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Mid-Cretaceous Episodic Magmatism and Tin Mineralization in Khingan-Okhotsk Volcano-Plutonic Belt, Far East Russia

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Abstract: Age of magmatism and tin mineralization in the Khingan-Okhotsk volcano-plutonic belt, including the Khingan, Badzhal and Komsomolsk tin fields, were reviewed in terms of tectonic history of the continental margin of East Asia. This belt consists mainly of felsic volcanic rocks and granitoids of the reduced type, being free of remarkable geomagnetic anomaly, in contrast with the northern Sikhote-Alin volcano-plutonic belt dominated by oxidized-type rocks and gold mineralization. The northern end of the Khingan-Okhotsk belt near the Sea of Okhotsk, accompanied by positive geomagnetic anomalies, may have been overprinted by magmatism of the Sikhote-Alin belt.

Tin-associated magmatism in the Khingan-Okhotsk belt extending over 400 km occurred episodically in a short period (95±10 Ma) in the middle Cretaceous time, which is coeval with the accretion of the Kiselevka-Manoma complex, the youngest accretionary wedge in the eastern margin of the Khingan-Okhotsk accretionary terranes. The episodic magmatism is in contrast with the Cretaceous-Paleogene long-lasted magmatism in Sikhote-Alin, indicating the two belts are essentially different arcs, rather than juxtaposed arcs derived from a single arc. The tin-associated magmatism may have been caused by the subduction of a young and hot back-arc basin, which is inferred from oceanic plate stratigraphy of the coeval accretionary complex and its heavy mineral assemblage of immature volcanic arc provenance. The subduction of the young basin may have resulted in dominance of the reduced-type felsic magmas due to incorporation of carbonaceous sediments within the accretionary complex near the trench. Subsequently, the back-arc basin may have been closed by the oblique collision of the accretionary terranes in Sikhote-Alin, which was subjected to the Late Cretaceous to Paleogene magmatism related to another younger subduction system. These processes could have proceeded under transpressional tectonic regime due to oblique subduction of the paleo-Pacific plates under Eurasian continent.

Keywords: Far East Russia, Khingan, Badzhal, Komsomolsk, Cretaceous granitoid magmatism, tin mineralization, Khingan-Okhotsk volcano-plutonic belt, Kiselevka-Manoma accretionary complex, Sikhote-Alin, marginal basin

1. Introduction

A large region of the Bureya and Badzhal Mountains to the north of the Amur River (Fig. 1) is a distinctive metallogenic province characterized by tin mineralization related to Cretaceous felsic magmatism. The Komsomolsk tin field (Km in Fig. 2) located in the eastern margin of the tin province, for example, has been one of the largest tin-producing fields in the former Soviet Union, since the initiation of systematic mining in the middle 1960's. The tin deposits in this province were formed in relation to volcano-plutonic complexes within the Khingan-Okhotsk volcano-plutonic belt which extends northeastward to the coastal region near the Sea of Okhotsk (Figs. 2 and 3). Its southwestern extension into China territory is somewhat enigmatic, but the belt appears to end near the Amur River because no significant tin mineralization is known in the Xiao Hinggan Ling Mountains within Heilongjiang Province (Fig. 1), although some Late Paleozoic to Mesozoic gold, copper and lead-zinc deposits and placer gold are distributed, according to the Mineral Resources Maps of China (1992). Thus the total length of the Khingan-Okhotsk volcano-plutonic belt exceeds 700 km, although the metallogenic feature of both ends of the belt requires further study.

Another important aspect of the Khingan-Okhotsk belt is its inland distribution of 300-600 km from the Sea of Japan coast (Fig. 3). Cretaceous igneous rocks are also widely distributed in the Sikhote-Alin belt, showing an apparently continuous and very wide distribution over the two belts (Fig. 2). Genesis of the unusually wide distribution of late Mesozoic magmatism in northeast Asia has been argued for many years (e.g., Uyeda and Miyashiro, 1974), but it is still a matter of debate. The Khingan-Okhotsk and Sikhote-Alin belts are not discriminated in

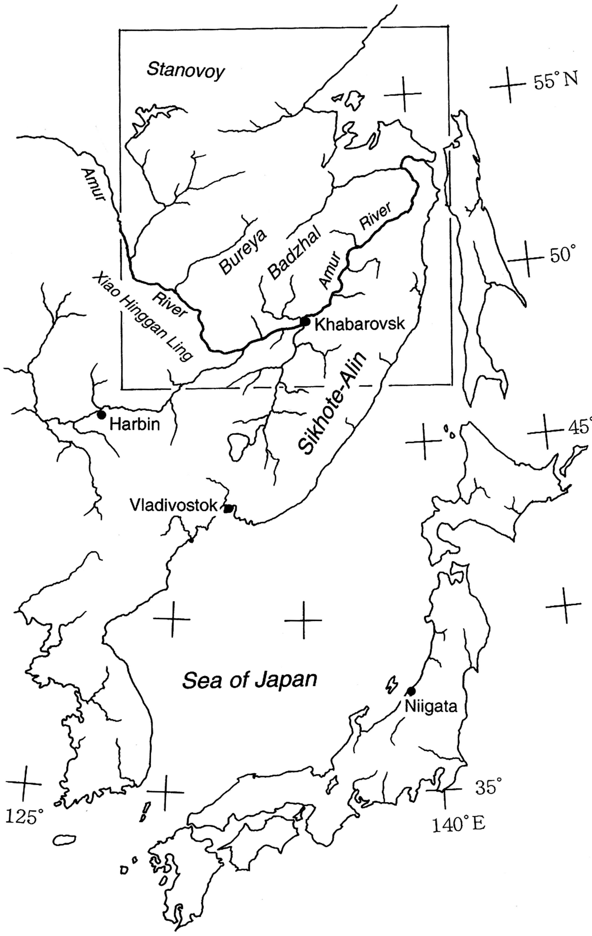

Fig. 1 Index map showing major mountain ranges and rivers. Rectangle shows the area of Figures 2 and 3.

usual geologic maps and appear to overlap in their northern parts. However, the two belts differ in metallogeny; the northern Sikhote-Alin belt is characterized by gold mineralization in contrast with the tin-rich Khingan-Okhotsk belt (e.g., Sato et al., 1996, 1998a, b, c, 2000a), suggesting a different style of igneous activity between the two belts. Therefore, the unusually wide distribution of the Cretaceous felsic magmatism over the two belts is to be reviewed, on the basis of detailed chronological data, in consideration of metallogeny which may reflect the style of magmatism.

The igneous activity of the Khingan-Okhotsk belt has been thought to have begun in the Barremian and lasted throughout the entire Late Cretaceous (Faure and Natal'in, 1992; Natal'in, 1993). In this case, the tin-rich Khingan-Okhotsk belt is not clearly discriminated in age from the northern Sikhote-Alin belt characterized by gold mineralization. If the two belts are coeval magmatic belt, nearly parallel arrangement of the two contrasting metallogeny may be a sort of zonation related to a single subduction system. However, recent knowledge on the accretionary wedges in the lower Amur region (e.g., Zyabrev, 1996) does not support such a simple model (Sato, 2000). On the other hand, recent radiometric age data suggest that the magmatic activity in the tin-rich province was a much shorter episodic event in the middle Cretaceous (Sato et al., 1998a) in contrast with the previous thought of long-lasted magmatism (e.g., Faure and Natal'in, 1992). In addition, the Mnogovershinnoe gold deposit (Mv in Fig. 2), the largest ore deposit in northern Sikhote-Alin (Sato et al., 1996), was found to have formed in the latest Cretaceous time (A. I. Khanchuk, 1997, pers. com.). It is likely that the Khingan-Okhotsk and Sikhote-Alin volcano-plutonic belts are different in age as well as in metallogeny and therefore different in tectonic setting, although comprehensive age data for igneous rocks in the whole region has not been accessible for us. Here, we present the geological outline and chronological data for the Khingan-Okhotsk tin province, and discuss the tectonic setting in consideration of stratigraphic data for the accretionary terrane. Our discussion will be focused mainly on the relation between the episodic tin-associated magmatism and the coeval subduction recognized as the accretionary complex in the lower Amur region, with the aim of a tectonic model for the genesis of the tin province.

2. Regional Geology

Tectonic divisions and distribution of igneous rocks around the Khingan-Okhotsk belt are illustrated in Figures 2 and 3. The tin province in the Bureya and Badzhal Mountains is divided into two basement terranes; Precambrian-Paleozoic continental block in the west and Mesozoic accretionary terrane in the east.

2.1. Bureya massif

The Bureya massif to the south of the Mongol-Okhotsk suture is a Precambrian-Paleozoic continental block, which is thought to have collided with the Siberian craton in Jurassic time (e.g., Zonenshain et al., 1990). This massif is usually depicted as a single tectonic unit, but it may consist of several independent blocks although the time of amalgamation is a matter of debate (Natal'in, 1993). According to the geologic maps published by DALGEOLOGIA (1991) and VSEGEI (1992), the Bureya massif consists mainly of Paleozoic granitoids with lesser amount of Archean to Proterozoic metamorphic and granitic rocks and Proterozoic to Paleozoic sedimentary rocks. Early Triassic granitoids are also sporadically distributed in the massif. Mesozoic clastic sediments locally cover the older units (Fig. 2). Jurassic igneous rocks are not recognized in the eastern part of the massif, although Cretaceous igneous rocks are widely distributed. Neogene to Quaternary alluvial and lake sediments (Zeya-Bureya Basin) widely cover the western part of the massif in the drainage of the Zeya River.

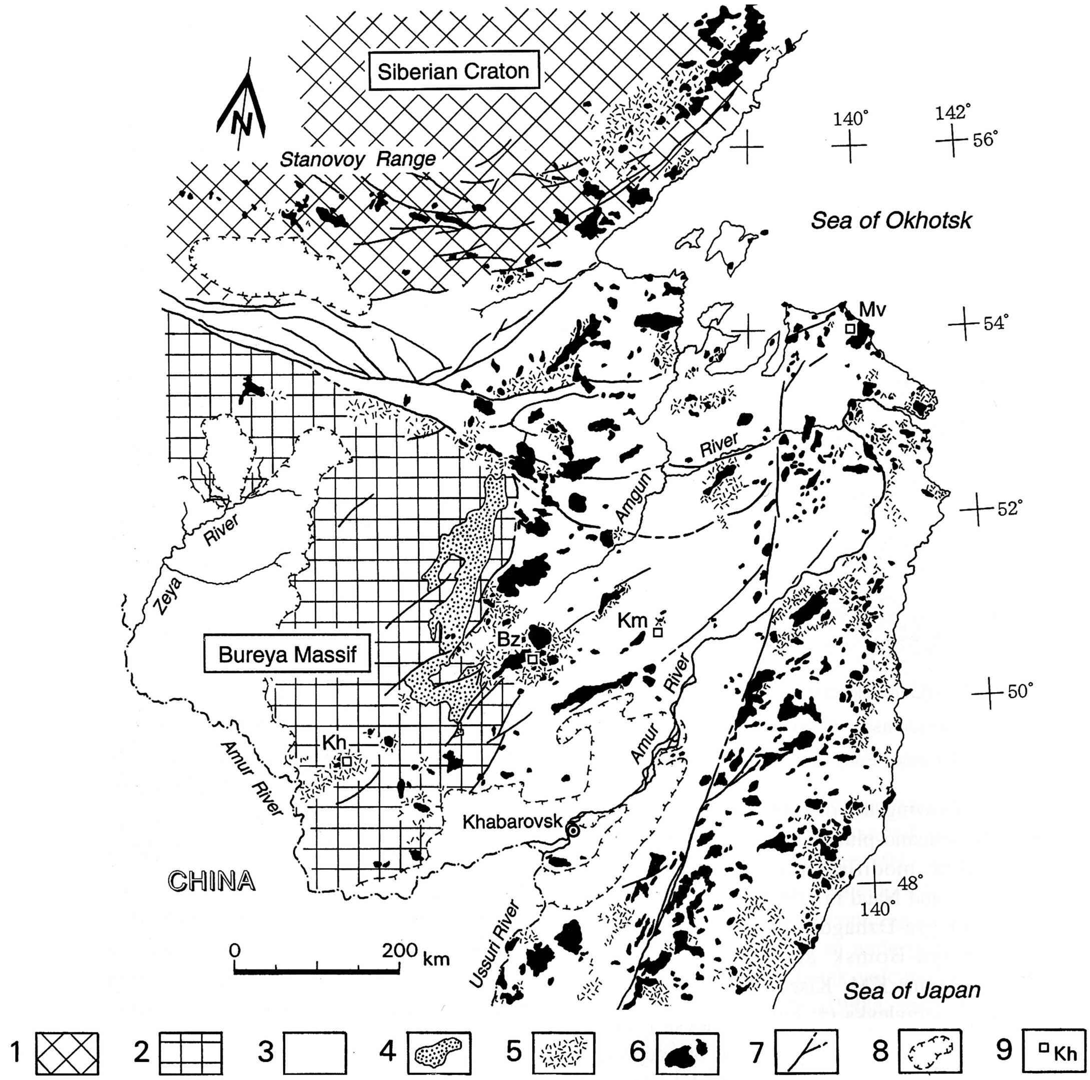

Fig. 2 Simplified geologic map showing the distribution of Cretaceous to Early Paleogene granitoids and volcanic rocks around the Khingan-Okhotsk Belt; based on 1:2,500,000 Geologic Map of Khabarovsk and Amur Provinces published in 1991.
1: Siberian craton with wide exposure of Jurassic granitoids along the Stanovoy Range. 2: Bureya massif, composed mainly of Paleozoic granitoids with lesser amounts of Triassic granitoids and Precambrian to Paleozoic sedimentary and metamorphic rocks. 3: Paleozoic-Mesozoic accretionary complex and turbidite (see Figs. 3 and 4). 4: Jurassic continental basin sediments; locally overlain by Early Cretaceous sediments. Note that Jurassic magmatic arc is not recognized in the Bureya massif. 5: Cretaceous to Early Paleogene volcanic rocks of intermediate to felsic composition. 6: Cretaceous to Early Paleogene granitoids, with local association of subvolcanic intrusion. 7: Major faults. 8: Neogene to recent sedimentary cover. 9: Large ore deposits; Kh: Khingan (Sn), Bz: Badzhal (Sn), Km: Komsomolsk (Sn+W+Cu); Mv: Mnogovershinnoe (Au+Ag).

2.2. Mesozoic accretionary terrane

The Mesozoic accretionary terrane consists mainly of Jurassic to Early Cretaceous sedimentary complexes which are divided into the Khabarovsk, Amur and Kiselevka-Manona complexes from northwest to southeast (Fig. 3). Age of the complexes tends to be younger toward southeast to the youngest Kiselevka-Manona complex of Albian-Cenomanian age (Zyabrev, 1996; Markevich et al., 1997). To the southeast of these complexes again, Jurassic to Early Cretaceous accretionary terrane of the Sikhote-Alin belt lies with a boundary named Amur Suture (Natal'in and Zyabrev, 1989; Faure and Natal'in, 1992). Although detailed stratigraphic study has been made only in limited areas because of poor exposure and hard access, available biostratigraphic data are presented below and in Figure 4 because they are essential for tectonic discussion. Age range of the stages is based on the Mesozoic geologic time scale proposed by Gradstein et al. (1995).

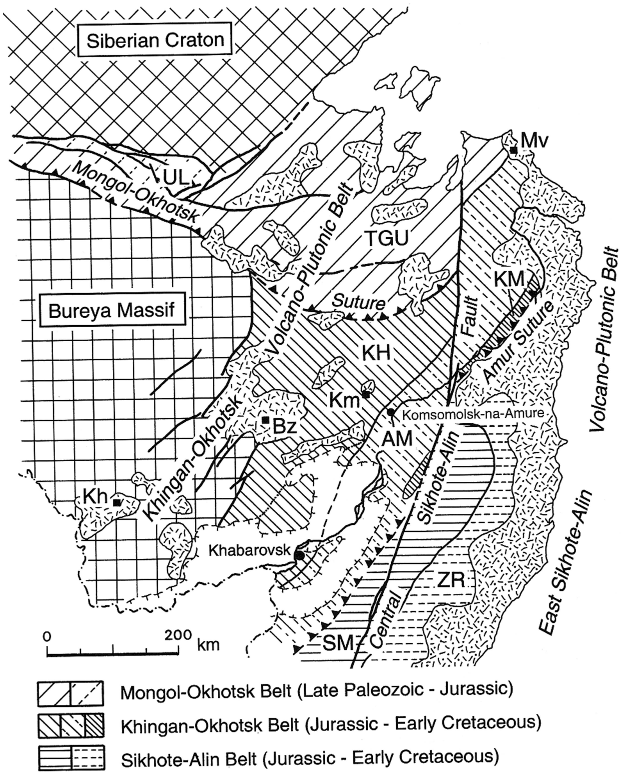

Fig. 3 Tectonic map showing the distribution of accretionary terranes and volcano-plutonic belts around the Khingan-Okhotsk Belt; modified from Natal'in and Zyabrev (1989), Faure and Natal'in (1992) and Natal'in (1993). TGU: Tukuringra-Dzhagdinsk, Galamsk and Ulbansk; UL*: Uniya-Bomsk and Lansk; KH: Khabarovsk; AM*: Amur; KM: Kiselevka-Manoma; SM: Samarka; ZR*: Zhuravlevka (*: turbidite dominated). Solid squares are large ore deposits; Kh: Khingan (Sn), Bz: Badzhal (Sn), Km: Komsomolsk (Sn+W+Cu) and Mv: Mnogovershinnoe (Au+Ag). East Sikhote-Alin volcano-plutonic belt is generally defined in Russian literatures as the belt dominated by Late Cretaceous-Paleogene volcanic rocks in eastern Sikhote-Alin. This belt is the eastern margin of the Late Cretaceous-Paleogene magmatic arc which extends over the whole Sikhote-Alin region and may overlap with the northeastern part of the Khingan-Okhotsk Belt (see the text in detail).

2.2.1. Khabarovsk complex: The Khabarovsk complex (KH in Fig. 3) has not been studied in detail, but some descriptions on the assemblage and age of oceanic fragments (basalt, limestone and chert) and matrix sediments suggest a close similarity to the Jurassic Samarka terrane in Sikhote-Alin (SM in Fig. 3) and the Mino-Tanba terrane in Southwest Japan. Natal'in (1993) divided this complex into two parts: the northern major part of triangular shape as the Badzhal complex and the southeastern part around Khabarovsk City as the Khabarovsk complex. He further suggested that the age of accretion to be Jurassic-Early Cretaceous and Early Cretaceous, respectively. Natal'in and Zyabrev (1989) cited reports which described the Hauterivian to Barremian (ca. 132-121 Ma) radiolaria from the sheared mudstone in the Khabarovsk City area and the Barremian-Albian (ca. 127-99 Ma) mollusca from the sheet of coherently layered turbidite in the Vandan Mountains about 70km to the north of Khabarovsk City. On the other hand, Kojima et al. (1991) and Wakita et al. (1992) re-examined the same outcrop within the city area, which was described by Natal'in and Zyabrev (1989). Extracted well-preserved radiolarians only from siliceous shales and cherts were identified to be of Early to Middle Jurassic age and of Middle Triassic age, respectively. They emphasized a strong similarity of the studied complex to the Jurassic-Early Cretaceous accretionary complexes in the Nadanhada terrane in eastern Heilongjiang Province of China and the Mino terrane of central Japan. In any case, the exposures around Khabarovsk City are extremely poor because the area is mostly covered by Cenozoic deposits of the Middle Amur Basin (Fig. 3), and the boundary between the Badzhal and Khabarovsk complexes is not clearly delineated (Natal'in, 1993). In this article, the Khabarovsk complex is defined as shown in Figures 3 and 4, to include both the Badzhal and Khabarovsk complexes by Natal'in (1993), in view of its contrasting lithology to the Amur complex described below. Although detailed stratigraphy of the Khabarovsk complex requires further study, its major accretion time can be assumed to be Jurassic. It is noted that no magmatic arc coeval with the Khabarovsk complex is recognized in the Bureya massif, therefore, suggesting that the complex may have been largely displaced from the initial place of accretion.

2.2.2. Amur complex: The Amur complex (AM in Fig. 3) consists of stacked tectonic sheets of Early Cretaceous turbidites probably of trench fill deposit (Natal'in and Zyabrev; 1989; Faure and Natal'in, 1993; Natal'in, 1993). These authors interpreted, according to the subduction zone tectonic model (Moore et al., 1985), that the Amur complex corresponds to an off-scraping zone, while the Natal'in's (1993) Khabarovsk complex to a deeper zone of underplating.

2.2.3. Kiselevka-Manoma complex: The Kiselevka-Manoma complex (KM in Fig. 3) forms a narrow belt along the southeastern margin of the Amur complex. This complex was thought to be an Early Cretaceous accretionary wedge containing Jurassic olistoliths of basalt, limestone and chert (Faure and Natal'in, 1992; Natal'in, 1993). Recently, its northeastern part near Kiselevka Village and Lake Udyl has been studied in detail in terms of age and provenance of sediments (Zyabrev, 1996; Nechaev et al., 1996; Markevich et al., 1997) and chemistry of basalts (Voinova et al., 1995). The Valanginian-

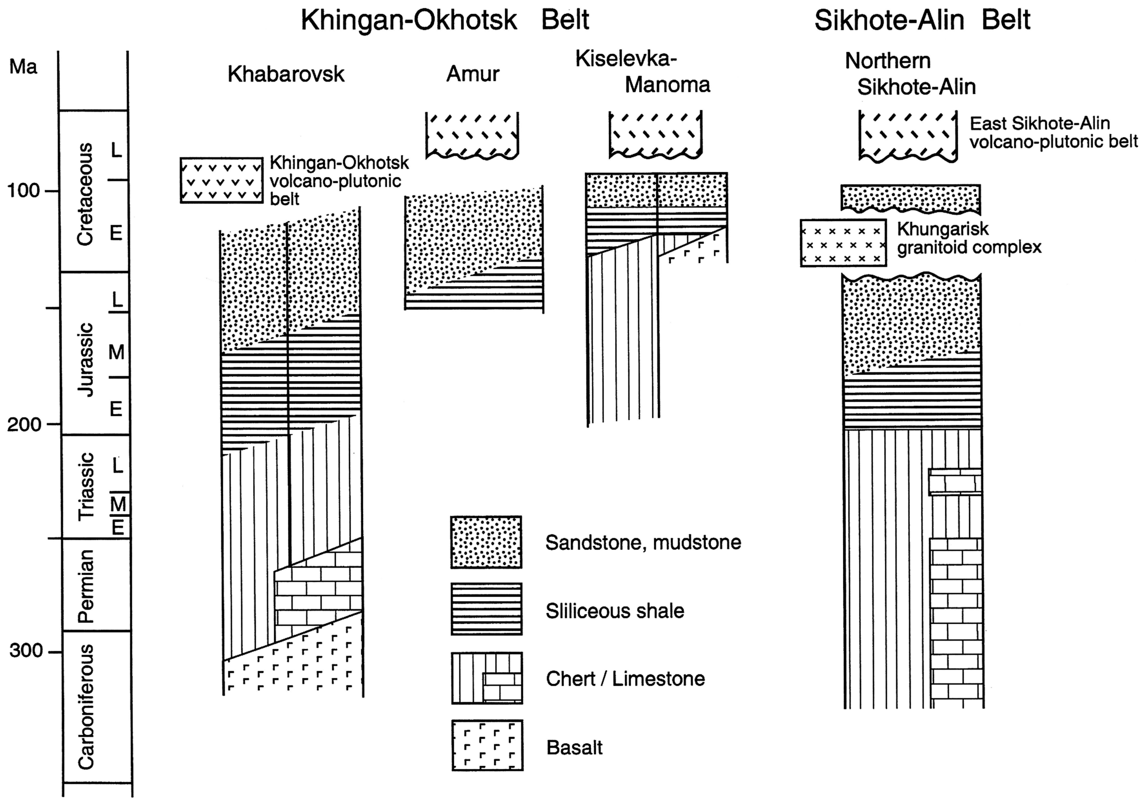

Fig. 4 Diagrams showing age relation between accretionary complexes and volcano-plutonic complexes in the Khingan-Okhotsk and northern Sikhote-Alin belts. The oceanic plate stratigraphy for the Khabarovsk and Amur complexes are depicted with some modification from Natal'in and Zyabrev (1989), Faure and Nata'in (1992), Wakita et al. (1992) and Natal'in (1993), in which comprehensive age constraints are not fully given. The Kiselevka-Manona terrane is based on Voinova et al. (1995) and Zyabrev (1996). Natal'in (1993) divided the Khabarovsk complex of Figure 3 into two parts; northern Badzhal and southern Khabarovsk, and interpreted that the southern part is an underplating zone coeval with the Amur complex of offscraping zone (Moore et al., 1985). Age of the Khingan-Okhotsk volcano-plutonic belt is based on radiometric age data for the Khingan, Badzhal and Komsomolsk tin fields (Sato et al., 1998a; see Fig. 5). Khungarisk granitoid complex, Russian name for Early Cretaceous peraluminous granitoid plutons, is depicted based on the radiometric age data for the Anyui and Bikin areas (Sato et al., 1998b; Sato et al., unpublished data). The East Sikhote-Alin volcano-plutonic belt is Late Cretaceous to Paleogene in age. Detailed biostratigraphic and radiometric studies have been done only in limited areas, thus the diagram is to be revised based on more extensive studies.

Barremian radiolarian assemblages were obtained from the upper part of chert sequences in addition to the known Jurassic radiolarians. The Hauterivian-Aptian radiolarians were identified in the lower part of siliceous shale. The Albian-Cenomanian assemblages were found in the clastic sediments, suggesting that subduction-accretion occurred in the Albian-Cenomanian time (ca. 112-94 Ma). Basalts within the basalt-chert complex were estimated to be Hauterivian to Barremian in age and yielded chemical similarities to oceanic island basalts or P-type MORB. Heavy mineral assembleges suggest a provenance of ensimatic island arc in the Valanginian-Barremian time. The relatively young oceanic fragments within the Kiselevka-Manoma complex is in contrast with those in the Khabarovsk and Samarka complexes, suggesting that a different, possibly relatively young, oceanic plate could have subducted in the middle Cretaceous time.

2.3. *Cretaceous magmatic belts*

Cretaceous magmatism mainly of felsic composition occurred in a very large region to the east of the Bureya massif (Fig. 2). There is no apparent break of the distribution of igneous rocks in usual geologic maps, but they appear to be divided into two belts: the Khingan-Okhotsk and the Sikhote-Alin (Fig. 3), of contrasting metallogeny, characterized by tin and gold mineralization, respectively (e.g., Sato et al., 1998a, b). This contrast is particularly distinctive in the middle to lower Amur region between 49°and 52°N and is well correlated with oxidation state of igneous rocks (Sato et al., 1998c). These metallogenic and petrographic contrasts are consistent with the idea that the two belts belong to different magmatic arcs (Natal'in and Zyabrev, 1989), but the genesis of the apparent double arcs is not well understood.

Table 1 Radiometric age data for igneous rocks and related tin deposits in the Khingan-Okhotsk volcano-plutonic belt.

Locality	No.[1)]	Rock[2)]	Age (Ma)	Method/Material[2)]	Ref.[3)]
Khingan					
Khingan deposit (drill core)	X-8	Qz-Mus greisen vein	96.5±2.4	K-Ar, Mus	1
ditto (Yubileinoe ore body)	X-11	Cas-Qz-Fdsp vein	95.8±2.0	K-Ar, K-fdsp	1
Badzhal					
Pravourmi deposit	PU2809-2	Cas greisen vein	91.8±2.3	K-Ar, Bt	1
Visokoe deposit	UVK4	ditto	90.2±2.3	ditto	1
Vostochnoe deposit	U114-79	ditto	90.3±2.3	ditto	1
Verkhneurmi pluton	BD-1	Bt granite	94.4±1.6	K-Ar, Bt	2
	BD-129	ditto	94.3±1.2	ditto	2
	ditto	ditto	93.7±2.7	Rb/Sr, Bt, K-fdsp, w.r.	2
	BD-10	Porphyritic Bt granite	92.6±1.2	K-Ar, Bt	2
Olgosinsk series	BD-28	Rhyolite	100.2±2.0	K-Ar, w.r.	2
	BD-28a	Altered ryolite	77.1±1.4	ditto	2
Badzhal subvolcanic complex	BD-131	Granite porphyry	95.9±1.3	K-Ar, An	2
	ditto	ditto	94.1±0.4	Ar/Ar, An	2
Urmi laccolith	BD-130	Rhyolite	91.4±1.3	K-Ar, An	2
	ditto	ditto	100.2±0.5	Ar/Ar, An	2
Pravourmi dyke	PU-12	Granite porphyry	90.4±1.0	K-Ar, K-fdsp	2
	ditto	ditto	97.6±0.6	Ar/Ar, K-fdsp	2
Others	BD-6	Bt granite porphyry dyke	90.3±1.2	K-Ar, Bt	2
	BD-133	Andesite	88.5±2.3	K-Ar, w.r.	2
	BD-132	Diorite porphyry	90.8±1.9	ditto	2
	BD-132a	Inclusion in diorite porphyry	95.0±2.1	ditto	2
Komsomolsk					
Solnochnoe deposit	94SA102(3)	Pegmatitic Qz vein	92.0±2.3	K-Ar, Bt	3
	GV25	Mo-Qz-Fdsp vein	86.2±1.8	K-Ar, K-fdsp	1
Chalba deposit	VG21	Cas-Mus-Tm greisen vein	83.9±1.7	K-Ar, Mus	1
	VG22	ditto	82.9±2.1	ditto	1
	VG23	Mus-Tm-Qz vein (Shirokoe vein)	85.1±1.8	ditto	1
	GV24	Qz-Fdsp-Mus vein in rhyolite	85.5±2.2	ditto	1
Chalba pluton	Gtab2-1	Granite	90.1±2.0	K-Ar, Bt	4
	Gtab2-2	ditto	101 ±5	ditto	4
	Gtab2-3	ditto	103 ±5	ditto	4
	Gtab2-5	ditto	90.1±2.0	ditto	4
	Gtab2-6	ditto	94.2±2.1	ditto	4
	Gtab2-7	ditto	114 ±5	ditto	4
	Gtab2-8	ditto	107 ±5	ditto	4
	Gtab2-9	ditto	86.5±1.9	ditto	4
Puril complex	Gtab3(1-6)	Granodiorite(?)	113 ±25	Rb/Sr, w.r., Bt, Hb	5
Kharpi[4)]					
Vysokiy Creek pluton	Gtab2-12	Granite	97.1±2.2	K-Ar, Bt	4
Daukhman pluton	Gtab2-13	ditto	102 ±5	ditto	4
ditto	Gtab2-14	Granodiorite	102 ±5	K-Ar, Amph	4
Merek[5)]					
Dusse-Alin pluton	GV-26	Cas-mineralized greisen	85.9±1.8	K-Ar, Mus	1

1) Sample numbers Gtab2 and 3 refer to Tables 2 and 3 in the references 4 and 5.
2) Mineral abbreviations: Amph, amphibole; An, anorthoclase; Bt, biotite; Cas, cassiterite; Fdsp, feldspar; Hb, hornblende; Mus, muscovite; Mo, molybdenite; Qz, quartz; Tm, tourmaline; w.r., whole rock.
3) References are 1: Ishihara et al. (1997), 2: Lebedev et al. (1997), 3: Sato et al. (1998a) and Sato et al. (unpublished data), 4: Gonevchuk et al. (1996); excluding ages without original data or for whole rock granite sample. Note that two age groups, 87-97 Ma and 101-114 Ma in their Table 2 were obtained by two different laboratories. 5: Gonevchuk et al. (1995).
4) and 5) About 50km south of Komsomolsk and about 100km north of Badzhal tin fields, respectively (see each reference).

Faure and Natal'in (1992) and Natal'in (1993) suggested that the Khingan-Okhotsk volcano-plutonic belt formed in an active continental margin which was accompanied by the coeval formation of the Early Cretaceous accretionary complex including the Amur complex. On the other hand, Faure and Natal'in (1992) indicated that the magmatic activity in this belt began in the Barremian and lasted throughout the entire Late Cretaceous, although direct chronological data were not presented. The age discordance between the magmatic arc and accretionary complex in their thought may be resolved on the basis of new radiometric age data for the tin deposits and surrounding igneous rocks within the Khingan-Okhotsk volcano-plutonic belt, which suggest a relatively short period of magmatism in the middle Cretaceous (ca. 95 ± 10 Ma) (Sato et al., 1998a).

3. Geology and Radiometric Age of Tin Fields in the Khingan-Okhotsk Belt

Major volcano-plutonic complexes in the Khingan-Okhotsk belt is accompanied by tin mineralization, although significant tin mineralization seems to be lacking in the northern part near the Sea of Okhotsk. The volcano-plutonic complexes accompanied by tin mineralization are practically free of geomagnetic anomalies (USSR Ministry of Geology, 1977), suggesting a predominance of the reduced-type igneous rocks poor in magnetite (Sato et al., 1998 a, b). Geology of the three major tin fields and available radiometric age data are briefly described below. The age data are summarized in Table 1 and illustrated in Figure 5 together with the data for granitoids and related ores from the Sikhote-Alin belt.

3.1. Khingan

The Khingan deposit (Kh in Fig. 2) is located about 20 km northeast of Obluche, a station of the Trans-Siberian Railway. The tin deposit consists of pipe-like orebodies in a breccia pipe within the Cretaceous Khingan-Olono volcano-plutonic complex which is composed mainly of rhyolite with lesser amounts of granite porphyry and some porphyrite dikes (Synyakov, 1975). To the north of the mine, Neogene basalts locally cover the Cretaceous volcano-plutonic complex and Paleozoic or older basement. The tin-bearing breccia pipe shows a rectangular shape of about 500 × 700 m, and extends vertically for more than 1000 m from the surface. It consists of angular blocks of the same rock type as the wall rocks without any other igneous rocks, suggesting a minor displacement from original place. Individual blocks of various sizes, commonly up to 10-50 m, are cemented by small fragments of surrounding rocks and hydrothermal minerals such as chlorite, sericite, fluorite and cassiterite. The lack of volcanic material among the blocks suggests that the breccia pipe was formed by tectonic and/or hydrothermal processes, rather than by magmatic explosion. The hydrothermal alteration assemblages are slightly different between shallow and deep levels. Topaz-bearing greisen was detected in a deep level by drilling (Korostelev et al., 1995). The mineralization is considered to have occurred at about 96 Ma, according to the K-Ar ages for K-feldspar (96.5 Ma) from tin ore in the upper level and muscovite (95.8 Ma) in the greisen from the drill core (Ishihara et al., 1997).

3.2. Badzhal

The Badzhal tin field (Bz in Fig. 2) is located in the upper reaches of the Urmi and Amugun Rivers within the Badzhal Mountains. This tin field is estimated to be one

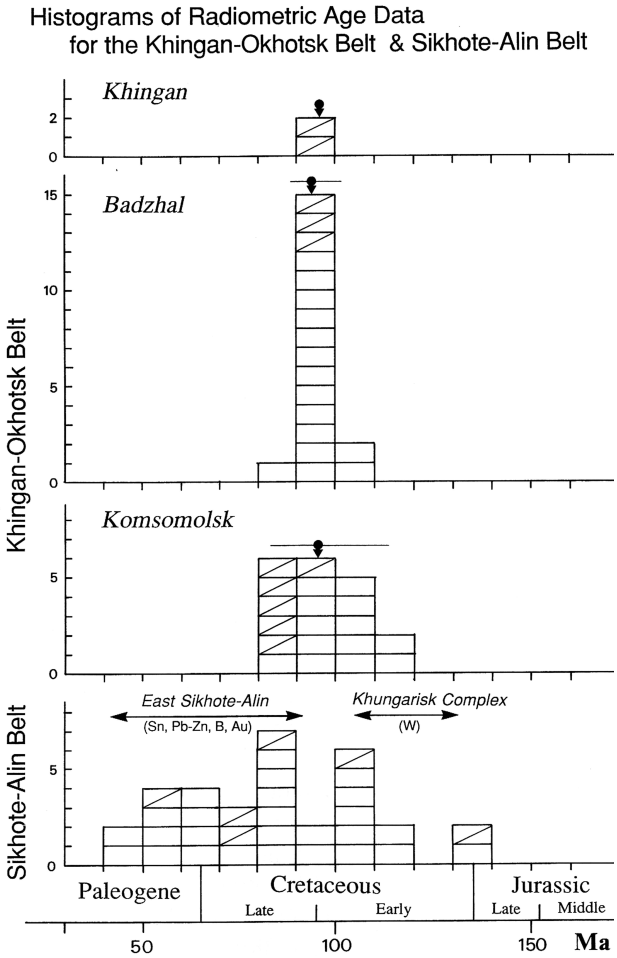

Fig. 5 Histograms of radiometric age data for the Khingan, Badzhal and Komsomolsk tin fields in the Khingan-Okhotsk volcano-plutonic belt (Table 1), with the data for granitoids and related mineral deposits in Sikhote-Alin (Sato et al., unpublished data) for comparison. Open box: granitoids (partly felsic volcanic rocks), box with bar: ores or altered rocks with mineralization.

of the largest tin fields in Russia, but it has not been developed because of its remoteness. There are many tin deposits and manifestations in the Badzhal volcano-plutonic complex which was emplaced near the eastern margin of the Bureya massif (Figs. 2 and 3) and is composed mainly of felsic volcanic and intrusive rocks (Strekopytov and Belov, 1994; Levedev et al., 1997). The major tin deposits are wolframite-bearing cassiterite quartz veins with greisen alteration. The tin mineralization is related to the intrusive bodies of granite and granite porphyry, which are thought to be apophyses of a large cryptobatholith under the ore field. Igneous rocks around the Verkhneurmi deposit were dated at 90-100 Ma (Lebedev et al., 1997) and biotites from the greisen alteration in the Pravourmiskoe and Vostochnoe deposits were dated at 92 and 90 Ma, respectively (Ishihara et al., 1997). These age data indicate that the magmatism and related tin mineralization in the Badzhal complex occurred in a relatively short time (ca. 100-90 Ma) in the middle Cretaceous, nearly the same age as the Khingan deposit.

3.3. Komsomolsk

The Komsomolsk tin field (Km in Fig. 2) is located about 40 km northwest of Komsomolsk-na-Amure City on the left bank of the Amur River. This tin field has been developed since 1960's, and it is one of the largest tin-producing districts in Russia. The tin deposits consist of many NS-trending cassiterite quartz veins occurring in the Jurassic accretionary complex and the overlying Cretaceous volcanic sequences (e.g., Radkevich et al., 1971; Asmanov et al., 1988). Wall rock alteration is characterized by strong tourmalinization, in contrast with the Khingan and Badzhal tin fields. The tin ores often contain economical amounts of chalcopyrite, scheelite, wolframite and other ore minerals. Mineral assemblages of the ores and wall rock alteration show a horizontal and vertical zonation which is centered by the Chalba pluton of granite composition. Volcanic and intrusive rocks in the Komsomolsk tin field are mainly rhyolite to andesite and granite to quartz diorite in composition, respectively, and their relation to the mineralization has been a subject of argument. We consider, on the basis of the zonal arrangement of the ores and alteration minerals, that the mineralization was related to granitic intrusion, rather than to quartz dioritic intrusion as previously proposed (Radkevich et al., 1971; Asmanov et al., 1988). Reliable radiometric age data fall in a relatively narrow range between 85 and 105 Ma, suggesting an episodic magmatism and mineralization around 95±10 Ma (Sato et al., 1998a). It should be noted that the mineralization is coeval with those in the Khingan and Badzhal tin fields. The Kharpi granitoid complex about 50 km south of the Komsomolsk tin field was also dated at nearly identical ages of about 97 Ma (Gonevchuk et al., 1996).

4. Discussion

4.1. Episodic magmatism and tin mineralization

Faure and Natal'in (1992) indicated that magmatism in the Khingan-Okhotsk belt lasted for a long time in Cretaceous from the Barremian to the end of Late Cretaceous. As described above, however, recent radiometric age data indicate that the magmatism and mineralization in the Khingan, Badzhal and Komsomolsk tin fields occurred in a relatively short period (95 ± 10 Ma) in the middle Cretaceous time (Fig. 5). The distance between the Khingan and Komsomolsk districts exceeds 400 km. It is remarkable that nearly synchronous magmatism and mineralization occurred in the three widely spaced tin fields within the southern Khingan-Okhotsk belt. Thus a question arises whether the coeval episodic event occurred throughout the entire belt. Yet it is now difficult to state whether the Khingan-Okhotsk belt is a uniform magmatic belt, because comprehensive chronological data for the whole region have not been available for us. It is rather likely that the style of magmatism in both ends of the belt is different from the major tin-rich region judged from the lack of apparent tin mineralization and the association of remarkable geomagnetic anomalies (Sato et al., 1998a). Future compilation of the original chronological and petrographical data in an accessible form, as well as new age dating, will greatly contribute to further understanding of the genesis of the Khingan-Okhotsk volcano-plutonic belt.

4.2. Magmatism and coeval subduction

It is concluded, at least for the major tin fields, that the magmatism and related mineralization in the Khingan-Okhotsk belt was an episodic event in the middle Cretaceous time (95±10 Ma). This result may solve the problem of age discordance between the magmatic arc and accretionary complex in the previous model for the Khingan-Okhotsk active margin (Faure and Natal'in, 1992). Faure and Natal'in (1992) correlated the long-lasted magmatism from the Barremian to Late Cretaceous with the Early Cretaceous accretionary complex within the Khabarovsk and Amur complexes, but did not discuss the Late Cretaceous complex. As illustrated in Figure 4, the episodic magmatism in the Khingan-Okhotsk belt is synchronous with the accretion of the Kiselevka-Manoma complex, but not with the Khabarovsk complex.

The Khabarovsk complex is thought to be mainly Jurassic in age, but the coeval magmatic arc has not been recognized in the Bureya massif. The Jurassic accretionary complex may be an allochthonous terrane displaced largely from the original place of accretion (Sato, 2000). The time of displacement is considered to be within the Early Cretaceous period, because the Khabarovsk complex juxtaposed with the Bureya massif before the magmatism of the Khingan-Okhotsk belt as clearly seen in the Badzhal volcano-plutonic complex (Figs. 2 and 6). Before the juxtaposition autochthonous sediments may have existed along a passive or transform margin of the Bureya massif and the coherent sediments could have been involved in exotic accretionary complexes. The coherently bedded clastic rocks containing Triassic and Jurassic megafossils (Natal'in, 1993) might partly be such an example. The Amur complex of Early Cretaceous age probably includes turbidites of transform margin environments as discussed later.

In contrast with the Khabarovsk complex, the Kiselevka-Manoma complex may be an autochthonous terrane correlated with the Khingan-Okhotsk magmatic arc. According to recent biostratigraphic studies (Zyabrev,

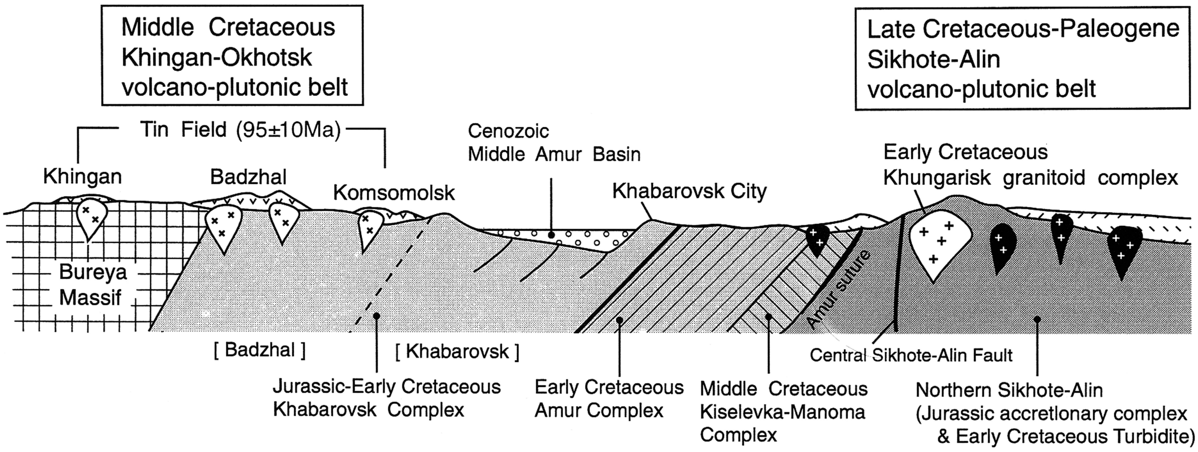

Fig. 6 Schematic NW-SE cross section through the Khingan-Okhotsk active margin and northern Sikhote-Alin; modified from Faure and Natal'in (1992) and Natal'in (1993).

1996; Markevich et al., 1997), the Kiselevka-Manoma complex is the Albian-Cenomanian (ca. 112-94 Ma) accretionary wedge containing Early Cretaceous chert and basalt (Fig. 4). The oceanic fragments are clearly younger than those in the Khabarovsk complex, indicating a difference between the subducted oceanic plates responsible for the two complexes. Detailed features of a subducted oceanic plate responsible for the Kiselevka-Manoma complex require further study, but an environment of back-arc basin is suggested from the assemblage and chemistry of heavy minerals (Nechaev et al., 1996, 1997). Nechaev et al. (1996, 1997) suggested a provenance of ensimatic island arc in the Valanginian-Barremian time. It is difficult to state whether the back-arc basin was a trapped basin or a rifted one or both. The occurrence of Jurassic chert (Fig. 4) may suggest the existence, at least partly, of trapped old oceanic basin. On the other hand, basalts overlain by Early Cretaceous chert (Fig. 4) were reported to have chemical affinity for intraplate oceanic island basalts (OIB) or P-type MORB (Voinova et al., 1995). If this interpretation is correct, it can be assumed that an ascent of the hot asthenosphere caused basaltic volcanism just before the subduction of the back-arc basin and the oceanic basalts were accreted with chert into the Kiselevka-Manoma complex. This scenario, though requiring critical review, is attractive for the consideration on the genesis of the episodic magmatism in the Khingan-Okhotsk volcano-plutonic belt .

4.3. *Tectonic model and related subject: Proposal of Sunda style tectonics*

4.3.1. Episodic magmatism caused by collapse of back-arc basin: Genesis of the episodic magmatism in the Khingan-Okhotsk belt is of particular interest in view of Cretaceous tectonic history in the northeast Asian active margin. The short-lived magmatism here is a remarkable feature in contrast with the long-lasted magmatism in Sikhote-Alin (Fig. 5) and Japanese Islands, a probable southern continuation of Sikhote-Alin before the opening of Sea of Japan, where felsic magmatism began at about 130Ma and continued throughout the entire Cretaceous up to Paleogene (e.g., Sato et al., 1992; Sato et al., 1998b). It is reasonable to consider, therefore, that the Khingan-Okhotsk and Sikhote-Alin belts were essentially different magmatic arcs, rather than juxtaposed arcs derived from a single arc.

However, the tectonic regime for the short-lived and relatively homogeneous magmatism of the Khingan-Okhotsk Sn belt extending over 400 km is unknown. On the basis of recent descriptions of the coeval Kiselevka-Manoma accretionary complex, we propose a model in which the episodic magmatism in the Khingan-Okhotsk belt was caused by the collapse of a back-arc basin (Figs. 7 and 8). The basin, named "Amur Basin" in this paper, is thought to have been created and lasted for a short period (ca. 135-110 Ma) in a left-lateral transpressional tectonic regime (Sato, 2000). As illustrated in Figure 7, modern analogue of this model is seen in the Sunda arc where the Andaman Basin was created in relation to strike-slip tectonics in Miocene (e.g., Fitch, 1972; Hamilton, 1979; Curray et al., 1979, 1982). Although the mirror image results in reversed east-west sense and the rate of convergence is different, we still can find some other similarities. For example, the Andaman Islands arc may correspond to the ensimatic arc suggested by Nechaev et al. (1997), and Sumatra region characterized by old continental crust and young accretionary complex, which are cut by and displaced along the Sumatra and Mentawai Fault Zones (e.g., Hamilton, 1979; Hutchison, 1989; Diament et al., 1992), may correspond to Sikhote-Alin and Japanese Islands in Early Cretaceous. Turbidites of the Early Cretaceous Amur complex could have partly been deposited in the "Amur Basin" (Fig. 8). Similar turbidites may be seen in the Andaman Basin near Malay Peninsula.

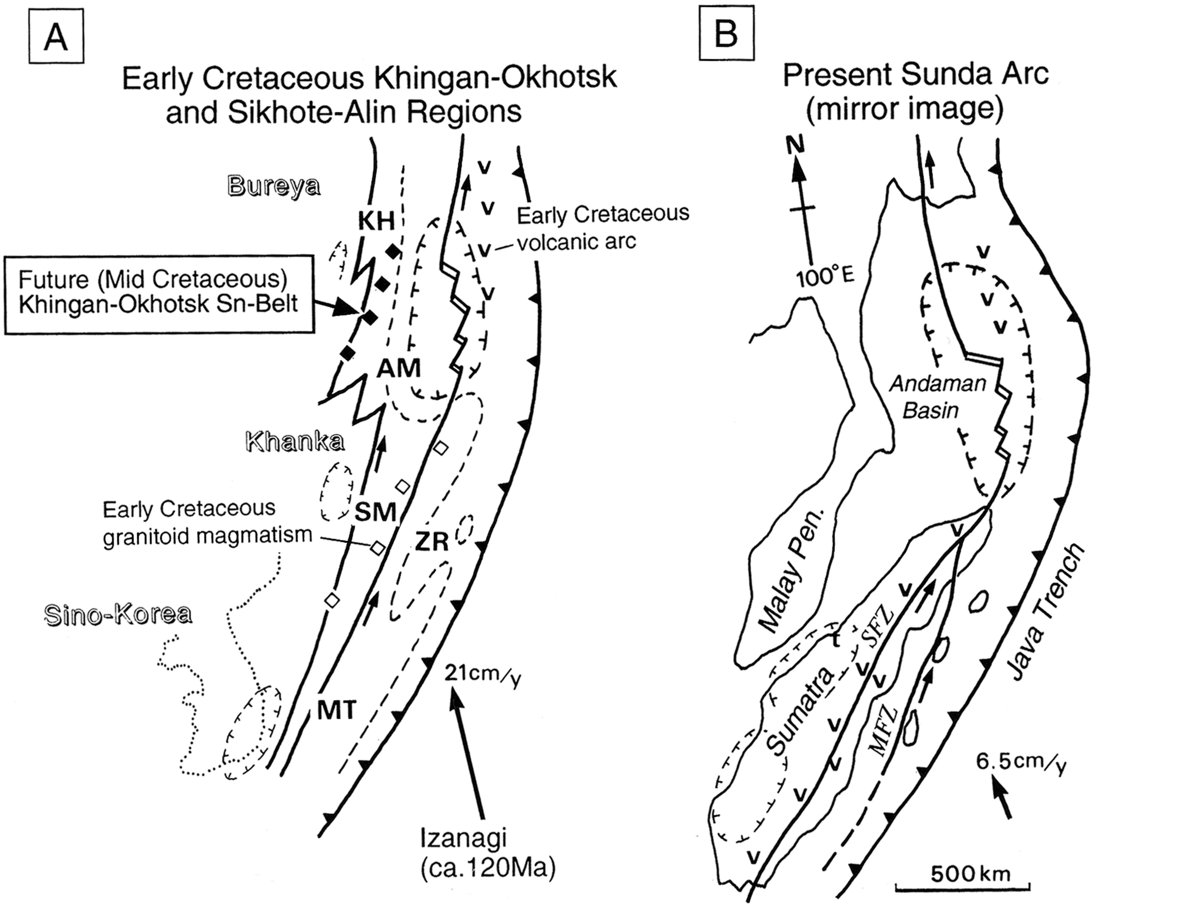

Fig. 7 A: Tectonic framework of the Early Cretaceous Khingan-Okhotsk and Sikhote-Alin regions. Abbreviation of terranes; KH: Khabarovsk, AM: Amur, SM: Samarka, ZR: Zhuravlevka, MT: Mino-Tanba. AM and ZR, composed mostly of turbidite, may have been deposited on the older accretionary complex and/or oceanic crust. Broken line shows inferred coast line. Convergence rate of the Izanagi Plate is based on Maruyama et al. (1997). B: Mirror image of the tectonic map of the present Sunda Arc is shown for comparison in the same scale; SFZ: Sumatra Fault Zone, MFZ: Mentawai Fault Zone, compiled from Hamilton (1979), Curray et al. (1979), Diament et al. (1992) and Howells (1997). Andaman Basin denotes the area of more than 2000 m in water depth. We postulate the Khingan-Okhotsk Sn-belt formed in relation to the collapse of the back-arc basin in the middle Cretaceous time. See the text for discussion.

The "Amur Basin" is presumed to have been relatively hot due to rifting or plume activity as discussed in the previous section. The Sn-associated reduced-type felsic magmatism is thought to have been caused by the subduction of the hot back arc basin and the significant crustal melting (Fig. 8) in a similar manner to the Middle Miocene Sn-associated reduced-type granitoid magmatism in the Cretaceous to Paleogene Shimanto accretionary zone of Southwest Japan (e.g., Ishihara, 1978; Ishihara et al., 1992). The Middle Miocene magmatism could have been caused by the interaction of Southwest Japan arc with the very young, and presumably hot, Shikoku Basin due to the opening of Sea of Japan (e.g., Kobayashi and Sato, 1979; Takahashi, 1986; Furukawa and Tatsumi, 1999). Subduction of a spreading ridge may result in more vigorous felsic magmatism near the trench than normal plate subduction (e.g., Thorkelson, 1996; Maruyama, 1997; Iwamori, 2000). A similar process could have occurred during the collapse of the "Amur Basin". This basin may have been closed subsequently by the collision of Sikhote-Alin block, resulted in formation of the Amur suture (Natal'in and Zyabrev, 1989; Natal'in, 1993), and termination of magmatism in the Khingan-Okhotsk belt.

Kasatkin et al. (1995) suggested, from the fault systems, that the ore veins in the Komsomolsk tin field formed under a left-lateral strike-slip stress fields with direction of compressional stress between NNW of the pre-ore stage and WNW of the post-ore stage. The counterclockwise rotation of the principal stress axes with time may likely reflect the tectonic process of basin collapse. Accumulation of similar observations in the wide region may give some insight into more realistic tectonic model.

After the closure of the basin, the Sikhote-Alin magmatic belt especially of Late Cretaceous to Paleogene age was formed preferentially along the present Sea of Japan coast, which is usually named in Russian literatures as the East Sikhote-Alin volcano-plutonic belt (Figs. 3, 6 and 8). The northeastern part of the Khingan-Okhotsuk belt may have been superimposed by the East Sikhote-Alin magmatic belt. The complicated distribution of granitoids with various magnetic susceptibility in north Sikhote-Alin (Romanovsky et al., 1996) could have been resulted from the superposition of two magmatic arc.

4.3.2. Subjects related to "Amur Basin" hypothesis: The "Amur Basin" hypothesis presented here is highly speculative and has much room for argument. For example, the volcanic arc illustrated in Figure 8 has not been identified in the present northern Sikhote-Alin region, although volcanic strata are widely recognized in Early Cretaceous sedimentary sequences. The volcanic strata are known to occur in the Hauterivian-Albian sequences, but their detailed mode of occurrence and lithology are poorly known except for a few localities, where petrochemical features of island-arc magmas were identified (Simanenko, 1992). In a described area near Vysokogorny, 150 km east of Komsomolsk-na-Amure, lava flows, tuff breccias and sills mainly of basalt to andesite composition are intercalated with mudstone containing fine-grained sandstone layers. This Early Cretaceous volcano-sedimentary sequence was intruded by Late Cretaceous granitoids and unconformably overlain by volcanic rocks of the East Sikhote-Alin volcano-plutonic belt. Simanenko et al. (1996) reported a Rb-Sr isochron age of 101 Ma with an initial Sr ratio of 0.7043 for the basaltic rocks in this area, although the samples seem to be altered. A possible site of this volcanism could be a marginal part in the "Amur Basin" where terrigenous deposits were derived from land areas. In any case, it seems to be difficult to identify a definite remnant of the volcanic arc, because original structures were significantly destroyed and widely covered by volcanic rocks during the Late Cretaceous to Paleogene orogeny.

Another aspect for the argument may be related to the left-lateral displacement in time and space. Our model requires large scale northward movement of the Jurassic accretionary complex during Early Cretaceous. Although there is no definite faults corresponding to the Sumatra and Mentawai Fault Zones in the Sunda arc (Fig. 7), some observations are consistent with the left lateral displacement. For example, the Khor block to the east of Khabarovsk is considered to be displaced from the Sergeevka terrane, a group of Cambrian ophiolitic rocks in the southeastern Khanka massif (Sato et al., 1993; Sato et al., 2000b) along the Central Sikhote-Alin Fault. The distance of displacement is estimated to be more than 300 km (Khanchuk, 1994, Fig. 1) and the time of strike-slip movement is thought to be contemporaneous with or slightly earlier than the 80-50 Ma volcanism (Zonenshain et al., 1990, p.109). Our preliminary survey and dating of granitoid plutons near the southern end of the Central Sikhote-Alin Fault suggest the time of major displacement was before 80 Ma. Otsuki and Ehiro (1992) evaluated left-lateral faulting from 60 to >240 km in a period of 120-80 Ma for the major faults in Northeast Japan, includ-

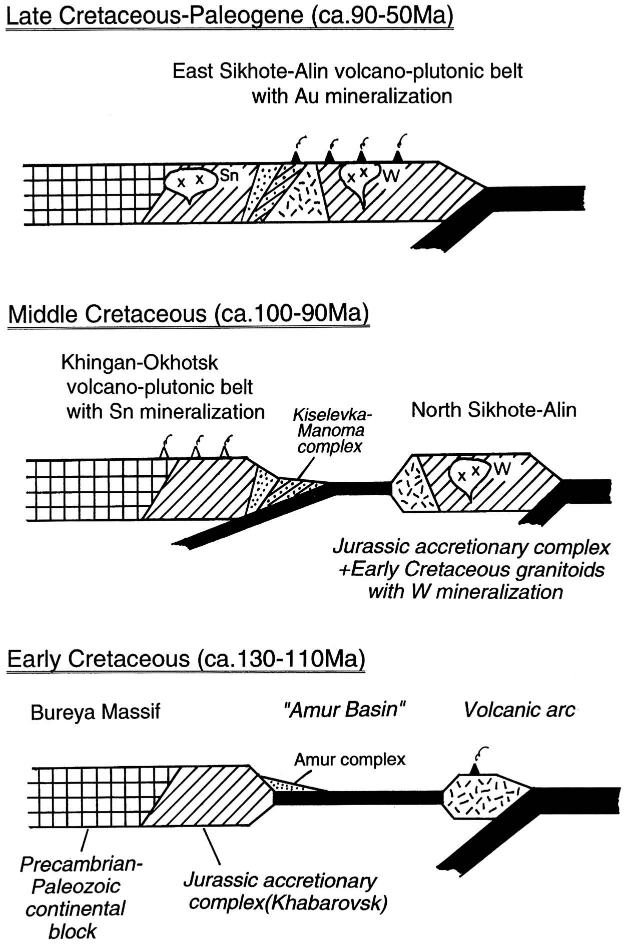

Fig. 8 Schematic illustration of tectonic history and mineralization in the Khingan-Okhotsk belt and northern Sikhote-Alin on the basis of the "Amur Basin" hypothesis. These processes are thought to have proceeded under a left-lateral transpressional tectonic regime due to the oblique subduction of paleo-Pacific plates; individual units, e.g., Bureya massif and Khabarovsk complex, may be bounded principally by left-lateral faults. Opening of the "Amur Basin" is considered to have occurred in a similar manner to the present Andaman Basin within the Sunada Arc. Closure of the basin may be caused by northward drift of the Sikhote-Alin belt and collision with the Khingan-Okhotsk belt due to higher-angle convergence. Solid and open triangles denote the oxidized- and reduced-type magmatism, respectively. Early Cretaceous granitoids, mostly of the reduced type, are distributed in Sikhote-Alin, and are accompanied by tungsten mineralization as seen at the Lermontovskaya and Bostok-2 skarn-type deposits.

ing the Tanakura Tectonic Line. Left-lateral displacements are also suggested for major tectonic lines in Southwest Japan, including the Median Tectonic Line (e.g., Ichikawa, 1980; Taira et al., 1983). From the paleo-biogeographic evidences, Tazawa (1993) suggested a very large left-lateral displacement of more than 1500 km along the Median Tectonic Line and the Tanakura Tectonic Line during Cretaceous-Paleogene time. Distribution of the Ryoseki- and Tetori-type floras (Kimura, 1987; Ohana and Kimura, 1995) is also consistent with the idea of large scale northward displacement of the ocean side of the Japanese Islands and a part of Sikhote-Alin. It is of interest to note that the style of convergence along the Asian continental margin may have changed greatly in the middle Cretaceous, from a highly oblique N-NNW convergence to a nearly orthogonal W-WNW one (e.g., Engebretson et al., 1985; Maruyama and Seno, 1986; Maruyama et al, 1997); this change seems to be coeval to the collapse of the “Amur Basin”.

5. Concluding Remarks

The Khingan-Okhotsk volcano-plutonic belt is characterized by the monotonous pattern of geomagnetic anomaly and tin mineralization, suggesting a reduced-type magmatism, in contrast with the northern Sikhote-Alin volcano-plutonic belt characterized by complicated positive anomalies and gold mineralization, suggesting an oxidized-type magmatism. Volcano-plutonic complexes in the northern end of the Khingan-Okhotsk belt near the Sea of Okhotsk are accompanied by positive magnetic anomalies, suggesting an overprinting of the East Sikhote-Alin volcano-plutonic belt.

Tin-associated magmatism in the Khingan-Okhotsk belt is concluded to have occurred episodically in a short period (95±10 Ma) in the middle Cretaceous time, in contrast with previous thought of long-lasted activity from Barremian to latest Cretaceous. The short-lived magmatism is remarkably different from the long-lasted magmatism in the Sikhote-Alin belt, from ca.130 Ma to ca.40 Ma, indicating that the two belts are essentially different arcs, rather than juxtaposed arcs derived from a single arc.

The episodic magmatism in the Khingan-Okhotsk belt is coeval with the accretion of the Kiselevka-Manoma complex, the youngest accretionary wedge in the eastern margin of the Khingan-Okhotsk accretionary terranes, where Early Cretaceous chert (up to early Aptian) and underlying basalt of MORB- or OIB-like chemistry occur within Albian-Cenomanian clastic matrix. The small time gap between the chert-basalt assemblage and clastic matrix suggests that subducted oceanic basin was at least partly young. An immature volcanic arc is suggested from heavy mineral assemblages within the Early Cretaceous sediments of the Kiselevka-Manoma complex. It is likely that the subducted oceanic basin was a back-arc basin similar to the modern Andaman Basin in the Sunda arc which is characterized by a strike-slip tectonics due to oblique plate convergence. The tin-associated magmatism in the Khingan-Okhotsk belt could have been caused by the subduction of very young and hot back-arc basin, and have resulted in formation of the reduced-type felsic magmatism due to involvement of the carbonaceous sediments within accretionary complex near the trench. Closure of the basin may have been completed by the northward drift of the Sikhote-Alin belt, and have resulted in the cessation of magmatism in the Khingan-Okhotsk belt. Change of configuration and style of convergence of the Izanagi and Pacific plates in middle Cretaceous appear to control tectonic and magmatic processes in the East Asian continental margin.

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