Transactions of the Royal Society of Edinburgh: Earth Sciences, **95**, 319–337, 2004

Crustal control on the redox state of granitoid magmas: tectonic implications from the granitoid and metallogenic provinces in the circum-Japan Sea Region

K. Sato, S. V. Kovalenko, N. P. Romanovsky, M. Nedachi, N. V. Berdnikov and T. Ishihara

ABSTRACT: Felsic magmatism has occurred over a large region of East Asia since Jurassic times and has provided important mineral resources such as tin, tungsten, base metals and gold. The circum-Japan Sea region preserves various geological records of active continental margins, including Jurassic to Early Tertiary magmatic arcs and subduction zones and pre-Jurassic continental basements, which were separated by the opening of the Japan Sea during the Miocene. The felsic magmatism in this region shows a wide variation in terms of redox state and related mineralisation, encompassing east–west contrasts around the Pacific Ocean. A review of granitoids and associated ore deposits in this region indicates that the character of the crust, sedimentary versus igneous, is an essential factor to control the redox state, and a tectonic setting may be an additional factor in some cases.

The reduced-type granitoids, characterised by tin mineralisation, were generated in carbon-bearing sedimentary crust which was composed mainly of accretionary complex material and not influenced by previous magmatism. Involvement of sedimentary materials is corroborated by oxygen, sulphur and strontium isotope data. The oxidised-type granitoids, characterised by gold or molybdenum mineralisation, were generated in igneous crust which was depleted in reducing agents as a result of previous magmatism. Granitoid magmatism in a given area tends to become more oxidised with time.

Jurassic accretionary complexes in East Asia are thought to have been largely displaced from the original place of accretion and stacked up against the northeastern margin in the Khingan and Sikhote–Alin Mountains. This region, dominated by sedimentary crust, was subsequently subjected to Cretaceous felsic magmatism and converted to a large province of reduced-type granitoids and tin–tungsten mineralisation. Diverse geodynamic processes, including the change of the arc-trench system, the creation and collapse of the back-arc basin and the collision of continents, may have prepared many favourable sites for the generation of reduced-type granitoids in northeast Asia. These processes may have resulted in a remarkable contrast with the Pacific margin of North America, where repeated arc magmatism during the Mesozoic formed granitoid batholiths of the oxidised-type.

The granitoid types may also be controlled by the tectonic setting and mode of magma emplacement. In the northern Kitakami area of Northeast Japan, Early Cretaceous episodic magmatism occurred in a Jurassic accretionary complex, and formed the oxidised-type granitoids accompanied by submarine bimodal volcanism associated with kuroko mineralisation. Granitoids of fissure-filling type emplaced under extensional environments may be oxidised, irrespective of basement geology, because of insignificant crustal input.

KEY WORDS: Accretionary complex, Cretaceous, granitoid type, Jurassic, Khingan, Korea, metallogeny, sedimentary crust, Sikhote–Alin, tin.

Granitoids and mineralisation around the Pacific Ocean show a remarkable contrast between the east and west sides. The Asian side is dominated by reduced-type granitoids and characterised by tin mineralisation. On the other hand, the Pacific margin of North America is dominated by oxidised-type granitoids and characterised by the lack of tin (e.g. Ishihara 1984). However, when examined closely East Asia is not homogeneous. For example, southeast China is very rich in tin, whilst northeast China and the Korean Peninsula are very poor, in fact practically free of Phanerozoic tin deposits (e.g. Sato 1982b; KIER 1983; Chinese Academy of Geological Sciences 1999). Far East Russia is very rich in tin, as the Sikhote–Alin, Khingan and Yana–Kolyma have been major tin-producing regions since the time of the Soviet Union (e.g. USSR Ministry of Geology 1987). The Japanese Islands include tin-rich and tin-barren provinces (e.g. Ishihara & Sasaki 1973).

Therefore, the circum-Japan Sea is a good area to increase the understanding of the genesis of granitoid types and related mineralisation (Sato 2000, 2003). In this paper, the authors review the characteristics of granitoids and mineralisation in the southern part of Far East Russia, with special emphasis on the redox state of granitoids and its correlation with basement geology, and compare them with the geological data for the Korean Peninsula and the Japanese Islands from the viewpoint of the tectonic history of East Asia.

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

The ilmenite- and magnetite-series classification of Ishihara (1977) is based essentially on the redox state of granitoid magmas. The two series granitoids are similar in major element composition except for their Fe^{3+}/Fe^{2+} ratio. Therefore, the two series can be named reduced-type and oxidised-type, respectively (Sato *et al.* 1992); these terms are used in this paper. The two types of granitoids are easily discriminated by measurement of magnetic susceptibility, even in the field, because ferric iron exists mainly in magnetite in the oxidised-type rocks. Magnetic susceptibility data for granitoids in Japan show a clear bimodal distribution (Sato *et al.* 1992), typically $<1 \times 10^{-3}$ SI for the reduced type and $10–50 \times 10^{-3}$ SI for the oxidised type. The boundary between the two types was placed at 100×10^{-6} emu/g (Ishihara *et al.* 1981), which approximately corresponds to 3×10^{-3} SI (Sato & Ishihara 1983). Accompanying mineralisation is quite contrasting. Tin is a representative ore element of the reduced-type granitoids, whilst gold and molybdenum mineralisations are related to the oxidised-type granitoids. These correlations, established in Japan, have also been confirmed in eastern Australia (e.g. Blevin & Chappell 1992) and in Far East Russia as described below.

Mesozoic to Cenozoic granitioids in the circum-Japan Sea region consists mainly of granite, granodiorite and tonalite. Most of them have chemical compositions of the I-type of Chappell & White (1974, 1992) (Takahashi *et al.* 1980; Jwa 1998; Jin *et al.* 2001; Sato & Chappell, unpublished data). The S-type or A-type granitoids do occur, but their occurrences are very limited. This paper focuses on a regional variation of the redox state of granitoids and its correlation with the metallogenic provinces from the viewpoint of the geodynamic history of East Asia. Individual petrochemical features including the I- and S-type classification will be reported elsewhere.

1. Khingan and Sikhote–Alin Mountains, Far East Russia

The Khingan and Sikhote–Alin Mountains (Fig. 1) are characterised by tin mineralisation related to Cretaceous felsic magmatism. Jurassic mineralisation is not known in this region of Far East Russia, although both Jurassic and Cretaceous mineralisations related to felsic magmatism are widely distributed in Korea and China.

The pre-Cretaceous basement of the Khingan and Sikhote–Alin Mountains is divided into two tectonic units: an older unit of Precambrian to Palaeozoic continental blocks on the continental side, and a younger unit of Jurassic to Cretaceous accretionary complexes and turbidite deposits on the oceanic side (Figs 2A, 5 & 11). The continental blocks, the Bureya massif in the north and Khanka massif in the south, consist mainly of Proterozoic to Palaeozoic igneous and metamorphic rocks, and subordinate Palaeozoic to Mesozoic sedimentary and volcanic sequences (e.g. Khanchuk *et al.* 1996; Sato *et al.* 2002, 2003b).

Cretaceous to Palaeogene felsic igneous activities occurred over a large region, including the above two units (Fig. 1). The igneous regions in southern Far East Russia are divided into two belts: the Khingan–Okhotsk Belt and Sikhote–Alin Belt (Fig. 2A). These two belts are considered to be juxtaposed arcs with differing geotectonic histories, showing an unusually broad distribution of igneous rocks in the Khingan and northern Sikhote–Alin Mountains, up to 700 km in an E–W direction.

1.1. The Khingan–Okhotsk Belt

The Khingan–Okhotsk Belt consists of many volcano–plutonic complexes, which are composed of granitoids and felsic volcanic rocks and associated with tin mineralisation (Sato *et al.* 2002). The Khingan (Kh), Badzhal (Bz) and Komsomolsk (Km) deposits are representative large tin deposits (Fig. 2A). The total length of this tin-associated volcano–plutonic belt exceeds 700 km, although both ends are not fully characterised. The northeastern end near the Okhotsk Sea appears to overlap with the Sikhote–Alin Belt. The southwestern extension beyond the Amur River, a national border with China, is somewhat enigmatic. Cretaceous volcanic rocks occur in the Xiao Hinggan Ling (Fig. 1), but no remarkable tin deposit is known in this region of northeast China (Chinese Academy of Geological Sciences 1999). Granitoids are widely exposed in this region, but they are mostly Palaeozoic age, as in the Bureya massif within Russia (Krasnyi & Peng 1996). The Khingan–Okhotsk tin belt is thought to be terminated near the Amur River.

Granitoids from the tin-associated volcano–plutonic complexes typically gave very low magnetic susceptibility values ($<1 \times 10^{-3}$ SI), and associated volcanic rocks are characterised by low Fe^{3+}/Fe^{2+} ratios of whole-rock chemical analyses (Mishin & Romanovsky 1994). This evidence indicates that the Khingan–Okhotsk Belt consists essentially of reduced-type rocks. This is consistent with the result of the aeromagnetic survey; the Khingan–Okhotsk Belt does not give rise to any significant magnetic anomalies (Fig. 2B). The northern part of this belt near the Okhotsk Sea is not well studied, but flat anomaly patterns suggest the paucity of magnetic minerals.

Regional variation of the magnetic anomalies correlates well with the tectonic provinces around the Khingan–Okhotsk Belt (Fig. 2A, B). It is remarkable that the flat pattern coincides with the regions of the accretionary complex in which the volcano–plutonic complexes of the Khingan–Okhotsk Belt are emplaced. The southern Siberian craton, Bureya massif and East Sikhote–Alin Volcano–Plutonic Belt (Fig. 2A) are characterised by a rugged magnetic anomaly pattern, indicating wide distribution of magnetite-bearing igneous rocks. Granitoids in the East Sikhote–Alin Volcano–Plutonic Belt have been corroborated to be the oxidised type, based on magnetic susceptibility data (Romanovsky *et al.* 1996). The complicated magnetic anomaly patterns in northern Sikhote–Alin may be biased by the presence of Neogene volcanic rocks.

Igneous activity of the Khingan–Okhotsk Belt has been thought to have begun in the Early Cretaceous (Barremian) and lasted throughout the entire Late Cretaceous (Faure & Natal'in 1992; Natal'in 1993). However, recent radiometric dating suggests that magmatism in this tin-rich belt was a much shorter episodic event in the middle Cretaceous (Sato *et al.* 2002). Radiometric age data for major tin deposits and the surrounding igneous rocks cluster at 95 Ma, although the deposits are separated by 100–200 km. This result suggests a short-lived tin-associated magmatic event in contrast with the long-lasted magmatism in Sikhote–Alin and the Japanese Islands (Sato *et al.* 1992, 2002). The Khingan–Okhotsk Belt is also clearly discriminated from the northern Sikhote–Alin Belt not only in age but also in metallogeny; the latter being characterised by gold mineralisation (Sato *et al.* 1996).

Cretaceous accretionary complexes are distributed to the southeast of the Khingan–Okhotsk Volcano–Plutonic Belt (Natal'in 1993; Sato *et al.* 2002). The Kiselevka–Manona complex (KM in Fig. 2A), the youngest accretionary complex in the Khingan and Sikhote–Alin Mountains, is distributed along the Amur suture, which is thought to be a tectonic boundary with Jurassic accretionary complexes in central Sikhote–Alin (SM in Fig. 2A). Detailed studies on radiolarian assemblages using specimens from good exposures near the Amur River (Zyabrev 1996; Markevich *et al.* 1997) indicate

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

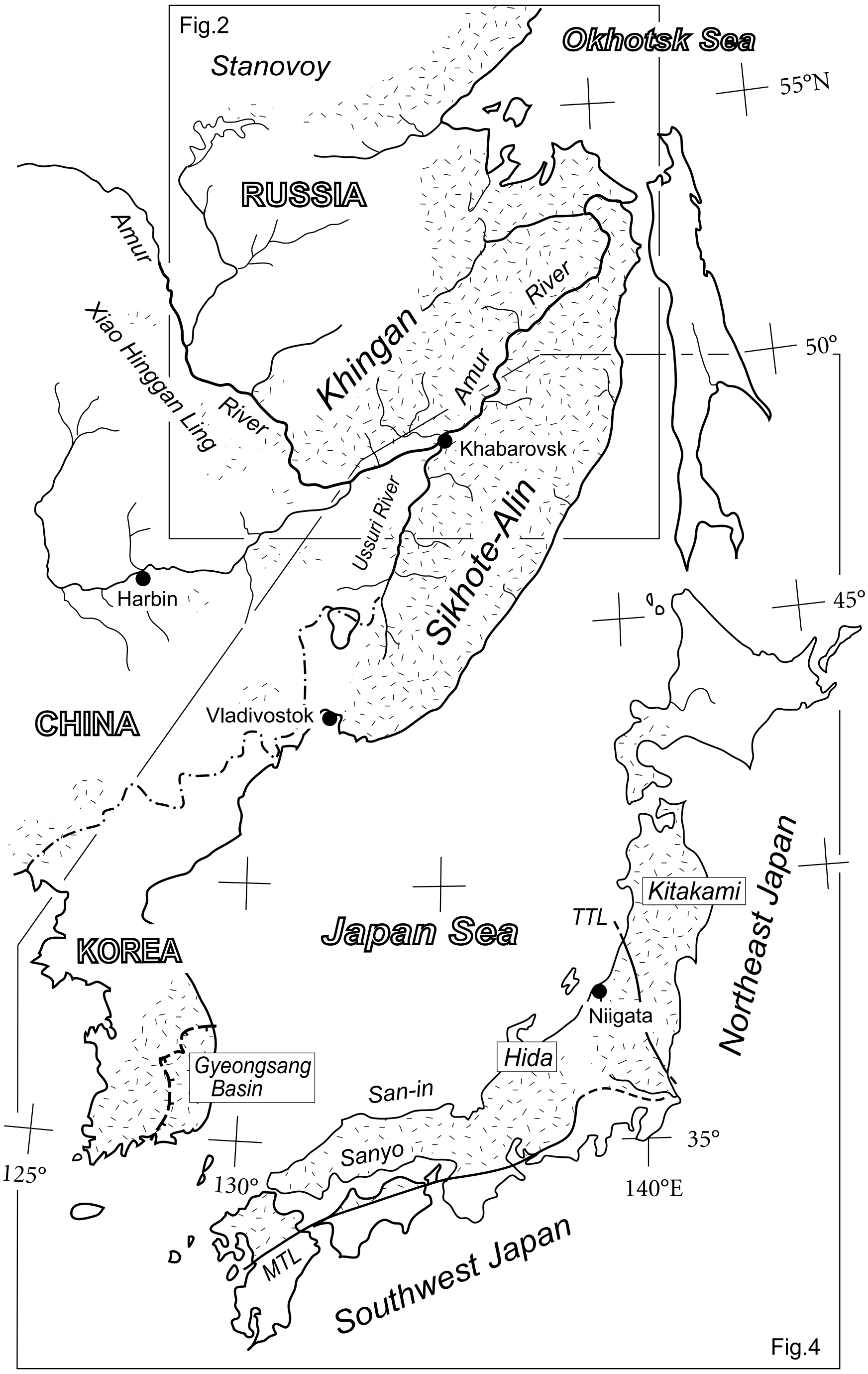

Figure 1 Map showing the distribution of Cretaceous–Palaeogene felsic magmatism in the circum-Japan Sea region, compiled from Sato *et al.* (1992), KIGAM (1995a) and Krasnyi & Peng (1996). (TTL) Tanakura Tectonic Line; (MTL) Median Tectonic Line. The national border between Russia and China coincides with the Amur and Ussuri Rivers. Xiao Hinggan Ling is also expressed as Lesser Khingan Mountains.

that the age of accretion was Albian–Cenomanian (ca. 110–90 Ma) in the middle Cretaceous. The apparent parallelism, in time and space, between the volcano–plutonic belt and the accretionary complex suggests that the Khingan–Okhotsk Belt and the Kiselevka–Manona complex represent a paired magmatic arc and subduction complex (Sato *et al.* 2002).

The Jurassic accretionary complex in central Sikhote–Alin occurs to the southeast of the Kiselevka–Manona complex, that is, the oceanic side is older than the continental side. These relationships between the accretionary complexes and igneous rocks within the Khingan–Okhotsk Belt and northern Sikhote–Alin Belt (Figs 2A, 3) suggest vigorous and complicated tectonic activity and magmatism over a relatively short period during the middle Cretaceous.

The Kiselevka–Manona complex includes Early Cretaceous bedded chert with basic tuffs and lavas below the middle Cretaceous clastic units (Nechaev *et al.* 1996; Zyabrev 1996; Markevich *et al.* 1997), indicating relatively young volcanism on an oceanic plate prior to subduction. Based on heavy mineral assemblages Nechaev *et al.* (1996) suggested the existence of an Early Cretaceous immature volcanic arc and back-arc basin in the present Lower Amur region. Sato *et al.* (2002) proposed a model of Sunda-style tectonics for the generation of the episodic reduced-type magmatism in the Khingan–Okhotsk Belt, assuming the existence of young back-arc basin such as the Andaman Basin (Fitch 1972; Hamilton 1979; Curray *et al.* 1979, 1982). That is, subduction of the young back-arc basin may have caused the episodic

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

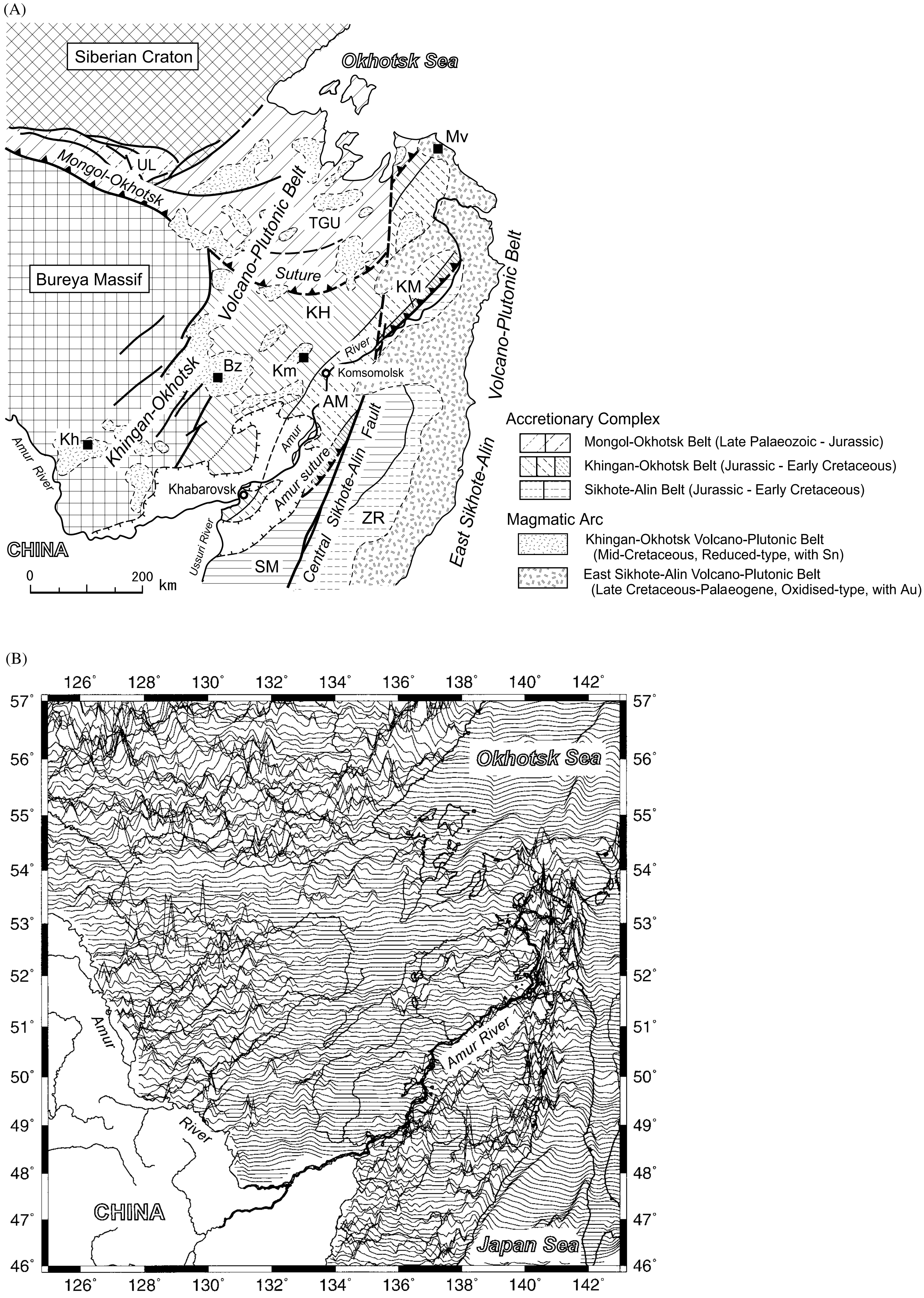

Figure 2 (A) and (B).

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

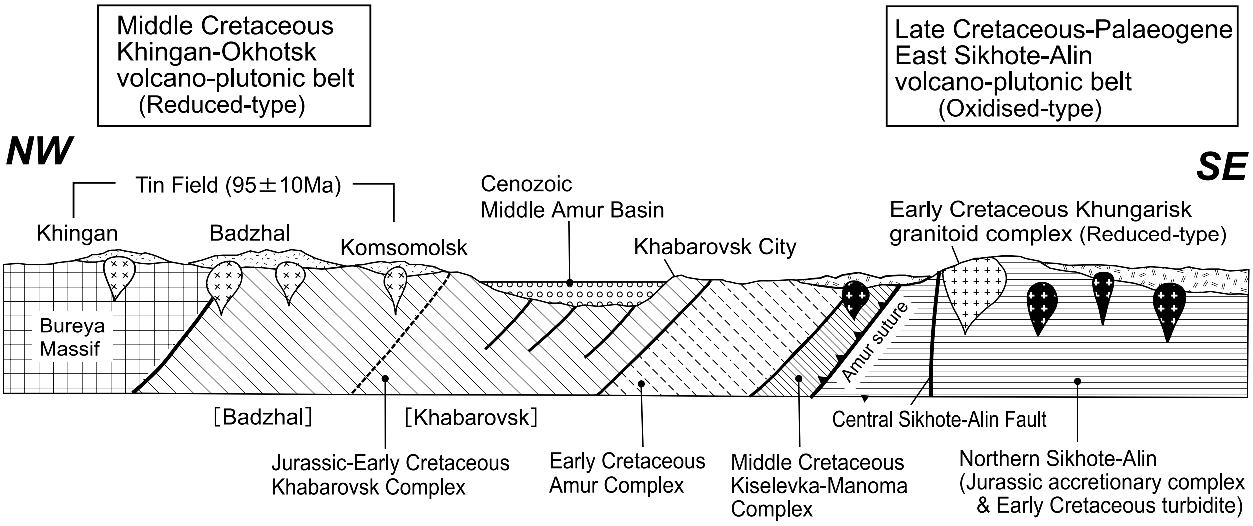

Figure 3 Schematic NW–SE cross section through the Khingan–Okhotsk active margin and northern Sikhote–Alin (Sato *et al.* 2002); modified from Faure & Natal'in (1992) and Natal'in (1993). Episodic magmatism and mineralisation in the Khingan–Okhotsk Tin Belt (95 ± 10 Ma) is coeval with the middle Cretaceous (Albian–Cenomanian) Kiselevka–Manoma complex (Voinova *et al.* 1995; Zyabrev 1996; Nechaev *et al.* 1996). The Khungarisk complex a conventional name for a group of Early Cretaceous granitoid plutons in north-central Sikhote–Alin.

magmatism in a similar manner to the Miocene tin-associated magmatism in the Outer Zone of Southwest Japan, which was caused by the subduction of the very young Shikoku Basin in relation to the opening of the Japan Sea (e.g. Kobayashi & Sato 1979; Furukawa & Tatsumi 1999).

1.2. The Sikhote–Alin Belt

The Sikhote–Alin Belt hosts Cretaceous–Palaeogene felsic magmatism which is associated with various mineral resources including tungsten, tin, base metals and gold (Fig. 4). The major part of the basement consists of Jurassic to Early Cretaceous accretionary complexes and turbidite deposits, but a Precambrian to Palaeozoic continental fragment of the Khanka massif occurs in southwestern Sikhote–Alin (Figs 5 & 11). Granitoid magmatism began at about 130 Ma in central Sikhote–Alin, and appears to have continued throughout the Cretaceous. Magmatism migrated eastwards to the present coastal regions, in the late Late Cretaceous to Palaeogene, resulting in the formation of the East Sikhote–Alin Volcano–Plutonic Belt. Detailed age variations in the granitoid magmatism within Sikhote–Alin require further study, but it is significant that magmatism lasted for more than 70 m.y. in contrast with the episodic Khingan–Okhotsk magmatism (Sato *et al.* 2002).

Compiled magnetic susceptibility data for most of granitoid plutons reveals regional distributions of the reduced- and oxidised-type granitoids in Sikhote–Alin (Romanovsky *et al.* 1996). In view of age and associated mineralisation as well as the magnetic susceptibility data, granitoid magmatism in Sikhote–Alin is divided into the following three provinces (Fig. 4): (1) the central Sikhote–Alin weakly magnetic province ($<1 \times 10^{-3}$ SI) composed essentially of the Cretaceous reduced-type granitoid plutons accompanied by tungsten and tin mineralisation; (2) the east Sikhote–Alin highly magnetic province ($\sim 3\text{–}30 \times 10^{-3}$ SI), composed mainly of late Late Cretaceous to Palaeogene oxidised-type granitoid plutons and volcanic rocks (East Sikhote–Alin Volcano–Plutonic Belt) that are locally accompanied by gold mineralisation (Sato *et al.* 1996, fig. 1); and (3) the southwest Sikhote–Alin highly magnetic province ($\sim 5\text{–}25 \times 10^{-3}$ SI), composed of Late Cretaceous oxidised-type granitoid plutons accompanied by gold mineralisation (Fig. 5). Province 1 constitutes a major part of Sikhote–Alin and includes many tungsten and tin deposits, such as the Vostok-2 (W skarn), Tigrinoe (Sn+W greisen) and Dubrovsk (Sn vein) deposits (Sato *et al.* 1993a; Khanchuk *et al.* 1996). Therefore, this province apparently represents the whole Sikhote–Alin Belt as a tungsten-tin metallogenic province. The magmatism and mineralisation in this province occurred over a long time interval (ca. 130–70 Ma), but their detailed variations within the province, particularly their relationships with those in province 2 require further reliable age data (Matsuda *et al.* 1998). Care has to be taken with dating because granitoids of province 1 near the coastal region are often influenced by the younger igneous activity of province 2. Provinces 1 and 3 correspond approximately to the region of Jurassic to Early Cretaceous sedimentary rocks and the Precambrian–Palaeozoic continental fragment, respectively (Figs 4 & 11). The relationship between these two provinces is well observed in the southernmost Sikhote–Alin as described below (Fig. 5), where the coast provides good exposures for the observation of across-arc variation of granitoids and basement rocks, compared with other areas in Sikhote–Alin.

Relationships between granitoid types, basement terranes and mineralisation in the southernmost Sikhote–Alin are

Figure 2 (A) Tectonic map showing the distribution of accretionary terranes and volcano–plutonic belts around the Khingan–Okhotsk Belt. Compiled from Natal'in & Zyabrev (1989), Faure & Natal'in(1992), Natal'in (1993), Krasnyi & Peng (1996), Romanovsky *et al.* (1996) and Sato *et al.* (2002). (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) large ore deposits; (Kh) Khingan (Sn); (Bz) Badzhal (Sn); (Km) Komsomolsk (Sn+W+Cu); and (Mv) Mnogovershinnoe (Au+Ag). (B) Magnetic anomaly map of the same region based on the data by USSR Ministry of Geology (1977). Profile interval is five minutes. Note that the flat pattern corresponds to the region of accretionary complex and igneous rocks of the Khingan–Okhotsk Volcano–Plutonic Belt which lacks significant magnetite, in contrast to the higher relief pattern for the southern Siberian craton, Bureya massif and East Sikhote–Alin Volcano–Plutonic Belt.

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

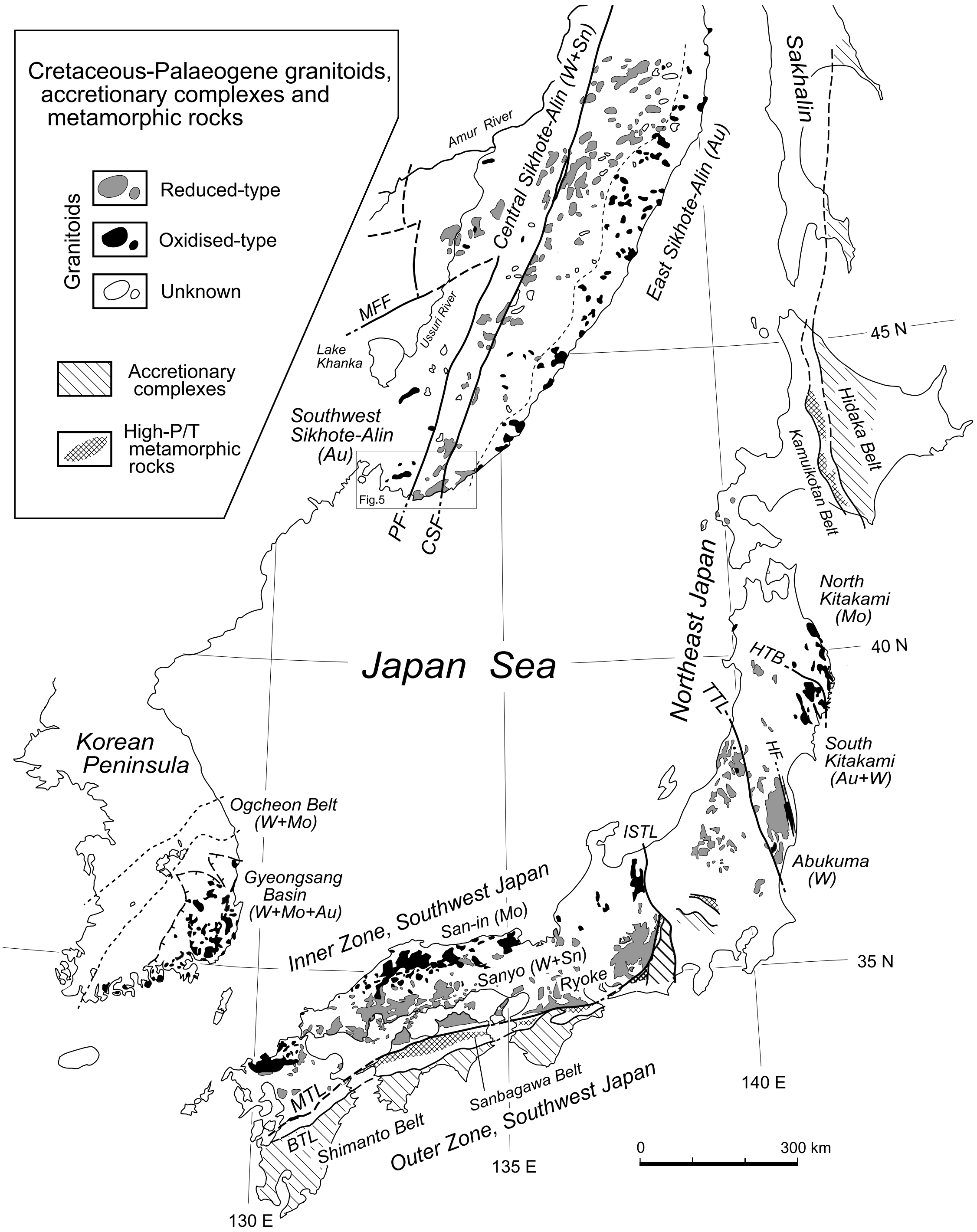

Figure 4 Distribution of Cretaceous–Palaeogene granitoids and metallogenic provinces in the circum-Japan Sea region. The distribution of reduced- and oxidised-type granitoids is based on Sato *et al.* (1992) for the Japanese Islands, Romanovsky *et al.* (1996) for Sikhote–Alin and Jin *et al.* (2001) for the Korean Peninsula. The metallogenic provinces were compiled from Ishihara *et al.* (1992) for the Japanese Islands, Sato *et al.* (1993a 1996) and Khanchuk *et al.* (1996) for Sikhote–Alin, and KIER (1983), KIGAM (1995b) and Jin *et al.* (2001) for the Korean Peninsula. Iron and base metals are excluded for simplicity because of their occurrences in both type granitoid provinces. Granitoid plutons in the central Ogcheon Belt in Korea mostly show low magnetic susceptibility values ($<1 \times 10^{-3}$ SI) corresponding to reduced-type, but this may be partly due to secondary alteration (see text). Both the Ogcheon Belt and the Gyeongsang Basin are characterised by tungsten and molybdenum mineralisation and the lack of tin. Accretionary complexes, high-P/T metamorphic rocks are from Geological Survey of Japan (1992), Kimura (1994) and Teraoka & Okumura (2003). See Figure 9 for ages of the geologic units. Major faults are: (BTL) Butsuzo Tectonic Line; (CSF) Central Sikhote–Alin Fault; (HF) Hatakawa Fault; (HTB) Hayachine Tectonic Belt; (ISTL) Itoigawa–Shizuoka Tectonic Line; (MFF) Mishan–Fushun Fault; (MTL) Median Tectonic Line; (PF) Partizansk Fault; and (TTL) Tanakura Tectonic Line. The MTL divides Southwest Japan into Inner Zone and Outer Zone.

shown in Figure 5. The Khanka massif, which is intruded by Late Cretaceous granitoid plutons, consists mainly of so-called 'Sergeevka gabbro'. This lithology consists of mafic to intermediate intrusive and metamorphic rocks probably of late Neoproterozoic to Cambrian age, with lesser amounts of Ordovician to Permian granitoids and Late Palaeozoic to Mesozoic volcanic and sedimentary rocks (Khanchuk *et al.* 1996). The eastern part of the massif occurs as a nappe on the

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

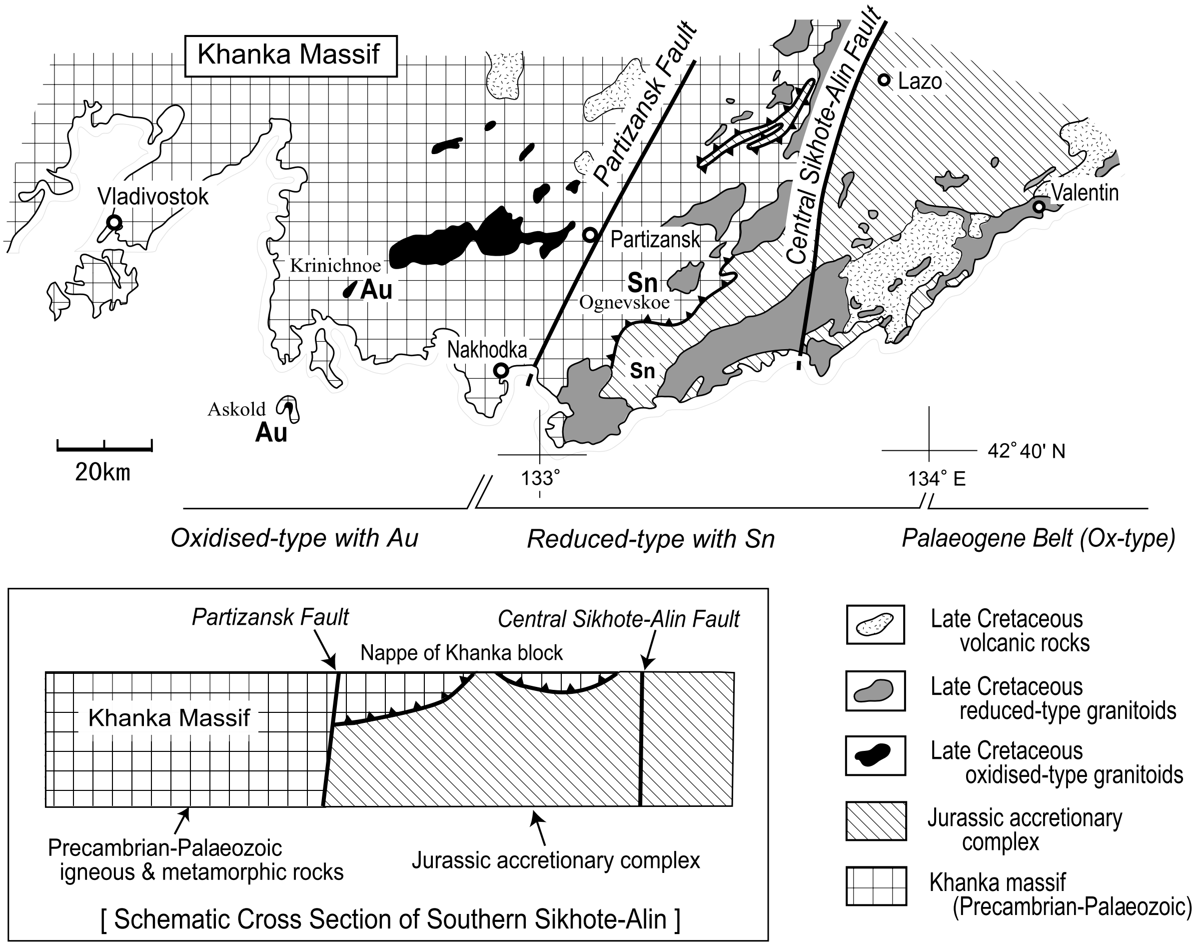

Figure 5 Simplified geologic map of southernmost Sikhote–Alin. The oxidised- and reduced-type plutons (ca. 80–90 Ma) are accompanied by Sn and Au mineralisation, respectively. Note that the distribution of the two type plutons correlates well with the Partizansk Fault. Rocks of the Khanka massif to the east of the Partizansk Fault occur as a nappe on the Jurassic accretionary complex (Sato *et al.* 1993b; Khanchuk *et al.* 1996) .

Jurassic accretionary complex, as shown in the cross section of Figure 5. The underlying Jurassic complex is exposed as a window in the nappe to the northeast of Partizansk City (Fig. 5).

The distribution of the reduced- and oxidised-type plutons correlates well with the Partizansk Fault; the oxidised-type on the west side and the reduced-type on the east side (Fig. 5). Plutons on both sides of the fault are nearly the same age (*ca.* 80–90 Ma), suggesting that the fault and nappe structures may have formed during the Early Cretaceous. Contrasting crust types are separated by the Partizansk Fault: continental crust of igneous affinity occurs to the west and accretionary wedge material of sedimentary affinity occurs to the east (Fig. 8). The Central Sikhote–Alin Fault occurs within the Jurassic accretionary complex and is not a significant boundary with respect to granitoid and metallogenic provinces, probably because the crust on both sides is similar.

The two types of granitoids separated by the Partizansk Fault have contrasting oxygen isotope compositions (Fig. 6). The reduced type has higher δ^{18}O values than the oxidised type, as in the Japanese Islands (e.g. Sato *et al.* 1992). The δ^{18}O values show a positive correlation with initial ^{87}Sr/^{86}Sr ratios (Fig. 7). These isotopic trends strongly suggest involvement of sedimentary materials in the generation of reduced-type granitoid magmas. Carbonaceous matter in the sedimentary rocks may have played an essential role in the formation of reducing conditions, as suggested by the isotopic studies on Japanese granitoids (Ishihara 1977; Sasaki & Ishihara 1979, 1980; Shibata & Ishihara 1979). The oxidised-type granitoids on the west side of the Partizansk Fault have low δ^{18}O values and initial ^{87}Sr/^{86}Sr ratios similar to the typical oxidised-type granitoids in Japan and Korea (Fig. 7). Involvement of sedimentary materials, if any, may have been insignificant for the genesis of the oxidised-type granitoids.

The authors consider that the contrasting features of granitoid types and mineralisation on each side of the Partizansk Fault basically reflect the remarkable difference in the dominant crust; sedimentary crust on the east and igneous crust on the west. The eastern side is essentially a zone of accretion, and had never been influenced by magmatism prior to the Late Cretaceous granitoid activity. On the other hand, the western side is a Precambrian–Palaeozoic continental block which had been subjected to magmatism prior to the Late Cretaceous granitoid activity (Fig. 8). This pre-Cretaceous repeated magmatism may have exhausted any reducing agents, leading to the formation of the oxidised-type granitoids in the younger magmatic event.

2. Korean Peninsula

Granitoids are widely distributed in the Korean Peninsula. Phanerozoic granitoids are divided by age into three major groups: Permian–Triassic, Jurassic and Cretaceous–Palaeogene (Fig. 8). The occurrence of Permian–Triassic granitoids is relatively minor except in the northeastern part of North Korea (KIGAM 1995a). Jurassic granitoid batholiths are widely distributed throughout the entire Korean Peninsula (Fig. 11), and are referred to as the Daebo granite. The Cretaceous–Palaeogene granitoids, the Bulguksa granite, are distributed

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

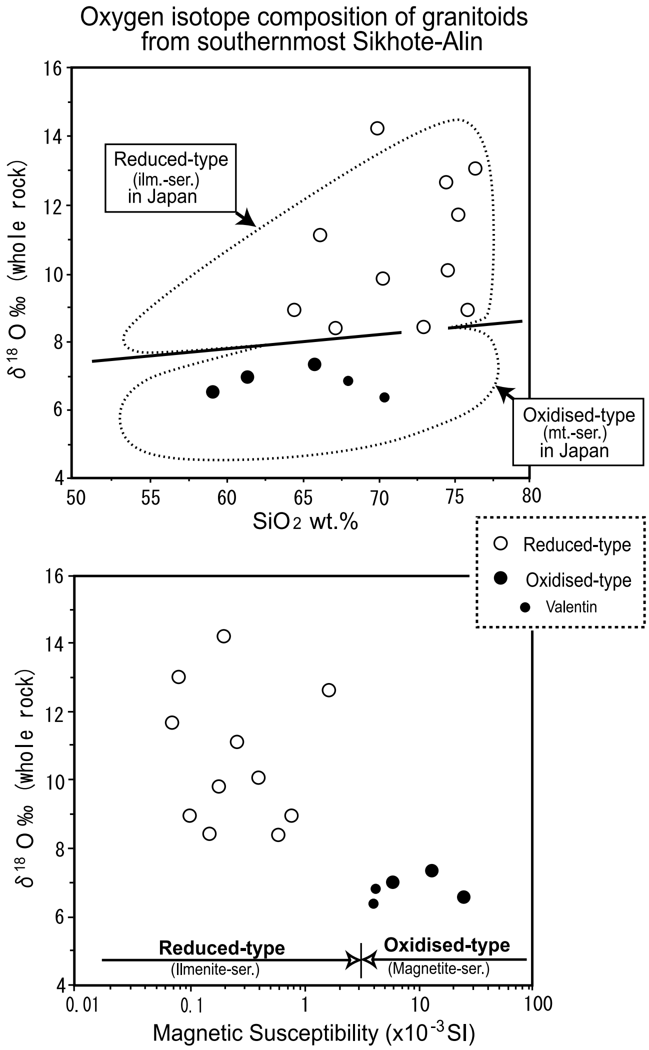

Figure 6 Contrasting oxygen isotope composition between the oxidised- and reduced-type granitoids from the Late Cretaceous plutons in southernmost Sikhote–Alin (see Fig. 5). Also included are data for a late Late Cretaceous weakly magnetic pluton near Valentin, which may be the western margin of the East Sikhote–Alin Volcano–Plutonic Belt (K.Sato, unpublished data). Data areas for the Japanese granitoids are based on Sato *et al.* (1992). The standard is SMOW.

mainly in the southern Korean Peninsula, particularly in the Gyeongsang Basin (Fig. 4). The Bulguksa granite tends to occur as relatively small plutons which often contain miarolitic cavities and are accompanied by volcanic equivalents, suggesting a shallower level of emplacement than that of the Daebo batholiths (e.g. Jin *et al.* 2001). Precambrian granitoids also occur in the Korean Peninsula; they are distributed mainly in North Korea, but are minor in South Korea (KIGAM 1995a).

A large number of radiometric ages have been reported for granitoids, mainly from South Korea (e.g. KIGAM 1995a). The age data are widely scattered from about 250 Ma to about 50 Ma without a clear gap between the two clusters around 170 Ma (Daebo) and 90 Ma (Bulguksa). The large age range is at least partly due to slow cooling of large batholiths, or secondary thermal events which are recorded in dated materials of low closure temperatures; such as biotite in a K-Ar system. Recent chronological studies, including U-Pb dating for zircon, suggest that the emplacement ages are more limited, to 200–160 Ma for the Daebo granite and 110–50 Ma for the Bulguksa granite, with a hiatus between the two (Sagong *et al.* 2003).

Relationships between granitoid types and mineralisation in the southern Korean Peninsula have been extensively studied since the 1980s. The Bulguksa granite consists mostly of the oxidised type, but a few plutons in the central Ogcheon Belt (Fig. 4), a Palaeozoic fold belt between the Gyeonggi massif in the north and Ryongnam massif in the south, are dominated by granitoids of low magnetic susceptibility corresponding to the reduced type (Ishihara *et al.* 1981). The low magnetic susceptibility values are at least partly due to secondary oxidation of magnetite to haematite (Jin *et al.* 2001); the granitoid types have not been fully discriminated. The Bulguksa magmatism in both the Gyeongsang Basin and the Ogcheon Belt is accompanied by tungsten, molybdenum, base metals and gold mineralisation. This magmatism has provided major mineral resources of South Korea (Shimazaki *et al.* 1981, 1987; Sato *et al.* 1981; KIER 1983).

The Daebo granite consists mainly of the reduced type, in contrast to the Bulguksa granite; the oxidised-type granitoids do occur but the genesis of their complicated distribution has not been resolved, although late stage pink granites tend to be magnetite-bearing (Jin *et al.* 2001; M.S. Jin 2003, pers. comm.). Gold-quartz veins occur in fault zones near the Daebo granite (e.g. KIGAM 1995b; Choi 2002), but their genetic relationship to granitoid magmatism is controversial because of age gaps between the granitoid emplacement and mineralisation (Jin *et al.* 2001). The apparent paucity of Jurassic mineralisation could be due to the relatively deep erosion levels of the Daebo batholiths. Permian–Triassic and Precambrian granitoids have very low magnetic susceptibility values ($<1 \times 10^{-3}$ SI) corresponding to the reduced type (Jin *et al.* 2001). The Permian–Triassic plutons are not accompanied by any significant mineralisation, but the Precambrian plutons in the northeast Ryongnam massif are accompanied by tin-bearing pegmatites.

The Bulguksa granite in the Gyeongsang Basin is characterised by low δ^{18}O values and initial ^{87}Sr/^{86}Sr ratios, which are similar to the typical oxidised-type granitoids in Japan and Sikhote–Alin, in contrast to the Daebo granite which is characterised by intermediate δ^{18}O values and high initial ^{87}Sr/^{86}Sr ratios (Fig. 7). The Bulguksa granite of low magnetic susceptibility in the central Ogcheon Belt (Fig. 4) shows crustal strontium and neodymium isotope signatures which are similar to the Daebo granite, rather than to the Bulguksa granite in the Gyeongsang Basin with its juvenile isotopic signatures (Kim *et al.* 1996), suggesting a similarity of source materials regardless of their emplacement ages. These granitoids with enhanced initial ^{87}Sr/^{86}Sr ratios are significantly different from the reduced-type granitoids in Japan and Sikhote–Alin (Fig. 7). The pre-Jurassic basement in the Korean Peninsula is dominated by Precambrian to Palaeozoic metasedimentary rocks (Lee 1988) which have very high initial ^{87}Sr/^{86}Sr ratios (Kim *et al.* 1996, Cheong & Chang 1997) and contain many graphite deposits (Gallagher 1963). The metasedimentary rocks, widely distributed in the Precambrian basement, may have been incorporated in the generation of the reduced-type granitoids with high initial ^{87}Sr/^{86}Sr ratios.

3. Japanese Islands

The relationships between granitoids and mineralisation in the Japanese Islands were extensively studied in 1970–80s, with special reference to their redox state (e.g. Tsusue & Ishihara 1974; Ishihara 1977, 1979; Czamanske *et al.* 1981). Compilation of the relevant metallogenic studies, combined with geochronological and isotopic studies (e.g. Sasaki & Ishihara 1979, 1980; Shibata & Ishihara 1979) established the granitoid and metallogenic provinces which are consistent with the major tectonic divisions of the Japanese Islands (Fig. 4) (Ishihara *et al.* 1992; Sato *et al.* 1992).

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

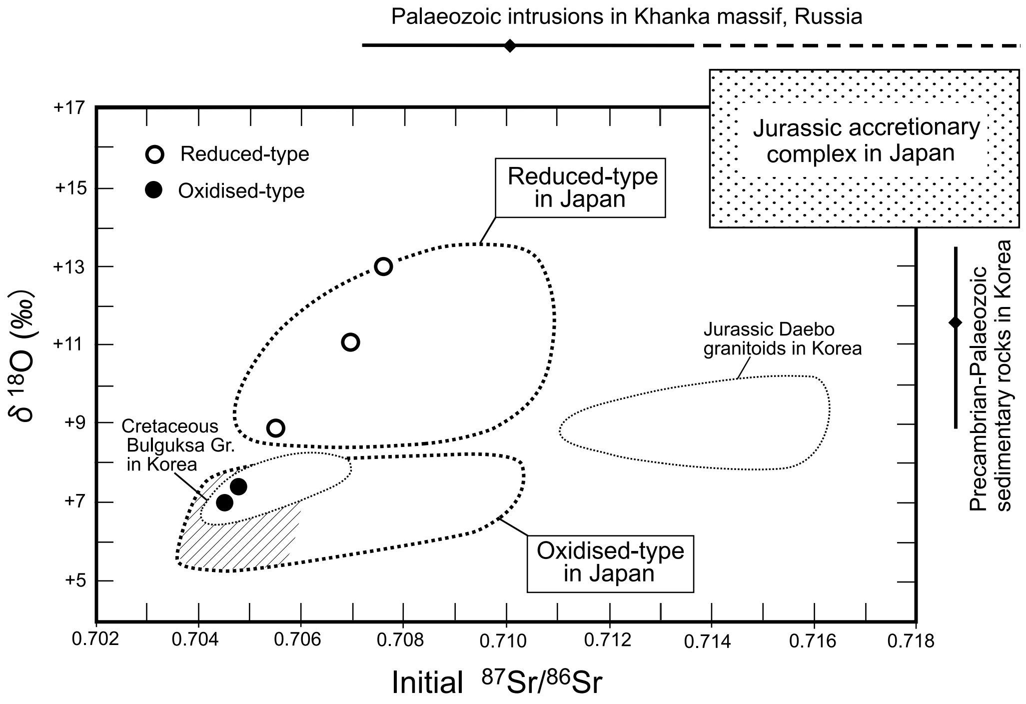

Figure 7 $\delta^{18}O$ (SMOW) versus initial $^{87}Sr/^{86}Sr$ (at 85 Ma) plot for the representative reduced- and oxidised-type granitoids in southernmost Sikhote–Alin (Fig. 5). Also shown are data areas for granitoids and the Jurassic accretionary complex (metasedimentary rocks from the Ryoke Belt) in Japan (Matsuhisa *et al.* 1982; Ishihara and Matsuhisa 2002). The oxidised-type granitoids in Japan generally have low initial $^{87}Sr/^{86}Sr$ ratios (hatched), but rarely have high values (~0·710) in the eastern San-in Belt within Southwest Japan (see Fig. 4). Data areas for the Korean granitoids are based on Kim *et al.* (1992, 1996); Jurassic Daebo (mainly reduced-type) and Cretaceous Bulguksa in the Gyeongsang Basin (oxidised-type), excluding the data for altered rocks. Available data for basement rocks are limited, but their ranges are shown by bars with diamonds of average values: Precambrian to Palaeozoic sedimentary rocks ($\delta^{18}O = +8{\cdot}9$ to $+13{\cdot}4$‰ ($n=3$)) in the southern Korean Peninsula (Kim *et al.* 1992, 1996) and Palaeozoic gabbroic to granitic intrusions (initial $^{87}Sr/^{86}Sr = 0{\cdot}707$ to $0{\cdot}720$ ($n=7$)) in the Voznesenka area within the Khanka massif (Ryazantseva *et al.* 1995).

Granitoids in Japan are divided by age into four groups: Palaeozoic, Jurassic, Cretaceous–Palaeogene and Neogene (e.g. Sato *et al.* 1992). Cretaceous–Palaeogene granitoids have the largest exposures and are most important with respect to metallogeny (e.g. Ishihara *et al.* 1992). The other groups have limited exposures and are less important or insignificant for metallogeny, although Middle Miocene granitoids emplaced in the Cretaceous–Palaeogene accretionary complex within the Outer Zone of Southwest Japan are characteristically accompanied by tin mineralisation (Fig. 9). Occurrences of Palaeozoic and Jurassic granitoids are very limited, and they are not accompanied by any significant mineralisation. The lack of Jurassic mineralisation of granitoid affinity in Japan is similar to that of the Khingan and Sikhote–Alin Mountains, and contrasts with the Korean Peninsula and eastern China.

The pre-Cretaceous basement of the Japanese Islands consists essentially of Jurassic accretionary complexes, as in the Khingan and Sikhote–Alin Mountains, with local occurrences of Palaeozoic continental fragments (e.g. South Kitakami, NE Japan), Palaeozoic to Early Mesozoic accretionary complexes (northwestern SW Japan) and late Palaeozoic–Jurassic metamorphic and igneous rocks (Hida, central Japan). The Jurassic Mino–Tanba terrane in Southwest Japan, for example, is thought to be a southern extension of the Jurassic Samarka terrane in Sikhote–Alin prior to the opening of the Japan Sea during the Miocene (Fig. 11) (Mizutani & Kojima 1992), suggesting a similar tectonic history between Japan and Sikhote–Alin in Jurassic to Palaeogene times (Figs 8 & 9).

The Cretaceous–Palaeogene granitoid magmatism in Japan changed its position and character with time (Figs 4 & 9). Magmatism was initiated in the Kitakami area of Northeast Japan at about 130 Ma, and ceased around 40 Ma in the western San-in Belt of Southwest Japan (e.g. Sato *et al.* 1992). The Early Cretaceous granitoids in Northeast Japan to the east of the Tanakura Tectonic Line (TTL in Figs 1 & 4) generally have less silicic compositions than the Japanese average and are characterised by low initial $^{87}Sr/^{86}Sr$ ratios (SrI <0·706) (Shibata & Ishihara 1979). They are divided into two provinces, Kitakami in the north and Abukuma in the south, with a boundary along the Hatakawa Fault (HF in Fig. 4). The granitoids in the Kitakami area (ca. 130–110 Ma) belong to the oxidised type, whilst those in the Abukuma area (ca. 120–100 Ma) are mainly of reduced type (Figs 4 & 9). The granitoids in Kitakami show the most juvenile isotopic features (SrI <0·705) regardless of basement geology: Palaeozoic continental fragment in the south and Jurassic accretionary complex in the north. The mineralisation is molybdenum in North Kitakami, gold with tungsten in South Kitakami and tungsten in Abukuma (Figs 4 & 9).

Granitoids in Southwest Japan were emplaced over a long time period from about 100 Ma to about 40 Ma (e.g. Sato *et al.* 1992; Suzuki & Adachi 1998). The granitoids in the Ryoke and Sanyo Belts within the Inner Zone to the north of the Median Tectonic Line (MTL in Figs 1 & 4) are relatively old (ca. 100–65 Ma) and mostly of reduced type (Figs 4 & 9) except for those at the western end in northern Kyushu near the Korean Peninsula. The granitoids in the Ryoke high-T/P metamorphic belt are generally barren, but those in the Sanyo Belt are associated with tungsten and tin mineralisation. The granitoids in the San-in belt are younger than in the Ryoke and Sanyo Belts (ca. 70–40 Ma) and of oxidised type with molybdenum mineralisation (Figs 4 & 9).

Isotopic compositions are variable within each belt of Southwest Japan, but the reduced-type granitoids have higher

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

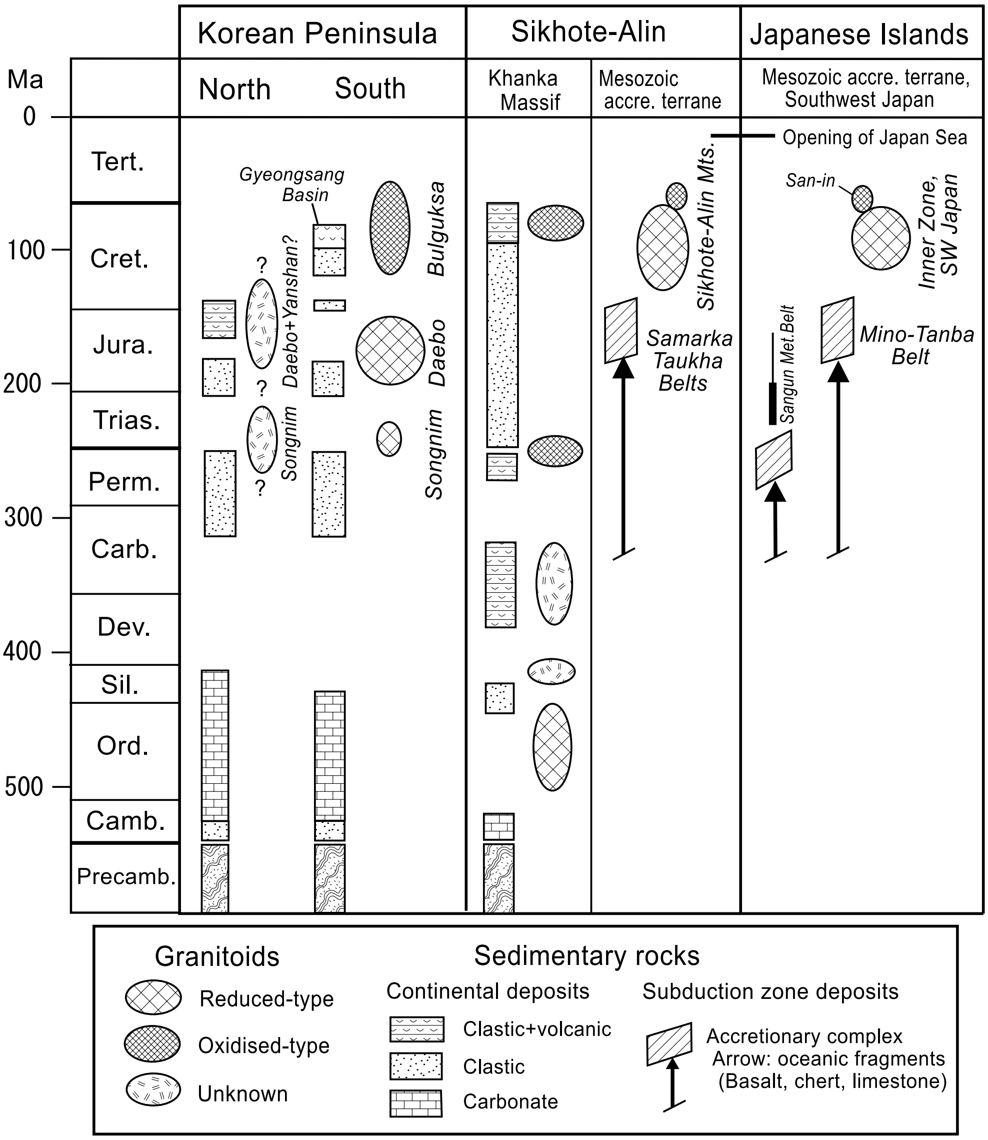

Figure 8 Diagram showing Phanerozoic granitoid magmatism in the circum-Japan Sea region. Figures 8 and 9 were compiled from following sources: for the Korean Peninsula: Ishihara *et al.* (1981), Lee (1988), KIGAM (1995a), Institute of Geology, State Academy of Sciences, DPR of Korea (1996) and Jin *et al.* (2001); for Sikhote–Alin: Mizutani & Kojima (1992), Sato *et al.* (1993a, b), Romanovsky *et al.* (1996), Khanchuk *et al.* (1996), Sato *et al.* (2003a) and this study; for the Japanese Islands: Isozaki & Itaya (1990), Mizutani & Kojima (1992), Geological Survey of Japan (1992), Ishihara *et al.* (1992) and Sato *et al.* (1992). Accretion age of the Jurassic accretionary complexes ranges from the latest Triassic to earliest Cretaceous, but mostly from Middle Jurassic to the earliest Cretaceous (Isozaki 1997; Matsuoka *et al.* 1998; Nakae 2000). Geologic ages are based on Gradstein *et al.* (1995). Little is known about either detailed age or types of granitoids in the northern Korean Peninsula. Note that the Palaeozoic history is remarkably different between the Khanka massif and Korean Peninsula, suggesting that they were situated in different continental blocks before their amalgamation in late Permian to Triassic times.

δ^{18}O values and initial ^{87}Sr/^{86}Sr ratios than the oxidised-type granitoids (Fig. 7). The oxidised-type granitoids in the San-in Belt generally have low initial ^{87}Sr/^{86}Sr ratios (<0·706), but occasionally show high values (~0·710) in its eastern part (Shibata & Ishihara 1979; Kagami *et al.* 1992; K. Sato, unpublished data).

The sulphur isotope composition of granitoids and related ore deposits shows a remarkable contrast between the reduced and oxidised types (Sasaki & Ishihara 1979, 1980). The δ^{34}S (CDT) values tend to be negative in the reduced-type granitoid belts (−14 to +2‰), and positive in the oxidised-type granitoid belts (−1 to +9‰). Gabbroids in the two granitoid belts show a consistent sulphur isotope trend, with δ^{34}S values of −4 to +3‰ in the reduced-type belt and +1 to +7‰ in the oxidised-type belt. These contrasts between the two granitoid belts are consistent with the results of oxygen and strontium isotope studies (Shibata & Ishihara 1979; Matsuhisa *et al.* 1982). The contrasts suggest that the reduced-type magmas admixed with the sediments of accretionary complexes rich in isotopically light biogenic sulphur, whilst the oxidised-type magmas were not influenced by the sedimentary sulphur and preserved signatures of the isotopically-heavy sea water sulphur which was introduced into magma systems through subduction of oceanic crust.

4. Discussion

4.1. Evolution of crust and granitoid types

4.1.1. Crustal control on redox state of granitoid magmas. A review of the granitoid and metallogenic provinces in the circum-Japan Sea region indicates that the nature of the crust,

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

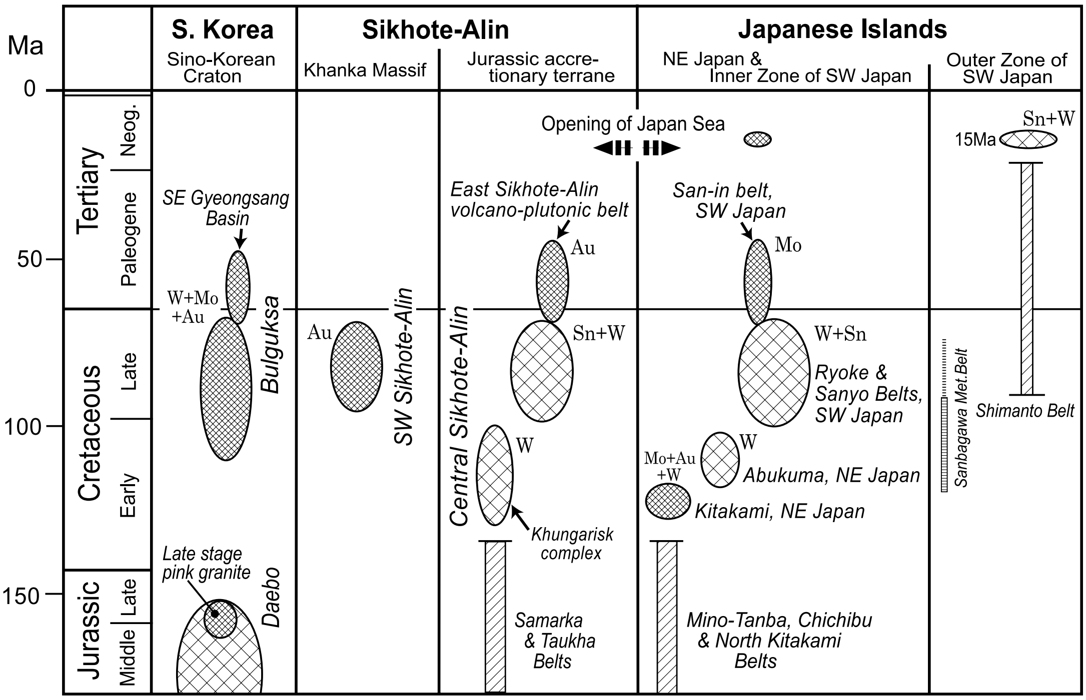

Figure 9 Detailed variation of granitoid types and related mineralisation in the circum-Japan Sea region since the Late Jurassic. Patterns are the same as in Figure 8. Note that younger magmatism tends to be of oxidised-type. See text for the unusual setting of the Kitakami area in Northeast Japan. Chemical symbols beside ellipsoids denote characteristic mineralisation. W mineralisation is related to both the reduced- and oxidised-type granitoids, but mineralogical features of W ores are different between the two types; skarn ores, for example, clearly reflect the different redox state of the two type granitoids (Sato 1980, 1982a).

whether sedimentary or igneous, is the most important control for the redox state of granitoid magmas. The reduced-type granitoids are generated in sedimentary crust which is composed mainly of accretionary complex material and has never been influenced by magmatism prior to the granitoid magmatism. On the other hand, the oxidised-type granitoids are generated in igneous crust which has been formed and/or modified by previous magmatism and depleted in reducing reagents such as sedimentary carbon. Therefore, the redox state of granitoid magmas in a given area tends to become more oxidised with time.

The distribution of the reduced-type and oxidised-type granitoids in the circum-Japan Sea region clearly reflects the tectonic histories of the crustal domains in which they are emplaced. Cretaceous reduced-type granitoids, which are most abundant in this region (Fig. 4), were formed in the terranes comprised of Jurassic accretionary complexes (Fig. 11). Cretaceous oxidised-type granitoids on the continental side were emplaced in older igneous crust; Precambrian to Palaeozoic continental block in the Khanka massif and Jurassic Daebo magmatic belt in the southern Korean Peninsula (Figs 4, 5 & 8). In the Kitakami area of Northeast Japan arc, however, Cretaceous granitoids occur in an unusual geologic setting (Fig. 9). They are of oxidised-type regardless of the nature of crust: Jurassic accretionary complex in the north compared with a Palaeozoic continental fragment in the south. This apparent anomaly will be discussed later.

The latest Cretaceous to Palaeogene granitoids of the oxidised type are distributed in coastal areas around the Japan Sea (Fig. 4): east Sikhote–Alin, San-in of Southwest Japan and eastern margin of the Gyeongsang Basin. The Palaeogene magmatism may have occurred in a relatively narrow zone within the Cretaceous magmatic belt, but this zone was fragmented and now occurs at the present coastal areas due to the opening of the Japan Sea during the Miocene. Miocene granitoids are minor and not described in this paper. It is noticed, however, that the plutons emplaced in the Shimanto accretionary complex are of reduced type, while those emplaced in the San-in Belt are of oxidised type (Fig. 9).

The relationship between the nature of the crust and the redox state of granitoids is distinct in the southernmost Sikhote–Alin, where Late Cretaceous granitoids were emplaced on both sides of the Partizansk Fault (Fig. 5), a deep fault between the Precambrian–Palaeozoic igneous crust of the Khanka massif and the Jurassic accretionary complex which had never been influenced by magmatism before the Late Cretaceous granitoid activity (Fig. 8). The accretionary complex is overlain by a nappe of the Khanka block (Fig. 5). The fault and nappe structure may have formed during the Early Cretaceous, and granitoid plutons were emplaced at about 80–90 Ma. Thickness of the nappe is estimated to be less than 8 km (S. V. Kovalenko, unpublished data), and the underlying Jurassic complex is locally exposed as a window. These relationships indicate that the nature of the crust of deep levels is more important than that of shallow levels for controlling the redox state of granitoid magmas, although the exact thickness of the nappe at the time of granitoid emplacement is not known.

Oxidised-type granitoid plutons are occasionally associated with marginal reduced facies along contacts with carbon-bearing sedimentary rocks (e.g. Sato 1991). The redox state of granitoid magmas could be locally changed in relatively shallow levels after intrusion, but it is difficult to explain the regional distribution of granitoid types by such a local process. Increasing Fe/(Fe+Mg) ratio for biotite and hornblende with increasing SiO_2 content of host granitoids from Sikhote–Alin suggests that oxidation during crystallisation near the level of intrusion (Czamanske *et al.* 1981) was not a general process (Sato *et al.* 1998). Occurrences of early formed magnetite in the oxidised-type granitoids also suggest that the granitoid types reflect the intrinsic conditions of granitoid magma genesis in the lower crustal environment. The granitoid provinces

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

shown in Figure 4 may reflect the redox state of their lower crustal source regions, although they may be locally modified by secondary processes.

The geologic relationship between granitoid types and structure of crust in the southernmost Sikhote–Alin (Fig. 5), coupled with oxygen and strontium isotope data (Figs 6 & 7), demonstrates that involvement of sedimentary rocks containing carbonaceous matter resulted in the generation of reduced-type magmas. This result is consistent with the systematics established in the Japanese Islands, suggesting that mantle-derived magmas assimilated lower crustal sedimentary rocks and fractionated to form the reduced-type granitoids. The mantle-derived magmas may also have assimilated lower crust of the Khanka massif, but they did not encounter sedimentary materials at deep levels.

Examples from the Korean Peninsula are not as simple in character. The Jurassic Daebo granite is dominated by the reduced-type, and characterised by intermediate $\delta^{18}O$ values and very high initial $^{87}Sr/^{86}Sr$ ratios in contrast with other reduced-type granitoids in the circum-Japan Sea region (Fig. 7). These isotopic features and their peraluminous compositions (Jin *et al.* 2001) suggest involvement of sedimentary protoliths present in old continental crust. Occurrences of many graphite deposits in Precambrian–Palaeozoic metasedimentary rocks in the Korean Peninsula (Gallagher 1963) suggest reducing conditions of the crust at the time of Daebo magmatism. It is noticed, however, that the Daebo granite also includes a significant proportion of oxidised-type rocks, and their distribution and genesis are not well understood (Jin *et al.* 2001). Precambrian granitoids occur in the southern Korean Peninsula, although their distribution is limited (e.g. KIGAM 1995a). The basement for the Jurassic granitoid magmatism could be heterogeneous. Precambrian granitoids are widely distributed in the northern Korean Peninsula, implying that Jurassic granitoids in such areas are dominated by oxidised type, although little is known about them. The redox type of the Cretaceous granitoid plutons in the Ogcheon Belt is also a matter for further study (Fig. 4). Low magnetic susceptibility (Jin *et al.* 2001) and isotopic composition similar to the Daebo granite (Kim *et al.* 1996) apparently suggest reduced type, but accompanying mineralisation is similar to the oxidised-type Bulguksa granite in the Gyeongsang Basin (KIER 1983). These granitoids appear to be altered oxidised-type plutons which are isotopically similar to the Jurassic oxidised-type plutons.

4.1.2. Role of tectonic setting and mode of magma emplacement: implications from the Kitakami area. General relationships between granitoid types and the lithology of crust discussed above do not fit with the Kitakami area of Northeast Japan (Fig. 9). The Kitakami area is divided into two subdivisions: the Palaeozoic continental fragment in the south and the Jurassic accretionary complex in the north. Early Cretaceous granitoids were emplaced into these two sub-divisions at 120 ± 10 Ma (e.g. Sato *et al.* 1992), but almost all plutons are composed of the oxidised-type granitoids except for local occurrences of marginal reduced facies along the contact with host sedimentary rocks. The granitoid plutons are elongated in a N–S direction (Fig. 4) and locally accompanied by submarine bimodal volcanic sequences (Harachiyama Group) associated with kuroko mineralisation at the Taro mine (Ebiko 1965; Kanisawa 1974). These granitoids and volcanic equivalents are unconformably overlain by conglomerate and sandstone (Miyako Group) of late Aptian to early Albian age (ca. 110 Ma) (e.g. Mori *et al.* 1992). Radiometric ages of granitoids and volcanic rocks fall in a narrow range between 130 and 110 Ma, regardless of various closure temperatures (Kawano & Ueda 1965; Shibata *et al.* 1978; Sato *et al.* 1992). These lines of evidence indicate that granitoids in the Kitakami area were emplaced at relatively shallow levels under an extensional environment within a short period and were quickly cooled and eroded. The elongated shape of the plutons and their low initial $^{87}Sr/^{86}Sr$ ratios ($<0{\cdot}705$) suggest a style of magma emplacement such as fissure-filling without significant interaction with crustal materials. The plutons have partly adakitic compositions, suggesting the genesis of granitoid magmas by partial melting of oceanic crust due to the subduction of a spreading ridge (Tsuchiya & Kanisawa 1994). The short-lived episodic magmatism in an extensional condition in the Kitakami area could be related to such an unusual tectonic setting.

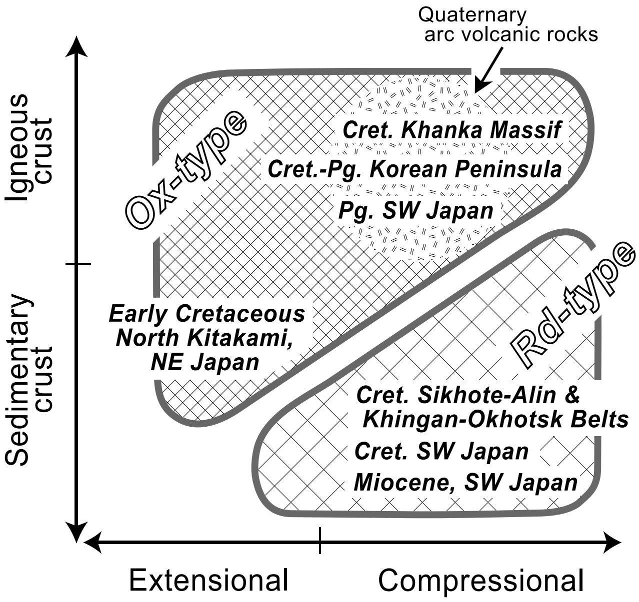

Figure 10 Schematic illustration of the relationship between granitoid types and the lithological and tectonic conditions of the crust. Quaternary arc volcanic rocks generally belong to the oxidised type. Abbreviations: (Cret) Cretaceous; (Pg) Palaeogene; (Ox) oxidised; (Rd) reduced.

The relationship between the Early Cretaceous Harachiyama Group and the underlying Jurassic accretionary complex is apparently conformable (e.g. Mori *et al* 1992). Radiolarian fossils in a clastic matrix of the accretionary complex near the Taro mine were identified to be of late Middle Jurassic age (*ca.* 160 Ma) (Matsuoka & Oji 1990), and sericite-quartz rocks from the Taro deposit were dated by the K-Ar method at 128 Ma (recalculated average age, Ueda *et al.* 1970). Therefore, the time gap between the beginning of Cretaceous felsic magmatism and the cessation of Jurassic subduction processes in the Taro area was shorter than 32 Ma. Felsic magmatism in the Kitakami area could have begun in a zone near a trench which was still in a marine environment, without significant uplift of the accretionary complex above sea level. It is likely that the temperature of the crust was relatively low, which promoted the brittle deformation favourable for the fissure-filling type emplacement of magmas and prevented the significant reaction of ascending magmas with host rocks. Stress and temperature conditions of the crust are considered to be additional important factors for the generation of granitoid types.

Figure 10 summarises the relationship between the granitoid types and their lithological and tectonic settings. If the intrusion of granitoid magmas are of fissure-filling type under extensional environments, they tend to be of oxidised type regardless of lithology of crust, as the crust is passive and does

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

not contribute to the magma chemistry. A Miocene oxidised-type granitoid pluton occurs in Tsushima, an island between Southwest Japan and the Korean Peninsula (Figs 1 & 9). This pluton has very low initial $^{87}Sr/^{86}Sr$ ratios (0·7037) (Shibata & Ishihara 1979). It could be an example of such an oxidised magma emplaced in igneous crust under extensional conditions related to the opening of the Japan Sea.

4.2. Geodynamic background of large tin provinces in northeast Asia

4.2.1. Distribution of Jurassic igneous rocks and accretionary complex. Jurassic felsic magmatism occurred extensively along the continental margin of East Asia, particularly in southeast China and the Korean Peninsula. However, this magmatism did not extend towards the north; the Bureya and Khanka massifs are practically free of Jurassic igneous rocks, although Jurassic continental deposits are present (Fig. 11). Granitoids are widely distributed in these massifs and over a large region around the Songliao Basin, but they are mostly Palaeozoic to Triassic in age (e.g. Krasnyi & Peng 1996; Wu *et al.* 2000).

The Jurassic magmatism appears to have extended from the Sino-Korean Craton towards the northwest within northeast China (Fig. 11). Volcanic rocks are widely distributed in the Da Hinggan Ling (Great Khingan Mountains), and granitoids and volcanic rocks are sporadically distributed in the areas east of Chanchung and Harbin. These areas are far from the continental margin (400–1400 km). Magmatism in the Da Hinggan Ling continued to Early Cretaceous times (e.g. Krasnyi & Peng 1996) and it is characterised by alkalic and bimodal composition (Ministry of Geology and Mineral Resources of China 1990; Lin *et al.* 1998). Early Cretaceous A-type plutons have chemical features suggesting an anorogenic environment (Wu *et al.* 2002). It is more likely that the magmatism in the Da Hinggan Ling was rift-related, not subduction-related. The Songliao Basin, which may have begun to form in the Late Jurassic (Ma *et al.* 1989; Okada 1999), also suggests an extensional tectonic environment in the inner continental region of northeast China.

The Bureya and Khanka massifs and a region to the south of the Mongol–Okhotsk suture are characterised by the lack of significant magmatism in the Jurassic (Fig. 11). The paucity of igneous rocks cannot be explained by erosion because of the occurrences of Jurassic continental deposits. These continental margin areas may have been passive or transform margins in the Jurassic (Fig. 12). The Stanovoy Range to the north of the Mongol–Okhotsk suture is a region of Jurassic magmatism (Fig. 11), suggesting subduction of the oceanic plate of the Mongol–Okhotsk Ocean beneath the Siberian Craton during the Jurassic (Fig. 12).

4.2.2. Reorganisation of accretionary complex. The Jurassic accretionary complexes to the east of the Bureya and Khanka massifs are not accompanied by significant arc magmatism on the continental side (Fig. 11). These areas may have been a transform margin during the Jurassic (Fig. 12), and the accretionary complexes are thought to be allochthonous units. This insight is consistent with the idea of secondary translation of accretionary complex proposed by Mizutani & Yao (1991) based on the palaeomagnetic data; low palaeolatitude values for the Jurassic accretionary complexes in Southwest Japan and pre-Jurassic continental fragments within them suggest their remarkable northward drift (e.g. Hirooka 1990).

Jurassic to Early Cretaceous plant fossils in eastern Eurasia are divided into two types: Tetori-type in the north from northeast China to Siberia, and Ryoseki-type in the south from southeast China to the Malay Peninsula, with an EW-trending transitional zone between the two provinces (Kimura 1987; Ohana & Kimura 1995). Distribution of the Ryoseki-type floras extends towards the north to Japan (Outer Zone of SW Japan and NE Japan) and Sikhote–Alin, showing an unusually curved boundary with the Tetori-type floras. For example, the Tetori- and Ryoseki-type floras occur in the Hida and Kitakami areas, respectively. This boundary may be reorganised to a normal pattern if we assume northward displacement of the Ryoseki-type areas in Japan and Sikhote–Alin.

Otsuki & Ehiro (1992) suggested large-scale left-lateral displacements along major faults in Northeast Japan in the middle Cretaceous. Early to mid-Cretaceous time appears to be a unique stage of vigorous tectonic activity in the circum-Japan Sea region. Large scale left-lateral displacements have also been suggested for the Tan-Lu and other NE–SW trending faults in the continental margin of East Asia (e.g. Xu *et al.* 1993). Xu *et al.* (1993) and Chen (1993) suggested that major horizontal displacement occurred during the Early Cretaceous, although the fault activity has a long history up to the Recent as evidenced by large earthquakes along this fault. Sinistral tectonic movement may have prevailed over a wide region of the continental margin as well as in the accretionary terrane (Fig. 11), although details of the times and distances of left-lateral displacements require further study.

The authors consider that the accretionary complexes in the Khingan and Sikhote–Alin Mountains were largely displaced from the original place of accretion, and formed into an unusually wide zone through the amalgamation with autochthonous sediments which may have been derived from the Mongol–Okhotsk suture zone and deposited in a transform margin off the Bureya massif (Fig. 12). The original place of accretion is thought to be an active margin of the Korean Peninsula and southeast China where Jurassic igneous rocks are widely distributed. This idea is illustrated in Figure 12, showing the configuration of continents based on palaeomagnetics (Enkin *et al.* 1992) and representative velocity vectors of oceanic plates with respect to East Asia (Maruyama & Seno 1986) in the Jurassic and Cretaceous. The Khingan and Sikhote–Alin regions are thought to be a transform margin in the Jurassic, as mentioned above, but changed to a convergent margin in the Cretaceous; Cretaceous convergence may have been oblique in the Early Cretaceous and orthogonal in the Late Cretaceous. The Mongol–Okhotsk Ocean is thought to have closed from west to east and disappeared at its eastern end in Early Cretaceous times (e.g. Zonenshain *et al.* 1990). The collision of East Asia with Siberia, combined with the oblique convergence of the palaeo-Pacific plate in the Early Cretaceous, could have resulted in large left-lateral displacements in the eastern margin of East Asia. This may be a major cause for the displacement of the accretionary terranes and the slices of continental fragments within them. The Early Cretaceous Amur basin proposed in the Sunda-style tectonic model (Sato *et al.* 2002) may have been formed in this process.

4.2.3. Background of tin-associated reduced-type magmatism. The displaced and stacked accretionary terranes and adjacent continental margins (Fig. 11) were changed to a zone of extensive felsic magmatism in Cretaceous times (Figs 1 & 4). The Cretaceous vigorous magmatism could be related to the remarkably high velocity of convergence as well as subduction of a spreading ridge (e.g. Uyeda & Miyashiro 1974; Jahn 1974; Maruyama *et al.* 1997), although the real cause is not well understood. The magmatism might have been a response to such a global process as superplume activity, because unusually large production rates of oceanic crust in middle Cretaceous times (ca. 125–80 Ma, Larson 1991) are synchronous with the peak of granitoid magmatism not only in the circum-Japan Sea region but also in the western North America (e.g. Armstrong 1988).

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

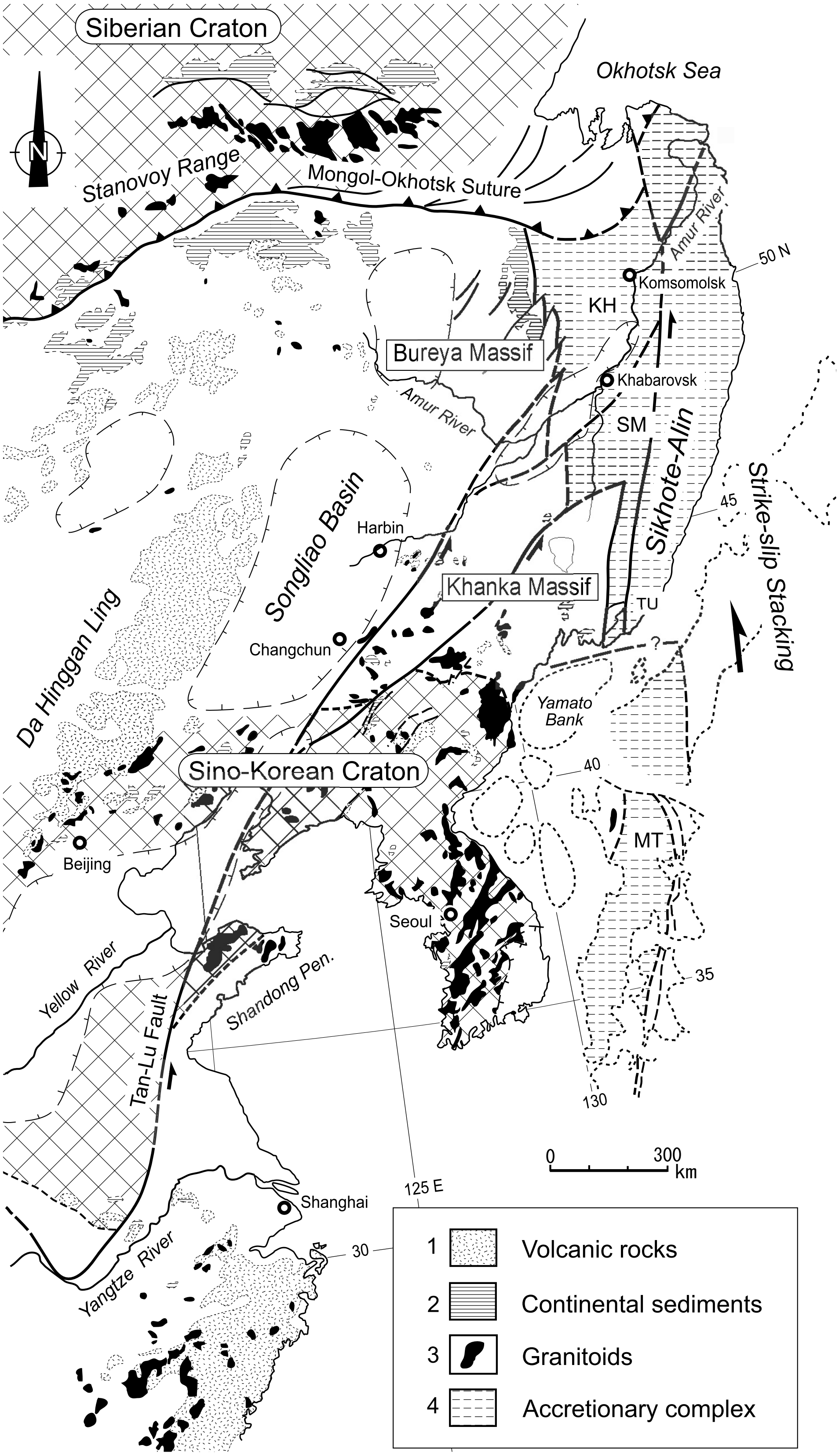

Figure 11 Distribution of Jurassic geologic units in East Asia. Modified from Sato (2000, 2003) with reference to Sato *et al.* (1992), Krasnyi *et al.* (1996) and Teraoka & Okumura (2003). Note that Jurassic igneous rocks are absent or scarce in the Bureya and Khanka massifs near Jurassic subduction complexes which are widely distributed in the Khingan and Sikhote–Alin Mountains. Jurassic magmatism occurred widely in east China and in the Korean Peninsula, but the magmatism extended to the Da Hinggan Ling (Great Khingan Mountains) in northeast China which is far away from the region of subduction complexes. Reconstruction of the Japanese Islands is based on palaeomagnetic studies (e.g. Otofuji *et al.* 1985) and bathymetric data of the Japan Sea. Accretionary complexes are: (KH) Khabarovsk; (MT) Mino–Tanba; (SM) Samarka; (TU) Taukha. Those in the Outer Zone of Southwest Japan (Chichibu) and Northeast Japan (North Kitakami) are omitted.

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

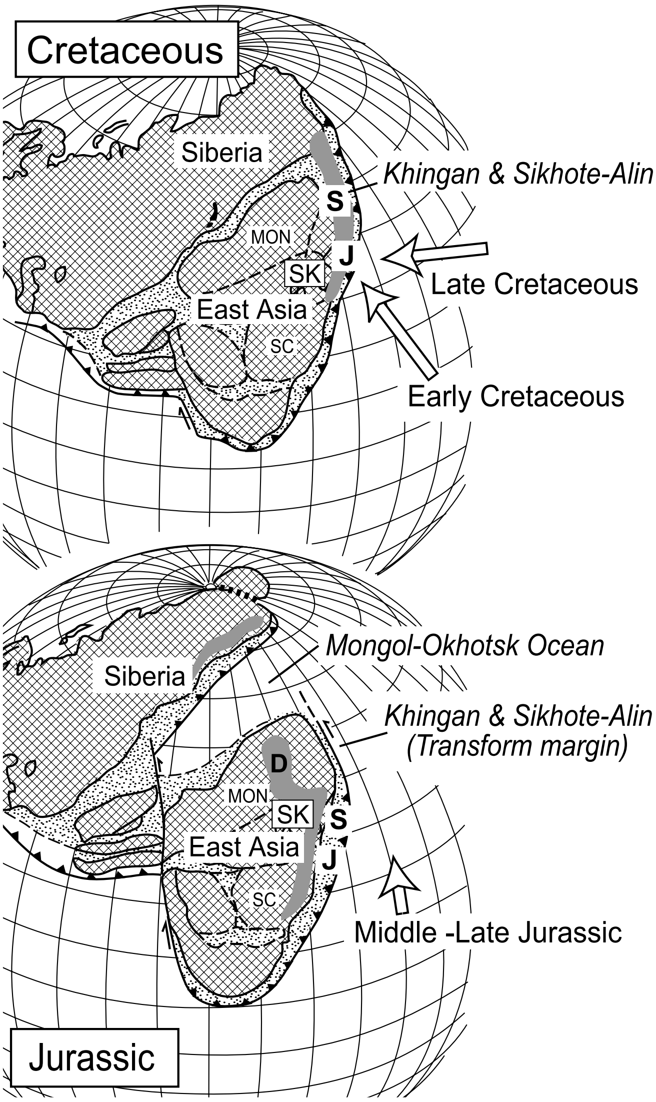

Figure 12 Distribution of continents and approximate velocity vectors of oceanic plate with respect to Asia in the Jurassic and Cretaceous, based on Enkin *et al.* (1992) and Maruyama & Seno (1986). Arrows are representative velocity vectors. Grey areas in the Cretaceous and Jurassic globes correspond to the areas of magmatism shown in Figures 1 and 11, respectively. Note that Jurassic magmatism in the Da Hinggan Ling (D) lasted to the Early Cretaceous, but is not shown in the Cretaceous globe. (J) Japanese Islands; (MON) Mongol Block; (S) Sikhote–Alin; (SC) South China Block; (SK) Sino-Korean Craton.

The Cretaceous felsic magmatism in the circum-Japan Sea region formed the reduced-type magmas accompanied by tin mineralisation in the regions of accretionary complexes, as exemplified in the Khingan–Okhotsk Belt, central Sikhote–Alin Belt and the Inner Zone of Southwest Japan (Fig. 9). Involvement of sedimentary materials in the generation of granitoid magmas may also be common in collision zones. Late Jurassic to Early Cretaceous tin-associated granitoids in the Yana–Kolyma region could be such examples (Parfenov 1991; Parfenov *et al.* 1999; Layer *et al.* 2001). Development of the sedimentary terrane before magmatism is the genetic background of the metallogenic provinces characterised by tin in northeast Asia.

4.3. East–west contrast around the Pacific

4.3.1. Tin-poor provinces in the circum-Japan Sea region. As discussed above, granitoid magmatism tends to become more oxidised with time, due to modification of the crust from sedimentary affinity to igneous affinity. The Cretaceous magmatism was superimposed on the Khanka massif and southern Korean Peninsula igneous crust, and resulted in the formation of the oxidised-type granitoids which are free of tin (Figs 4 & 9). The Palaeogene magmatism was localised to the present coastal areas of the Japan Sea, where extensive magmatism occurred in the Cretaceous (Fig. 4). The overprinted Palaeogene activity resulted in the formation of the oxidised-type granitoids, which are accompanied by molybdenum or gold, but not by tin (Fig. 9).

Granitoids are widely distributed in northeast China. Their ages range from Precambrian to Cretaceous, but granitoid types are not well known. However, the paucity of tin and occurrences of gold and molybdenum deposits in this region (Chinese Academy of Geological Sciences 1999) imply that the granitoids, at least those of later stages, are dominated by the oxidised type. Permian to Early Cretaceous A-type granitoids have been reported to be magnetite-bearing (Wu *et al.* 2002).

4.3.2. Pacific margin of North America. The Pacific margin of North America is a typical tin-poor region, as indicated at the beginning of this paper. Arc magmatism in the Pacific margin occurred for a long time during the Mesozoic (e.g. Dickinson 1976; Armstrong 1988; Burchfiel *et al.* 1992). The Cretaceous Sierra Nevada batholith is a representative and well-studied example of the oxidised-type granitoids (Bateman *et al.* 1991). The batholith was emplaced in a Jurassic magmatic arc (e.g. Dickinson 1981; Bateman 1983). The repeated magmatism in a convergent margin over a long time period may be a reason why the reduced-type granitoids and tin deposits are scarce in the Pacific margin of North America. One of the exceptional occurrences of the reduced-type granitoid belt is seen in the Cretaceous Peninsular Ranges Batholith (Gastil *et al.* 1990). The boundary between the oxidised- and reduced-type granitoid belts coincides approximately with the boundary of the Triassic–Jurassic volcanic arc to the west and the back-arc sedimentary basin to the east (Gastil 1993). This relationship, supported by higher $\delta^{18}O$ values (Silver *et al.* 1979, cited in Gastil *et al* 1990) for the reduced-type belt suggests generation of the reduced-type granitoids in sedimentary crust.

4.3.3. East–west contrast. The reduced-type granitoids are minor in the Pacific margin of North America, whilst they are dominant in East Asia. The oxidised-type granitoids occur in East Asia, as mentioned above, but their proportion within the whole of East Asia is relatively small. Generation of the reduced-type granitoid magmas requires a change from sedimentary terranes to magmatic belts which may be caused by the change of subduction system or collision of continents. This process was not common in the monotonous convergent margin of western North America. The remarkable contrast of granitoid types and mineralisation around the Pacific may be a consequence of different geodynamic histories between the east and west sides.

5. Concluding remarks

Mesozoic felsic magmatism provided major mineral resources in East Asia. The style of magmatism and mineralisation is highly variable within the circum-Japan Sea region, encompassing the contrast between the east and west side of the Pacific rim. The granitoid magmatism and related mineralisation in this region has been examined from the viewpoint of the redox state of granitoid magmas and its relation with geodynamic history of the area of magmatism. It is concluded that the reduced-type granitoids were formed in the sedimentary crust which is composed mainly of accretionary complexes and have never been influenced by previous magmatism, whilst the

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

oxidised-type granitoids were formed in the igneous crust which is depleted in carbonaceous matter due to previously repeated or intense magmatism. Thus granitoid activity in a given area tends to be changed to oxidised-type with time.

A wide zone of sedimentary crust in the Khingan and Sikhote–Alin Mountains in Far East Russia is thought to have been formed by a strike-slip stacking of Jurassic accretionary complexes from the original place of accretion near the Korean Peninsula or southeast China. This zone provided favourable sites for the reduced-type felsic magmatism accompanied by tin mineralisation in the Cretaceous; the magmatism may have been caused by vigorous subduction of the palaeo-Pacific plate. The Early Cretaceous oblique subduction may have caused the left-lateral strike-slip displacement of the accretionary complexes, including sliced continental fragments towards the north, under a Sunda-style tectonic regime, and resulted in the formation of the Khingan–Okhotsk tin belt in mid-Cretaceous times (Sato *et al*. 2002). Early Cretaceous granitoids are of reduced-type in central Sikhote–Alin, but of oxidised-type in the Kitakami area (Figs 4 & 9), suggesting different tectonic environments; transpressional in central Sikhote–Alin, but transtensional in the Kitakami area. However, palinspastic reconstruction of the Early Cretaceous magmatism is not easy because of probable secondary displacement or modification of geologic units by Late Cretaceous–Palaeogene activities. The general scenario of Cretaceous tectonic activity and magmatism over the whole circum-Japan Sea region has great potential for more detailed study.

The change of sedimentary terranes to sites of magmatism is an essential factor for the generation of the reduced-type granitoid provinces and tin-rich metallogenic provinces. Such a situation may have occurred at various stages in the geodynamic history of northeast Asia, in contrast with western North America, where a monotonous subduction system operated for a long period in the Mesozoic. The Late Jurassic–Early Cretaceous tin province in the Yana–Kolyma region of northeast Russia is thought to have been formed by a collision activity that may be another suitable process for the formation of reduced-type granitoid magmas through the involvement of sedimentary materials. Eurasia is a collage of cratons and continental blocks cemented by Phanerozoic orogenic belts (e.g. Maruyama *et al*. 1989). Collision processes may have provided a large amount of sediments to surrounding oceans. Weathering and sedimentary processes in the biosphere may have prepared ^{18}O, ^{32}S and ^{87}Sr-enriched isotopic features as well as C-bearing reducing conditions in the sedimentary crust. This is a recycling process and, at the same time, a reducing process affecting continental crust. In northeast Asia, the recycled and reduced sedimentary crust was involved in new magmatism over large regions, resulting in the formation of the provinces of the reduced-type granitoids and tin mineralisation.

6. Acknowledgements

We thank I. N. Kigai, A. A. Brublevsky, S. M. Rodionov, S. V. Korenbaum, A. I. Khanchuk, V. G. Gonevchuk, G. A. Gonevchuk, V. P. Simanenko, V. P. Nechaev, S. V. Vysotskiy, and M. Enjoji for their help in the field work and administrative matters. Thanks are also due to Mrs T. Hirose, M. Obata and S. Hirano of the Consulate-General of Japan at Vladivostok and Khabarovsk, Mrs T. Nagai and Y. Yukimatsu of the Japanese Embassy in Moscow for their support to our activity in Russia. Helpful suggestions for age dating by Dr. K. Suzuki of Nagoya University, kind correction of the English by Dr. L. C. Hsu of Nevada University, and critical reviews of the manuscript by Drs. B. Jahn, C. Hart and E. Horikoshi are also greatly appreciated. This work was carried out as a part of an international cooperative research project, ‘Metallogeny of the Circum-Japan Sea Region’, authorised by the Committee on Science and Technology Cooperation between Japan and Russia, with financial support from the Science & Technology Agency and Ministry of Education of Japan and the Russian Academy of Sciences.

7. References

Armstrong, R. L. 1988. Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera. *Geological Society of America, Special Paper* **218**, 55–91.

Bateman, P. C. 1983. A summary of critical relations in the central part of the Sierra Nevada batholith, California, U.S.A. *Geological Society of America, Memoir* **159**, 241–54.

Bateman, P. C., Dodge, F. C. W. & Kistler, R. W. 1991. Magnetic susceptibility and relation to initial 87Sr/86Sr for granitoids of the central Sierra Nevada, California. *Journal of Geophysical. Research* **96**, 19,555–68.

Blevin, P. L. & Chappell, B. W. 1992. The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. *Transactions of the Royal Society Edinburgh: Earth Sciences* **83**, 305–16.

Burchfiel, B. C., Cwan, D. S. & Davis, G. A. 1992. Tectonic overview of the Cordilleran orogen in the western United States. *In* Burchifiel, B. C., Lipman, P. W. & Zoback, M. L. (eds) *The Geology of North America Volume G-3, The Cordilleran Orogen: Conterminous U.S.*, 407–79. Boulder, Colorado: Geological Society of America.

Chappell, B. W. & White, A. J. R. 1974. Two contrasting granite types. *Pacific Geology* **8**, 173–4.

Chappell, B. W. & White, A. J. R. 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society Edinburgh: Earth Sciences* **83**, 1–26.

Chen, P. 1993. Timing of displacement along the Tancheng-Lujian fault zone and the migration of Late Mesozoic volcanism in eastern China. *In* Xu, J. (ed.) *The Tancheng-Lujian Wrench Fault System*, 51–74. Chichester: John Wiley & Sons.

Cheong, C. S. & Chang, H. W. 1997. Sr, Nd, and Pb isotope systematics of granitic rocks in the central Ogcheon Belt, Korea. *Geochemical Journal,* **31**, 17–36.

Chinese Academy of Geological Sciences 1999. *Minerogentic Series Map of Mineral Deposits of China, 1:5,000, 000*. Beijing: Geological Publishing House.

Choi, S. G. 2002. The genetic implications of Mesozoic gold-silver mineralization, South Korea. *Mesozoic Sedimentation, Igneous Activity and Mineralization in South Korea. Korea Institute of Geoscience and Mineral Resources, Special Publication* **1**, 216–26.

Curray, J. R. Moore, D. G., Lawver, L. A., Emmel, F. J., Raitt, R. W., Henry, M. & Kieckhefer, R. 1979. Tectonics of the Andaman Sea and Burma. *In* Watkins, J. S., Montadert, L. & Dickerson, P. W. (eds) *Geological and Geophysical Investigations of Continental Margins. AAPG Memoir* **29**, 189–98. Tulsa, Oklahoma: American Association of Petroleum Geologists (AAPG).

Curray, J. R., Emmel, F. J., Moore, D. G. & Raitt, R. W. 1982. Structure, tectonics and geological history of the Northeastern Indian Ocean. *In* Narin, A. E. M. & Stehli, F. G. (eds) *The Ocean Basins and Margins*, **6**, 399–45. New York, NY: Plenum.

Czamanske, G. K., Ishihara, S. & Atkin, S. A. 1981. Chemistry of rock-forming minerals of the Cretaceous–Paleocene batholith in southwestern Japan and implications for magma genesis. *Journal of Geophysical Research* **86**, 10431–69.

Dickinson, W. R. 1976. Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western north America. *Canadian Journal of Earth Sciences.* **13**, 1268–87.

Dickinson, W. R. 1981. Plate tectonics and the continental margin of California. *In* Ernst, W. G. (ed.) *The Geotectonic Development of California*, 1–28. Englewood Cliffs, New Jersey: Prentice-Hall.

Ebiko, T. 1965. Geologic features and prospecting of the Taro mine, Iwate Prefecture, Japan. *Mining Geology* **15**, 109–13. [In Japanese, with English abstract.]

Enkin, R. J., Yang, Z., Chen, Y. & Courtillot, V. 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the Present. *Journal of Geophysical Research* **97**, 13,953–89.

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

Faure, M. & Natal'in, B. 1992. The geodynamic evolution of the eastern Eurasian margin in Mesozoic times. *Tectonophysics* **208**, 397–411.

Fitch, T. J. 1972. Plate convergence, transcurrent fault, and deformation adjacent to Southeast Asia and the western Pacific. *Journal of Geophysical Research* **77**, 4432–60.

Furukawa, Y. & Tatsumi, Y. 1999. Melting of a subducting slab and production of high-Mg andesite magmas: unusual magmatism in SW Japan. *Geophysical Research. Letters* **26**, 2271–4.

Gallagher, D. 1963. *Mineral Resources of Korea, Volume 6B: Non-Metallics and Miscellaneous Metals*. USOM/Korea: Mining Branch, Industry & Mining Division.

Gastil, R. G. 1993. Prebatholithic history of peninsular California. *Geological Society of America, Special Paper* **279**, 145–56.

Gastil, R. G., Diamond, J., Knaack, C., Walewender, M., Marshall, M. Boyles, C., Chadwick, B. & Erskine, B. 1990. The problem of the magnetite/ilmenite boundary in southern and Baja California, California. *Geological Society of America, Memoir* **174**, 19–32.

Geological Survey of Japan 1992. *Geological Map of Japan, 1:1,000,000* (3rd edn). Tsukuba, Japan: Geological Survey of Japan.

Gradstein, F. M., Agterberg, F. P., Ogg, J. G., Hardenbol, J., Veen, P. V., Thierry, J. & Huang, Z. 1995. A Triassic, Jurassic and Cretaceous time scale. *In* Berggren, W. A., Kent, D. V., Aubry, M. P. & Hardenbol. J. (eds) *Geochronology Time Scales and Global Stratigraphic Correlation. SEPM Special Publication* **54**, 95–126. Tulsa, Olkahoma: Society for Sedimentary Geology (SEPM).

Hamilton, W. 1979. Tectonics of the Indonesian Region. *United States Geological Survey Professional Paper,* **1078**. Washington, DC: United States Government Printing Office.

Hirooka, K. 1990. Paleomagnetic studies of pre-Cretaceous rocks in Japan. *In* Ichikawa, K., Mizutani, S., Hara, I., Hada, S. & Yao, A. (eds) *Pre-Cretaceous Terranes of Japan, Publication of IGCP* **224**. *Pre-Jurassic Evolution of Eastern Asia*, 401–5. Osaka, Japan: International Geological Correlation Program (IGCP).

Institute of Geology, State Academy of Sciences, DPR of Korea 1996. *Geology of Korea*. Pyongyang: Foreing Languages Books Publishing House.

Ishihara, S. 1977. The magnetite-series and ilmenite-series granitic rocks. *Mining Geology* **27**, 293–305.

Ishihara, S. 1979. Lateral variation of magnetic susceptibility of the Japanese granitoids. *Journal of the Geological Society of Japan* **85**, 509–23.

Ishihara, S. 1984. Granitoid series and Mo/W-Sn mineralization in East Asia. *Geological Survey of Japan, Report* **263**, 173–208.

Ishihara, S., Lee, D. S. & Kim, S. Y. 1981. Comparative study of Mesozoic granitoids and related W-Mo mineralization in southern Korea and southwestern Japan. *Mining Geology* **31**, 311–20.

Ishihara, S., Sasaki, A., & Sato. K. 1992. *Metallogenic Map of Japan, 1:2,000,000 Map Series* **15-2, 3**. Tsukuba, Japan: Geological Survey of Japan.

Ishihara, S. & Matsuhisa, Y. 2002. Oxygen isotope constraints on the genesis of the Cretaceous-Paleogene granitoids in the Inner Zone of Southwest Japan. *Bulletin of the Geological Survey of Japan* **53**, 421–38.

Ishihara, S. & Sasaki, A. 1973. *Metallogenic Map of Japan, 1:2,000,000 Map Series* **15-1**. Tsukuba, Japan: Geological Survey of Japan.

Isozaki, Y. 1997. Jurassic accretionary tectonics of Japan. *The Island Arc* **6**, 25–51.

Isozaki, Y. & Itaya, T. 1990. Chronology of Sanbagawa metamorphism. *Journal of Metamorphic Geology* **8**, 401–11.

Jahn, B. 1974. Mesozoic thermal events in southeast China. *Nature* **248**, 480–3.

Jin, M. S., Lee, Y. S. & Ishihara, S. 2001. Granitoids and their magnetic susceptibility in South Korea. *Resource Geology* **51**, 189–203.

Jwa, Y. J. 1998. Temporal, spatial and geochemical discriminations of granitoids in South Korea. *Resource Geology* **48**, 273–84.

Kagami, H., Iizumi, S., Tainosho, Y. & Owada, M. 1992. Spatial variations of Sr and Nd isotope ratios of Cretaceous-Paleogene granitoid rocks, Southwest Japan Arc. *Contributions to Mineralogy and Petrology,* **112**, 165–77.

Kanisawa, S. 1974. Granitic rocks closely associated with the Lower Cretaceous volcanic rocks in the Kitakami Mountains, Northeast Japan. *Journal of the Geological Society of Japan* **80**, 355–67.

Kawano, Y. & Ueda, Y. 1965. K-Ar dating on the igneous rocks in Japan (2)-Granitic rocks in Kitakami massif. *Journal of the Japanese Association of. Mineralogy, Petrology and Economic Geology* **53**, 143–54. [In Japanese, with English abstract.]

Khanchuk, A. I., Ratkin, V. V., Ryazantseva, M. D., Golozubov, V. V. & Gonokhova, N. G. 1996. *Geology and Mineral Deposits of Primorsky Krai*. Vladivostok: Dalnauka.

Kim, K. H., Satake, H. & Mizutani, Y. 1992. Oxygen isotopic compositions of Mesozoic granitic rocks in South Korea. *Mining Geology* **42**, 311–22.

Kim, K. H., Park, S. S. & Na, C. K. 1996. Nd and Sr isotopic signatures of Mesozoic granitoids in South Korea. *Resource Geology* **46**, 215–26.

Kimura, G. 1994. The latest Cretaceous-early Paleogene rapid growth of accretionary complex and exhumation of high pressure series metamorphic rocks in northwestern Pacific margin. *Journal of Geophysical Research* **99**, 22147–64.

Kimura, T. 1987. Geographic distribution of Palaeozoic and Mesozoic plants in East and Southeast Asia. *In* Taira, A. & Tashiro, M. (eds) *Historical Biogeography and Plate Tectonic Evolution of Japan and Eastern Asia*, 135–200. Tokyo: Terrapub.

Kobayashi, K. & Sato, T. 1979. Tectonics and evolution of ocean-continent boundary zone (I). *Iwanami Earth Science Series* **11**, 175–252. [In Japanese.]

Korea Institute of Energy and Resources (KIER) 1983. *Metallogenic Map of Korea, 1:1,000,000 scale*. Seoul, Korea: KIER.

Korea Institute of Geology, Mining & Materials (KIGAM) 1995a. *Isotope Age Map of Plutonic Rocks in Korea., 1:1,000,000 scale*. Taejon, Korea: KIGAM.

Korea Institute of Geology, Mining & Materials (KIGAM) 1995b. *Isotope Age Map of Ore Deposits in Korea., 1:1,000,000 scale*. Taejon, Korea: KIGAM.

Krasnyi, L. I. & Peng, Y. (eds) 1996. *Geological Map of Amur Region and Adjacent Areas, scale 1:2,500,000*. A. P. Karpinsky All-Russian Geological Research Institute (VSEGEI), Amurgeolkom and Bureau of Geology and Mineral Resources of Heilongjiang Province. Harbin, Sankt-Petersburg & Blagoveshchensk.

Larson, R. L. 1991. Latest pulse of the Earth: evidence for a mid-Cetaceous superplume. *Geology* **19**, 547–50.

Layer, P. W., Newberry, R., Fujita, K., Parfenov, L., Trunilina, V. & Bakharev, A. 2001. Tectonic setting of the plutonic belts of Yakutia, northeast Russia, based on 40Ar/39Ar geochronology and trace element geochemistry. *Geology* **29 (2)**, 167–70.

Lee, D. S. (ed.) 1988. *Geology of Korea*. Seol, Korea: Geological Society of Korea, Kyohak-Sa, Publishing Co.

Lin, Q., Ge, W., Sun, D., Wu, F., Won, C. K., Min, K. D., Jin, M. S., Lee, M. W., Kwon, C. S. & Yun, S. H. 1998. Tectonic significance of Mesozoic volcanic rocks in northeastern China. *Scientia Geologica Sinica* **33**, 129–39. [In Chinese, with English abstract.]

Ma, L., Yang, J. & Ding, Z. 1989. Songliao Basin-An intracratonic continental sedimentary basin of combination type. *In* Zhu, X. (ed.) *Chinese Sedimentary Basins, Sedimentary Basins of the World* **1**, 77–87. Amsterdam: Elsevier.

Markevich, P. V., Zyabrev, S. V., Filippov, A. N. & Malinovskiy, A. I. 1997. East flank of the Kiselevka-Manoma terrane: An island arc fragment in the accretionary prism. *Geology of the Pacific Ocean* **13**, 295–338.

Maruyama, S., Liou, J. G. & Seno, T. 1989. Mesozoic and Cenozoic evolution of Asia. *In* Ben-Avraham, Z. (ed.) *The Evolution of the Pacific Ocean Margins. Oxford Monographs on Geology and Geophysics* **8**, 75–99. New York: Oxford University Press.

Maruyama, S., Isozaki, Y., Kimura, G. & Terabayashi, M. 1997. Paleogeographic maps of the Japanese Islands: Plate tectonic synthesis from 750 Ma to the present. *The Island Arc* **6**, 121–42.

Maruyama, S. & Seno, T. 1986. Orogeny and relative plate motions: Example of the Japanese Islands. *Tectonophysics* **127**, 305–29.

Matsuda, T., Sakiyama, T, Enami, R., Otofuji, Y., Sakhno, V. G., Matunin, A. P., Kulinich, R. G. & Zimin, P. S. 1998. Fission-track ages and magnetic susceptibility of Cretaceous to Paleogene volcanic rocks in southeastern Sikhote-Alin, Far East Russia. *Resource Geology* **48**, 285–90.

Matsuhisa, Y., Sasaki, A., Shibata, K. & Ishihara, S. 1982. Source diversity of the Japanese granitoids: An O, S and Sr isotope approach. *Abstracts of the 5th International Conference on Geochronology, Cosmochronology and Isotope Geology*, 239–40. Nikko, Japan.

Matsuoka, A., Yamakita, S., Sakakibara, M. & Hisada, K. 1998. Unit division for the Chichibu Composite Belt from a view point of accretionary tectonics and geology of western Shikoku, Japan. *Journal of the Geological Society of Japan* **104**, 634–53. [In Japanese.]

Matsuoka, A. & Oji, T. 1990. Middle Jurassic radiolarian fossils from the Magisawa Formation in the Taro Belt, North Kitakami Mountains. *Journal of the Geological Society of Japan* **96**, 239–41. [In Japanese.]

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

Ministry of Geology and Mineral Resources of China 1990. *Geologic Map of China, 1:500,0000*. Beijing: Geological Publishing House.

Mishin, L. F. & Romanovsky, N. P. 1994. Reduction-oxidation environments and metallogeny of igneous ore systems of the southern Far East. *Geology of the Pacific Ocean* **9**, 997–1011.

Mizutani, S. & Kojima, S. 1992. Mesozoic radiolarian biostratigraphy of Japan and collage tectonics along the eastern continental margin of Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **96**, 3–22.

Mizutani, S. & Yao, A. 1991. Radiolarians and terranes: Mesozoic geology of Japan. *Episodes* **14**, 213–16.

Mori, K., Okami, K. & Ehiro, M. 1992. Paleozoic and Mesozoic sequences in the Kitakami Mountains (A05). *In* Adachi, M. & Suzuki, K. (eds). *29th International Geological Congress (IGC) Field Trip Guidebook* vol. 1, 81–114. Nagoya: Nagoya University.

Nakae, S. 2000. Regional correlation of the Jurassic accretionary complex in the Innner Zone of Southwest Japan. *Memoir of the Geological Society of Japan* **55**, 73–98. [In Japanese, with English abstract.]

Natal'in, B. A. 1993. History and modes of Mesozoic accretion in Southeastern Russia. *The Island Arc* **2**, 15–34.

Natal'in, B. A. & Zyabrev, S. V. 1989. Structure of Mesozoic Rocks of the Amur River Valley. *Field trip guide book for International Symposium on Tectonics, Energy and Mineral resources of Northwest Pacific, Khabarovsk, September, 1989*. Khabarovsk: Far East Branch of USSR Academy of Sciences. [In Russian and English.]

Nechaev, V. P., Markevich, P. V., Malinovsky, A. I., Philippov, A. N. & Vysotskiy, S. V. 1996. Tectonic setting of the Cretaceous sediments in the Lower Amur region, Russian Far East. *Journal of the Sedimentological Society of Japan* **43**, 69–81.

Ohana, T. & Kimura, T. 1995. Late Mesozoic phytogeography in eastern Eurasia with special reference to the origin of angiosperms in time and site. *Journal of the Geological Society of Japan* **101**, 54–69. [In Japanese, with English abstract.]

Okada, H. 1999. Plume-related sedimentary basins in East Asia during the Cretaceous. *Palaeogeography, Palaeoclimatology, Palaeoecology* **150**, 1–11.

Otofuji, Y., Matsuda, T. & Nohda, S. 1985. Opening mode of the Japan Sea inferred from the palaeomagnetism of the Japan Arc. *Nature* **317**, 603–4.

Otsuki, K. & Ehiro, M. 1992. Cretaceous left-lateral faulting in Northeast Japan and its bearing on the origin of geologic structure of Japan. *Journal of the Geological Society of Japan* **98**, 1097–112. [In Japanese, with English abstract.]

Parfenov, L. M. 1991. Tectonics of the Verkhoyansk-Kolyma Mesozoides in the context of plate tectonics. *Tectonophysics* **199**, 319–42.

Parfenov, L. M, Vetluzhskikh, V. G., Gamyanin, G. N., Davydov, Yu. V., Deikunenko, A. V., Kostin, A. V., Nikitin, V. M., Prokop'yev, A. V., Smelov, A. P., Supletsov, V. M., Timofeyev, V. F., Fridovskiy, V. Yu., Kholmogorov, A. I. & Yakovlev, Ya. V. 1999. Main metallogenic units of the Sakha Republic (Yakutia), Russia. *International Geology Review* **41**, 425–56.

Romanovsky, N. P., Gurovich, V. G. & Sato, K. 1996. Magnetic susceptibility and metallogeny of granitoids in the Circum-Japan Sea region. *Geology of the Pacific Ocean* **12**, 965–76.

Ryazantseva, M. D., Gerasimov, N. S. & Govorov, I. N. 1995. Rubidium-strontium isochrones and petrogenesis of igneous rocks in the Voznesensk ore-bearing area, Primorie. *Geology of the Pacific Ocean* **11**, 579–96.

Sagong, H., Kwon, S. T. & Ree, J. H. 2003. Origin of the 160-110 hiatus in the Mesozoic magmatism of South Korea. *5th Hutton Symposium, Abstract with Program*, 125. *Geological Survey of Japan, Interim Report* **29**.

Sasaki, A. & Ishihara, S. 1979. Sulfur isotopic composition of the magnetite-series and ilmenite-series granitoids in Japan. *Contributions to Mineralogy and Petrology* **68**, 107–15.

Sasaki, A. & Ishihara, S. 1980. Sulfur isotope characteristics of the granitoids and related mineral deposits in Japan. *Proceedings of the 5th International Association on the Genesis of Ore Deposits (IAGOD) Symposium*, 325–35. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

Sato, K. 1980. Tungsten skarn deposit of the Fujigatani mine, Southwest Japan. *Economic Geology* **75**, 1066–82.

Sato, K. 1982a. Characteristics of tungsten skarns in Japan, two contrasting types. *In* Hepworth, J. V. & Yu, H. Z. (eds) *Proceedings of the Symposium on Tungsten Geology, Jiangxi, China, 1981*, 203–9. Bandung ESCAP/RMRDC (Economical and Social Commission for Asia and the Pacific/Regional Mineral Resources Development Centre) of the United Nations and Geological Publishing House in Beijing.

Sato, K. 1982b. Tungsten deposits in China. *Chishitsu(Geology) News*, 31–44. [In Japanese.]

Sato, K. 1991. Miocene granitoid magmatism at the island-arc junction, central Japan. *Modern Geology* **15**, 367–99.

Sato, K. 2000. Granitoids and mineralization in the Khingan-Okhotsk and Sikhote-Alin regions, Far East Russia: Crustal structure and granitoid series. *Gekkan-Chikyuu (Earth Monthly), Special Publication* **30**, 162–70. [In Japanese.]

Sato, K. 2003. Metallogeny in the circum Japan Sea region: crustal structure and granitoid series. *In* Society of Resource Geology (ed.) *Resource and Environmental Geology*, 61–70. Tokyo: Society of Resource Geology. [In Japanese.]

Sato, K., Shimazaki, H. & Chon, H. T. 1981. Sulfur isotopes of the ore deposits related to felsic magmatism in the southern Korean peninsula. *Mining Geology* **31**, 321–6.

Sato, K., Ishihara, S. & Shibata, K. 1992. Granitoid Map of Japan. *Geological Atlas of Japan* (2nd edn). Tsukuba: Geological Survey of Japan.

Sato, K., Lavrik, N. I. & Vrublevsky, A. A. 1993a. Geology and mineral deposits in Skhiote-Alin, Russia. *Chishitsu(Geology) News* **468**, 16–26. [In Japanese.]

Sato, K., Ishihara, T., Vrublevsky, A. A. & Ishihara, S. 1993b. Distribution of magnetic anomalies and igneous rocks in southern Sikhote-Alin, Far East Russia. *Chishitsu(Geology) News* **470**, 18–28. [In Japanese.]

Sato, K., Rodionov, S. M. & Enjoji, M. 1996. Mnogovershinnoe Au deposit in northern Sikhote-Alin, Far East Russia. *Chishitsu (Geology) News* **501**, 37–44. [In Japanese.]

Sato, K., Ishihara, T., Rodionov, S. M., Nedachi, M., Vrublevsky. A. A., Khanchuk, A. I., Romanovsky, N. P. & Enjoji, M. 1998. Mid-Cretaceous episodic magmatism and tin mineralization in the Khingan-Okhotsk volcano-plutonic belt, Far East Russia. *Abstract for Resource Geology 1998 Annual Meeting, P-2*. Tokyo: Society of Resource Geology.

Sato, K., Vruvlevsky, A. A., Rodionov, S. M., Rmanovsky, N. P. & Nedachi, M. 2002. Mid-Cretaceous epispdic magmatism and tin mineralization in Khingan-Okhotsk volcano-plutonic belt, Far East Russia. *Resource Geology* **52**, 1–14.

Sato, K., Suzuki, K., Nedachi, M., Terashima, S., Kovalenko, S. V., Ryazantseva, M. D, Vrublevsky. A. A. & Khanchuk, A. I. 2003a. Fluorite deposits at Vonesenka in the Khanka massif, Russia: Geology and age of mineralization. *Resource Geology* **53**, 193–211.

Sato, K., Nedachi, M., Suzuki, K., Ishihara, T., Vrublevsky. A. A., Rodionov, S. M., Berdnikov, N. A., Romanovsky, N. P., Kovalenko, S. V., Korenbaum, S. A. & Khanchuk, A. I. 2003b. Granitoids and mineralization in the Circum-Japan Sea region: Crustal structure and granitoid types. *5th Hutton Symposium, Abstract with Program*, 133. *Geological Survey of Japan, Interim Report* **29**.

Sato, K. & Ishihara, S. 1983. Chemical composition and magnetic susceptibility of the Kofu granitic complex. *Bulletin of the Geological Survey of. Japan* **34**, 413–27. [In Japanese, with English abstract.]

Shibata, K., Matsumoto, T., Yanagi, T. & Hamamoto, R. 1978. Isotopic ages and stratigraphic control of Mesozoic igneous rocks in Japan. *In The Geologic Time Scale, AAPG Studies in Geology* **6**, 143–64. Tulsa, Oklahoma: American Association of Petroleum Geologists (AAPG).

Shibata, K. & Ishihara, S. 1979. Initial 87Sr/86Sr ratios of plutonic rocks from Japan. *Contributions to Mineralogy and Petrology* **70**, 381–90.

Shimazaki, H., Sato, K. & Chon, H. T. 1981. Mineralization associated with Mesozoic felsic magmatism in Japan and Korea. *Mining Geology* **31**, 297–310.

Shimazaki, H., Shibara, K., Uchiumi, S., Lee, M. S. & Kaneda, H. 1987. K-Ar ages of some W-Mo deposits and their bearing on metallogeny of South Korea. *Mining Geology* **37**, 395–401.

Silver, L. T., Taylor, H. P. & Chappell, B. 1979. Some petrological, geochemical, and geochronological observations of the Peninsular Ranges batholith near the international border of the U. S. A. and Mexico. *In* Abbott, P. L. & Todd, V. R. (eds) *Mesozoic Crystalline Rocks: San Diego, California*, 83–110. San Diego State University: Department of Geological Sciences.

Suzuki, K. & Adachi, M. 1998. Denudation history of the high T/P Ryoke metamorphic belt, southwest Japan: constraints from CHIME monazite ages of gneisses and granitoids. *Journal of Metamorphic Geology* **16**, 23–37.

Takahashi, M., Aramaki, S. & Ishihara, S. 1980. Magnetite-series/ilmenite-series vs. I-type/S-type granitoids. *Mining Geology, Special Issue* **8**, 13–28.

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

Teraoka, Y. & Okumura, K. 2003. *Geological Map of East Asia, scale 1:3,000,000*. Tsukuba: Geological Survey of Japan.

Tsuchiya, N. & Kanisawa, S. 1994. Early Cretaceous Sr-rich silicic magmatism by slab melting in the Kitakami Mountains, northeast Japan. *Journal of Geophysical Research* **99**, 22,205–220.

Tsusue, A. & Ishihara, S. 1974. The iron-titanium oxides in the granitic rocks of Southwest Japan. *Mining Geology* **24**, 13–30. [In Japanese, with English abstract.]

USSR Ministry of Geology 1977. *Magnetic Anomaly Map of USSR, scale 1:2,500,000*. Leningrad: USSR Ministry of Geology. [In Russian.]

USSR Ministry of Geology 1987. *Map for useful minerals in the USSR., 1:5,000,000*. Leningrad: USSR Ministry of Geology. [In Russian.]

Ueda, Y., Yamaoka, K. & Onuki, H. 1970. K-Ar dating on the host rocks of the Taro mine, Iwate Prefecture-specially on the origin of ore deposits. *Journal of the Japanese Association of Mineralogy, Petrology and Economic Geology* **63**, 259–65. [In Japanese, with English abstract.].

Uyeda, S. & Miyashiro, A. 1974. Plate tectonics and the Japanese Islands: A synthesis. *Geological Society of America, Bulletin* **85**, 1159–70.

Voinova, I. P., Zyabrev, S. V. & Prihodko, V. S. 1995. Petrochemistry of Early Cretaceous intraplate oceanic basalts of the Kiselevka-Manoma terrane, northern Sikhote Alin. *Geology of the Pacific Ocean* **11**, 971–90.

Wu, F., Jahn, B., Wilde, S. & Sun, D. 2000. Phanerozoic crustal growth: U-Pb and Sr-Nd isotopic evidence from the granites in northeastern China. *Tectonophysics* **328**, 89–113.

Wu, F., Sun, D., Li, H., Jahn, B. & Wilde, S. 2002. A-type granites in northeastern China: age and geochemical constraints on their petrogenesis. *Chemical Geology* **187**, 143–73.

Xu, J., Ma G., Tong, W., Zhu, G. & Lin, S. 1993. Displacement of the Tancheng-Lujian wrench fault system and its geodynamic setting in the northwestern circum-Pacific. *In* Xu, J. (ed.) *The Tancheng-Lujian Wrench Fault System*, 51–74. Chichester: John Wiley & Sons.

Zonenshain, L. P., Kuzmin, M. I., & Natapov, L. M. 1990. Geology of the USSR: A Plate- Tectonic Synthesis. *American Geophysical Union, Geodynamic Series* **21**.

Zyabrev, S. V. 1996. Cretaceous radiolarian fauna from the Kiselyovsky subterrane, the youngest accretionary complex of the Russian continental far east: Paleotectonic and paleogeographic implications. *The Island Arc* **5**, 140–55.

K. SATO and T. ISHIHARA, Geological Survey of Japan, Higashi 1-1-1 Central 7, Tsukuba, 305-8567, Japan.
e-mail: sato.gsj@aist.go.jp

S. V. KOVALENKO, Committee on Geology and Mineral Resources of Primorie Province, Vladivostok, Russia.

N. P. ROMANOVSKY and N. V. BERDNIKOV, Institute of Tectonics and Geophysics, Russian Academy of Sciences, Khabarovsk, Russia.

M. NEDACHI, Faculty of Sciences, Kagoshima University, Kagoshima, Japan.

MS received 4 December 2003. Accepted for publication 12 September 2004.

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press

https://doi.org/10.1017/S0263593300001103 Published online by Cambridge University Press