Pre-Neogene tectonics of the Sea-of-Japan region: A view from the Russian side

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Pre-Neogene tectonics of the Sea-of-Japan region: A view from the Russian side

Alexander I Khanchuk*

Abstract This is a review paper presenting an original regional plate-tectonic model based on the data recently obtained on the geological structure and history of the Sea-of-Japan region. Several paleogeographic schemes for the Jurassic-Cretaceous time represent the author's geodynamic model for the development of this region. This model is clearly distinctive from the previous ones by postulating that the Californian-type transform margin has been one of the most significant geodynamic settings in the Mesozoic-Cenozoic East Asia. The author's paleogeodynamic model includes a geologic reconstruction of the pre-Neogene position of the Japanese Islands according to which the Central Sikhote-Alin, Tanakura and Median faults were parts of a single Early Cretaceous tectonic line. In addition, Early Cretaceous and Paleogene transform plate boundaries, Jurassic and Late Cretaceous supra-subduction continental margins, and Early Cretaceous island arc are recognized. The Early Cretaceous strike-slip movements likely resulted in a gigantic S-form structure of Sikhote Alin. Some Early Cretaceous and Paleogene magmatic rocks are recognized to indicate specific geodynamic structures, namely "slab windows".

Key Words: plate tectonics, East Asia, Paleozoic, Mesozoic, Cenozoic, Californian-type transform margin, slab window.

Introduction

This is a review paper presenting original regional plate-tectonic models based on the data recently obtained on the geological structure and history of the Sea-of-Japan region. Paleogeodynamic analysis is used herein as a research method related to the theory of plate tectonics. This method applies in retrospect the models of geodynamic settings existing now between and inside the modern lithospheric plates. Currently, most researchers believe that plate tectonics is based on convective flows within the upper mantle, while plume tectonics is connected with some hot and high-density flows ascending from the Earth's core toward the lower mantle (Dobretsov and Kirdyashkin 1994 ; Maruyama 1994 ; Rundkvist et al. 2000). Definite rock assemblages and tectonic movements, whose specific features are used for paleogeodynamic reconstruction, characterize each geodynamic setting. A lack of information on deep-seated rocks in the modern environments as well as evolutionary changes of the mantle composition sufficiently limits application of paleogeodynamic analysis. Nevertheless, the method is widely used as it has given researchers an additional instrument to evaluate a validity of the retrospective models that have been made using another approach. Recently, even geologists who did not adopt the plate tectonics concept apply some elements of paleogeodynamic analysis in their works. Polemics on this issue is considered to be fruitful if it does not grow into revision of the basic ideas of plate tectonics, which in the last twenty-year period has been supported by various scientific facts. Among them are the recent plate motions recorded by the direct instrumental observations and paleomagnetic data, different sedimentation rates between continental margins and oceanic environments reported by the deep-sea drilling, etc.

During the last decade, in the region under consideration, several researches and reviews on accretionary, collisional, strike-slip, and rifting paleogeodynamics have been carried out (Khanchuk et al. 1989a ; Utkin 1989, 1999 ; Zonenshain et al. 1990 ; Natal'in 1991 ; Nokleberg et al. 1994, 1998 ; Sengör and Natal'in 1996 ; Bogdanov and Filatova 1999).

A concept of the pre-Neogene tectonics in the Sea-of-Japan region is related to the reconstruction of the East Asian continental margin as it was before the opening of the Sea of Japan. The new version of correlation between tectonic structures of the Russian and Japanese sides of the sea, which is discussed in this paper, has been made according to the scenarios based on the paleomagnetic data and Miyashiro-type orogeny (Otofuji 1996 ; Maruyama 1997).

Major structural elements of the southern Far East Russia

Various types of geodynamic settings repeatedly appeared in the geological history of the study region. Related struc-

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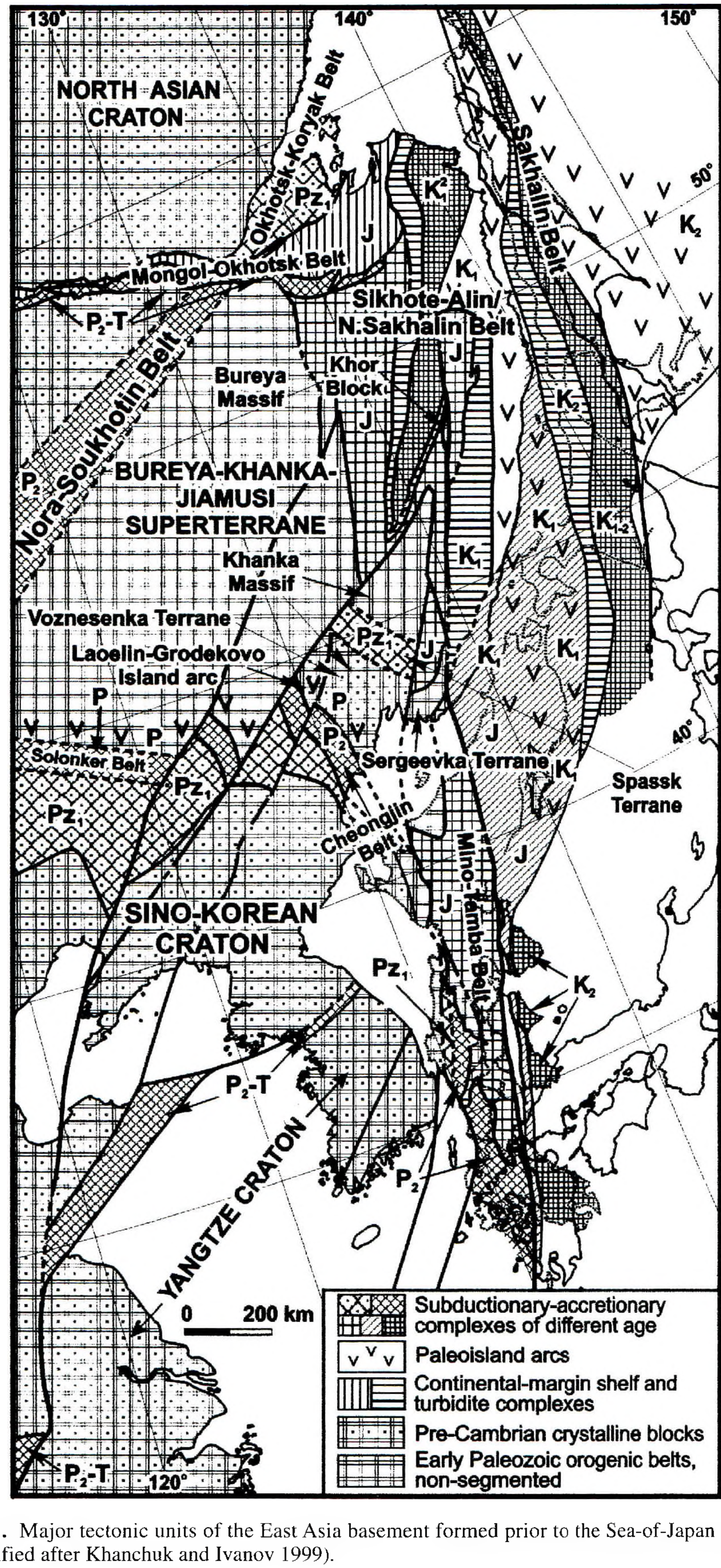

Fig. 1. Major tectonic units of the East Asia basement formed prior to the Sea-of-Japan opening (modified after Khanchuk and Ivanov 1999).

tures and rocks are clearly divided into complexes of the two types : (1) heterogeneous blocks of the basement bounded by faults (terranes) ; and (2) overlying assemblages composed of volcanic and sedimentary rock sequences separated from each other and from underlying terranes by sedimentary (stratigraphic) contacts. In addition, the belts of intrusions, which occur across and/or along the boundary of different terranes, are distinguished (Parfenov et al. 1998).

Recently a considerable progress has been achieved on identification of geodynamic nature of major structural units of the southern Far East. Of particular value are the works by Parfenov (1984) and Natal'in (1991) who have developed the principal paleogeodynamic models. At the same time, because of a lack of information available, many ideas remain to be discussed. A generalized tectonic scheme of the East Asian basement and its overlying assemblages are represented in Figs. 1 and 2, respectively. Therein, the generally accepted structural units: the North Asian (Siberian) Craton, Khanka and Bureya massifs, all evolved as continents or their parts since Middle Paleozoic time, are clearly distinguished from the epioceanic orogenic belts varying in age of the main folding and formation of their continental lithosphere. The latter are the Mongol-Okhotsk (Mesozoic), the Sikhote Alin-North Sakhalin (Early-Late Cretaceous), and the Sakhalin (Paleogene) belts. In addition, some researchers have distinguished the Okhotsk-Koryak orogenic belt (Khanchuk and Belyaeva 1993). Let us dwell on the questions that remain to be discussed and solved.

Bureya-Khanka-Jiamusi (BKJ) superterrane

Khanka and Bureya massifs

The Khanka and Bureya massifs as well as several massifs located in China (the Jiamusi and some others) are regarded here as elevations of ancient crystalline rocks situated inside the Middle Paleozoic superterrane that has not been named in literature yet. Below it is noted as the BKJ (Bureya-Khanka-Jiamusi) superterrane. This structure is distinguished as a combined tectonic unit since its components altogether are bounded by the same fold belts, namely Nora-Soukhotin accretionary complex to the west and the Cheongjin accretionary complex (named as belts in Fig. 1) to the south, both of which are of Late Paleozoic age. These complexes were resulted from the closure of the western and eastern branches of an ocean basin existed in between the North-China and Bureya-Khanka-Jiamusi continents during the Mid-Late Paleozoic time.

According to another plate tectonic model (Sengör and Natal'in 1996), the Bureya and Khanka massifs are considered as portions of the Sino-Korean craton and surrounding Early Paleozoic orogenic belts. However, our study shows that the Khanka massif is heterogeneous, and includes particular terranes as follows (Khanchuk et al. 1996).

Voznesenka terrane

The Voznesenka terrane consists of the Late Riphean(?) - Cambrian terrigenous and carbonate rocks deposited in a continental-margin environment and intruded by the Early Ordovician (450 Ma) and Late Silurian (411 Ma) granites (Belyatsky et al. 1999 ; Khetchikov et al. 1995).

Spassk terrane

The Spassk terrane or suture (Natal'in 1991) is recognized to the north of the Voznesenka terrane. The Spassk terrane is an accretionary-wedge terrane, and is composed of Early Paleozoic turbidites containing blocks of Cambrian ophiolite, chert, and limestone. In its typical subduction melange known as the "sandy-shale" suite (Khanchuk et al. 1996), well-preserved blocks of oceanic ribbon chert with abundant Cambrian microfossils have been found (Kemkin and Rudenko 1997).

Khanka and Bureya massifs to the north of the Spassk terrane

In the Khanka and Bureya massifs to the north of the Spassk terrane, the metamorphic domes showing the greenschist to granulite facies metamorphism predominate. The Late Riphean-Cambrian limestone, ophiolite, and siliceous-terrigenous deposits represent an original rock assemblage of the massifs. There is no evidence for the previously suggested Archean or Lower Proterozoic age of the deeply metamorphosed rocks from the Khanka and Bureya massifs. The age of the initial low-temperature metamorphism of the Khanka massif rocks, based on Sm-Nd isotopic dating, is 733 ± 25 m.y. (Mishkin et al. 2000). The recent ion-probe analyses of zircon grains from granulitic rocks of the Jiamusi massif showed that the correspondent metamorphism occurred 502 ± 8 and 498 ± 11 Ma, that is in the Late Cambrian (Wilde et al. 1997). At the same time, the granulites of the Jiamusi massif are considered by most researchers to be similar to those of the Khanka massif.

Overlying assemblage of the Bureya and Khanka massifs

The strata overlying the Bureya and Khanka massifs range in age from Silurian to Cenozoic. In the Khanka massif, the Upper Ordovician-Silurian terrigenous deposits are distributed. Continental and shallow-water sedimentary, volcanic and plutonic rocks formed in relation to rifting during Devonian-Carboniferous time. The magmatic rocks are mostly rhyolites (95%) and belong to the bimodal series. Basalts are characterized by high titanium and aluminum contents. The Permian deposits of the Khanka terrane are represented by

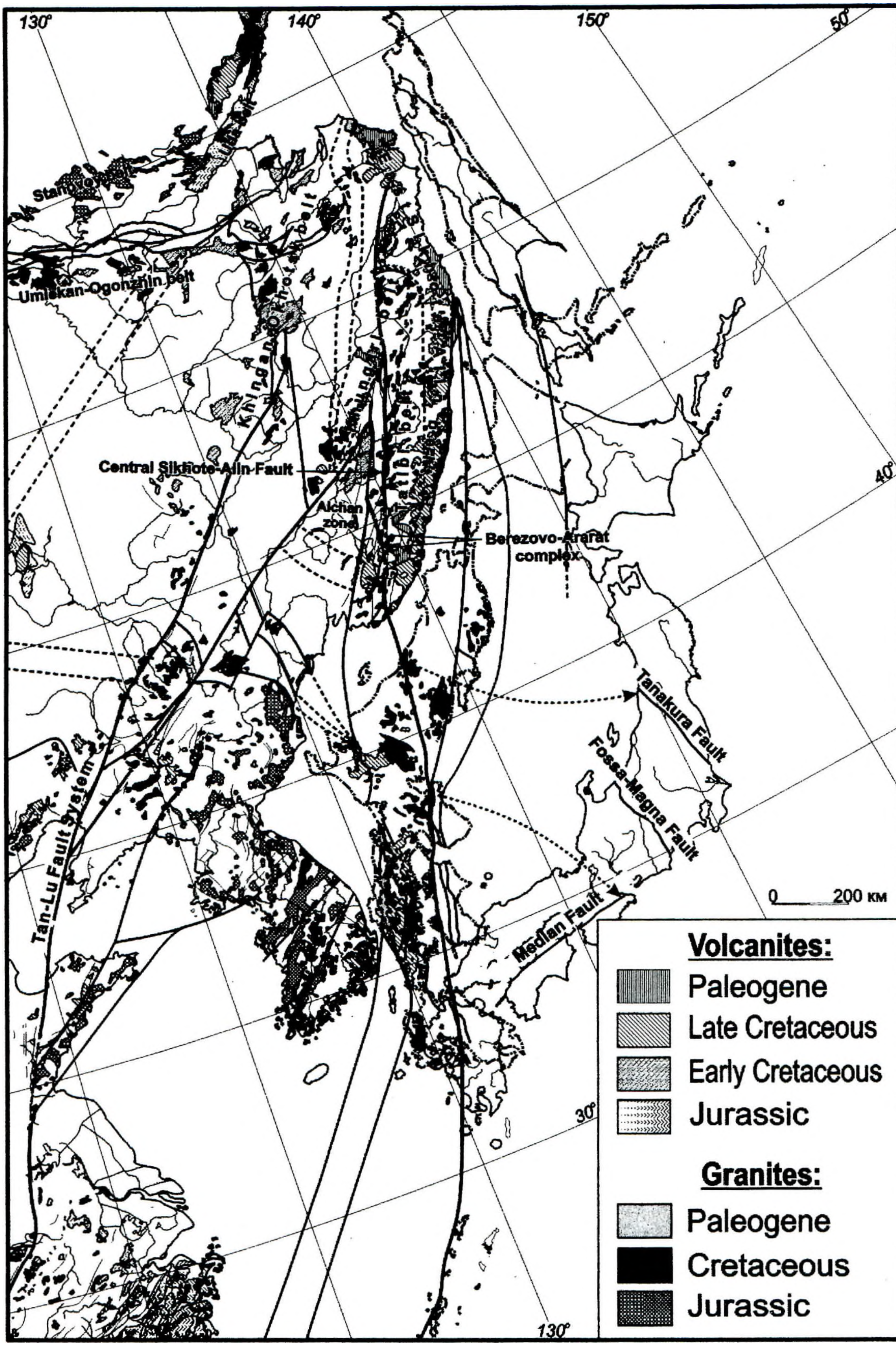

Fig. 2. The Mesozoic and Paleogene volcanic and plutonic complexes of the East Asia. The pre-Neogene reconstruction of relative positions of the complexes was modified from Khanchuk and Ivanov (1999).

rift-related series of rocks formed within a marginal sea beyond the Laoelin-Grodekovo island arc mentioned below. The associated basalts contain up to 2 wt.% of TiO_2 that is typical for rift-related basic volcanic rocks. The Late Permian rift-related granites are common as well (Levashev 1991). The Triassic consists of shallow-marine and continental deposits. In the southern part of the Khanka terrane, the Late Triassic (Norian) tuffs have been found (Korzh 1959). The Jurassic includes shallow-marine and continental terrigenous deposits locally containing lenses of limestone and sparse pyroclastic rocks.

The rock sequences overlying the Bureya and northern Khanka massifs are different from those in the southern areas, where scarce outcrops of the Devonian terrigenous rocks represent the Middle Paleozoic. The Permian and Triassic rocks, which are similar in composition to those described in the southern Primorye, occur only in the area of the Bolshie Churki Ridge (a left bank of the Amur river, south of Birobidzhan City) within the Bureya massif (Kotlyar et al. 1997). In the remaining areas, Late Triassic and Late Jurassic to Early Cretaceous deposits have been recorded. The Bureya massif is quite special because of widely distributed granites of the Early Ordovician, Permian, and, less commonly, Late Triassic age.

Laoelin-Grodekovo terrane

The Laoelin-Grodekovo terrane occupies the southwestern margin of the BKJ superterrane, and consists of Permian island-arc-related volcano-plutonic complexes. Locally, the Lower Silurian volcanic and sedimentary rocks are distributed. This terrane marks the rear part of an epicontinental island arc, whose frontal part is characterized by the subduction-accretionary complex exposed in North Korea and China.

Sergeevka terrane

The Sergeevka terrane is a specific tectonic unit that forms nappes and klippes over the Jurassic Samarka accretionary-wedge terrane belonging to the Sikhote-Alin/North-Sakhalin orogenic belt (see below). The sergeevka terrane has been folded together with the Samarka terrane. Some fragments of the Sergeevka terrane have been displaced along the Central Sikhote-Alin Fault, the northernmost of which is named the Khorsky block (Khanchuk 1993).

The Sergeevka terrane is composed of large plutons of synkinematic, gneissose hornblende gabbro and diorite. Although the latter prevail, they are collectively called the "Sergeevka gabbroids" The Sergeevka gabbroids contain blocks of metamorphosed oceanic rocks and gneissose granite with xenoliths of metaterrigenous rocks (Sinitsa and Khanchuk 1991). Emplacement of the synkinematic intrusions with the dates of 528-504 Ma likely resulted from melting of the subduction-related rocks (Khanchuk et al. 1996). The Early Ordovician (492 Ma) granites in turn intrude into the Cambrian plutonic rocks. Upper Devonian volcaniclastic rocks transgressively overlie the Sergeevka gabbroids (Sinitsa 1998), while the Permian deposits rest in a similar way upon the Ordovician granites. The relationship between the Sergeevka plutons and Permian deposits remains enigmatic, because researchers have not yet observed the boundary between the rocks mentioned. The Permian is represented by marine and terrestrial, volcanic and sedimentary deposits including large limestone bodies. Some volcanic rocks are interpreted as related to supra-subduction arc and back-arc rift (Levashev et al. 1989 ; Levashev 1991). The Permian formations are overlain by the Triassic and Jurassic rocks represented by continental and shelf deposits to the west and upper-continental-slope ones to the east. Among the marine deposits, the Late Jurassic subaerial rhyolites (Monakinsky Formation) and presumably supra-subductional andesites (Okrainsky Formation) have been described (Khanchuk et al. 1996). In addition, the Early Cretaceous (Berriasian?) alkaline picrites and basalts (Pogsky Formation) are recorded in some areas of the Sergeevka terrane (Khanchuk et al. 1996).

Sikhote Alin-North Sakhalin orogenic belt

The Sikhote-Alin region of the belt incorporates six terranes : the Samarka, Badzhal, Zhuravlevka-Amur, Taukha, Kema, and Kiselevka-Manoma ones (Fig. 3).

Samarka terrane

The Samarka terrane is exposed along the eastern edge of the Khanka massif. It consists of the Jurassic turbidites containing inclusions of the Devonian ophiolite, Permian and Triassic chert, and Upper Paleozoic limestone (Khanchuk et al. 1988, 1989a ; Volokhin et al. 1990 ; Kemkin and Khanchuk 1993). This and similar terranes, the Mino-Tamba belt in Japan and the Nadanhada terrane in China, are fragments of the same Jurassic accretionary complex (Kojima 1989).

Badzhal terrane

The Badzhal terrane is exposed along the eastern side of the Bureya massif (Fig. 3). In the author's opinion, it is a part of the same Jurassic accretionary complex as the Samarka terrane. A continuous chain of the allochthonous Upper Triassic chert-limestone alternation outcrops along the northeastern and northern Samarka terrane and the eastern Nadanhada and Badzhal terranes gives evidence for this conclusion (Khanchuk 1993). It should be noted that Natal'in (1991) distinguished the Khabarovsk accretionary complex of the Cre-

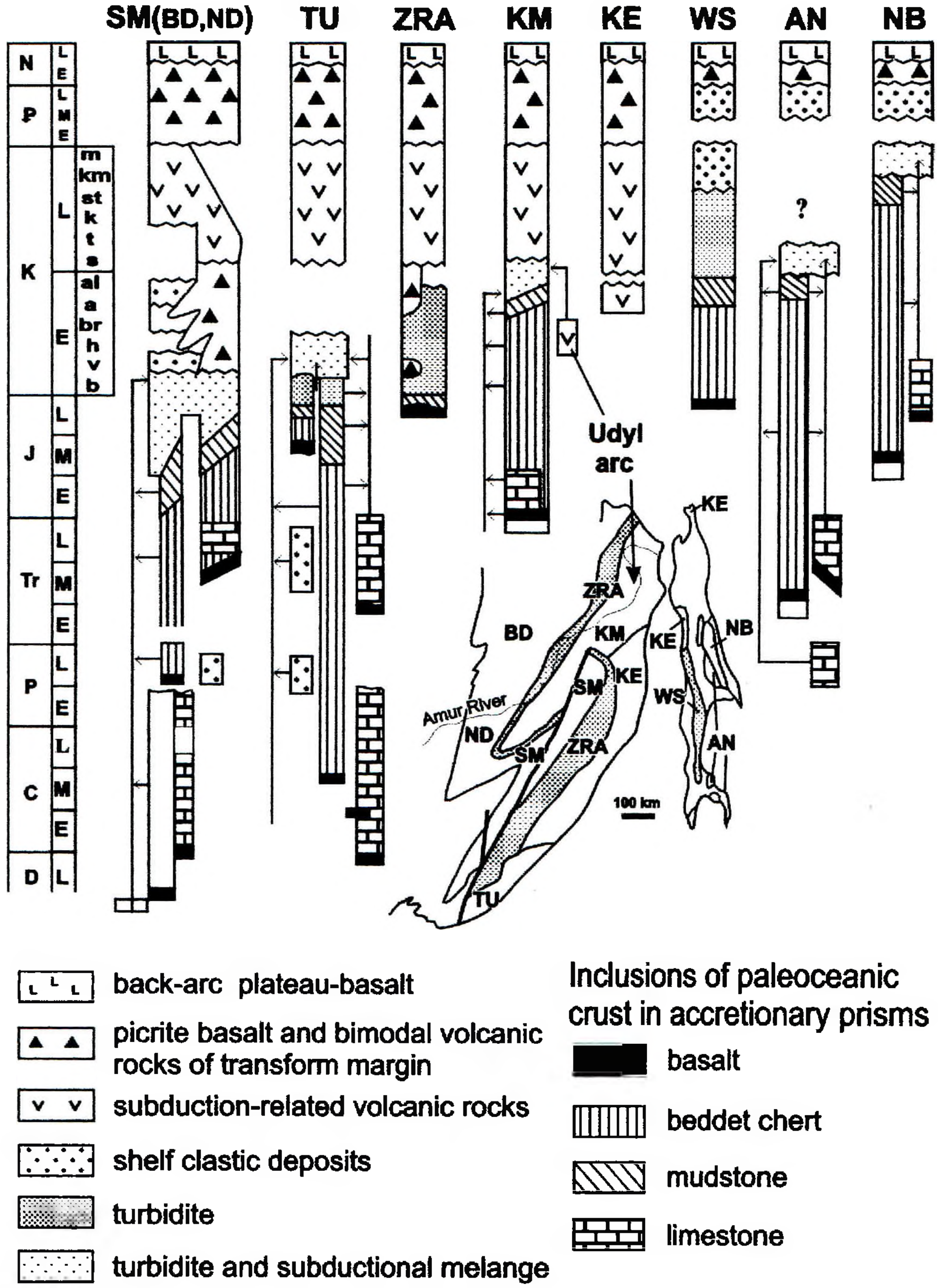

Fig. 3. Tectono-stratigraphic columns of terranes and overlapping formations of the Sikhote Alin'-North Sakhalin and Sakhalin-Hokkaido orogenic belts. The abbreviations above the columns and on the scheme indicate the terrane names, as follows: AN - Aniva, BD - Badzhal, KE - Kema, KM - Kiselevka-Manoma, NB - Nabil, ND - Nadanhada, SM - Samarka, TU - Taukha, WS - West-Sakhalin, ZRA - Zhuravlevka-Amur.

taceous age, contacting to the west with the Precambrian continental block and, thus, as a suture separating the Badzhal and Samarka terranes (Sengör and Natal'in 1996, p.595). However, the recent investigations showed the Jurassic age of the Khabarovsk accretionary complex (Zyabrev and Matsuoka 1999). Consequently, they proved the suggestion of a common Jurassic accretionary wedge continuously elongated to the east of the BKJ superterrane. Unlike the Samarka terrane, the Badzhal terrane is characterized by numerous nappes predominated by the Upper Triassic continental terrigenous rocks and lacking in ophiolite.

Taukha terrane

The Taukha terrane is located in the southern Sikhote-Alin region and is interpreted as the Tithonian-Early Cretaceous accretionary complex composed of three subterranes. (1) The western subterrane consists of spreading-type basalts overlain by the Upper Jurassic chert (Erdagou Formation; Simanenko et al. 2001). (2) The central subterrane consists of the Neocomian turbidites with blocks of the Triassic and Jurassic chert, Triassic limestone and paleoguyot-related basalt. (3) The southeastern subterrane consists of the Tithonian turbidites with fragments of the Devonian-Permian guyots and Permian-Triassic chert. These subterranes are covered by nappes of the Permian, Upper Triassic and Early Cretaceous continental-margin terrigenous rocks (Khanchuk et al. 1989b; Volokhin et al. 1990 ; Kemkin and Khanchuk 1993; Golozoubov and Khanchuk 1995 ; Kemkin and Kemkina 1998 ; and others). Major structures of the subterranes mentioned are tilted to the southeast. The Taukha terrane may be a part of the Early Cretaceous subduction complex associated with the coeval arc-related volcanic rocks found in the northeastern Honshu and southwestern Hokkaido Islands of Japan (Kiminami et al. 1992).

Zhuravlevka-Amur terrane

The Zhuravlevka-Amur terrane, composed of the Early Cretaceous terrigenous deposits of about 10 km thick, is located along the Jurassic accretionary-wedge (the Samarka and Badzhal terranes). Integration of the Zhuravlevka (distinguished by Khanchuk 1994) and Amur (distinguished by Natal'in 1991) terranes into one structural unit has been inferred from a characteristic distribution of the Valanginian Buchia-bearing strata that continuously extends as an S-shaped band from the south to the north of the Sikhote-Alin region (Fig. 3). The Zhuravlevka-Amur terrane consists of shelf deposits and turbidites with alkaline picrite and basalt flows at the Valanginian horizon. At the base of the Zhuravlevka part of the Zhuravlevka-Amur terrane, basalts and siliceous rocks of Late Jurassic (?) age are locally exposed. This suggests that a sedimentary complex, some part of which was deposited at the foot of a continental slope (Golozoubov and Khanchuk 1995), represents the Zhuravlevka-Amur terrane.

Kema terrane

The Kema terrane is a fragment of the Aptian-Albian island arc (Simanenko 1986).

Kiselevka-Manoma terrane

The Kiselevka-Manoma terrane was originally classified as the Early Cretaceous (starting from the Berriasian) accretionary complex with blocks of the Jurassic basalts and cherts (Natal'in 1991). More recently, this complex was dated as Middle Cretaceous based on the Aptian-Albian age of the turbidite in the complex (Khanchuk et al. 1994). At the same time, the pre-Aptian Early Cretaceous rocks were identified as formations of the oceanic plate (Zyabrev 1994 ; Khanchuk et al. 1994). In addition, an allochthonous fragment of the Hauterivian-Barremian island arc is found in the area of the Kiselevka-Manoma accretionary complex (Markevich et al. 1996).

Northern Sakhalin region

The pre-Cenozoic geologic complexes of the North Sakhalin are similar to the coeval ones of the Sikhote-Alin region. In the Kamyshovy Ridge on the Tatar Strait coast, Simanenko (1986) has described some fragments of the Aptian-Albian island arc. The similar formations are recorded on Shmidt Peninsula (southern part of Sakhalin Island) as well, and they are considered to be northern extensions of the Kema terrane.

Sakhalin (Hokkaido) orogenic belt

Continental crust of the Sakhalin (Hokkaido) orogenic belt was formed in Eocene time. The Middle-Late Cretaceous terrigenous complex of the West-Sakhalin terrane, a fragment of which outcrop also on the Shmidt Peninsula, marks its western boundary. The accretionary-wedge terranes with the Upper Albian-Lower Paleogene turbidite are widespread in a central part of the belt (Rozhdestvensky 1993 ; Khanchuk et al. 1989a ; Kimura et al. 1992). They include the Permian, Triassic, and Upper Jurassic fragments of paleoguyots as well as the Triassic limestone and ophiolite. Greenschist and glaucophane schist replacing the original accretionary-wedge rocks are common. In the eastern part of the belt, the Late Cretaceous island-arc terrane (Grannik 1991 ; Rozhdest-vensky 1993) containing fragments of the Jurassic-Cretaceous boninite (Vysotsky et al. 1998) was found. Collision-related granites of about 40 Ma also occur in the belt (Ivanov et al. 1998).

Mongol-Okhotsk orogenic belt

Terranes representing this belt vary in origin (Parfenov et al. 1999). In the east of the belt, the Paleozoic accretionary-wedge terranes and the Jurassic turbidite-basin terranes resulted from the closure of the Mongol-Okhotsk Ocean are present. Their relationships with each other and with the surroundings are still uncertain because of the lack of dating and other origin-indicating data. For example, considering the Galam terrane (Southern part of the Okhotsk-Koryak orogenic belt) as a part of the Mongol-Okhotsk belt is doubtful, because the Lower Paleozoic oceanic formations are widespread in the Galam terrane, whereas, in other terranes of this belt, oceanic complexes are not older than the Silurian-Devonian (Parfenov et al. 1999). Analysis of the Cambrian archaeocyathean assemblages (beginning from the Late Atdabanian ones) collected from numerous locations of the Far East indicated that they belong to the two paleo-biogeographic provinces: the Afro-Siberia-Antarctic and Cordillera-Koryak ones. Archaeocyatheans from the Khanka massif for the entire Early Cambrian time belong to the Siberia sub-province of the Afro-Siberia-Antarctic province (Belyaeva 1987 ; Khanchuk and Belyaeva 1993). Archaeocyatheans from the Bureya massif also belong to the Siberia subprovince and differ from the Khanka ones only by minor characteristics : the Khanka fossils are closer to those from the West Sayany and Tuva regions while the Bureya ones are more similar to those from the East Sayany region (Belyaeva and Kashina 1983). The Botomian-Toyonian archaeocyathean assemblages in the Galam terrane certainly differ from all the coeval assemblages known in other regions of the Far East and belong to the Cordillera-Koryak paleo-biogeographic province (Belyaeva 1987). The Silurian and Early-Middle Devonian fauna in the Galam terrane are quite similar to that of the Russian North East (Parfenov et al. 1999). In addition, the Galam terrane is similar in rock assemblage to the Ganychalan terrane in the Koryak Highland (Khanchuk et al. 1992), which in turn is comparable with the Livengud terrane in Alaska. All these lines of evidence allow us to consider the Galam terrane as a constituent of the Okhotsk- Koryak orogenic belt.

Fault tectonics and Mesozoic-Cenozoic volcanism

Fault tectonics plays an important role in paleogeodynamics of the region. The primary strike-slip character of the region was first distinguished by Ivanov (1960) and then developed by Utkin (1989, 1999) and some other researchers.

One of the major geological characteristics of the Russian Far East is a widespread distribution of the Mesozoic and Cenozoic volcanic rocks. Within the Mongol-Okhotsk and Sikhote-Alin orogenic belts and the BKJ continental superterrane, the following stages in development of the Cretaceous and Cenozoic magmatic formations may be recognized.

The Neocomian. Alkaline volcanic-plutonic and plutonic series of transform continental margin.

The Middle Cretaceous - Cenomanian. Calc-alkaline and latite-shoshonite volcanic-plutonic and plutonic series of transform margin characterized by granitoids highly various in compositions.

The Cenomanian - Maastrichtian. Calc-alkaline and shoshonite series of supra-subductional continental margin.

The Paleogene (late Maastrichtian?) - Miocene. Calc-alkaline series of transform margin and Late Miocene - Pliocene tholeiite/alkaline-basalt intra-plate series.

Paleogeodynamic reconstructions

Recently it becomes more and more obvious that the interaction of lithospheric plates along the northeastern margin of Asia exhibited transform character in certain periods of geologic time, like the present-day plate interaction along the western margin of North America. (Khanchuk et al. 1997; Khanchuk and Ivanov 1999). That geodynamic regime may have been due to oblique subduction of a spreading ridge under the continental margin. The oblique subduction likely resulted from lateral sliding of an oceanic plate. The spreading ridge submerged under the continental margin and broke it into several blocks that began moving separately northward along strike-slip faults. Geophysical studies of North America showed that cessation of subduction led to destruction of the subducted lithospheric slab (Benz et al. 1992). As a result, at the bent of the broken slab and along the transform faults, some ruptures intruded by asthenospheric matter occurred. The North American geologists termed such ruptures as slab windows (Dickinson and Snyder 1979 ; Benz et al. 1992). The magmatic sequence of a typical slab window includes abundant masses of potassic ignimbrite (rhyolite) that presumably resulted from melting of lithosphere above the asthenospheric diapir (Rytuba 1996). After that, the asthenospheric diapir produces bimodal volcanic series (rhyolite and basalt) (Rytuba 1996). Similar sequences was recently described for the Mesozoic and Cenozoic volcanic complexes of the Russian Far East, that allowed us to distinguish the transform-type continental margins there (Khanchuk 2000). Previously, these margins and magmatic complexes were considered to be of rift-related (associated with strike-slip faulting) and/or intra-plate environments, but not subduction-related ones (Filatova 1988 ; Shcheglov 1984).

Pre-Mesozoic geodynamics

According to Belyaeva (1987) the Cambrian archaeocyatheans of the Voznesenka terrane belong to the Australian paleobiogeographic province. The paleomagnetic data suggest that this terrane was situated near the equator in Cambrian (Bretshtein et al. 1997). These data as well as the paleogeographic reconstructions of East Asia (Maruyama et al. 1997) indicate that the Voznesenka terrane, which is the oldest one in the region discussed, is a fragment of the Cambrian passive margin of the Gondwanaland. Other Early Paleozoic terranes of the BKJ superterrane likely represent different geodynamic settings associated with the paleo-Asian ocean. From the Late Cambrian to Early Ordovician, they accreted to the Gondwanaland margin (Wilde et al. 1999) : the Laoelin-Grodekovo terrane is a fragment of the island arc accreted in Late Silurian time ; the Sergeevka terrane is a part of the Early Paleozoic orogenic belt of the Gondwanaland margin. The Devonian-Carboniferous bimodal magmatic complex characterized by a repeated contrasting alternation of basalts and rhyolites is related to the split of Gondwanaland, as a result of which the BKJ superterrane formed.

Mesozoic and Cenozoic reconstructions

Jurassic plate boundaries

Along the southern North Asian Craton, the Jurassic suprasubductional magmatic arc is commonly recognized (Parfenov 1984 ; Sengör and Natal'in 1996). However, this model may be reasonable only for the eastern part of the area, namely, the Uda zone where the Upper Jurassic andesitic rocks are abundant (Krasilov et al. 1992). There are no certain data about the Jurassic volcanic rocks along the craton margin to the west of the Uda belt (Fig. 2). On small-scale maps, the large granite masses observed along the Stanovoy belt are characterized by the distinctive strike-slip-related morphology and dated as Late Jurassic (Natal'in 1991). However, based on the modern isotopic study, age of these granitic intrusions is Early Cretaceous (Moiseenko et al. 1999). In addition, geochemical characteristics of the granites indicate that they are not related to subduction (Antonov 1998).

At the boundary of the Mongol-Okhotsk belt and the North Asian Craton, the two Jurassic turbidite-basin terranes are exposed : the Un'ya-Bom and Ul'ban terranes (on the west and on the east of the Mongol-Okhotsk belt, respectively) that took up their present position in Cretaceous time as a result of large-scale left-lateral strike-slip faulting (Natal'in 1991). The Ul'ban turbidites were likely deposited in a common basin with the Un'ya-Bom turbidites, because their age and composition are close to each other. No arc magmatic rocks are associated with the turbidites mentioned, indicating that the Jurassic continental margin was probably formed as a transform plate boundary of the Californian type (Khanchuk and Ivanov 1999), rather than it was related to subduction (Parfenov et al. 1999). This relationship between the Early Cretaceous volcanic rocks and granites in the southeastern margin of the North Asian craton is similar to that in the Californian Bay area and the Basin and Range Province in the western U.S. (Zonenshain et. al. 1990 ; Kuzmin 1985).

According to paleomagnetic data, the BKJ superterrane was not sufficiently displaced during the Jurassic time (Scotese 1997), and thus the closure of the Mongol-Okhotsk ocean was resulted from the lateral motion of Siberia associated with its clockwise rotation. Formation of the Jurassic accretionary complex in Sikhote-Alin was not associated with intense supra-subduction volcanism that was confirmed by the recent heavy-mineral study of the clastic rocks of the Samarka terrane. The lack of the supra-subduction volcanism suggested an oblique convergence between the oceanic and continental plates (Nechaev et al. 1997). At the end of Jurassic period, a subduction of the mid-ocean ridge beneath the continental margin took place (Fig. 4), as is evident from the foregoing data on the occurrences of Late Jurassic MOR basalts within Early Cretaceous terranes in the Sikhote-Alin region.

Early Cretaceous transform plate boundary

In the Sikhote-Alin region, a transform continental margin was reconstructed at the Jurassic/Cretaceous boundary. Here, to the east of the margin of the Paleozoic BKJ continental superterrane, the Jurassic accretionary-wedge terranes (Samarka, Nadanhada, and Badzhal, see Fig. 3) and, then, the Early Cretaceous turbidite-basin terrane (Zhuravlevka-Amur), marking transition from subduction to sliding of the oceanic plate, are distinguished. Prior to the Late Hauterivian time, tectonic extension likely predominated in the area from the following reasons. Clayey sediments associated with alkaline basalts were mostly formed on a continental slope and at its foot. The magmatic rocks are represented by ultramafic-mafic-syenite plutons with characteristic oblique orientation to the principal direction of the Early Cretaceous strike-slip displacements (Fig. 5) (Utkin 1989), as well as by lavas, dikes, pipes, and other small bodies of picrite, meimechite and basalt, all associated with the Jurassic accretionary-wedge terranes. From petrochemical and mineralogical data for the Dayan complex (Fig. 5), one of the local representatives of this magmatic association, the intrusive and volcanic rocks are similar to the Cenozoic shoshonites-absarokites and

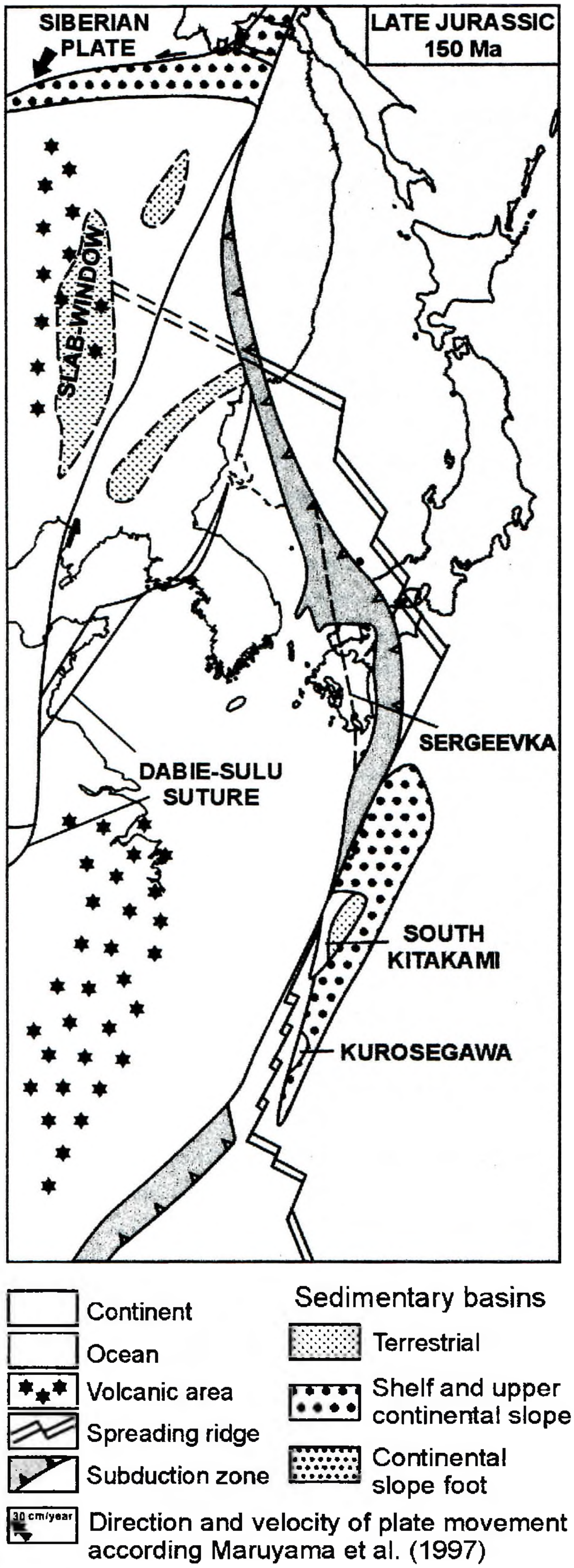

Fig. 4. Paleogeographic scheme of East Asia in the Late Jurassic. The symbols apply also to Figs. 6, 7 and 8.

lamproites related to the crustal extension of the western U.S. (Moiseenko and Sakhno 2000).

During Hauterivian-Cenomanian time, alternation of tension and extension regimes in both space and time was typical for the area discussed (Figs. 6 and 7). In that time, volcanic depressions and granite belts were forming. The sinistral strike-slip movements became more intense on the continental margin that initiated deposition of sandy and flysch sediments on the continental slope. The Central Sikhote-Alin Fault and its extensions into Japan (the Tanakura and Median faults) inherited the lithospheric plate boundary and were similar to the present San Andreas Fault in California. The Jurassic-Early Cretaceous accretionary-wedge and Early Cretaceous island-arc terranes (Taukha and others situated now in northeastern Japan) were displaced from their original locations over a distance of about 1,000 km northward and then accreted to the continental margin in Albian time (Matsukawa et al. 1997). No evidence for subduction beneath the East Asian margin at the end of Albian time has been found (Maruyama et al. 1997). To the west of the Central Sikhote-Alin Fault, along the BKJ continent boundary, the Jurassic accretionary wedge was translated northward for the distance of at least 700 km (Figs. 1 and 5) that was estimated by straightening the S-form Sikhote-Alin structure and other geometrical reconstructions (Utkin 1989). According to the paleobotanical data, the Sergeevka terrane occupied its present-day position in the Early Cretaceous being transferred northward for up to 15° of latitude (that is over 1,500 km) along strike-slip faults in Hauterivian-Aptian time (Golozoubov et al. 1999). This terrane can be considered as a fragment of continental margin that hung over the subduction zone and then was cut off and displaced along with the accretionary wedge. In Japan, the Jurassic accretionary wedge was tectonically duplicated along the Median fault in Late Hauterivian time (Tazawa 1993; Matsukawa et al. 1997). The strike-slip faults cut a marginal part of the BKJ continent into separate blocks that were displaced northward. This motion resulted in the characteristically jagged borderline of the continent on the east. The Hauterivian-Cenomanian sinistral strike-slip movements formed a giant S-pattern structure of the Sikhote-Alin (Fig. 5) and initiated formation of a granitic-metamorphic layer of its Earth's crust (Fig. 7). At the northeastern end of the Samarka terrane, the Anyui dome formed by the Albian metamorphism represents a metamorphic core of this new crust (Natal'in et al. 1994).

To sum up, the Sikhote-Alin continental crust formed for 60 m.y. (from Middle Jurassic to Albian), including the following two major events : (1) formation of the accretionary-

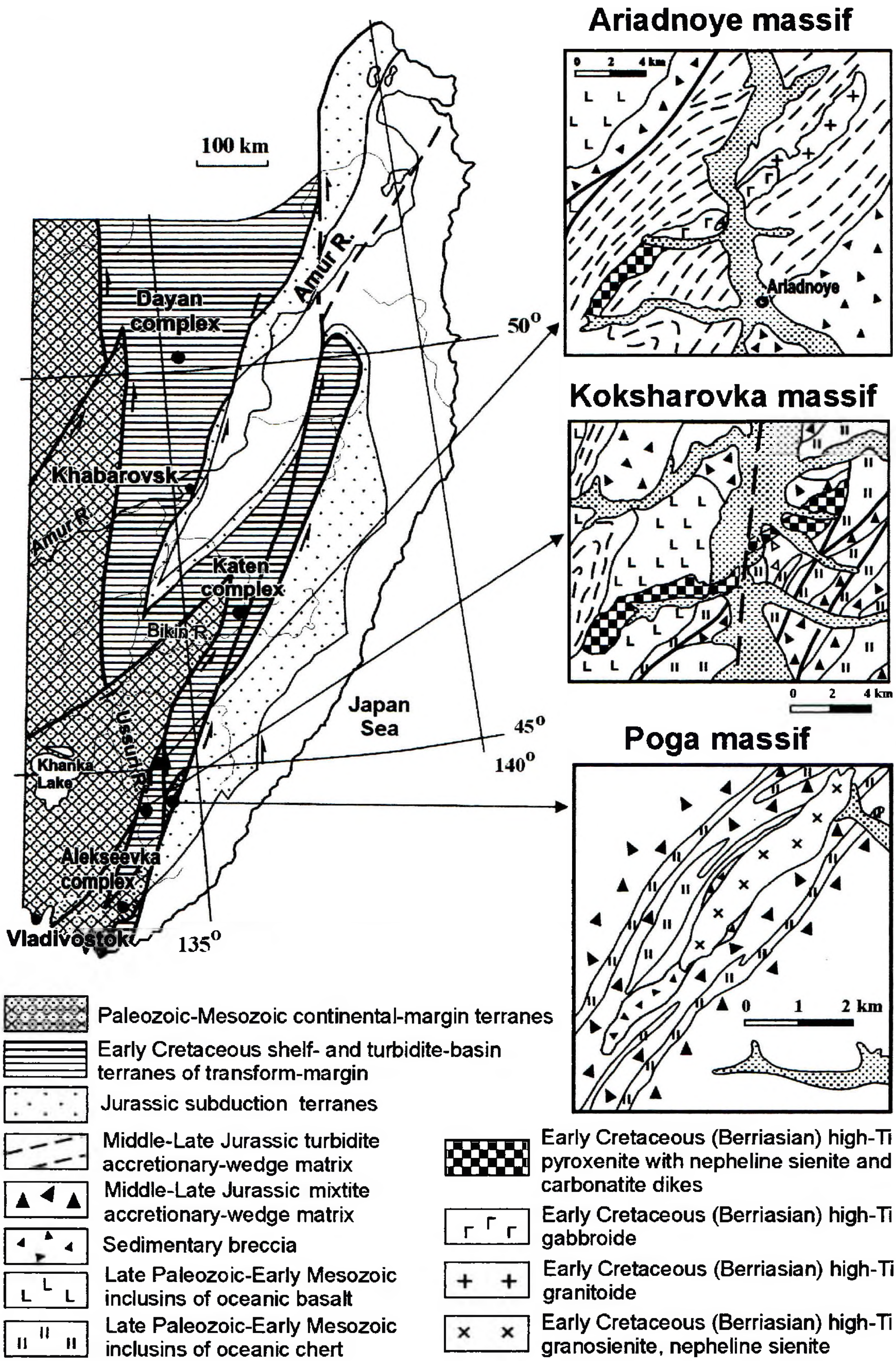

Fig. 5. Alkaline ultramafic-mafic complexes of the Early Cretaceous transform margin of the Sino-Korean craton (Khanka massif).

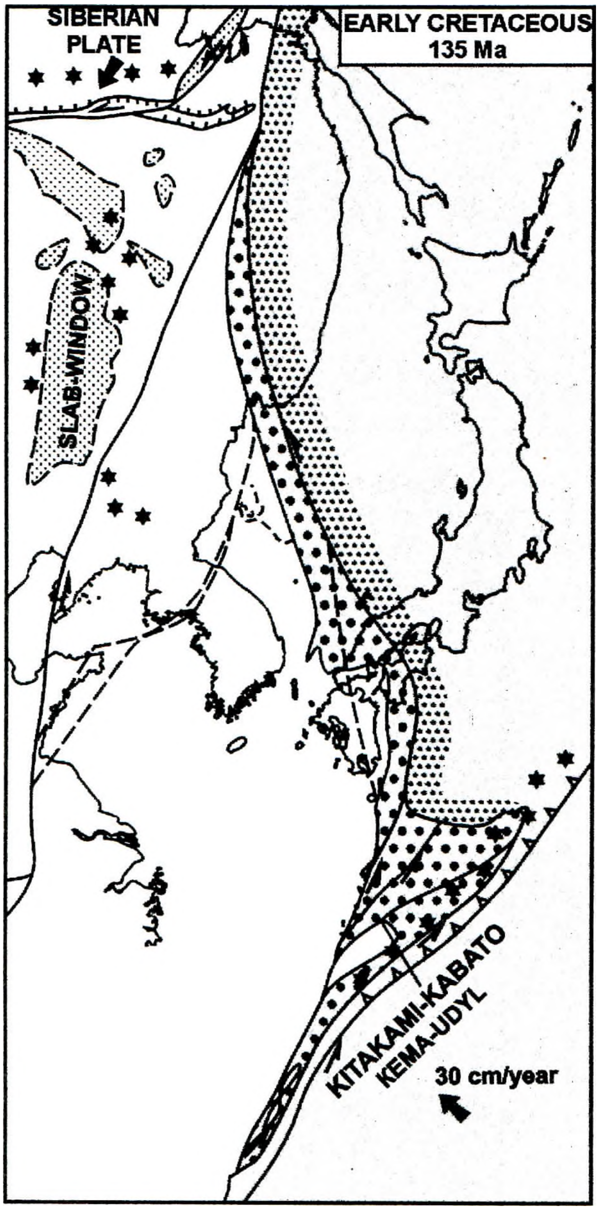

Fig. 6. Paleogeographic scheme of East Asia in early Hauterivian time. See Fig. 4 for explanation of the symbols.

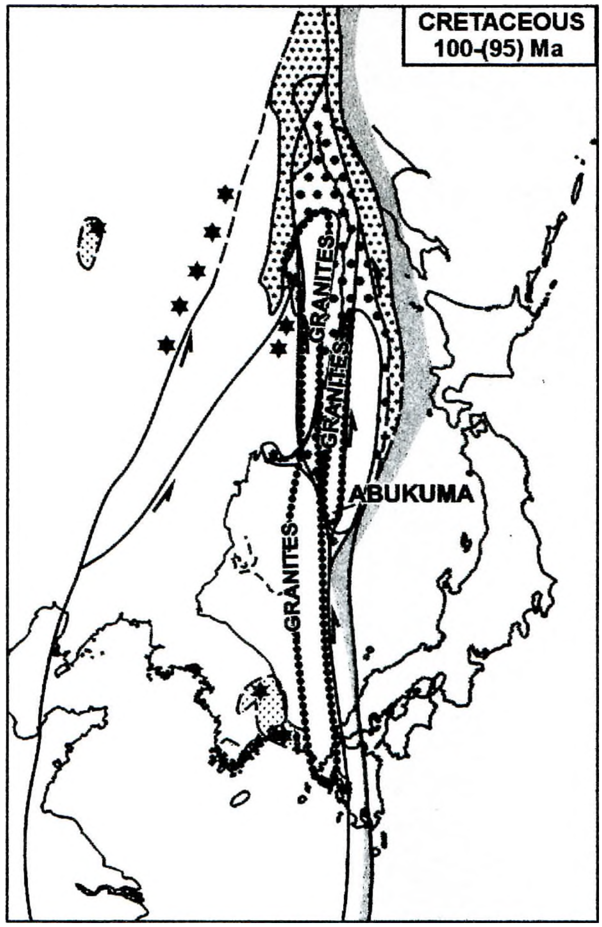

Fig. 7. Paleogeographic scheme of East Asia in late Albian - early Cenomanian time. See Fig. 4 for explanation of the symbols.

wedge, turbidite-basin, and island-arc terranes ; and (2) their collision with the continental margin, that was associated with the large-scale sinistral strike-slip displacements. Therein lies a radical distinction on initial conditions of the Early Cretaceous strike-slip faulting between the author's conclusions and those of the previous paleogeodynamic models. For example, Utkin (1989, 1999) suggested an ancient continental lithosphere under Sikhote-Alin that suffered extensional tectonism before the large-scale strike-slip movements.

The Mid-Cretaceous-Cenomanian volcanic-plutonic complexes mark the formation of continental lithosphere in the Sikhote-Alin region. They are exposed in the following regions : 1) a broad zone extending southwestward from the Mongol-Okhotsk belt through the Badzhal terrane and the Bureya massif into China, 2) the northernmost tip of the Khanka massif, 3) the boundary between the Khanka massif and Sergeevka terrane, and 4) the Zhuravlevka-Amur terrane.

In the northern part of the region, these complexes are commonly combined into volcanic-plutonic belts, namely, the Umlekan-Ogonzhin and Khingan-Okhotsk ones (see Fig. 2). At the same time, outcrops of the rock complexes of these belts are isolated from each other and are aligned parallel to the general trend of the regional strike-slip faults. A brilliant example is the Alchan zone (Fig. 2) bounded by two strike-slip faults and located at the northern wedge-shaped termination of the Khanka massif (Amel'chenko et al. 2001). The most detailed study of the Mid-Cretaceous-Cenomanian volcanic-plutonic complexes was carried out in the Badzhal-

Bureya and Berezovo-Ararat areas (Fig. 2).

Moiseenko and Sakhno (2000) have described petrology of the rocks from the northern part of the study area. The volcanic rocks in the areas are characterized by high-Mg andesites that are not related to subduction in the present active continental margins. These rocks are clearly different from subduction-related andesites and dacites in higher abundance of Nb and lower contents of Rb and Sr. In addition, the distinctive features of the volcanic rocks in the Badzhal-Bureya and Berezovo-Ararat areas are approximately equal amounts of alkali- feldspar and plagioclase (like in monzonite) and significant role of potassium in the melts, while alkali-feldspar content is quite low in the volcanic rocks. Petrologically, the Middle Cretaceous-Cenomanian volcanic rocks from the Badzhal-Bureya and Berezovo-Ararat areas are similar to those from the Californian transform geodynamic setting (Gonevchuk 1999).

In the southern part of the Sikhote-Alin region, the Hauterivian-Cenomanian volcanic-plutonic complexes of the transform margin are represented by the Berezovo-Ararat complex composed of large monzonitoid plutons and small flows of trachyandesite and andesitic trachybasalt. Many geological observations indicate the Aptian-Cenomanian age of the Berezovo-Ararat complex, while K-Ar dating results range from 95 to 113 Ma (Gonevchuk 1999). Aggregates of pyroxene from the Ararat intrusion are interpreted to indicate picritic composition of the initial melt (Gladkov 1982 ; Gonevchuk 1999). The olivine/two-pyroxene paragenesis of the rocks evidences that the initial melting occurred under low-pressure conditions (Wilson 1989). This and compositional characteristics of the Berezovo-Ararat complex eliminate any possibility of its formation above a subduction zone and probably evidence its relation to a slab window.

To the south of the Berezovo-Ararat area, some gold-bearing granitoid intrusions are known. As suggested by Gonevchuk (1999), they are related to the Berezovo-Ararat complex. The existing dissimilarities are linked to slightly different conditions of the magma crystallization.

Plutonic assemblages of the Hauterivian-Cenomanian stage of the transform margin development include also granitoid intrusions conformable to the strike-slip faulting. Among them are distinguished the Hauterivian-Aptian Khungari belt (Fig. 2), which is located along the northern border of the Khanka massif, and the Albian-Cenomanian Tatibi belt (Fig. 2), which is found along the Central Sikhote-Alin Fault further northeastward at the wedge-shaped edge of the massif. The granitoids from the accretionary-wedge and turbidite-basin terranes belong to the ilmenite series, whereas those from the

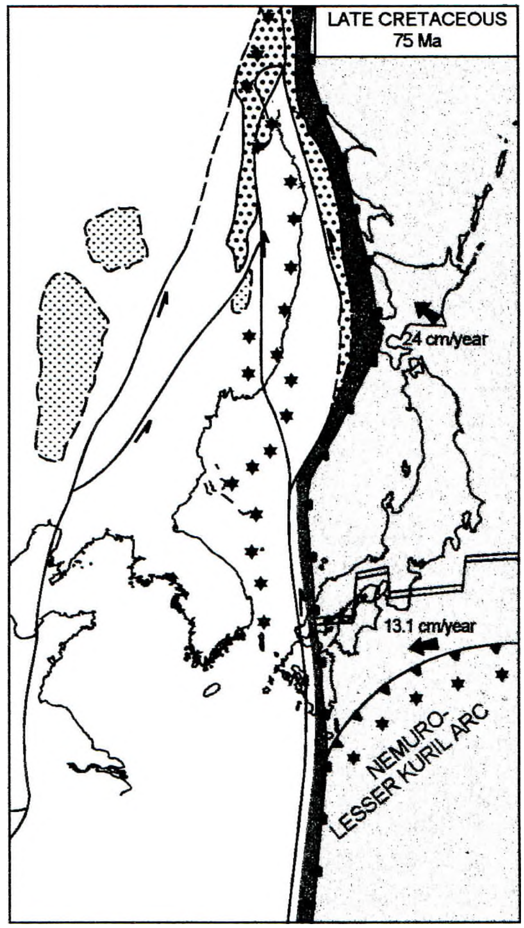

Fig. 8. Paleogeographic scheme of East Asia in the Campanian time. See Fig. 4 for explanation of the symbols.

Khanka massif correspond to the magnetite series (Romanovsky 1999). This is supposedly related to the Earth's crust types; in the Khanka massif, granite-metamorphic crust evolved prior to the Early Cretaceous time, while in the Sikhote-Alin region, the crust was just forming at that time.

Late Cretaceous-Cenozoic plate boundaries

The Cenomanian-Maastrichtian stage of the regional magmatism is manifested by formation of the East Sikhote-Alin volcanic-plutonic belt that is reconstructed as supra-subductional one (Fig. 8). The East Sikhote-Alin volcanic-plutonic belt overlapped most terranes in the Sikhote-Alin region and is composed of felsic volcanic rocks with lesser amounts of andesites and basalts, which were predominant in Cenomanian-Maastrichtian time (Govorov 1984). The transverse zonation common in the supra-subduction belts is characteristic of the East Sikhote-Alin volcanic-plutonic belt.

At the boundary between Cretaceous and Early Paleogene, within the East Sikhote-Alin volcanic belt, serious changes in magmatism occurred. The Paleogene-Miocene magmatic rocks formed volcanic depressions oriented in a sublatitudinal direction crossing the belt. The following general magmatic sequences are recognized for this time : (1) the Paleocene rhyolites (ignimbrites) replaced by basalts and intermediate rocks only in the southernmost part of the region where Russia borders Korea ; (2) the Eocene-Oligocene bimodal series predominated by basalts ; (3) the Oligocene-Miocene high-aluminum basalts. Martynov (1999) studied basalts of these assemblages in detail, and strongly suggested that the Paleogene-Miocene magmatism in the region is related to rifting and have no link to subduction.

Conclusion

The Precambrian and Early Paleozoic tectonic units of the Sea-of-Japan region are fragments of the Gondwanaland. The Bureya and Khanka represent some parts of its Early Paleozoic orogenic belt. The Devonian and Early Carboniferous magmatic rocks of the Bureya-Khanka-Jiamusi superterrane are related to the Gondwanaland collapse. The Late Paleozoic accretionary complexes, which were formed in the epicontinental volcanic arc and associated back-arc rifts, are related to subduction of the oceans between the Yangtze-Sino-Korean cratons and the Bureya-Khanka-Jiamusi superterrane. The Triassic and Early Jurassic tectonic units represent fragments of the passive continental margin.

The Mid-Mesozoic and Cenozoic orogenic belts were resulted from a complex subduction-transform interrelation between the oceanic, back-arc and continental plates in the area of the Asian continental margin.

In the Sikhote-Alin region, subduction of the spreading ridge beneath the continental margin occurred at the Jurassic/Cretaceous boundary. After that, in Early Cretaceous time, the slab-window magmatism took place on the continental margin. The Early Cretaceous tectonic units of the Sikhote-Alin and Japan represent a lateral row consisting of the transform continental margin, back-arc basin, and island arc. The latter two were accreted to the continent on the background of the large-scale sinistral strike-slip motions along the transform plate border line at the Early/Late Cretaceous boundary. Fragments of this tectonic system are the Central Sikhote-Alin, Tanakura, and Median faults.

The Late Cretaceous continental-margin arc fixes a new subductional line of the Asian continent. The Paleogene and Early Miocene tectonic units of the Sea-of-Japan region are related to the transform continental margin.

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A．I．ハンチューク（Александр Иванович Ханчук）．2001．
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要　旨

この総説では，日本海地域の地質構造と地質発達史について，最近得られたデータに基づき，独自の広域的なプレート構造論的モデルを提供する．添付したいくつかのジュラ・白亜紀古地理復元図が，この地域の発達史に関する著者の地球動力学的モデルを表現している．このモデルは，カリフォルニア型のトランスフォーム大陸縁が中生代～新生代の東アジアにおける最も重要な地球動力学的構造場であったとする点で，従来のモデルと明瞭に異なる．著者のモデルによって先新第三紀における日本列島の位置を地質学的に復元すると，中央シホテアリン断層・棚倉構造線・中央構造線は，白亜紀前期には１本の構造線であったと考えられる．白亜紀前期と古第三紀におけるトランスフォーム型大陸縁に加えて，ジュラ紀と白亜紀後期の沈み込み型大陸縁および白亜紀前期の島弧も認識されるが，シホテアリンの地質図に見られる巨大なＳ字構造は，白亜紀前期の横ずれ変位の結果と考えられる．さらに，一部の白亜紀前期・古第三紀火成岩類の性質は，特殊な動力学的構造場，即ち「スラブ・ウィンドウ」の存在を示すと考えられる．