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Lermontovskoe Tungsten Skarn Deposit: the Oldest Mineralization in the Sikhote-Alin Orogen, Far East Russia

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Abstract: Lermontovskoe tungsten skarn deposit in central Sikhote-Alin is concluded to have formed at 132 Ma in the Early Cretaceous, based on K-Ar age data for muscovite concentrates from high-grade scheelite ore and greisenized granite. Late Paleozoic limestone in Jurassic – early Early Cretaceous accretionary complexes was replaced during hydrothermal activity related to the Lermontovskoe granodiorite stock of reduced type. The ores, characterized by Mo-poor scheelite and Fe^{3+}-poor mineral assemblages, indicate that this deposit is a reduced-type tungsten skarn (Sato, 1980, 1982), in accordance with the reduced nature of the granodiorite stock.

The Lermontovskoe deposit, the oldest mineralization so far known in the Sikhote-Alin orogen, formed in the initial stage of Early Cretaceous felsic magmatism. The magmatism began shortly after the accretionary tectonics ceased, suggesting an abrupt change of subduction system. Style of the Early Cretaceous magmatism and mineralization is significantly different between central Sikhote-Alin and Northeast Japan; reduced-type and oxidized-type, respectively. The different styles may reflect different tectonic environments; compressional and extensional, respectively. These two areas, which were closer together before the opening of the Japan Sea in the Miocene, may have been juxtaposed under a transpressional tectonic regime after the magmatism.

Keywords: Lermontovskoe, Bikin, Russia, tungsten skarn deposit, K-Ar muscovite age, Early Cretaceous magmatism, redox state, reduced-type granitoid, accretionary complex, plate reorganization, Kitakami, Northeast Japan

1. Introduction

Sikhote-Alin and the Japanese Islands were situated in the active continental margin of East Asia during the Mesozoic and early Cenozoic time, but were separated by opening of the Japan Sea in the Miocene. The two regions consist mainly of Jurassic accretionary complexes and Cretaceous to early Tertiary felsic igneous rocks which are accompanied by mineralization including tin and tungsten (Ishihara et al., 1992; Rodionov, 2005; Sato, 2003; Sato et al., 1992, 1993, 2002, 2004b, 2005). The time spans of the felsic magmatism in the two regions are practically identical (ca.130-50 Ma), but the types of magmatism, particularly their redox state and character of related mineralization within individual regions, are significantly different. This difference makes it difficult to reconstruct the original configuration of the two regions before the opening of the Japan Sea. To better understand the metallogenic provinces and their tectonic background in the circum-Japan Sea region, reliable age data are required. In this paper, the results of age determinations on the Lermontovskoe tungsten deposit in central Sikhote-Alin are reported and their tectonic significance is discussed in comparison with the metallogenic provinces of the Japanese Islands.

2. Outline of Geology

2.1. Regional geology

Pre-Miocene metallogeny of the Khingan and Sikhote-Alin regions in Far East Russia and of the Japanese Islands are characterized by hydrothermal mineralization related to felsic magmatism of Cretaceous to Paleogene age (Sato, 2003; Sato et al., 2002, 2004b). Jurassic magmatism is practically absent in these regions in contrast to the Korean Peninsula and eastern China. The pre-Cretaceous basement of the Khingan and Sikhote-Alin regions is divided into two major tectonic units: an older unit of Precambrian to Paleozoic continental blocks on the continental side, and a younger unit of Jurassic to Early Cretaceous accretionary complexes and turbidite deposits on the ocean side (Fig. 1). The continental blocks, the Bureya massif in the north and Khanka massif in the south, consist mainly of Proterozoic to Paleozoic igneous and metamorphic rocks, and subordinate Paleozoic sedimentary and volcanic sequences. The basement of the Japanese Islands consists essentially of the younger unit with minor occurrences of sliced older unit (Fig. 1).

Cretaceous to Paleogene felsic magmatism occurred over a large region including the above older and younger

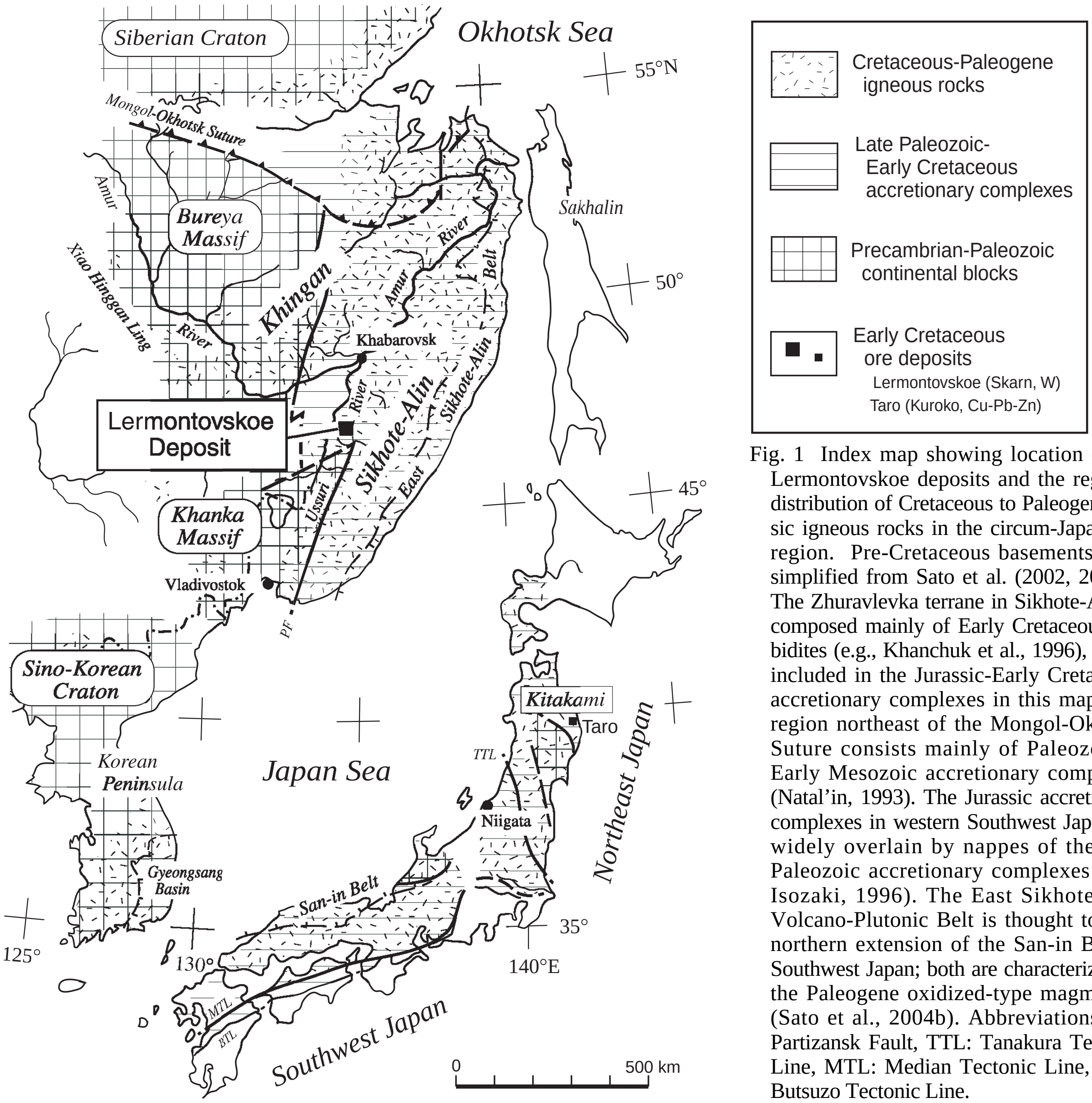

Fig. 1 Index map showing location of the Lermontovskoe deposits and the regional distribution of Cretaceous to Paleogene felsic igneous rocks in the circum-Japan Sea region. Pre-Cretaceous basements were simplified from Sato et al. (2002, 2004b). The Zhuravlevka terrane in Sikhote-Alin is composed mainly of Early Cretaceous turbidites (e.g., Khanchuk et al., 1996), and is included in the Jurassic-Early Cretaceous accretionary complexes in this map. The region northeast of the Mongol-Okhotsk Suture consists mainly of Paleozoic to Early Mesozoic accretionary complexes (Natal'in, 1993). The Jurassic accretionary complexes in western Southwest Japan are widely overlain by nappes of the Late Paleozoic accretionary complexes (e.g., Isozaki, 1996). The East Sikhote-Alin Volcano-Plutonic Belt is thought to be a northern extension of the San-in Belt of Southwest Japan; both are characterized by the Paleogene oxidized-type magmatism (Sato et al., 2004b). Abbreviations; PF: Partizansk Fault, TTL: Tanakura Tectonic Line, MTL: Median Tectonic Line, BTL: Butsuzo Tectonic Line.

tectonic units in Russia and the Japanese Islands (Fig. 1). The igneous regions within Russia are divided into two belts: the Khingan-Okhotsk Belt and Sikhote-Alin Belt (Sato et al., 2002). These two belts are considered to be juxtaposed arcs with different geotectonic histories, showing an unusually broad distribution of igneous rocks (Sato et al., 2004b).

Both the redox state of the Cretaceous to Paleogene felsic magmatism and character of associated mineralization show a systematic regional variation with the pre-Cretaceous basement geology (Sato et al., 2004b). Cretaceous reduced-type granitoids and volcanic rocks are widely distributed in the Khingan-Okhotsk Belt and major part of the Sikhote-Alin Belt, and are accompanied by tin and tungsten mineralization. The Lermontovskoe and Vostok 2 tungsten deposits are representative examples in Sikhote-Alin (Sato et al., 1993; Khanchuk et al., 1996). The large regions occupied by these belts are characterized by reduced type igneous rocks underlain by the Jurassic accretionary complexes.

In contrast, granitoids in the Khanka massif within southwestern Sikhote-Alin are of the oxidized type accompanied by gold mineralization, although they are also Cretaceous in age. No significant tin mineralization is associated with them (Sato et al., 2004b). The East Sikhote-Alin Volcano-Plutonic Belt along the Japan Sea coast (Fig. 1) consists of the latest Cretaceous to Paleogene oxidized-type volcano-plutonic complexes accompanied by gold mineralization. These two regions of oxidized igneous rocks accompanied by gold mineralization are characterized by earlier intense magmatism; Paleozoic in the Khanka massif and Cretaceous in the

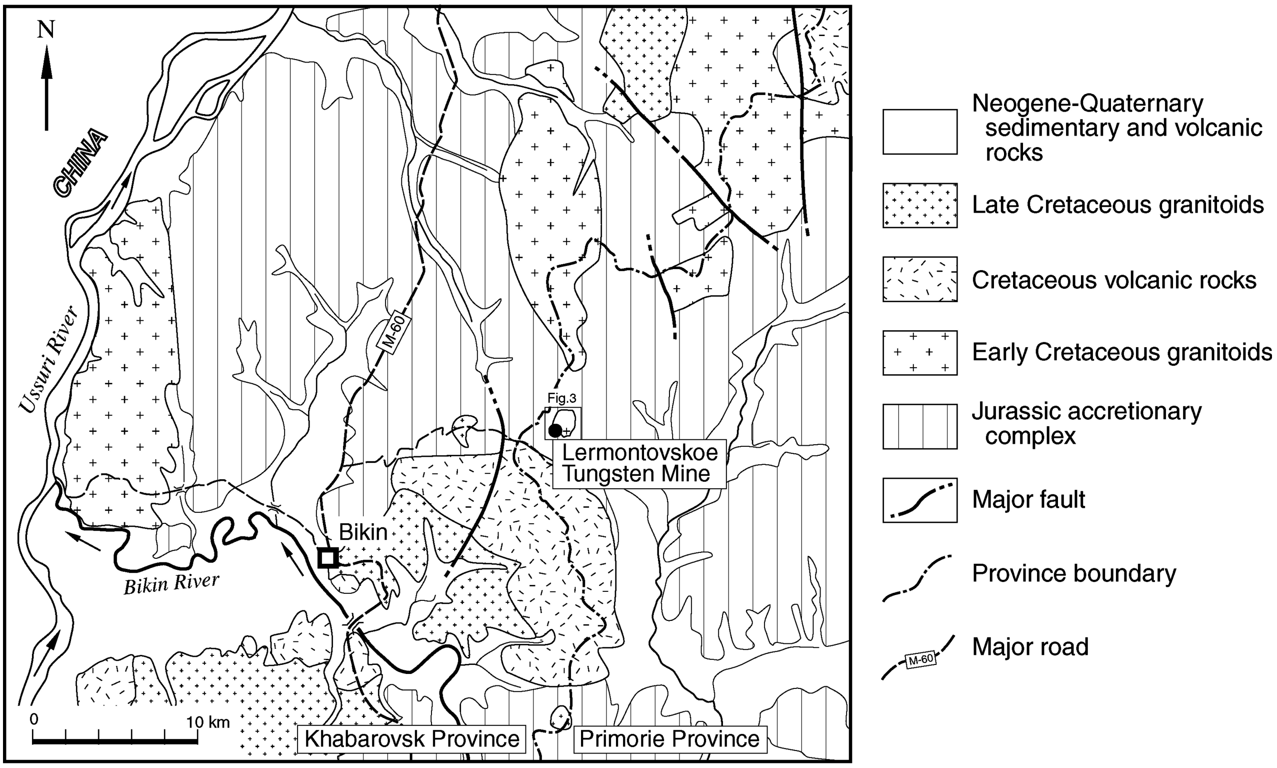

Fig. 2 Simplified geologic map of the Bikin area in central Sikhote-Alin, Far East Russia, based on the quadrangle geologic map by VSEGEI (1968) and Filippov (1983). Jurassic accretionary complexes consist of mudstone, sandstone and chert (Triassic to Jurassic) with limestone and basaltic volcanic rocks (Late Paleozoic). Cretaceous volcanic sequences around Bikin are called Archansk series which is thought to be Early Cretaceous, while those in northeastern corner are considered to be Late Cretaceous (see text). Neogene basalts are in the southeastern part of this map.

East Sikhote-Alin Volcano-Plutonic Belt. These correlations between the redox state of felsic magmatism and history of magmatism are also recognized in the Japanese Islands, and are considered to be related to the involvement of carbonaceous materials in sedimentary rocks acting as reducing agents (Sato et al., 2004b).

2.2. Geology of Bikin area

The Lermontovskoe deposit is located in the northwestern margin of Primorie Province near Bikin City (Fig. 2). Basement of the Bikin area belongs to the Samarka terrane which consists mainly of Jurassic accretionary complexes (Filippov et al., 1988; Khanchuk et al., 1996) similar to those of the Mino-Tanba Belt in Southwest Japan (Mizutani, 1987; Kojima, 1989). Filippov (1983) and Filippov et al. (1988), based on conodont and radiolarian fossils, demonstrated that sedimentary sequences in this area show a general NE trend and are composed mainly of Triassic to Jurassic chert and Jurassic to Early Cretaceous terrigenous sediments with local Paleozoic limestone and basic volcanic rocks. The terrigenous sediments are mainly Jurassic but the youngest are estimated to be early Early Cretaceous from Berriasian to Valanginian age (ca. 144-132 Ma, Gradstein et al., 1995). Limestone is of exotic origin and Carboniferous and Permian foraminifera have been reported (USSR Ministry of Geology, 1969). Lenses of exotic limestone provide the host rocks for the Lermontovskoe skarn ores.

According to Filippov (1983), the Jurassic to early Early Cretaceous accretionary complexes are unconformably overlain by Cretaceous subaerial volcanic rocks of andesite to rhyolite composition and intruded by coeval granitoids. The lower and upper units of the volcanic sequences were estimated to be Aptian-Albian and Senonian-Danian, respectively, based on spore and pollen analyses, but their exact ages require further study. Ages of granitoid plutons were estimated mainly from intrusive relations. One of the Early Cretaceous granitoid batholiths on the bank of the Ussuri River to the west of Bikin (Fig. 2), identified as reduced type from magnetic susceptibility and microscopic observation, has given ca.110 Ma K-Ar ages on biotites and a ca.128 Ma monazite age by the CHIME method (Sato et al., in prep.). Reliable radiometric data are very scarce, and no magnetic susceptibility data are available for the volcanic rocks in this area. However, magnetite was reported to be a common accessory mineral in the Late Cretaceous granitoid plutons (Nikiforova, 1973), suggesting that the younger granitoids are

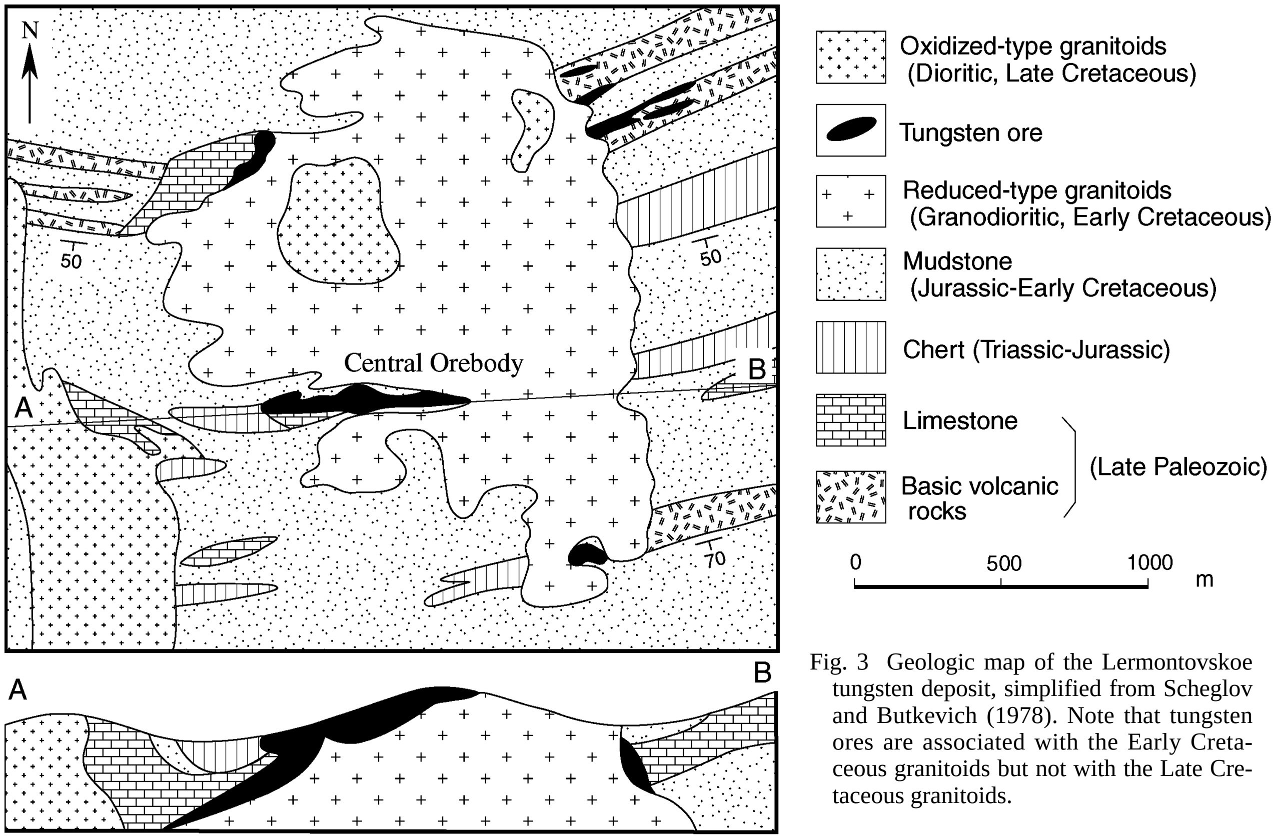

Fig. 3 Geologic map of the Lermontovskoe tungsten deposit, simplified from Scheglov and Butkevich (1978). Note that tungsten ores are associated with the Early Cretaceous granitoids but not with the Late Cretaceous granitoids.

of the oxidized type. Basic dykes of probable Cenozoic age are also observed in this area.

2.3. Geology of Lermontovskoe deposit

The Lermontovskoe deposit is classified as a large tungsten deposit with ore grade of 0.7-3 % WO_3 (Khanchuk et al., 1996), although detailed tonnage data have not been disclosed. Scheelite-bearing skarn ores occur in limestone near an Early Cretaceous stock of granodiorite composition (Figs. 3 and 4B). This stock (herein named Lermontovskoe stock) was emplaced in the southeastern limb of an antiform in the Jurassic host strata which are composed mainly of ENE-trending terrigenous sediments and chert with local intercalations of limestone and basic volcanic rocks. Surface area of the stock is about 2.5×1.0 km, but its intrusive contact dips outward at 25-70 degrees, suggesting that the present surface is close to the top of an original dome-like pluton (Fig. 3).

The apical part of the pluton is relatively felsic and fine-grained, and strongly greisenized (Scheglov and Butkevich, 1978). Contact metamorphism around the stock is recognized in a 0.6-1 km wide zone. Cordierite, pyroxene and rarely garnet are seen near the contact. Limestone is strongly recrystallized. Besides the granodioritic stock, small dioritic intrusions probably of Late Cetaceous age and basic dykes probably of Neogene age are observed in the mine area (Fig. 3). A dioritic intrusion and a dyke gave high magnetic susceptibility values of about $13\text{-}17\times10^{-3}$ SI and $19\text{-}25\times10^{-3}$ SI, indicating the oxidized type. These high values are in contrast with low values, less than 1×10^{-3} SI, corresponding to the reduced type, for some outcrops of the Lermontovskoe stock.

The skarn ores formed by the replacement of limestone beds within the thermally metamorphosed sequences composed of chert, siliceous shale and basic volcanic rocks (Fig. 3; Figs. 4B and 4C). Endoskarn within the granodiorite is practically absent (Scheglov and Butkevich, 1978). The ores are dominated by pyroxene skarn with minor occurrences of vesuvianite, wollastonite and garnet skarns. Clinopyroxene, the most common primary skarn mineral, is replaced by actinolite in the subsequent alteration. Actinolite is locally altered to chlorite. Scheelite grains are widely distributed in these skarns and show clear blue fluorescent color indicative of practically Mo-free chemistry, which is a distinctive feature of the reduced-type tungsten skarns (Sato, 1980, 1982). Sulfide minerals are mainly pyrrhotite with lesser chalcopyrite.

Another type of scheelite mineralization is associated with greisen alteration. The greisen alteration may have occurred subsequently to the skarn formation in the apical part of the granodiorite stock and metamorphosed and skarnized host rocks (Ivanov, 1974). The alteration is pervasive in granodiorite and it occurs as veins in the host rocks. Pegmatitic quartz veins are locally seen in the

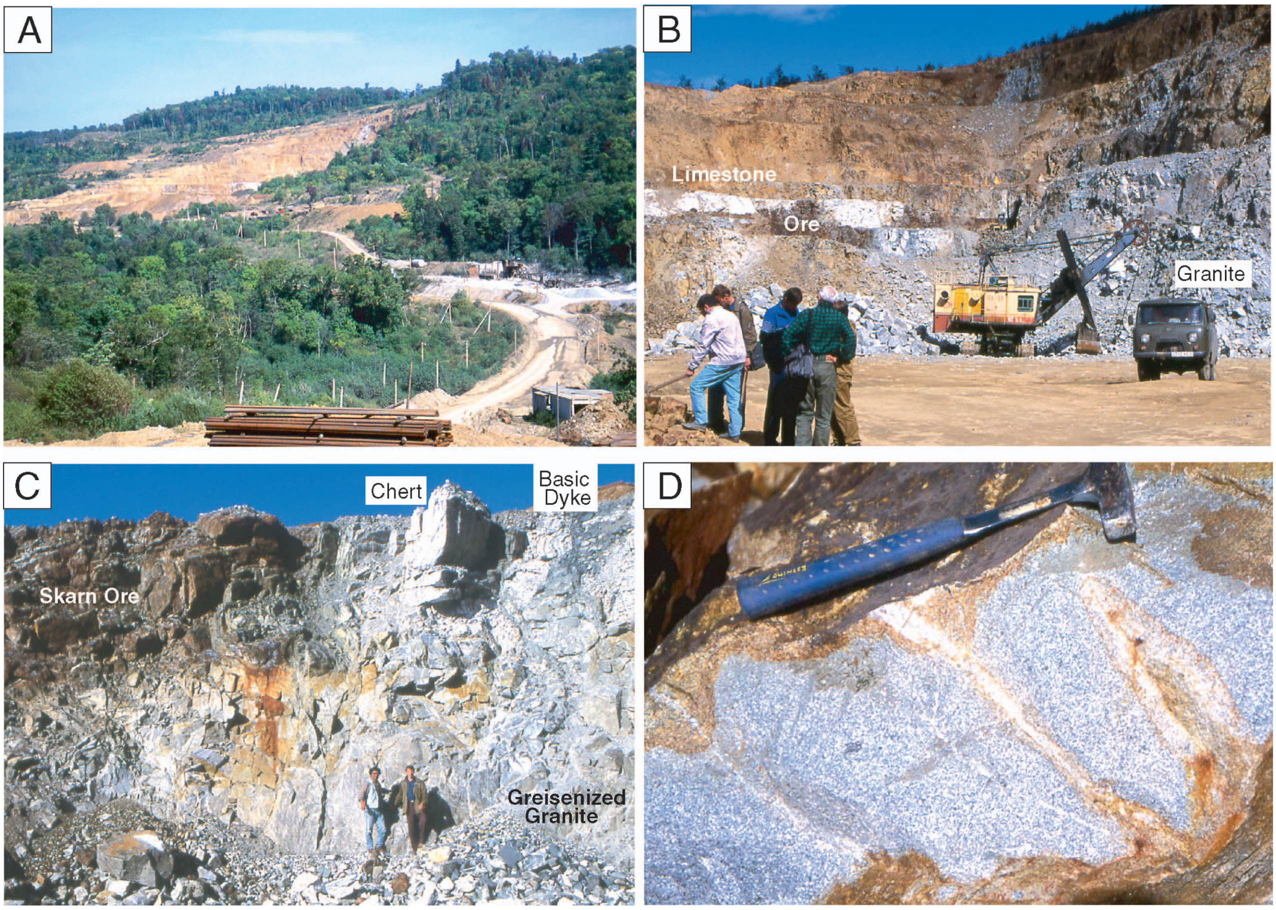

Fig. 4 Photographs of the Lermontovskoe deposit (September, 1993). A) Topography of the mine area. Central Orebody open pit in the background, B) Open pit of the Central Orebody, C) Mode of occurrence of ore and granite, D) Pegmatitic quartz veins in greisenized granite.

greisenized granodiorite (Fig. 4D). The greisen-like ores, composed mainly of quartz, muscovite, apatite, scheelite and calcite, may have replaced the skarn ores near the greisenized granodiorite. Scheelite in this type ores is generally more coarse-grained (up to 1.5 cm) and abundant than in the skarn ores, but it also shows a clear blue fluorescent color. Apatite is concentrated in some zones which are inferred to be conduits for ore solution (Scheglov and Butkevich, 1978). Minor sulfide minerals are mainly pyrrhotite, pyrite and arsenopyrite.

Ore minerals besides scheelite, pyrrhotite, arsenopyrite and pyrite in the Lermontovskoe ores include chalcopyrite, sphalerite, marcasite and wolframite (Ivanov, 1974; Scheglov and Butkevich, 1978). Oxidized ores occur near the surface (down to 30 m), and goethite, scheelite, tungstite and wolframite were identified in them.

3. Radiometric Dating

3.1. *Samples for dating*

Two muscovite-rich samples were collected at the open pit of the Central Orebody in September, 1993, when the mine activity was stopped. This is the largest orebody of the Lermontovskoe deposit, estimated to contain more than 90 per cent of the total tungsten ore reserve. The Central Orebody occurs at the southwestern contact between the Lermontovskoe stock and host Jurassic strata (Fig. 3). Metamorphosed sediments, recrystallized limestone and greisenized granite as well as skarn and greisen-like ores were exposed in the open pit at the time of the author's visit (Fig. 4A-C). Microscopic features of the samples are shown below. Muscovite concentrates for K-Ar age dating were prepared by conventional techniques using a magnetic separator and heavy liquid. The concentrates were 40-60 or 60-80 mesh (Table 1) and the possible contaminants in their concentrates were estimated to be less than 1 per cent.

Sample 93091602 (Greisenized granite): This sample consists mainly of quartz, plagioclase, K-feldspar, biotite and muscovite (Fig. 5A-B). Muscovite occurs as clear and euhedral-subhedral crystals of 0.2-1.5 mm, and the mineral occasionally forms aggregates.

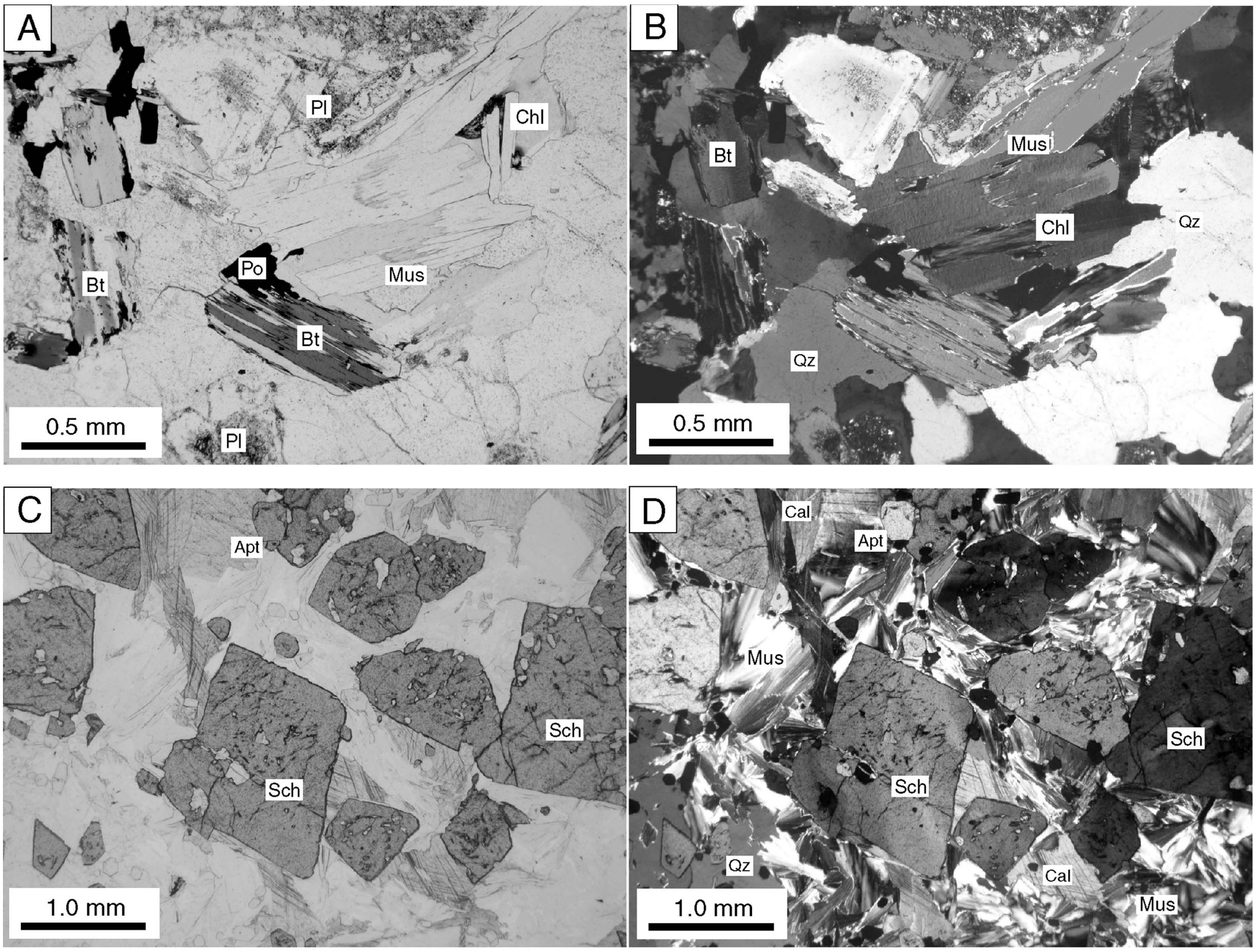

Fig. 5 Photomicrographs of the dated specimens from the Central Orebody. A) Greisenized granite (93091602, open nicols), B) 93091602 (cross nicols), C) High grade tungsten ore (93091607, open nicols). Scheelite includes euhedral apatite. D) 93091607 (cross nicols). Mineral abbreviations are Pl: plagioclase, Bt: biotite, Mus: muscovite, Chl: chlorite, Qz: quartz, Sch: scheelite, Apt: apatite, Cal: calcite and Po: pyrrhotite.

Relatively large euhedral crystals appear to be of magmatic origin. Plagioclase (0.2-2 mm) and biotite (0.2-1 mm) are partly replaced by sericite and chlorite, respectively. Accessory minerals include apatite, zircon and calcite. Scheelite was not observed in this sample. Interstitial sulfide minerals are mainly pyrrhotite with minor occurrences of chalcopyrite and arsenopyrite.

Sample 93091607 (High grade scheelite ore): This sample consists mainly of scheelite (0.1-7 mm), muscovite (0.1-1 mm), apatite (0.01-0.2 mm), calcite and quartz. Muscovite-calcite aggregates with some quartz form the matrix of euhedral scheelite crystals (Fig. 5C-D). Euhedral apatite crystals are distributed in the matrix and also included in the scheelite crystals. No opaque mineral was seen in this sample.

3.2. Result

Results of the dating are summarized in Table 1. The two muscovite samples gave identical ages of 132±7 Ma. It can be concluded, from the mode of occurrence of ores (Fig. 3), that the Lermontovskoe deposit was formed in the Early Cretaceous during the intrusion of the granodiorite stock. This may also be the intrusion age of the Lermontovskoe stock, previously estimated as Early Cretaceous. We suggest that younger dioritic intrusions probably of Late Cretaceous age are not

Table 1 K-Ar age data for muscovite from the Lermontovskoe tungsten skarn deposit in central Sikhote-Alin, Far East Russia.

Sample No.	Rock	K (%)	Rad. ^{40}Ar (scc/g×10^{-5})	Atm.^{40}Ar (%)	Age (Ma)
93091602	Greizenized granite	8.58	4.57	5.3	132±7
		8.54	4.57	5.9	132±7
					(av.)132±7
93091607	High grade scheelite ore	8.83	4.69	2.6	132±7
		8.80	4.72	2.9	132±7
					(av.)132±7

λ_β=4.962×10^{-10}/y, λe=0.58110^{-10}/y, ^{40}K/K=0.01167 atom%
Measurement by Teledyne Isotopes, USA

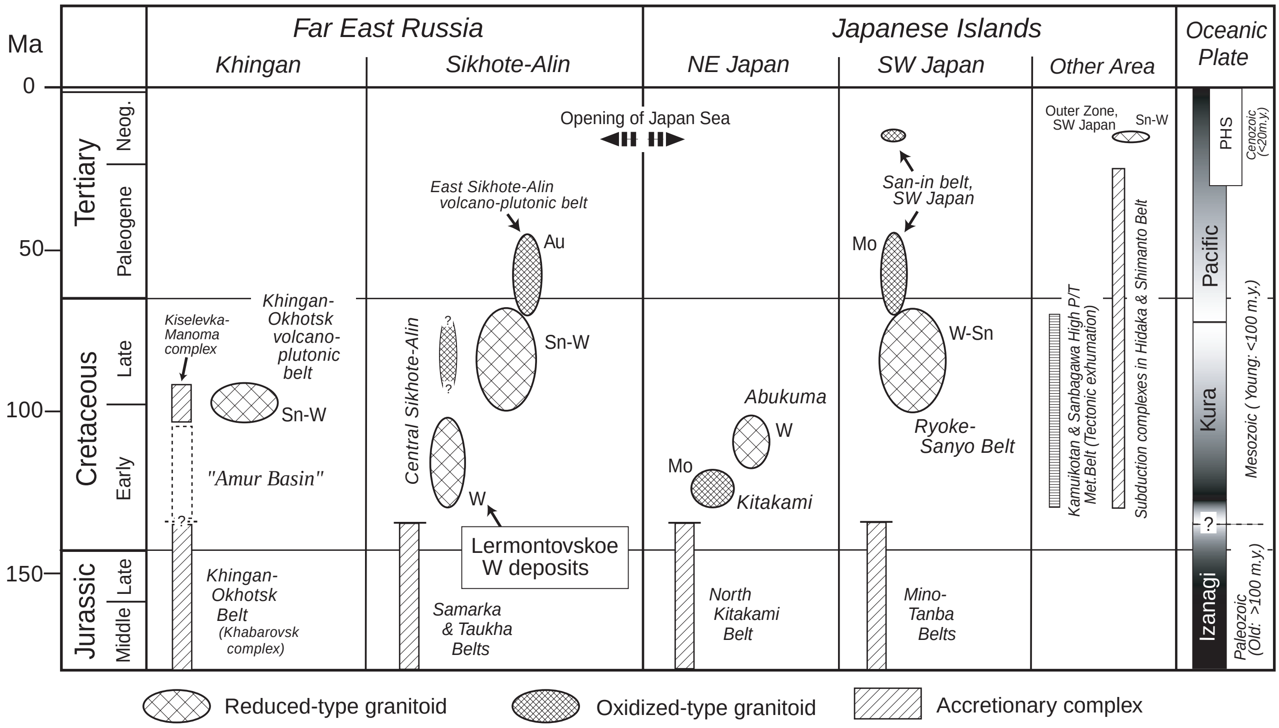

Fig. 6 Correlation of granitoid activity and related mineralization between Far East Russia and the Japanese Islands; Southwest Japan granitoids also shown. Initiation of granitoid magmatism appears to coincide with a significant oceanic plate reorganization, probably from old to young plates; subducted oceanic plates and their ages are based on Maruyama (1997). Early Cretaceous magmatism and hypothetical "Amur Basin" are considered to have been generated under a Sunda-style tectonic environment (Sato et al., 2002, 2004b).

directly related to the mineralization (Fig. 3).

4. Discussion

4.1. Oldest and reduced-type mineralization in Sikhote-Alin orogen

The Lermontovskoe tungsten deposit is concluded to have formed at ca.132 Ma in the Early Cretaceous and to have been genetically related to the Lermontovskoe granodiorite stock. The Mo-poor chemistry of scheelite and Fe^{3+}-poor mineral assemblage suggest that the deposit formed in relatively reducing conditions (Sato, 1980, 1982). This is consistent with classification of the granodiorite as reduced type, and with the younger dioritic intrusions of oxidized type not having a genetic link with the mineralization (Fig. 3) although exact age of the younger intrusions is to be determined.

Early Cretaceous granitoid batholiths are widely distributed in the Bikin area (Fig. 2), although their detailed age and petrographical data are not yet available. However, as mentioned above, one of the batholiths of reduced type on the Ussuri River bank was dated at ca.110 Ma for biotite and at ca.128 Ma for monazite (Sato et al., in prep.). These are interpreted to be cooling and intrusive ages, respectively, and may be representative for Early Cretaceous large batholiths in the Bikin area. In contrast, the Lermontovskoe stock and tungsten deposit are considered to have cooled rapidly due to their small size (Fig. 2) because the closure temperature of muscovite in the K-Ar system is estimated to be relatively low, around 350 degree C (e.g., Kaneoka, 1998, p. 20). Further chronological studies are required for more detailed thermal history of granitoids and ore deposits, but it is important to recognize that granitoid magmatism and related mineralization at the Lermontovskoe deposit is the oldest so far known in the Sikhote-Alin orogen (Fig. 6).

4.2. Tectonic environment and correlation with metallogenic province of the Japanese Islands: an evidence of abrupt change of plate configuration

The Bikin area is thought to have been situated near a trench in the Jurassic to early Early Cretaceous on the basis of the age of the accretionary complexes. The youngest terrigenous sediment within the accretionary complexes is Valanginian in age (Filippov, 1983; Filippov et al., 1988) which is 137-132 Ma according to the geochronological time scale by Gradstein et al. (1995). This suggests that the subduction zone changed quickly to a site of felsic magmatism (ca.132 Ma), and that the style of plate configuration in the Sikhote-Alin region significantly changed during Valanginian time (Fig. 6).

A similar episode is also recognized in the northern Kitakami area of Northeast Japan (Figs. 1 and 6) where granitoid and coeval volcanic activity occurred at 130-120 Ma shortly after accretionary tectonics ceased (Sato et al., 2004b). The granitoids in the Kitakami area is of oxidized type (e.g., Sato et al., 1992), in contrast to those in the Bikin area. Bimodal volcanism occurred in a submarine environment, with kuroko mineralization at the Taro mine (Sato et al., 2004a), in contrast to the subaerial unimodal volcanism in the Bikin area. The Early Cretaceous volcanism in the Bikin area may have occurred after uplift of the Jurassic to early Early Cretaceous accretionary complexes, suggesting a compressional environment in contrast to an extensional environment in the Kitakami area. This difference in stress regime may have affected the redox state of felsic magmatism (Sato et al., 2004b).

The Bikin and Kitakami areas were closer together before the opening of the Japan Sea in the Miocene. It is peculiar that nearly coeval but significantly different kinds of magmatism coexisted in a relatively small region within the active margin of East Asia. This could be a result of displacement of the Kitakami area toward north from its position during magmatism because the tectonic regime in the Early Cretaceous is characterized by the highly oblique convergence of the paleo-Pacific plate and East Asia (e.g., Maruyama and Seno, 1986; Sato et al., 2004b). Sato et al. (2002) proposed a Sunda-style tectonic model for the genesis of the Khingan-Okhotsk Volcano-Plutonic Belt. The Kitakami area may also have been involved in this tectonic regime. This area is thought to have occupied a local extensional environment within the transpressional regime. However, any palinspastic reconstruction is difficult because the paleo-position of the Kitakami area in the Early Cretaceous is poorly constrained due to tectonic and thermal reorganization during Late Cretaceous and Cenozoic orogenies.

Initiation of the Cretaceous felsic magmatism in the Jurassic to Early Cretaceous accretionary terranes suggests an abrupt change in the subduction system along the East Asian continental margin. We propose three possibilities which may have influenced this abrupt change: (1) change of subducted oceanic plates, (2) collision of East Asia with Siberian continent, and (3) superplume activity.

Oceanic plate stratigraphic data for the accretionary complexes suggest that ages of subducted oceanic plates decreased (e.g., Isozaki, 1996; Maruyama, 1997). They were old (>100 m.y.) during the Jurassic to Early Cretaceous time when the Samarka terrane was formed, but young (<100 m.y.) during the Late Cretaceous to Paleogene when voluminous felsic magmatism occurred in the whole circum-Japan Sea region (Fig. 6). A very young plate including a spreading ridge is thought to have subducted in the Late Cretaceous (e.g., Maruyama, 1997).

The second possible geodynamic event which may have affected the East Asian convergent margin is closure of the Mongol-Okhotsk ocean due to the collision of East Asia with the Siberian craton. This ocean is thought to have closed from west to east, and to have disappeared in the Early Cretaceous (Zonenshain et al., 1990). Closure may have promoted left-lateral displacement in the East Asian continental margin.

The third factor is superplume activity in the South Pacific (e.g., Larson, 1991). The age of initial Cretaceous felsic magmatism and mineralization in Sikhote-Alin and the Japanese Islands around 130 Ma is close to that of the abrupt increase in oceanic crust production which has been related to superplume activity in the South Pacific. This activity may have increased the rate of subduction in East Asia and other convergent margins around the Pacific Ocean. Vaughan (1995) noted that apparent tectonic responses to this pulse are recognized in many areas of the Pacific Rim.

Further study is required to fully understand the magmatism and metallogeny in the circum-Japan Sea region and their geodynamic background.

5. Conclusions

The Lermontovskoe tungsten skarn deposit in central Sikhote-Alin formed at 132 Ma based on K-Ar data for muscovite concentrates from scheelite ore and granitoid. Late Paleozoic limestone in the Jurassic accretionary complexes was replaced during hydrothermal activity related to Early Cretaceous granitoids of reduced type. The ores, characterized by Mo-poor scheelite and Fe^{3+}-poor mineral assemblages, indicate that this deposit formed in a reduced environment related to the reduced-type granodioritic magma.

The Lermontovskoe deposit is the oldest mineralization in the Sikhote-Alin orogen. The granitoid magmatism and related mineralization in the Bikin area, central Sikhote-Alin occurred shortly after the accretionary tectonics ceased, suggesting an abrupt change of the subduction system around 135 Ma in Valanginian time.

No coeval granitoid and metallogenic provinces are recognized in the Japanese Islands, where Early Cretaceous granitoid magmatism and mineralization are dominantly the oxidized type as seen in the Kitakami area of Northeast Japan. Tectonic environments in central Sikhote-Alin at the time of granitoid magmatism may have been different from those in the Kitakami area; compressional and extensional, respectively. This difference may have controlled the different redox state of granitoid magmas in the two areas. The close proximity of the two areas which formed in significantly different tectonic regimes can be explained if that they were juxtaposed under a transpressional tectonic regime during the Early Cretaceous.

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