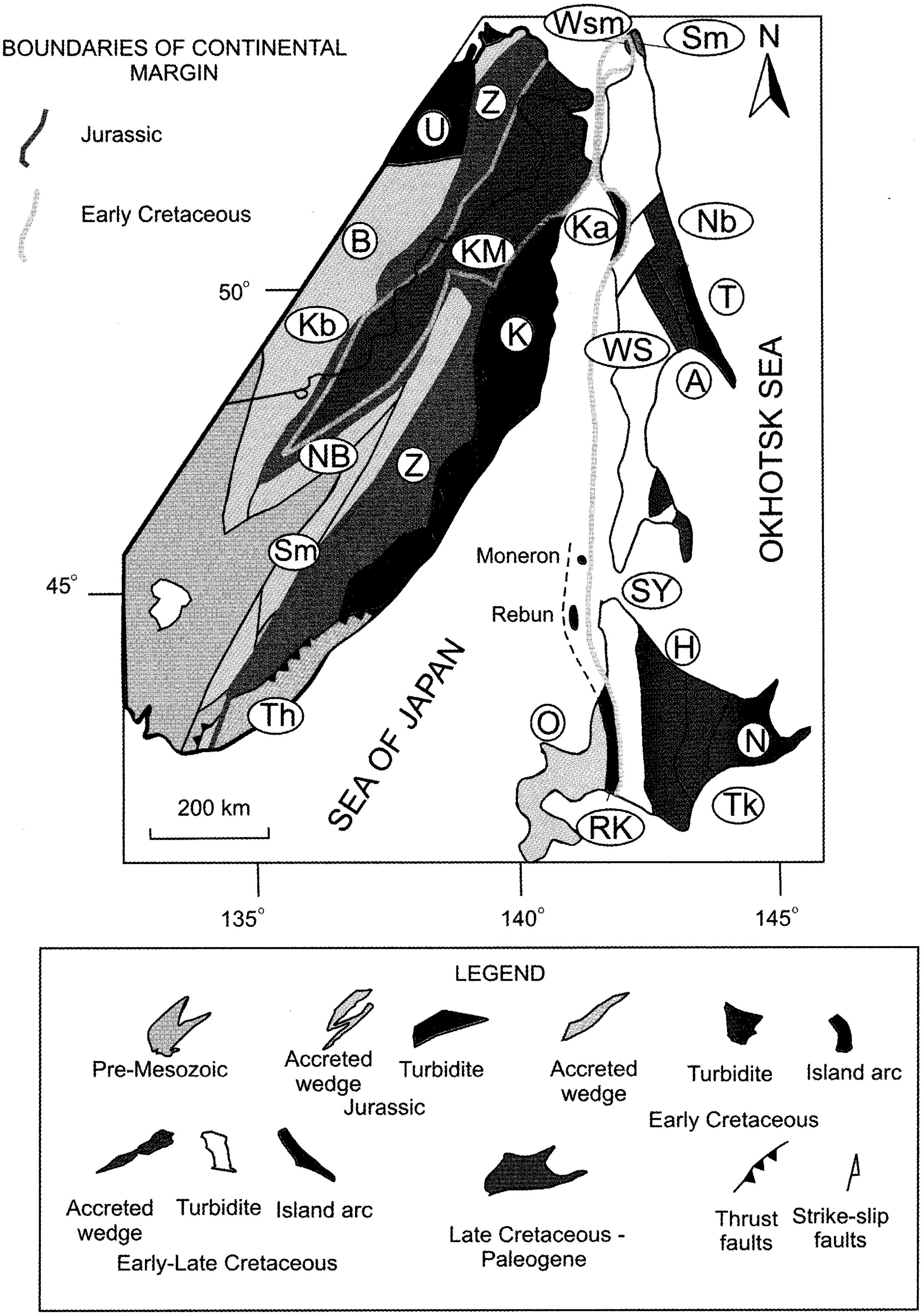


Fig. 2 : Tectono-stratigraphic terranes of Southeast Russia and adjacent area of Northeast Japan: Sm - Samarka, NB - Nadan'khada-Bikun, Kb - Khabarovsk, B - Badjal, U - Ul'ban, KM - Kiselevka-Manoma, Th - Tauha, Z - Zhuravlevka, K - Kema, WS - West Sakhalin, A - Aniva, Nb - Nabil, Sm - Schmidt, Wsm - West Schmidt, Ka - Kamyshovy, T - Terpenia, O - Oshima, RK - Rebun-Kabato, SY - Sorachi-Yezo, H - Hidaka, Tk - Tokoro, N - Nemuro. Scheme is adopted after Simanenko et al. (2004).

According to interpretation by Natal'in et al. (1994), volcanic activity in this island arc could mark initiation of a new subduction boundary (Pacific plate subduction) at the beginning of the Albian (110-107 Ma) after the collision of the Anui microcontinent (Kema terrane) with a continental margin. A subduction beneath an active continental margin was expressed with dominating silicic volcanic eruptions in the East Sikhote-Alin volcano-plutonic belt at the Coniacian through the Companian. The early and late lavas of the belt (Cenomanian and Maastrichtian, respectively) were represented with large volume andesites (Simanenko, Khanchuk, 2003). The Aptian-Albian Moneron-Samarga island arc system could transform into an Andean-type active continental margin in the Cenomanian with transition to long-term activity of the East Sikhote-Alin volcanic belt as it was proposed by Parfenov and Natal' in (1986).

Paleozoic and Mesozoic accreted complexes of southern Sikhote-Alin are well correlated lithologically, biostratigraphically, and geochronologically with those of the Inner Zone of Southwest Japan (e.g. Khanchuk, 2000 ; Ishiwatari and Tsujimori, 2003). This link allows searching coeval Late Mesozoic tectonic processes in frontal accreted complexes and within the continent presuming the common geodynamic context. The Sanbagawa Belt in Southwest Japan exhibits an accreted wedge of the Kula-Izanagi plate. The maximum zircon age consistent with fossil records shows deposition of sediments on oceanic plate at 148-134 Ma. Metamorphic rims of zircons from quartz eclogite and associated metasandstone indicate downgoing wedge material at 132-112 Ma with eclogite faces metamorphism peaked at 120-110 Ma. This is consistent with Rb-Sr whole-rock isochron ages of high-grade pelitic schists at 116 ± 10 Ma. Subsequent exhumation by wedge extrusion with re-equilibration in conditions of epidote-amphibolite facies resulted in 100-90 Ma^{40}Ar/^{39}Ar age of amphibole. Further development was expressed with domal uplift at 90-80 Ma (K-Ar and ^{40}Ar/^{39}Ar ages of white mica) and ultimate emplacement to surface in the latest Cretaceous - Eocene (e.g. Okamoto et al., 2004) (Fig. 3). Itaya and Fujino (1999) showed variations of measured K-Ar ages of phengites from a single outcrop between 86 and 75 Ma due to varied dynamic recrystallization of the rocks. An age interval can be attributed to a metamorphic event only in whole, being in reality a reflection of various kinetic parameters of argon diffusion from minerals.

The Late Mesozoic tectonic events at the mainland of Asia were contemporaneous with transition in kinematics of the Sanbagawa wedge from downgoing subduction to extrusional exhumation. The subduction could develop contemporaneously with the Aptian-Albian Moneron-Samarga arc system, the extrusional exhumation being coeval to the Late

Cretaceous magmatism of the East Sikhote-Alin volcano-plutonic belt developed at the continental margin.

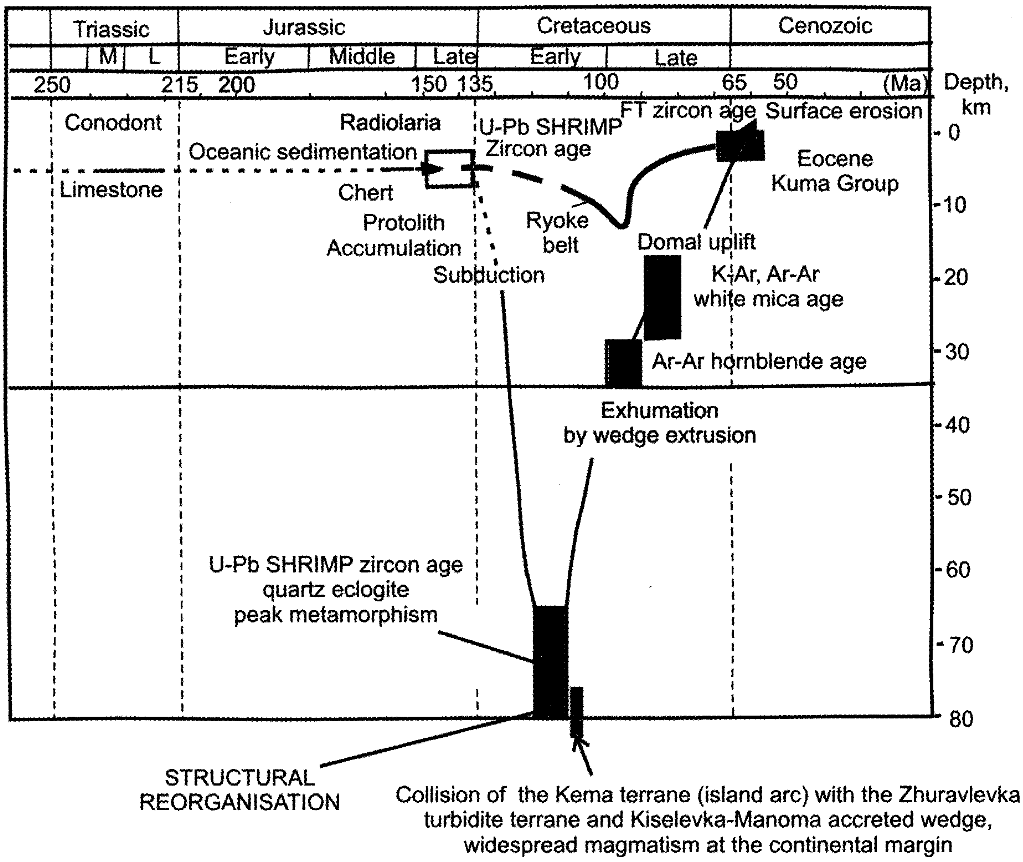


Fig. 3 : Comparison of metamorphic chronology in the Sanbagawa and Ryoke belts with collision of the Anui microcontinent (Kema terrane). Geochronological data of Natal'in et al. (1994), Suzuki and Adachi (1998), Okamoto et al. (2004), and authors. Scheme is modified after Okamoto et al. (2004).

3. 2. 2. Magmatism

The 157-147 Ma volcanic rocks of the Huoshiling Formation and those of 136-113 Ma of the Yingcheng Formation in the Songliao basin are uniform dacites and rhyolites with arc signatures (Wang et al., 2002). Absence of temporal variations of rock compositions does not assume a change in geodynamics between 147 and 136 Ma, when the Mongolia-Okhotsk Ocean was supposed to close along the whole length as it was suggested by Kravchinsky et al. (2002) or can indicate that the initial closure (accretion), expressed in magmatic hiatus, was followed by extensional regime favored to rejuvenation of magmatism in conditions similar to those before the ocean closure.

Volcanic activity along the Mongolia-Okhotsk suture of both the Mongolia-Transbaikal and Songliao areas occurred at 136-113 Ma and finalized simultaneously with a phase of tectonic deformations at 114-112 Ma. ^{40}Ar-^{39}Ar ages of volcanic rocks from the

Maly Khingan and adjacent areas fall largely within the Albian time interval of 108-105 Ma. This interval is comparable to ^{40}Ar-^{39}Ar ages obtained for metamorphic rocks and S-type granites related to collision of the Anui microcontinent (Kema terrane) (Natal'in et al., 1994). Extinction of volcanism in the Songliao basin at 113 Ma and volcanic eruptions in areas to the north between 108 and 98 Ma demonstrate the northward migration of magmatic processes.

Taking into account a relation of the 157-113 Ma monotonous magmatism in the Songliao basin to processes accompanied and postdated subduction of the Mongolia-Okhotsk plate and connection of the 108-105 Ma magmatic pulse with Pacific geodynamics, a structural reorganization with transition from the Mongolia-Okhotsk to Pacific subduction-related magmatism should be constrained at time interval of 113-107 Ma. Some K-Ar and Rb-Sr ages of gabbro and diorite intrusions and Mg-andesites from the Inner Zone of Southwest Japan (San-in and San-yo belts) are within interval of 110-101 Ma (Iizumi et al., 2000). These rocks are coeval to lavas accompanied and postdated structural reorganization at the Khingan-Okhotsk continental margin.

Fig. 3 shows a temporal evolution of metamorphism in the Ryoke belt adjacent to the Sanbagawa. According to CHIME monazite ages, the lower amphibolite facies metamorphism of this zone had peak at ca. 95 Ma simultaneously with commencement of granitic magmatism. In the western part of the Ryoke belt (modern coordinates), magmatism lasted until ca. 85 Ma, whereas in the eastern part continued to ca. 68 Ma (Suzuki and Adachi, 1998). Activity of the East Sikhote-Alin volcanic belt has not been constrained in terms of radiogenic isotope ages. For the time being, its activity is referred in general to the Late Cretaceous (Simanenko, Khanchuk, 2003) and therefore can be comparable with magmatism evolution in the Ryoke belt. In a back-side region of the East Sikhote-Alin volcano-plutonic belt, Late Cretaceous volcanic rocks were recorded in sequences of the Partizansk, Alchan, and Middle Amur basins, but were not found in more westerly distant the Songliao and Amur-Zeya basins (Kirillova, 2003). The latter basins are situated more than 300 km west of the volcano-plutonic belt.

3.3. Early Cenozoic

3.3.1. Magmatism

Recently published K-Ar and Rb-Sr ages of Early Cenozoic volcanic rocks in East Asia fall mostly within two time intervals: (1) the Thanetian centered at 60-55 Ma and (2) the Lutetian centered at 48-43 Ma. Southeast Sakhalin is of particular interest for reconstruction of both the Thanetian and Lutetian events. Here metamorphosed melange after sedimentary rocks from the collisional Susunai terrane was dated by K-Ar method using mica separates at 64.5-54 Ma (Gouchi et al., 1992). An age interval of 49-41 Ma was obtained by K-Ar method using biotite separates from the Aniva S-type granitoid intrusion (Ivanov et al., 1989).

The Thanetian events are widespread around the Okhotsk Sea plate. Gabbroic intrusions, dikes, and volcanic rocks from Shikotan (Lesser Kuril islands) showed a range of K-Ar dates from 62 to 55 Ma (Govorov, 2002). In Southwest Sakhalin, a dacite and a rhyolite from Starodinka River yielded ages of 58 ± 2 Ma and 56 ± 2 Ma, respectively.

Tholeiitic basalts erupted simultaneously with initiation of basin subsidence in North China, Subei and South China Sea in time interval of 64-58 Ma (Zhou et al., 1988). Volcanic eruptions were controlled by the Yitong-Yilan and Mishan-Fushun faults - two north branches of the Tan-Lu fault zone. The Shuangliao Qixingshan volcanoes of the western part of the area produced alkali olivine basalts and basanites with mantle peridotites. In the southeastern part of the Amur-Zeya basin, located in the Far East of Russia adjacent to the Northeast China, a K-Ar age of 58 ± 2 Ma was measured for Mg-andesite flow from the Birma River.

In South Sikhote-Alin, tuffs and ignimbrites of the Bogopolye Formation from the Yakutinskaya volcanic structure were dated in a range of 60-51 Ma by Rb-Sr isochron method using mineral separates. The relative age variations were consistent with a stratigraphic sequence (Popov, Grebennikov, 2001). An age of 54.8 ± 1.8 Ma was reported for volcanic rocks from the same area (Okamura et al., 1998). Two samples of welded tuffs were dated by K-Ar (biotite) and fission-track (zircon) methods (Otofuji et al., 1995 ; 2003 ; Matsuda et al., 1998). One sample yielded dates of 50.6 ± 1.2 Ma (K-Ar) and 47.9 ± 2.6 Ma (FT), another one showed dates of 52.6 ± 1.3 Ma (K-Ar) and 52.1 ± 3.2 Ma (FT). These results were comparable with the estimates of the upper age limit of the Bogopolye formation (Popov, Grebennikov, 2001).

The rocks of the Bogopolye Formation dated at 53-50 Ma were characterized with high magnetic susceptibility and correlated with the Paleogene volcanic rocks in the San'in belt of Southwestern Japan (Otofuji et al., 1995 ; 2003 ; Matsuda et al., 1998). Ages of welded tuffs of the Wangsan Formation of the southeastern tip of Korea were constrained by K-Ar method at 57-46 Ma (e.g. Song et al., 1998).

Beside the Bogopolye Formation, the Sijanov Formation was involved in dating by fission-track method in Sikhote-Alin. This unit was composed of andesitic to rhyolitic welded tuffs with low magnetic susceptibility and yielded fissure-track range of dates from

54.8 Ma to 46.8 Ma (Matsuda et al., 1998). The Sijanov Formation was geologically constrained to be stratigraphically lower than the Bogopolye Formation. Therefore, the eruption age of the Sijanov Formation tuffs should be older than 60 Ma, their younger fission-track dates could reflect a reset ages by a thermal event.

In the Lutetian interval, K-Ar ages were determined at 48-44 Ma for Liyang basalts, North China (Zhou et al., 1988), 45.8 ± 1.1 Ma for a basalt of the Suvorov Formation, South Sikhote Alin (Otofuji et al., 1995), and 47.3 ± 1.8 Ma for a basalt from the same area (Okamura et al., 1998). In Southwest Primorye, the Rb-Sr-isochron age of 46.2 ± 0.5 Ma with $(^{87}Sr/^{86}Sr)_i$ 0.70502 ± 0.00003 and MSWD 1.1 was obtained for a dacite, plagioclase, and biotite of the Shkolnaya extrusion of the Narva Formation (Rasskazov et al., 2004).

In Western Transbaikal, there was a long lull in Late Cretaceous sedimentation between the Albian and Maastrichtian showing relatively calm tectonic environment. Sedimentation began at the Mesozoic-Cenozoic boundary and lasted all through the Cenozoic. Nephelinite and basalt of the Iringa Formation in the Eravna depression (Western Transbaikal) yielded ages of 53.3 ± 1.6 Ma and 50.6 ± 1.6 Ma, respectively (Ivanov et al., 1995). A K-Ar age of 56 ± 4 Ma was obtained for a basalt sample from the same area. K-Ar dates of 61, 59, 57 and 53 Ma were presented by Devyatkin (2004) for basalts from South Mongolia and dates of 68, 59, and 57 Ma for those from Central Mongolia. In an area west of Lake Baikal, the age of 59 ± 5 Ma was calculated also kinetically as the closure age of K-Ar isotopic system for large biotite crystals preserved in a profile of weathering crust. Timing of the closure was interpreted as a moment of weathering cessation due to tectonic reactivation, uplift, and erosion (Logachev et al., 2002). Paleocene basalts from this area - from a volcano-sedimentary unit in the Elovsky spur, the Tunka rift valley - are strongly affected by allitic-type weathering mantles. Such kind of weathering processes could occur only in conditions of the Early Cenozoic warming.

In West Transbaikal, the Lutetian K-Ar ages of 48-39 Ma were determined for basalts situated in the Khilok basin (Ivanov et al., 1995), 300 km southwest of the Thanetian basalts from the Eravna depression. An age of 43 Ma was measured for a basalt sample from Central Mongolia (Devyatkin, 2004).

3.3.2. The 65-50 Ma structural reorganization : expression in East Asia

There was a major reorganization of global plate motions from Mesozoic to Cenozoic patterns in the Early Cenozoic between 53.5 and 37.5 Ma (Rona and Richardson, 1978). One of the remarkable events – India-Asian collision – is dated at 66-50 Ma. We compare the

Early Cenozoic compression in South Eurasia with accretional events in Southeast Sakhalin and Central Hokkaido. In the Thanetian, the Okhotsk Sea plate was accreted to Eurasia. The initial phase of accretion was expressed by deformations and high-grade metamorphism between 64 and 54 Ma in the Susunai and Kamuikotan terranes. By the Lutetian, these processes vanished resulting in emplacement of the S-type granitoids of the Aniva intrusion and similar granitoids in the Eastern zone of Central Hokkaido.

Respectively, volcanic impulses of ca. 58-50 and 48-43 Ma are referred to the beginning and end of the Thanetian-Lutetian structural events. It is interesting to note a spatial redistribution of volcanic eruptions from the Thanetian to Lutetian. The Thanetian sedimentation and magmatism were focused along the eastern margins of the Mongolian, North China, and South China blocks, as well as in the Tunka-Eravna rift zone and South Mongolian basin of Central Asia. The Lutetian magmatism again was concentrated along the eastern margins of the Mongolian, North China and South China blocks but was shifted in Central Asia toward the northwestern boundary of the Mongolian block (Fig. 4). We propose that, similar to the Indian indenter, an interaction between the Okhotsk Sea plate and Eurasia could play a role of a key trigger for initiation of the Thanetian rifting and magmatism in East and Central Asia. As the processes of plate interaction in East Asia vanished, a relative role of collision in the south, between India and Eurasia, increased causing intermittent deformations and magmatism in Central Asia.

Paleomagnetic studies in Sikhote-Alin revealed counterclockwise rotation in the Late Cretaceous−Early Paleogene. This phenomenon was explained firstly in terms of left-lateral motion along north-south trending strike-slip faults. Further analyses of data showed, however, contradiction of this interpretation to paleomagnetic results on the eastern margin of the North China Block. The Bogopolye Formation deposited in the southeastern margin of the ridged Mongolian block without significant rotation relative to Eurasia since 53-51 Ma. The stratigraphically lower volcanic rocks of the Sijanov Formation and Kisin Grope, the earliest ignimbrites of the Late Cretaceous Monastyrskaya and Primorskaya Series of the East Sikhote-Alin volcanic belt, were emplaced when this block rotated counterclockwise up to 41° ± 16°. The rotation was directed oppositely relative to the one of the eastern part of North China Block reconstructed for the latest Early Cretaceous, Late Cretaceous, and post-Cretaceous. This spatial relationship was suggested to be analogous to the one associated with the Early-Middle Miocene opening of the Sea of Japan and to be caused by "a net horizontal force toward the ocean side" (Otofuji et al., 2003 ; p. 210).

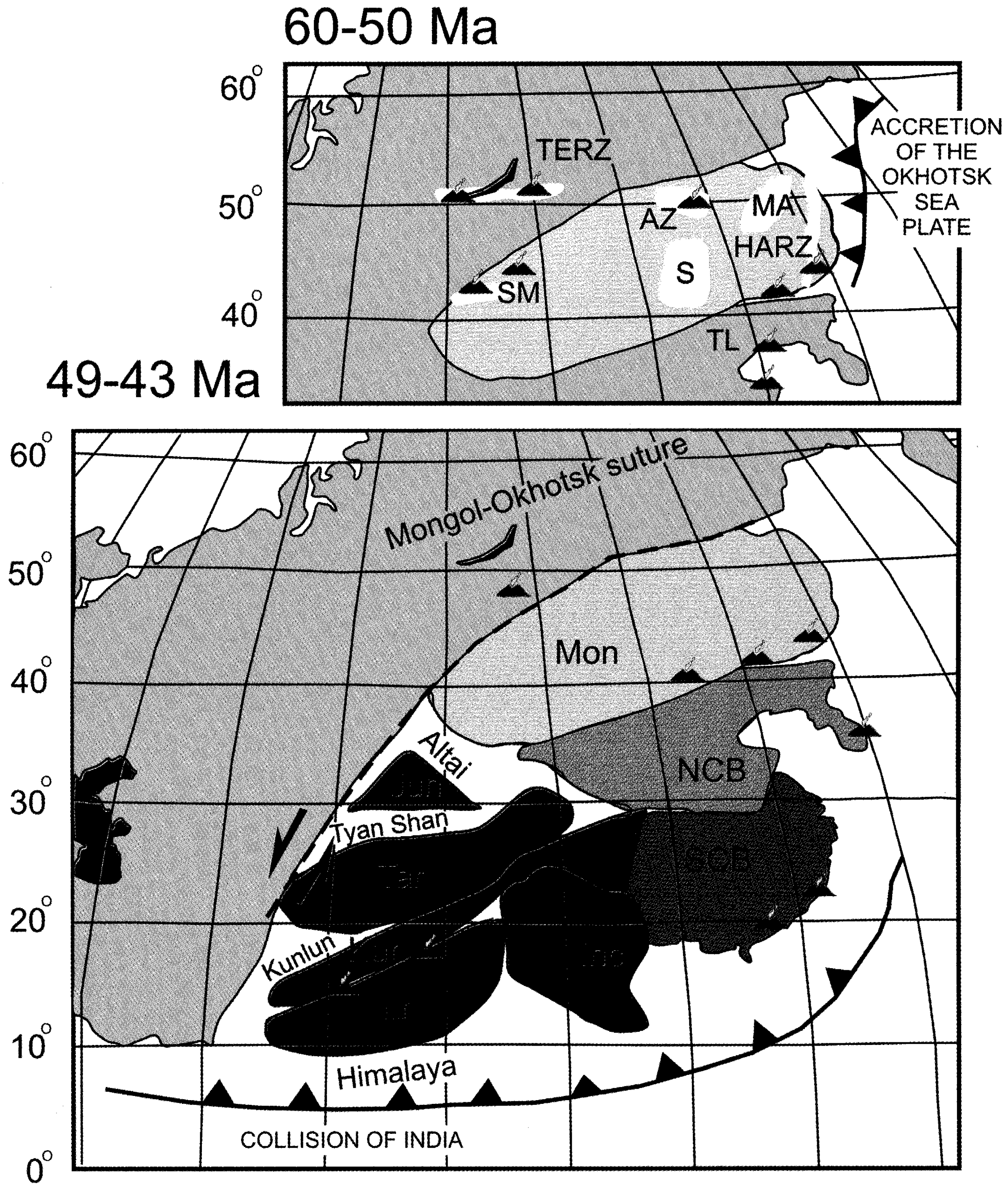


Fig. 4 : Structural and magmatic changes in Inner Asia from 65-50 Ma (A) to 49-43 Ma (B). At the former time interval, tectonic reactivation of East Asia was connected with accretion of the Okhotsk Sea plate. Sedimentation and magmatism were distributed at the Tan-Lu fault zone (TL), Hasan-Amur Rift Zone (HARZ), Amur-Zeya basin (AZ), Tunka-Eravna rift zone (TERZ), and South Mongolian basin (SM). At the latter time interval, within plate deformations of some areas in Inner Asia became dominated by extrusion tectonics caused by India-Asia collision. A scheme of Halim et al. (1996) was adopted for blocks moved since the Cretaceous to the Present as inferred from paleomagnetic data. Block abbreviations are: SCB - South China Block, NCB - North China Block, Mon - Mongolia, Jun - Junggar, Tar - Tarim, Kun - Kunlun, Lh - Lhasa, Inc - Indochina. At 49-43 Ma, magmatic activity was manifested at the southeastern and northwestern boundaries of the Mongolian block, eastern margins of the North China and South China blocks.

3. 4. Middle-Late Cenozoic

3. 4. 1. Sea of Japan back-arc region between the Okhotsk Sea and Philippine Sea plates

Sea of Japan region has a particular history as compared to the Philippine Sea and Okhotsk Sea plates. The former plate originated as an individual tectonic unit by means of back-arc rifting and spreading initiated since ca. 55 Ma with commencement of its subduction beneath Eurasia at ca. 10 Ma (e.g. Deschamps and Lallemand, 2002). Similarly, the Okhotsk Sea plate formed as a tectonic block composed of multiple coalescent (probably in process of opposed subduction) Late Phanerozoic magmatic belts (Govorov, 2002). The block could drift during subduction of the Kula-Izanagi plate beneath Eurasia. Sea of Japan was opened at the continental margin between these two plates.

Similar to the Philippine Sea plate, the back-arc conditions in Sea of Japan caused spreading and formation of new crust with oceanic characteristics. Reconstructions based on magnetic lineation in the Philippine plate focus on two stages of extensional history from ca. 55 Ma to 35-30 Ma recorded in the Western Philippine basin and subsequent extensional events at 30-15 Ma in the Shikoku and Parece Vela basins (e.g. Deschamps and Lallemand, 2002). The latter time interval coincided with Sea of Japan opening. It was agued that the Central Japan trench-trench-trench triple junction did not exist before ca. 15 Ma, there was a plate in the space between the Southwest Japan and Shikoku basin. The triple junction originated at the Philippine Sea plate in the Early-Middle Miocene when it collided with the Japan margin (Hibbard and Karig, 1990).

3. 4. 2. The currently active Pacific slab: geodynamic significance of a shape

Plate margins in the Okhotsk Sea, Philippine Sea plates and Eurasia, bounded with the western part of the Pacific plate, underwent Late Cenozoic extension. Here this process is examined in terms of the Pacific slab deformations.

A shape of the currently active Pacific slab was defined by a top of the seismic zone (Gudmundsson and Sambridge, 1998). The accurate data set was obtained with improved travel times and procedures for depth determination. Three segments divided by flexures were recognized to descend, respectively, beneath the overriding (1) Okhotsk Sea plate, (2) Philippine Sea plate, and (3) Eurasia (Fig. 5).

The prominent feature of the currently active Pacific slab is the Hokkaido-Amur flexure, which stretches landward from a junction between the Japan and Kuril trenches bellow Southwest Hokkaido to the southern end of the Middle Amur basin. Another slab flexure goes from a junction between the Izu Bonin and Japan trenches bellow Central Honshu and the southeastern edge of Korea (Fig. 5 A).

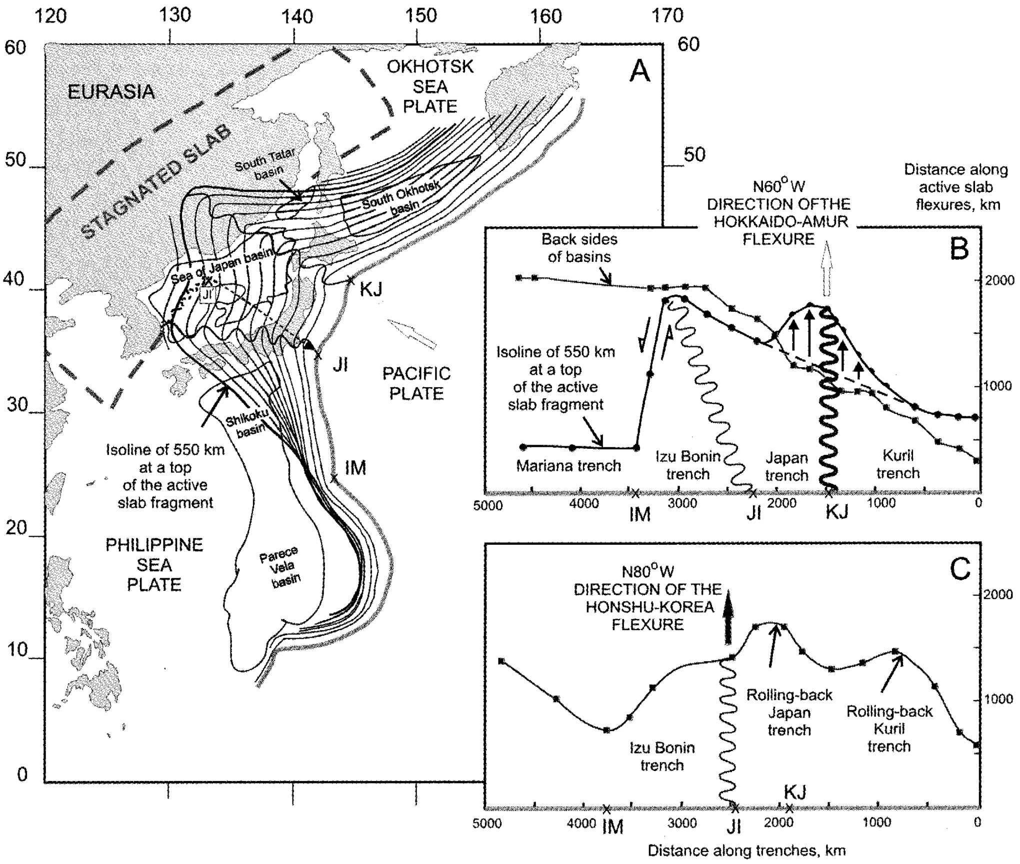


Fig. 5 : Contours of the depth (km) to the top of seismically active subducting Pacific slab (Gudmundsson and Sambridge, 1998) (A). Position of the stagnated slab-like fragment is the same as in Fig. 1. (B) and (C) are graphs showing geometrical relations between trenches (violate lines) and slab flexures (green lines) and also between trenches and back sides of the Late Cenozoic deep basins (pink lines). Trench junctions: KJ - Kuril-Japan, JI - Japan-Izu Bonin, IM - Izu Bonin-Mariana. Direction of the Pacific plate motion on (A) coincides with direction of the Hokkaido-Amur slab flexure on (B) (shown by an open arrow). Orientation of the Honshu-Korea slab flexure, shown by a blue arrow on (C), resulted from the Sea of Japan opening. Approximate shift of the Japan-Izu Bonin trench junction is shown on (A) by blue dashed line along an arrow directed from the former location of the eastern tip of SW Honshu at the northwestern part of Sea of Japan (JI' within a square) to its current position JI. This shift took place in opposite direction relative to motion of the Pacific plate. Vertical arrows on (B) emphasize relative elevation of the Hokkaido-Amur flexure above the main facet of the Pacific slab extending along the Eurasia-Okhotsk Sea sector of relatively steady subduction. The oppositely directed arrows demonstrate transform-like relation at the Honshu-Korea flexure between the Eurasia-Okhotsk Sea and Philippine Sea sectors of the Pacific slab.

Fig. 5 B demonstrates a plot of the modified slab configuration in respect to a common straight trench shown as abscissa. The lowest fully defined isoline of 550 km was chosen to plot the slab projection from a trench to the surface. The parameter increases with decreasing of the slab dipping. Hence, the graph allows relative comparisons of slab dipping. It is compiled at direction of the Hokkaido-Amur flexure. The measured distances of the projection increase from 700 km at the northeastern tip of the South Okhotsk basin to 1820 km at the Honshu-Korea flexure, sharply decreasing along the Shikoku basin. The Hokkaido-Amur flexure is interpreted as a superimposed structure expressed with a relative high of the projection up to 1760 km (relative decrease of dipping). The flexure is trending N60° W in accordance with the long-term Pacific-Eurasia convergence. A gentle slope of the line from the South Okhotsk basin to the Honshu-Korea flexure is attributed to slab configuration existed before northwestern propagation of the Hokkaido-Amur flexure. Hence, the line from the South Okhotsk basin to the Honshu-Korea flexure is a characteristic of the boundary between the Pacific plate and Okhotsk Sea-Eurasia sector just after quick clockwise turn of Southwest Japan at ca. 15 Ma. Sharp descending of the line toward Mariana trench shows a transform-like shift of the Pacific plate boundary between the Okhotsk Sea-Eurasia and Philippine Sea sectors.

To elucidate spatial relation between the Pacific plate shape and subduction-related extension, we plotted also distances from trenches to back-side boundaries of deep basins in coordinates of Fig. 5 B. The distances gradually increase along the profile as slab dipping decreases. The largest distance is defined between the Izu Bonin trench and the western boundaries of the Sea of Japan and Shikoku basins. The correlation may reflect growing rolling-back effect from the middle part of the Kuril trench through the Japan to the Izu Bonin trench. Without further discussion of extensional kinematics in overriding plates, we emphasize only that significant variation of rolling-back effect is inferred here simply from geometrical relations between extensional structures and trenches at direction of the Pacific plate motion.

Graph of Fig. 5 C demonstrates variations of distances between trenches and back-side parts of marginal basins in direction of the Honshu-Korea flexure. The latter flexure stretches obliquely relative to Pacific-Eurasia convergence. The oceanward trench retreat, accompanied formation of the Honshu-Korea flexure, focuses at two maxima centered at the Japan and Kuril trenches when compared with the western boundaries of Sea of Japan and the South Tatar basins, respectively.

The Honshu-Korea flexure appears to originate due to retreat of the Japan-Izu Bonin junction during opening of Sea of Japan. Timing of these processes was constrained by paleomagnatic data. Northeast Honshu was subjected to counterclockwise rotation as long as back arc opening proceeded and Southwest Honshu underwent quick clockwise rotation at about 15 Ma (Otofuji, 1996). On basis of paleomagnetic study at the forearc of the Northeast Honshu, Hoshi and Takahashi (1999) emphasized the earlier rotation of the area between 21 and 18 Ma as compared to Southwest Honshu. Shift of the latter to the present-day position was in opposite direction relative to motion of the Pacific plate. This is consistent with former location of a trench along the mainland of Eurasia and subsequent structural reorganization of overriding plate margins due to rolling-back effect.

The Hokkaido-Amur slab flexure coincides spatially with the high-velocity divider separating the Sovgavan-Uda and Amur low-velocity anomalies (Fig. 1 B). These were formed above the northeastern and southwestern slopes of the Hokkaido-Amur slab flexure, respectively. The Honshu-Khingan high-velocity divider could originate due to similar mechanism. Taking into account possible connection of the latter with landward propagation of the Pacific slab flexure, we speculate that the Honshu-Khingan high-velocity divider also originated due to concentrated landward propagation of the Pacific slab. Respectively, North Korea and Amur low-velocity anomalies could reflect convective instability above slopes of the Honshu-Khingan slab flexure. In process of structural reorganization, the flexure became inactive being converted to stagnated part of the slab, while low-velocity anomalies retained.

The shape of the currently active Pacific slab can be explained by a scenario which involves : (1) initial significant landward propagation of the Honshu-Khingan flexure, governed by relatively steady subduction processes in the Eurasia-Okhotsk Sea sector, (2) transform-like shift at the Pacific plate boundary between the Philippine Sea and Eurasia-Okhotsk Sea sectors responsible for initiation of quick trench retreat at 15 Ma with jump of activity from the Honshu-Khingan flexure to the Honshu-Korea one, and (3) the active landward propagation of the slab at the Hokkaido-Amur flexure.

3. 4. 3. South Primorye as a key area for understanding the Middle-Late Cenozoic magmatic evolution above slab flexures

A stratigraphic sequence of volcanic and volcano-sedimentary rocks includes the units : (1) Narva (rhyolites and dacites), (2) Zaisan (Middle-Upper Eocene calc-alkaline basalts and andesites), (3) Klerk (Upper Eocene high-Ti basalts and trachyandesites), (4) Kraskino (Lower Oligocene rhyolites and dacites), and (5) Slavyanka (Upper Oligocene basalts and andesites) (Figs. 6, 7). The Slavyanka unit was followed by the Lower Miocene coal-bearing sediments and lavas of the Sineutesovsky Formation, the Miocene alluvium of the Ust'-Suifun Formation and the Middle Miocene - Pliocene basaltic lavas of the Shufan Formation. The stratigraphic scheme was compiled on basis of geological mapping, paleontological data, and isotopic dating of volcanic rocks by K-Ar, $^{40}Ar/^{39}Ar$, and Rb-Sr methods (e.g. Rasskazov et al., 2004).

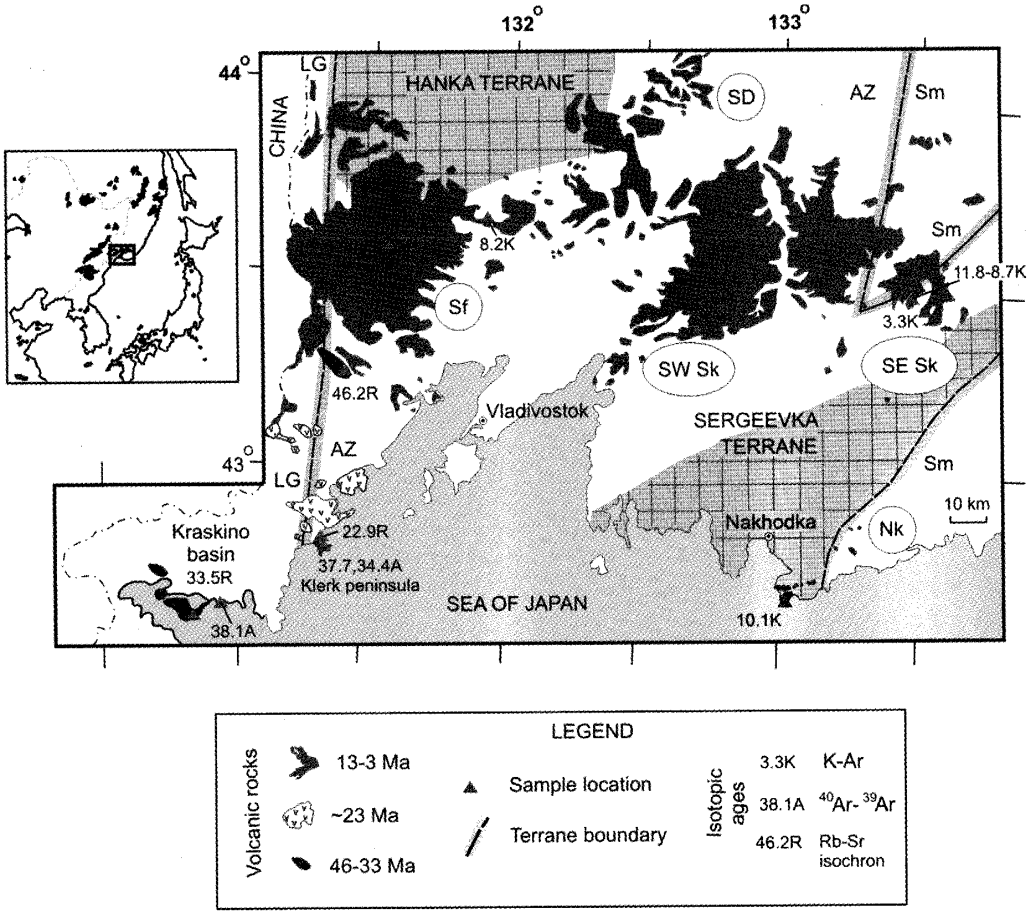


Fig. 6 : Middle-Late Cenozoic volcanic rocks of South Primorye. Volcanic rocks of 46-33 Ma: Narva Formation (46 Ma), Klerk stratum (38-34 Ma), Zaisan Formation (>33 Ma), and Kraskino Formation (~33-32 Ma). Volcanic rocks of ~23 Ma are the Slavyanka Formation. Volcanic rocks of 13-3 Ma are the Shufan Formation. Tectono-stratigraphic units: LG - Laoelin-Grodekov terrane, AZ - Arsenev zone of the Khanka terrane, Sm - Samarka terrane. Isotopic ages are after Okamura et al. (1998) and Rasskazov et al. (2003a, 2004).

Volcanic rocks of the Narva Formation dated at 46 Ma were mentioned in the previous section as the unit related to the Lutetian event followed the Early Cenozoic structural reorganization. The Zaisan Formation occurs in the Kraskino basin. This unit was recorded in drill holes above sediments of the Paleocene - Lower Eocene Nazimov Formation and Eocene-Oligocene flora-bearing part of the Hasan Formation but below lavas of the Kraskino volcano-plutonic complex. The Kraskino basin exhibited the southern part of the Hasan-Amur rift zone trending northeastward up to the Amur mouth.

Lavas from the Klerk peninsula are moderately alkaline basalts with high abundances of TiO_2 (1.5-2.1 wt%) and P_2O_5 (0.55-0.92 wt%), moderately concentrations of MgO (1.8-6.2 wt%), and elevated Al_2O_3 (16.1-17.7 wt%). Trace element ratios, such as Ba/Nb, Ba/La, Ce/Pb etc, are typical for intraplate basalts. High-Ti basalts have no genetic links with calc-alkaline lavas of the Zaisan Formation and are referred here as a separate

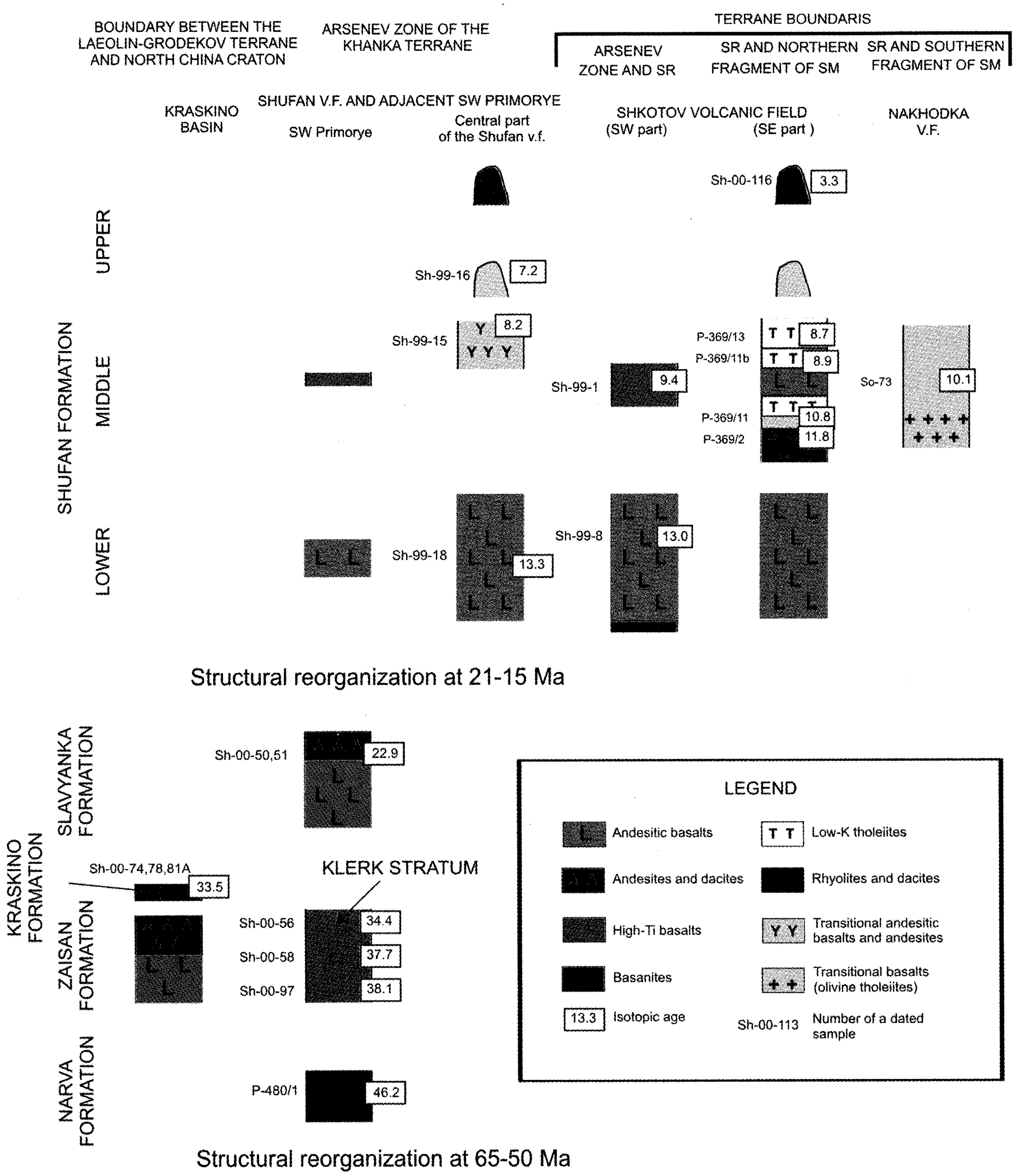


Fig. 7 : A sequence of the Middle through Upper Cenozoic volcanic rocks in South Primorye. Locations of dated samples are shown in Fig. 6.

stratigraphic unit called 'Klerk stratum'.

Two samples of high-Ti basalts from the Klerk peninsula yielded whole rock $^{40}Ar/^{39}Ar$ plateau ages of 37.7 ± 1.3 Ma and 34.4 ± 1.0 Ma. One more $^{40}Ar/^{39}Ar$ plateau age of 38.1 ± 1.3 Ma was obtained for high-Mg basalt dike in the Lukin cape (sample Sh-

00-97, see location on Fig. 6). The dike was the latest one in a rhyolite-dacite-basalt dike sequence. The age obtained is comparable within analytical error with the older age of the high-Ti basalts from the Klerk peninsula. No dating of dacites and rhyolites was performed in K-Ar isotopic system because these rocks could loose radiogenic argon due to heating by younger basaltic dikes.

Rhyolites from the Kraskino Formation yielded the whole rock Rb-Sr isochron age of 33.5 ± 1.1 Ma with $(^{87}Sr/^{86}Sr)_i$ of 0.70467 ± 0.00003 and MSWD of 0.7. This unit was formed after high-Ti basalts of the Klerk peninsula. Taking into account stratigraphic sequence of the Zaisan and Kraskino units, high-Ti basalts of the Klerk stratum are considered as coeval to calc-alkaline basalts and andesites of the Zaisan complex (Fig. 7).

The Slavyanka Formation includes two stratigraphic members. The lower one consists of agglomerate tuffs with rare basalt lava flows. The upper member exhibits trachyandesitic, andesitic, and dacitic lavas as well as trachydacitic and dacitic plagues. An age of the upper member was constrained by Rb-Sr isochron at 22.9 ± 0.3 Ma obtained for two K-feldspar separates and their host rocks of the Nerpa dacite dome. The initial strontium isotope ratio was 0.70416 ± 0.00002 and MSWD 0.8. An age of the lower (basaltic) member of the Slavyanka Formation was not measured.

Late Cenozoic volcanic activity was expressed in formation of four volcanic fields : Shufan, Shkotov, Sandugan, and Nakhodka (Fig. 6). The Shufan volcanic field occupies a margin of the uplifted basement of the Hanka terrane, the subsided Arsenev zone, and adjacent area of the Laoelin-Grodekov terrane, which is situated largely in Northeast China. The Sandugan volcanic field is trending northeastward along the boundary between the Arsenev zone and uplifted basement of the Khanka terrane. The Shkotov volcanic field lies mainly within the Arsenev zone and partly at a margin of the Samarka terrane. The Nakhodka volcanic field is located at the southeastern boundary of the Sergeevka terrane.

K-Ar ages and geochemical data showed three time intervals in evolution of the Late Cenozoic magmatism : (1) interval of initial eruptions at 13.3-13.0 Ma, (2) intermediate interval between 12 and 8 Ma, and (3) finalizing interval from 7.2 to 3.3 Ma. The initial eruptions of uniform andesitic basalts flooded a vast area and created large volcanic shield. In the southwestern part of the Shkotov volcanic plateau, this unit was predated by basanites. The middle stage, also voluminous, was exhibited by eruptions of different lava compositions varied from low-K tholeiitic basalts, andesitic basalts, andesites through moderately alkaline Ti-rich megaplagiophyric basalts and olivine tholeiites to highly alkaline basanites. The final stage was marked by lava flows and extrusions of minor bodies of olivine tholeiites and basanites with deep-seated inclusions (Rasskazov et al., 2003a).

We interpret the Middle Cenozoic magmatism of Southwest Primorye as a result of convective instability in the mantle wedge above the northern slope of the Honshu-Khingan slab flexure. The structural reorganization between 21 and 15 Ma was expressed by a magmatic lull in South Primorye. The subsequent rejuvenation of magmatism in the Shkotov and Shufan volcanic fields at ca. 13 Ma was governed by landward propagation of the Hokkaido-Amur slab flexure reflecting convective instability in the mantle wedge above the southern slope of the latter.

3.4.4. Successive evolution of magmatic sources in Northeast Japan Arc

Magmatic evolution of the Northeast Japan Arc reflects subduction of the Pacific plate along the Japan Trench. Volcanic rocks from this arc showed sharp increasing neodymium and decreasing strontium isotope ratios at 15 Ma (e.g. Shuto et al., 1993 ; Ohki et al., 1994). Fig. 8 presents interpretation of a successive change of basaltic through intermediate compositions from this arc in coordinates of initial strontium isotopic ratio ($^{87}Sr/^{86}Sr)_0$ versus 1000/Sr. This type of diagram is usually used for identification of mixing trends.

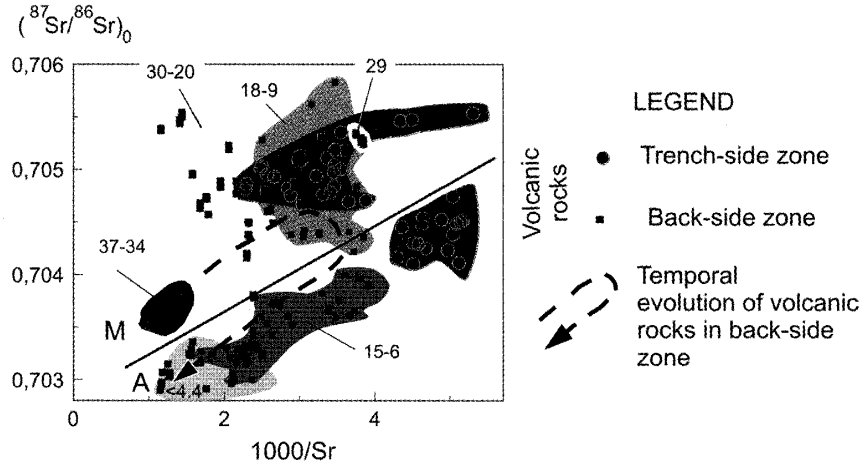


Fig. 8 : $(^{87}Sr/^{86}Sr)_0$ vs 1000/Sr in Middle-Late Cenozoic volcanic rocks of basaltic through intermediate compositions (SiO_2 < 60 wt%) from trench-side - transitional and back-side zones the Northeast Japan Arc. Volcanic rocks from the trench-side - transitional zone have ages <23 Ma. C and S are volcanic material of this zone probably derived from the mantle wedge of the continental margin and subducting slab, respectively. For volcanic rocks from the back-side zone, ages are shown in Ma. Temporal evolution of magmatic sources is directed from isotopically depleted mantle component M of South Primorye (Rasskazov et al., 2003a), to the asthenospheric-like composition A. Data are from (Shuto et al., 1993; Ohki et al., 1994).

Volcanic rocks from the trench-side and transitional zone are subdivided into fields S and C. The former represents a material derived from subducting slab with lower Sr concentration and its depleted isotope composition, as the latter exhibits isotopically more enriched material with elevated Sr abundance from the mantle wedge overriding by the continental lithosphere. Subdivision into two sources was manifested in volcanic rocks from back-side zone reflecting in temporal evolution of magmatism.

Evolution of the mantle wedge processes demonstrates successive decrease of Sr (increase of 1000/Sr) in time interval from 37 to 9 Ma. The oldest lavas of 37-34 Ma were isotopically similar to most depleted mantle component in lavas from South Primorye. The youngest volcanic rocks of 18-9 Ma overlap the C field of the trench-side compositions. Therefore, the evolution of the mantle wedge processes is exhibited by temporal change from mantle sources typical for the continental margin to those of the trench-side zone. Eruptions of material derived from subducting slab in the back-side zone at 15-6 Ma resulted in shift of compositions from the field C of the diagram with decreasing $(^{87}Sr/^{86}Sr)_0$ and 1000/Sr. During the last 4.4 Ma, there was further shift of isotopic compositions with more pronounced decreasing $(^{87}Sr/^{86}Sr)_0$ and 1000/Sr.

3.4.5. Magmatism before and during opening Sea of Japan

There was a magmatic lull between 43 and 38 Ma in Western Pacific (e.g. Deschamps and Lallemand, 2002). Before this time interval, magmatism was predominated by crustal melting focused at two areas: (1) South Primorye with adjacent Southeast Sakhalin and Hokkaido, (2) Southeast Korea and adjacent Southwest Japan. Fig. 9 shows that the former magmatic area was possibly spatially connected with the Sikhote-Alin slab flexure trending from the hypothetic trench junction along the boundary between the Okhotsk Sea plate and Eurasia.

Tectonic reactivation of the continental margin accompanied with mantle-derived magmatism at 38-34 Ma in the northern part of the East Sikhote-Alin, North and South Sakhalin, Okushiri island, and Oga peninsula, Northeast Honshu (Okamura et al., 1998; Fukase and Shuto, 2000; Rasskazov et al., 2004). High-Ti lavas of the latter location, dated at 33.5 Ma, are geochemically comparable to high-Ti lavas from the Klerk peninsula.

Basaltic magmatism of Southwest Primorye was apparently finalized at 33-32 Ma by silicic eruptions of the Kraskino Formation. Coeval silicic magmatic activity was dated at 33.5-31.7 Ma by K-Ar method on unaltered biotite separates from granites of the Hamada cauldron located in the Inner Zone of Southwest Japan (Imaoka et al., 2001). Granites and volcanic rocks of I-type magnetite series emplaced at 30 Ma were considered as the youngest events in the Cretaceous-Paleogene San-in belt (Iizumi et al., 2000). In the Kyeongsang basin of the southeastern tip of the Korean peninsula, granites are comparable geochronologically and compositionally with granites from the San-in belt of Southwest Honshu (Kim et al., 1997).

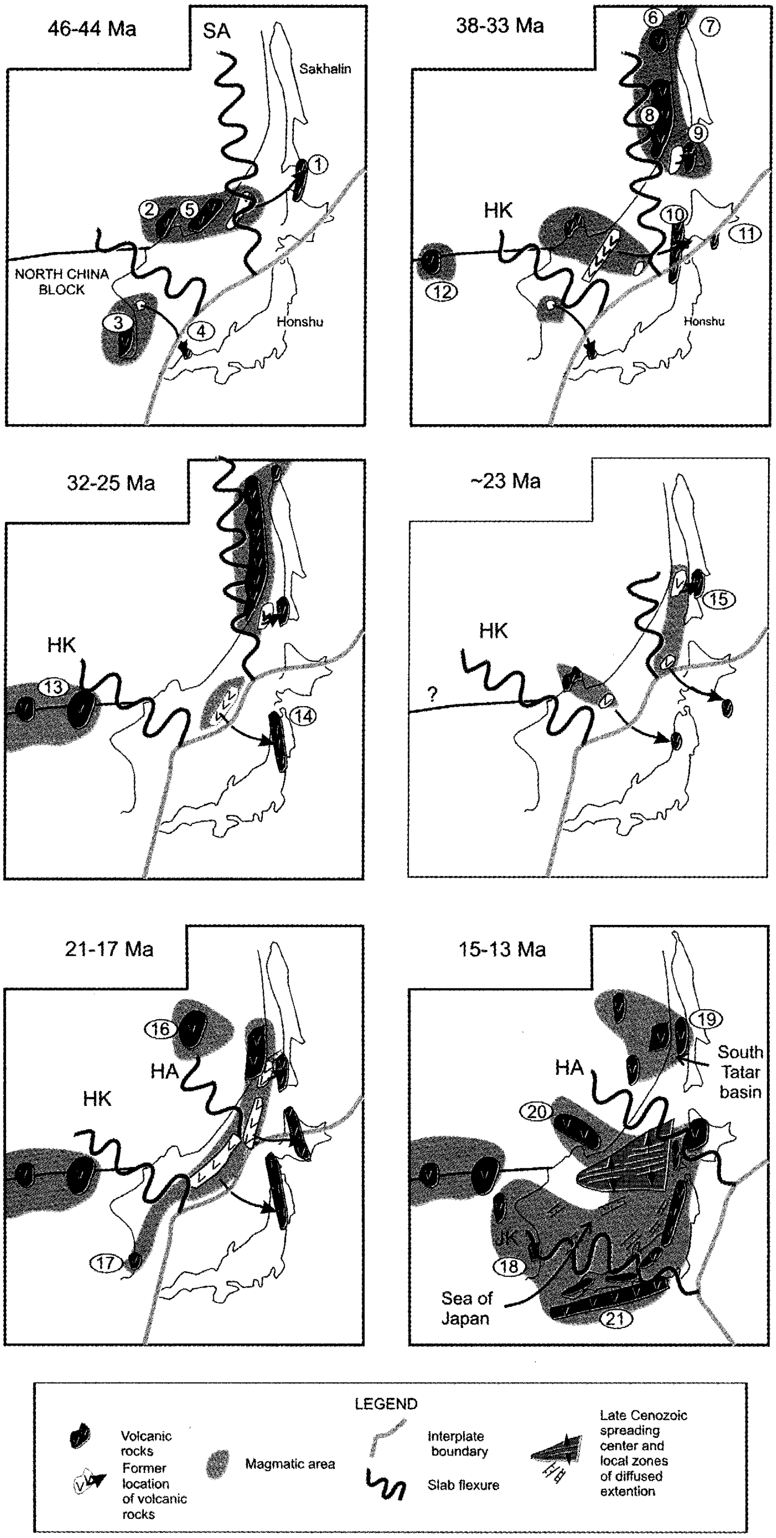


Fig. 9 : Spatial-temporal distribution of Middle-Late Cenozoic magmatism in East Asia before and simultaneously with opening of Sea of Japan. Volcanic areas: 1 - Southeast Sakhalin and East zone of Central Hokkaido, 2 - Southwest Primorye, 3 - Korea, 4 - Inner zone of Southwest Japan, 5 - southern part of East Sikhote-Alin, 6 - northern part of East Sikhote-Alin, 7 - Schmidt peninsula in North Sakhalin, 8 - central part of East Sikhote-Alin, 9 - Chekhov zone of Southwest Sakhalin, 10 - Okushiri, 11 - southern part of West zone in Central Hokkaido, 12 - northeastern part of Shansi rift, 13 - Tan-Lu, 14 - Northeast Honshu, 15 - Southwest Sakhalin, 16 - Maly Khingan, 17 - Southeast Korea (area south of the Hyeongsan fault), 18 - Pohang basin (area north of the Hyeongsan fault), 19 - Lesogorsk zone of Southwest Sakhalin, 20 - Shkotov and Shufan plateaus, 21 - Southwest Japan.

Volcanism of 38-32 Ma was localized partly in areas of the previous 46-44 Ma eruptions in the back-side of the Northeastern Honshu arc between the Sikhote-Alin and Honshu-Khingan flexures. Some eruptions extended along the west-east trending lineament concordant to the northern boundary of the North China Block. The earliest basalt of the Shansi rift of China (Fanshi) yielded a K-Ar age of 35.9 ± 0.3 Ma (Xu et al., 1996). The eastern end of the lineament was in Central Hokkaido.

In East Sikhote-Alin, magmatism rejuvenated along north-south trending lineament spatially connected with the Shikhote Alin slab flexure (Fig. 9). Here and in adjacent areas of North and South Sakhalin, intermittent volcanic activity lasted between 38 and 25 Ma. Trace element signatures of erupted lavas showed involvement of subduction-related component. Magmatic quiescence in the Schmidt peninsula (northern tip of Sakhalin) at ca. 25 Ma was marked by a phase of highly alkaline basanite magmatism reflected temporal transition from mantle wedge processes to melting of continental lithospheric mantle.

A volcanic episode of ca. 23 Ma was recognized in the Uetsu area of Notheast Honshu (Yamaji, 1990) and in Southwest Primorye. The latter area was characterized by subduction-related K-rich basalts, andesites, and dacites of the Slavyanka complex (Rasskazov et al., 2004). Coeval eruptions were dated in the Makarov district of Southeast Sakhalin (Takeuchi, 1997) and at the DSDP site 439 located about 150 km south of the Cape Erimo of Hokkaido (e.g. Maeda, 1990). The episode of 23 Ma falls within the 25-20 Ma magmatic hiatus in East Sikhote-Alin (Tatsumi et al., 2000). Fig. 8 demonstrates concentration of volcanic activity along the northeastern wing of the Honshu-Khingan flexure and the eastern wing of the Sikhote-Alin one.

Magmatism of 21-17 Ma is of particular interest as the process developed prior to the main event of structural reorganization at 15 Ma. Volcanic eruptions took place in Northeast Honshu and Sea of Japan showing arc-type trace element signatures. In Central Hokkaido, long-term arc magmatism was considered to finalize at 17 Ma (Maeda, 1990). According to new data, high-Ti non-arc type basalts erupted here at 19 Ma (Okamura et al., 2000) or from 19 to 14 Ma (Hirose and Nakagawa, 1999). These lavas are coeval with those from the Chekhov Formation of the Chekhov zone in Southwest Sakhalin dated at 21-17 Ma. However, lavas of the latter formation show arc-type trace element signature changed to the non-arc type at ca. 16.2 Ma with northward shift of volcanism to the Lesogorsk zone (Rasskazov et al., 2005). Similar temporal shift was recognized in Southeast Korea, where mostly andesitic lavas with arc-type trace element signature erupted south of the Hyeongsan fault between 22 and 16 Ma being postdated by basalts with “within-plate” characteristics in the area north to the Hyeongsan fault (Pohang basin) at 15-13.6 Ma (Song et al., 1998).

Activity of the Hokkaido-Amur flexure probably began between 21 and 17 Ma. As a result, subduction progressed simultaneously along two direct flexures, Honshu-Khingan and Hokkaido-Amur. Volcanic eruptions were distributed along their outer slopes and between the flexures in the Northeast Honshu Arc.

3.4.6. Magmatism after opening Sea of Japan

After 15 Ma, East Asia was developed to new spatial-temporal pattern of deep-seated processes responsible for a long-term magmatic activity lasted in the continental margin from ca. 15 Ma to 3 Ma. Spatial-temporal variations of trace elements and Sr isotopes in lavas from the Middle Amur basin and South Primorye demonstrate three intervals in magmatic evolution: (1) the initial of 15-13 Ma, (2) intermediate of 11-8 Ma, and (3) finalizing of 5-3 Ma. The initial 15 Ma episode of the Middle Amur basin was dominated by alkaline mantle magmatism. In South Primorye, the episode of 13 Ma was characterized by large volume subduction-related andesitic basalts predated by basanites. The intermediate stage of 11-8 Ma was expressed in both regions by eruptions of magmatic liquids of variable compositions ; in the former - basanites, leucitites, hawaiites, transitional (olivine-hypersthene-normative) basalts, and andesitic basalts, in the latter - basanites, hawaiites, transitional olivine-hypersthene-normative basalts, andesitic basalts, low-K tholeiitic basalts, trachyandesites, and andesites. At the final stage, both regions revealed highly alkaline mantle-derived magmatic activity (Rasskazov et al., 2003 a, b).

The central part of East Sikhote-Alin and western shore of Sakhalin (Lesogorsk zone) were magmatically similar to the Middle Amur basin reflecting common processes in the South Tatar region of mantle instability.

Common processes of mantle instability in the Sea of Japan region were responsible for similarities of magmatism in South Primorye and Southwest Honshu. The 13 Ma episode of voluminous andesitic basalts in the former was coeval to eruptions of high-Mg andesites of the Setouchi volcanic belt dated by K-Ar method within a short period of 13.2 ± 0.4 Ma (Tatsumi et al., 2001). The 11-8 Ma interval of magmatism from varying sources of South Primorye also has a coeval magmatic counterpart in Southwest Japan. Morris and Itaya (1997) demonstrated that basalts and basaltic andesites of the Matsue Formation, dated at 11.0 ± 1.5 Ma, covered the whole range of Sr-Nd-isotopic compositions of Cenozoic basalts from Southwest Japan. Temporally, volcanic rocks from Southwest Japan show generally decreasing strontium isotope ratios with increasing neodymium isotope ratios as role of the subcontinental lithospheric end-member decreased and role of the lower crustal one increased. No typical MORB or MORB-like source materials were identified in this area (Terakado et al., 1997).

We examine resemble magmatic events at 13 and 11-8 Ma in South Primorye and Southwest Japan as manifestation of coeval activity in the mantle wedge above southern wings of the active Japan-Korea and Hokkaido-Amur slab flexures in the back-arc mantle instability region of Sea of Japan, in distance over 1000 km from the Japan Trench.

4. Discussion

4.1. Constraints on development of lower mantle processes

The Earth's evolution is believed to be governed by variations of the thermal conditions in the lower and upper mantle which regulated exchange of material at the 670-km boundary. Numerical models show efficiency of an avalanche mechanism for global change of convective structure from mainly one-layered to two layered state. This model presumes an initial state of the mantle when local layering of convection could produce no material exchange between upper and lower mantles. Then, the 670-km boundary layer could be destabilized by avalanches of cold upper mantle material with return flows from the hot lower mantle. Inducing of a local decrease of the upper mantle viscosity might cause initiation of plumes rising from the 670-km discontinuity. A restoration of local layering would occur with simultaneous heating of the upper mantle and cooling of the lower mantle. These processes could result in decreasing exchange of material and destroying of the 670-km thermal layer (e.g. Machetel, Humler, 2003). A peak production rate of ocean crust between 120 and 100 Ma was interpreted as a manifestation of a "superplume" that originated near the core-mantle boundary. According to retrospective analysis of plate kinematics in the frame of fixed hot spots, plates possessed rather high kinetic energy during time interval of 100-84 Ma after Mesozoic plume activity. The minimum of the kinetic energy was achieved at about 43 Ma (Larson, 1991 ; Lithgow-Bertelloni, Richards, 1998).

The high-velocity anomaly defined as the "Pacific slab" penetrating from the Japan Trench to the lower mantle (van der Voo et al., 1999) is a time-integrated characteristic of subduction processes lasted during the Mesozoic and Cenozoic. The fragments, which are stagnated at the level of the lower mantle, can be attributed to the Mesozoic subduction of oceanic plates.

We propose that subduction of the Mongolia-Okhotsk plate beneath East Asia prior to its closing at ca. 140 Ma was important precursor for the Cretaceous and Cenozoic geodynamics. The structural reorganization at ca. 140 Ma resulted only in partial change of magmatic pattern. The Kula-Izanagi slab was dipping in the opposite direction relative to the Mongolia-Okhotsk slab. At 120-110 Ma, the Kula-Izanagi slab could contribute a dense material to fragments of the stagnated Mongolia-Okhotsk slab. Particular conditions of relatively low viscosity in the lower mantle at the Cretaceous Quiet Period of 119-83 Ma favored disturbance of the 660-km discontinuity accompanied with mass exchange between transition zone and lower mantle. As a result, a dense slab fragment (or fragments) drowned down the lower mantle and a returned flow of the hot mantle created conditions for widespread magmatism around the Mongolia-Okhotsk slab at 122-113 Ma. Therefore, the lower mantle beneath East Asia became anomalously overloaded with dense material of the Mongolia-Okhotsk and Kula-Izanagi plates. The subsequently subducted Kula-Izanagi and Pacific slabs could penetrate into the transition zone but not into anomalously dense highly viscose lower mantle. Beneath East Asia, the slab material was spread above the 660-km discontinuity, although it could drown steeply into the lower mantle with normal physical characteristics beneath the North Kuril and South Izu-Bonin island arcs. The structural reorganization of East Asia resulted in initiation of slabs subduction from Northwest Pacific occurred at 113-107 Ma under accompaniment of voluminous magmatism of 108-105 Ma.

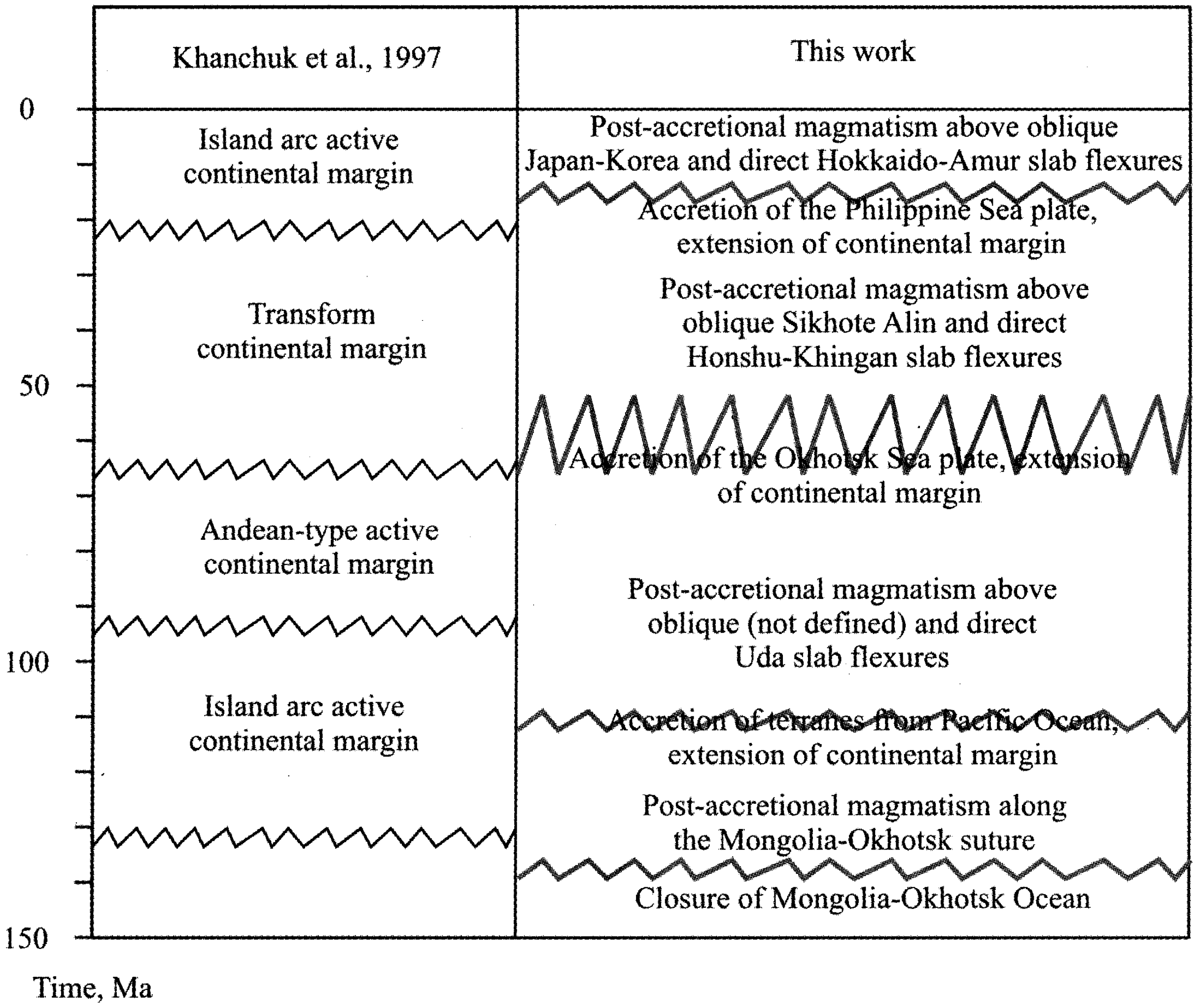
4. 2. Origin of East Asian anomalous mantle region

The anomalous mantle region of East Asia could originate due to particular subduction style at the Pacific-Eurasia convergent zone. Oceanic slabs penetrated into transition zone being flattened in a process of landward propagation. If the transition zone water-rich (Karato, 2003), slabs could induce its destabilization, resulting in ascending of fluids up to the 200-350 km level and in development of melting processes. This mechanism seems plausible because a flat subduction into the shallow mantle prevents magmatic activi ty. For instance, the currently active flat fragment, downgoing as deep as 200 km, causes a magmatic gap in the central part of the Andean volcanic belt (Cahill and Isacks, 1992).

Numerical simulations of deformation and dynamics of horizontally lying slab beneath East Asia demonstrated possibility of steep subduction with appearance of a flat fragment assuming ca. 40-Ma history of the Pacific slab (e.g. Yoshioka and Sanshadokoro, 2002). Low-velocity anomalies of the whole Transbaikal domain were explained also within a frame of the Middle-Late Cenozoic geodynamics (Rasskazov et al., 2003). Spatial coincidence between the high-velocity slab-like fragment in the mantle transition zone and low-velocity

Transbaikal domain at depth of 200-350 km requires, however, a discussion of the whole history of the anomalous region in terms of common Mesozoic through Cenozoic subduction. Connecting the shape of its southern part with the Middle-Late Cenozoic subduction history of the currently active Pacific slab, we propose that the northern part can be related to similar processes of the earlier subduction history (Table 1). The proposed model shown on Fig. 10 takes into account : (1) magmatism evolution connected with the Mesozoic and Cenozoic subduction history of oceanic plates, (2) effect of accretion of the Philippine Sea and Okhotsk Sea plates, and (3) mechanism of lateral translation of slab flexures during structural reorganization recognized from analysis of the active Pacific slab shape.

Table 1 : Tectonic and magmatic evolution of East Asia inferred from geological data (Khanchuk et al.,1997) and analysis of magmaic activity (this work)



Khanchuk et al., 1997	This work
Island arc active continental margin	Post-accretional magmatism above oblique Japan-Korea and direct Hokkaido-Amur slab flexures
	Accretion of the Philippine Sea plate, extension of continental margin
Transform continental margin	Post-accretional magmatism above oblique Sikhote Alin and direct Honshu-Khingan slab flexures
	Accretion of the Okhotsk Sea plate, extension of continental margin
Andean-type active continental margin	
	Post-accretional magmatism above oblique (not defined) and direct Uda slab flexures
Island arc active continental margin	Accretion of terranes from Pacific Ocean, extension of continental margin
	Post-accretional magmatism along the Mongolia-Okhotsk suture
	Closure of Mongolia-Okhotsk Ocean

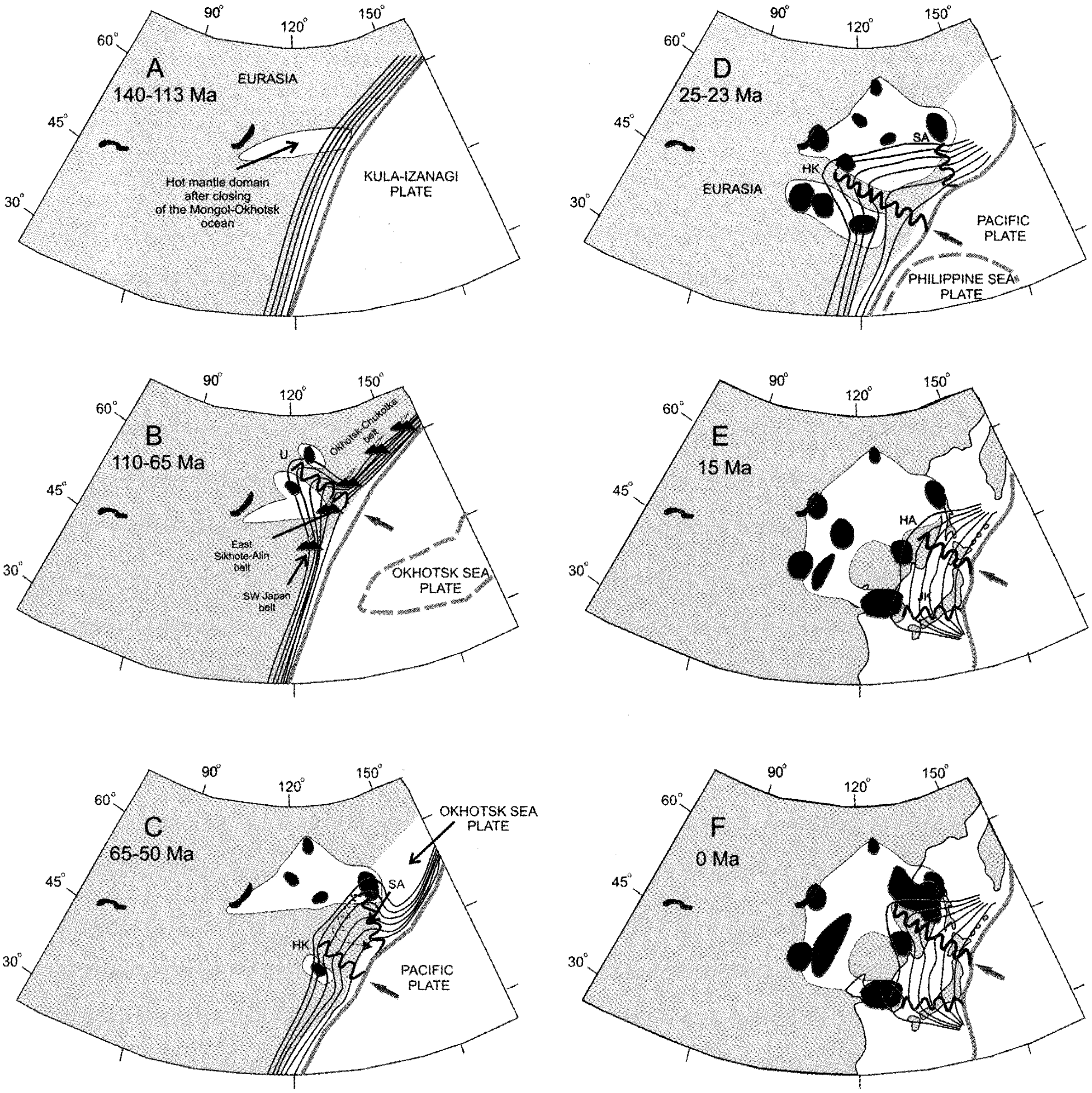


Fig. 10 : Scheme of successive formation of the Transbaikal low-velocity domain at depth of 200-350 km beneath East Asia as inferred from evolution of subduction-related magmatism during the Mesozoic and Cenozoic. Anomalies are shown as in Fig. 1 and slab flexures as in Fig. 5. The latter are in order of activity: U - Uda, SA - Sikhote-Alin, HK - Honshu-Khingan, HA - Hokkaido-Amur, JK - Japan-Korea. An arrow indicate active subduction at direction of slab flexure.

The Early Cretaceous remnant hot zone beneath the Mongolia-Okhotsk suture zone played a role of an heterogeneity favored to inducing the Uda slab flexure of the Kula-Izanagi plate beneath Eurasia by mechanism similar to the Late Cenozoic one. The oblique flexure could exist to the south of the Uda one assuming mechanism of northward translation of flexures. In the Cretaceous, before accretion of the Okhotsk plate, the gentle directly subducted slab fragment might extend landward for more than 1000 km beneath Aldan shield of the Siberian craton producing the most remote low-velocity Lena anomaly.

Accretion of the Okhotsk Sea plate was contemporaneous to reorganization of the subduction system in East Asia between 65 and 50 Ma. The Uda flexure could not continue subducting beneath Eurasia beyond the accreted Okhotsk Sea plate. Similar to the Early-Middle Miocene transition from the Honshu-Khingan to the Japan-Korea flexure, the Uda one was transferred to the Sikhote-Alin one simultaneously with extension of continental margin between the North China and Siberian cratons and clockwise rotation of East Sikhote-Alin. The north-south orientation of the active Sikhote-Alin flexure was oblique in respect to the northeastward motion of the Pacific plate. Magmatism in the Paleogene Terpenia magmatic belt of East Sakhalin (Fig. 2) could just postdate the main rotation similar to the high-Mg andesitic 13 Ma Setouchi magmatic belt of Southwest Japan.

After the magmatic lull of 43-38 Ma, volcanic activity rejuvenated along the eastern wing of the Sikhote-Alin slab flexure probably reflecting a back-side drag effect beyond the landward moving slab flexure. This area became a locus of extension in the Tatar Strait. Magmatism of back-arc type marked activity of the Sikhote-Alin slab flexure lasted until 25 Ma. Afterwards, downgoing motion concentrated at the Honshu-Khingan slab fragment. The latter was responsible for formation of low-velocity anomalies distributed along the southern boundary of the Transbaikal domain. We speculate that significant landward propagation of the Honshu-Khingan slab flexure at 25-23 Ma triggered perturbation of the mantle material in the western portion of the Transbaikal low-velocity lens expressed in initiation of volcanism in the Baikal Rift System at 22-21 Ma.

Tomographic image in Fig. 1 C shows a low-velocity domain at depth of 50-200 km extended from the Philippine Sea toward continental margin. Low-velocity mantle upwelling could initially concentrated beneath the Philippine Sea plate producing back-arc spreading at 30-15 Ma and could cause heating of the shallow mantle beneath continental margin during Early-Middle Miocene accretion. Coalescence of the Philippine Sea low-velocity domain with the subduction-related low-velocity anomalies beneath the continental margin could produce the main extensional effect in Sea of Japan simultaneously with tectonic relaxation and cessation of spreading in the Shikoku basin at about 15 Ma. The Hokkaido-Amur high-velocity divider between the Philippine Sea and Okhotsk Sea low-velocity domains possibly separates dynamically disconnected mantle regions.

Conclusions

Oceanic plate subduction played a leading role in evolution of Mesozoic through Cenozoic magmatism and tectonics in East Asia generating the high-velocity anomaly in the mantle transition zone between 410 and 660 km and the low-velocity Transbaikal domain identified above the transition zone at depth of 200-350 km. The anomalous mantle region was a result of time-integrated subduction processes temporally changed due to structural reorganizations at ca. 140, 113-107, 65-50, and 21-15 Ma.

Mesozoic subduction processes defined the northern margin of the anomalous mantle region. The Mongolia-Okhotsk Ocean closed by ca. 140 Ma and left dense slab material with a low-velocity domain responsible for magmatic activity lasted along the Mongolia-Okhotsk suture until 113 Ma. During the Cretaceous Quiet Period of 119-83 Ma, the Mongolia-Okhotsk slab, combined with the subducted Kula-Izanagi slab material, drowned into the lower mantle. By 65 Ma, the directly subducted slab fragment of the Kula-Izanagi plate extended landward for more than 1000 km beneath Aldan shield of the Siberian craton.

The Early Cenozoic structural reorganization was contemporaneous to accretion of the Okhotsk Sea plate to Eurasia and could produce the Sikhote-Alin slab flexure with trench rolling-back motion, block rotations, and extension at the continental margin. The slab flexure was oblique relative to plate convergence and widened to the south due to landward growing of the directly subducted Honshu-Khingan slab flexure. The latter was responsible for perturbation of the mantle material along the southern margin of the anomalous region.

The Late Cenozoic subduction developed similarly. The structural reorganization was coeval to accretion of the Philippine Sea plate to Eurasia resulting in formation of the Japan-Korea oblique slab flexure, trench rolling-back effect, block rotations, and extension at the continental margin. The current subduction activity of the Pacific slab is exhibited by the oblique Japan-Korea and direct Hokkaido-Amur flexures.

The suggested scenario for magmatism evolution in East Asia assumes that oblique flexures never developed during ordinary regime of oceanic plate subduction and formed due to structural reorganization of subduction system accompanied accretion to East Asia of plates or terranes. Activity of an oblique flexure explains development of magmatism with arc-type signatures in a distance over 1000-2000 km from a trench. Such magmatism took place at a transitional period of slab adaptation to new structural conditions and temporal transformation of oblique flexure into directly subducted slab fragment. The Late Mesozoic development was apparently favored to northward translation of subduction processes focused on the direct Uda flexure. After the 65-50 Ma and 21-15 Ma tectonic events, the direct Honshu-Khingan and Hokkaido-Amur slab flexures were formed due to southward and northward translations of subduction processes, respectively.

Acknowledgments

Authors are grateful to authorities of the Center for Northeast Asian Studies of the Tohoku University, Director of the Center Katsuyoshi YAMADA for financial support of the cooperative project. The administrative assistance of Maiko OGURA and the help in computer drawing of Tatiana RASSKAZOVA are highly appreciated. The paper was prepared partly on basis of data obtained during the cooperative study of the Siberian and Far East Divisions of Russian Academy of Sciences on a project N70, projects of the Russian Science Foundation for Basic Research grants 03-05-64036, 03-05-65218, and 05-05-64393.

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