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Origin of the Cenozoic–Mesozoic magnetite-series and ilmenite-series granitoids in East Asia

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Abstract

Among the Phanerozoic granitoids of East Asia, the most prevailing Cenozoic–Mesozoic rocks are reviewed with respect to gabbro/granite ratio, bulk composition of granitoids, redox state, and O- and Sr-isotopic ratios. Quaternary volcanic rocks, ranging from basalt to rhyolite, but typically felsic andesite in terms of bulk composition in island arcs, are oxidized type, possibly due to oxidants from subducting oceanic crust into the source regions. Miocene plutonic rocks in the back-arc of Japan could be a root zone for such volcanism but are more felsic in composition. Cenozoic–Mesozoic plutonic zones are classified by (1) the redox state (magnetite/ilmenite series), and (2) average bulk composition (granodiorite/granite). The granodioritic magnetite series occur with fairly abundant gabbro and diorite in the back-arc of island arcs (Greentuff Belt) and intercontinental rapture zones (Yangtze Block). These rocks are mostly juvenile in terms of the $^{87}Sr/^{86}Sr I$ and $\delta^{18}O$ values.

The granitic magnetite series with some gabbroids occur in rapture zones along the continental coast (Gyeongsang Basin, Fujian Coast) and the back-arc of island arc (Sanin Belt). They were generated mostly in felsic continental crust, with the help of heat and magmas from upper mantle. The generated granitic magmas had little interaction with C- and S-bearing reducing materials, due probably to extensional tectonic settings. The $\delta^{18}O$ value gives narrow ranges but the $^{87}Sr/^{86}Sr I$ ratio varies greatly depending upon the age and composition of the continental crust. Granitic ilmenite-series are characterized by high $\delta^{18}O$ values, implying much contribution of sediments. The $^{87}Sr/^{86}Sr I$ ratios are low in island arcs but very high in continental interior settings. Amount of mafic magmas from the upper mantle seems a key to control the composition of granitoid series in island arc settings, while original composition of the protolith may be the key to control granitoid composition in continental interiors.

Keywords: East Asia; Mesozoic; Cenozoic; Granitoids; Redox state; $\delta^{18}O$ value; $^{87}Sr/^{86}Sr I$; Origin

1. Introduction

Oxygen fugacity of a given magma is one of the most important factors to be examined in solid earth science, because of what it tells us about source rock(s) and also its role on what ore metals are precipitated in ore deposits in and around the given pluton. The metals concentrated as S-combined components, such as Mo, Cu, Zn, Pb, Ag and bisulfide Au are empirically known to be concentrated in oxidized magnetite-series granitoids, but only small amounts of metallic minerals are associated with reduced ilmenite-series magmas (Ishihara, 1977). The oxygen fugacity of granitic magmas is known to have ranged over two to three orders of magnitude since the earliest Archean, depending upon the age and emplacement mechanism of granitic magmas (Czamanske et al., 1981; Ishihara et al., 2006).

The western Pacific rim is characterized by the development of marginal basins, and Phanerozic magmatism tend to occur in island arcs and continental margins around the basins. The magmas are mostly produced in subduction settings, called "subduction factory" by Tatsumi (2005), either as direct or indirect product of melting of the mantle wedge and the overlying continental crust, forming the continuous volcano-granitic complexes of the Circum-Pacific orogenic belts (Ishihara, 1998). Production of the granitic magmas, thus formation of continental crust, varies based upon characteristics of each factory. In the western Pacific rim, development of felsic basement and accretionary complexes is very important for granitic magmatism.

In this paper, redox state as well as the source of granitic magmatism will be reviewed from Quaternary to the early

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Mesozoic from the Japanese Islands, Korean Peninsula and China. The readers may refer to a separate paper (Ishihara et al., 2006) about the Archean history of granitoid series.

2. Quaternary magmatism of the Japanese island arcs

The Japanese island arcs are located above three major plates, which show a complicated subducting plate motion (Fig. 1). Yet the Quaternary volcanoes shown best by the volcanic front, the most trench side of the volcanoes, are distributed generally parallel to the arc–trench systems. Volcanoes in eastern Hokkaido belonging to the southwestern-most Kuril arc are located horizontally 250 km from the Kuril trench, those of the northeast Japan arc 300 km from the Japan trench, those of the Izu–Mariana arc 200 km from the Izu–Mariana trench, and those of the Kyushu arc 200 km from the Ryukyu trench (Fig. 1). Seismic Wadachi–Benioff zone is generally located 100–150 km below the volcanic front. A number of native sulfur (with some pyrite) deposits are concentrated around the Quaternary volcanoes of the volcanic front (Ishihara, 1974).

These Quaternary volcanic rocks are mostly basalt and mafic andesite along the Izu–Mariana chain. Rhyo-dacites are also common, thus exhibiting a bimodal pattern (Fig. 2). The felsic magmas in this ensimatic environment must have been generated within the andesitic crust by dehydration melting (Tamura and Tatsumi, 2002). The Quaternary rocks are mostly mafic and felsic andesites having a silica peak at 59% in the northeast (NE) Japan arc, whereas in the southwest (SW) Japan arc, where the arc is the most mature of the three, the rocks are dominantly felsic andesites followed by dacites and rhyolites including abundant ignimbrites (Fig. 2). All the volcanic rocks contain titanomagnetite in the groundmass and as phenocrysts. In the aeromagnetic map (Makino et al., 1992), strong magnetic anomalies are observed along the volcanic front of the oceanic Izu–Bonin arc and sialic Japanese island arc, so that the Quaternary volcanic rocks belong to magnetite series of Ishihara (1977). Since the fresh upper mantle is reduced (e.g., Horoman peridotite of JP-1 with Fe_2O_3/FeO of 0.33, Imai et al., 1995), the present upper mantle underneath the volcanoes must have been metasomatized by oxidants. The mantle wedge above subduction zones may be

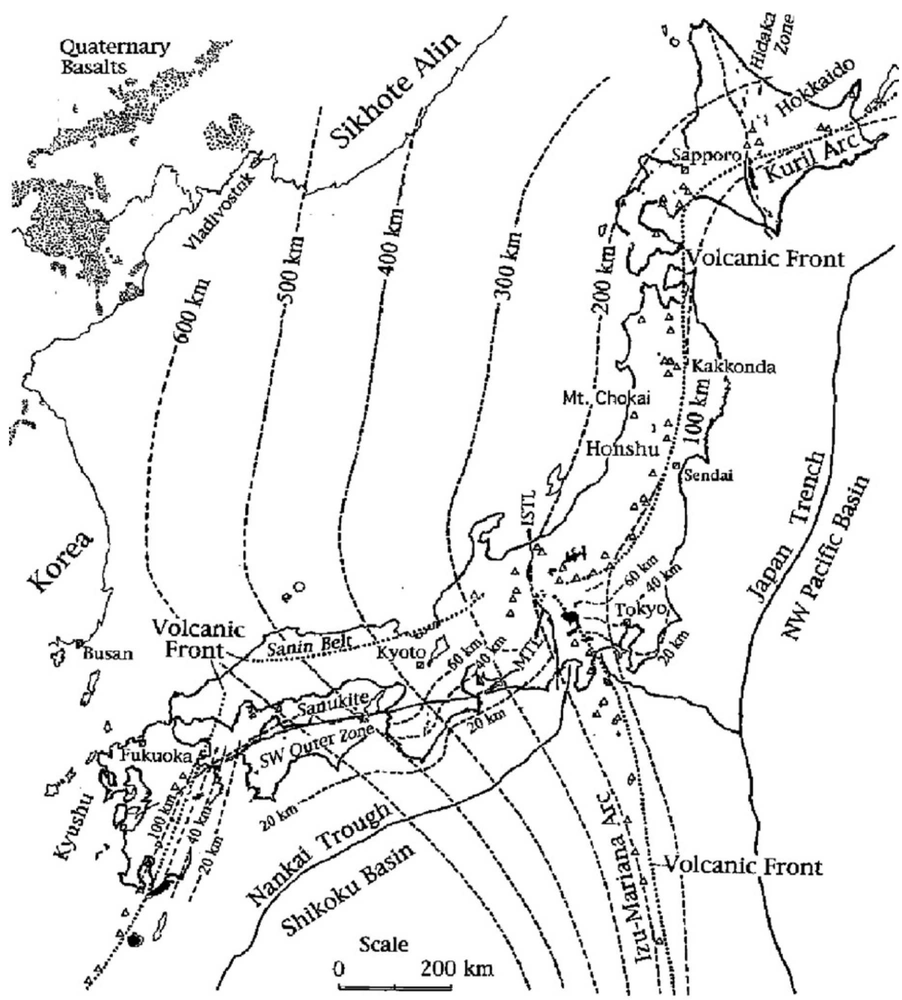

Fig. 1. Present geodynamic elements and distribution of Miocene granitoids (solid bodies) in and around the Japanese Islands (complied from Geol. Surv. Japan, 1992). Broken line, depth contour of the upper boundary of subducting two plates. △: active volcanoes. MTL, Median Tectonic Line; ISTL, Itoigawa–Shizuoka Tectonic Line.

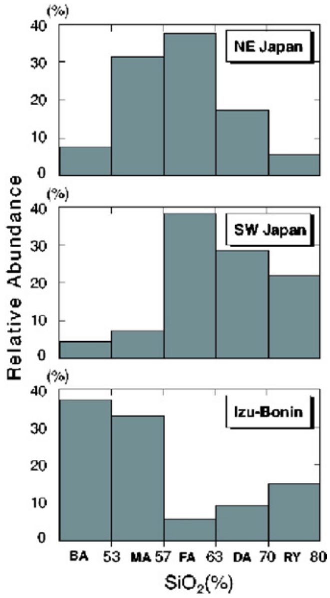

Fig. 2. Relative amounts of Quaternary volcanic rocks of representative three arcs in Japan. BA, basalt, MF, mafic andesite, FA, felsic andesite, DA, dacite, RY, rhyolite (after Tatsumi, 2003). Mafic rocks are predominant in the most juvenile Izu–Bonin islands, andesitic in the NE Japan Arc, and felsic andesite to rhyolite in the matured SW Japan arc. These volcanic rocks essentially belong to the magnetite series.

ubiquitously oxidized relative to oceanic and ancient cratonic mantle by oxidizing agents from the subducted slab (Parkinson and Arculus, 1999).

The volcanic rocks are also different in the across-arc direction. The silica content increases but alkali content decreases toward the volcanic front in basalts of the northeast Japan arc. Hydrous mafic silicates are predominant in andesitic rocks far from the volcanic front (Sakuyama, 1977). Titano-magnetite and iron oxides are always reported in these volcanic rocks (e.g., Isshiki, 1987; Nakano and Tsuchiya, 1982), indicating that these Quaternary rocks were derived from oxidized source rocks. Phenocrystic magnetite is common in hornblende andesite occurring along the back-arc side, and the bulk ferric/ferrous ratio is much higher than those along the volcanic front (e.g., Mt. Chokai, Nakano and Tsuchiya, 1982; Fig. 1). Both water and oxygen fugacities appear to be higher in the back-arc side than in the volcanic front side.

Pliocene magmatism is similar to that in the Quaternary volcanic fields. Plutonic rocks are known at two places in the Plio-Pleistocene time: Granitoids discovered by drilling in the Kakkonda geothermal field of northern Honshu (K–Ar age ~0.34 Ma, Doi et al., 1995) and late Pliocene–Quaternary granitoids (1.9–0.8 Ma, Harayama, 1992). These are largely composed of magnetite-series granodiorites having magnetic susceptibility values around $20–38\times10^{-3}$ SI.

3. Miocene paired plutonic belts

Miocene magmatism occurs mostly in the subduction-associated Quaternary volcanic fields along the back-arc side, known as the Tohoku Greentuff belt of NE Japan and the Sanin Greentuff belt of SW Japan. Plutonic rocks of the Greentuff belt may be the root zone of the volcanism, similar to the Quaternary volcanism. High-Mg andesites and related felsic volcanic rocks of Miocene age are present toward the fore-arc side (Seto inland-sea region) of the Greentuff Belt, SW Japan (Sato, 1982). All these rocks belong to magnetite series. Strongly magnetic low-K series occurs in the northern tip of the Izu–Mariana arc (Kawate and Arima, 1998), while the Miocene volcanic rocks are only weakly magnetic in the Seto inland sea region (Ishihara, 1979). Further to the fore-arc side, reduced ilmenite-series granitoids occur mostly in the Shimanto accretionary complex, accompanying small amounts of effusive facies and gabbroids. These rocks are called the outer zone granitoids of SW Japan (Fig. 1). Similar ilmenite-series magmatism of Paleogene to Miocene ages is seen in the Hidaka belt, Hokkaido.

Plutonic rocks of the Greentuff belt are largely Miocene in age, the period when bimodal volcanism occurred (Ishihara, 1974), and are composed mainly of hornblende–biotite quartz diorite and granodiorite including gabbroids, and limited monzogranite. In the silica histograms (Fig. 3), the most abundant range is that of dacite, which is the plutonic equivalent of granodiorite. Therefore, the average composition seems to be more felsic than the bulk composition of the Quaternary volcanic rocks of NE Japan arc (compare Figs. 2 and 3). These plutonic rocks and their subvolcanic equivalents are genetically associated with rich base and precious metal veins and rhodochrosite–Ag–Pb–Zn vein deposits.

The most juvenile ($^{87}Sr/^{86}SrI=0.7036$, Shibata and Ishihara, 1979) low-K Tanzawa pluton has very high contents of magnetite (up to 4 vol.% magnetite in gabbro) and low $\delta^{18}O$ values (average +5.5‰, Ishihara and Matsuhisa, 2005). Thus, the Tanzawa gabbro and tonalite must have been generated from oxidized ^{18}O-depleted low-K igneous source rocks from upper mantle and lower crust. The normal-K magnetite-series Kofu granodiorite has an average $\delta^{18}O$ value of +7.4‰ and $^{87}Sr/^{86}SrI$ ratio of 0.7051, and might have been generated from oxidized calc–alkaline basaltic rocks underplated in the island arc, then locally reduced by the interaction with the wall rocks of the Shimanto Supergroup (Ishihara and Matsuhisa, 2005). The other plutonic rocks have $^{87}Sr/^{86}SrI$ ratios of 0.7037 to 0.7055 and $\delta^{18}O$ values up to +9‰.

In the outer zone of SW Japan, on the other hand, granitic magmatism occurred only once in Miocene, which is post-tectonic to the deformed Paleogene Shimanto Supergroup. Juvenile gabbroids ($^{87}Sr/^{86}SrI=0.7031–0.7038$) intruded at the same time with the granitic activity. Mingling of basaltic and granitic magmas is observed at several places (e. g., Ashizuri-misaki and Hinokage valley of the Okueyama pluton). The granitoids belong to the ilmenite-series and is composed mostly of granodiorite (63–70% SiO_2; Fig. 3) and minor monzogranite (70–80% SiO_2) with relatively high $^{87}Sr/^{86}SrI$ ratios of 0.7062–0.7083. These rocks are locally associated with Sn – base metal – As skarns and vein deposits, and independent Sb and Hg veins.

These Miocene granitoids are high in $\delta^{18}O$ values and low in magnetic susceptibility, so that a good reverse correlation is obtained together with the Miocene magnetite-series granitoids of NE Japan arc (Fig. 4). They are considered to have formed by mingling and mixing of gabbroic magmas from the upper mantle

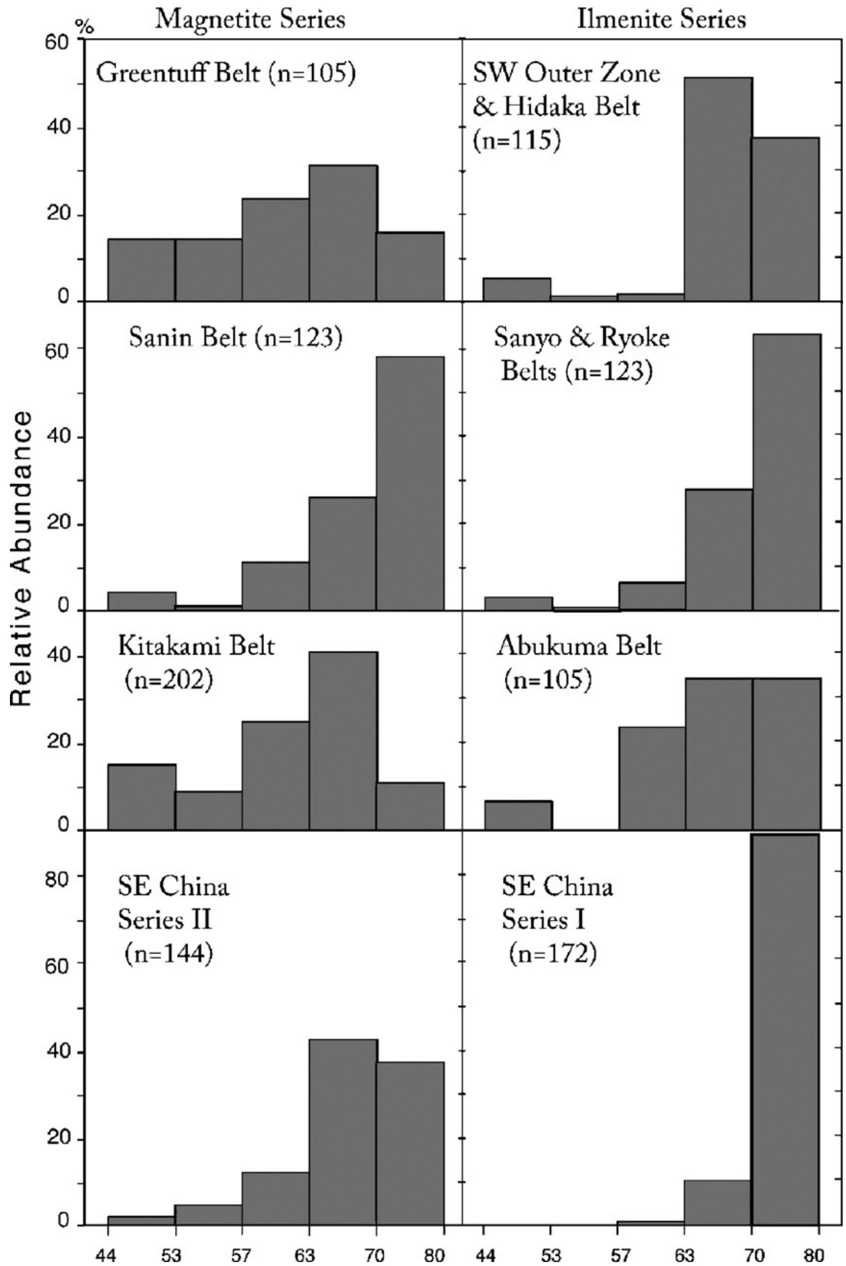

Fig. 3. Relative abundance of SiO_2 contents of Miocene to Cretaceous plutonic rocks in Japan and SE China. The SiO_2 data for Japan are from Hattori and Nozawa (1959), Ono and Soya (1974), Ishihara (1971, 2003), Ishihara and Wu (2001), Ishihara and Murakami (2004), Ishihara and Tani (2004), Ishihara and Matsuhisa (1999, 2002, 2004, 2005), and Kamei and Takagi (2003). For SE China, Series I is Jurassic granitoids of the Cathasia Block; Series II is mostly Cretaceous rocks from the SE coastal zone and the Yangtze Block (modified from Ishihara and Wang, 1999).

with melts originated from the mafic lower crust and meta-sediments that belong to the accretionary complex of the Shimanto Supergroup (Ishihara and Matsuhisa, 1999). Based upon oxygen isotope values, the mingling ratios of the sediments vary from 65% (Mimaki stock) in rocks intruded into the Shimanto sedimentary belt to 0% (Ishizuchiyama stock) in those intruded in the Sanbagawa high *P*/low *T* meta-igneous belt.

In the western and eastern parts of central Hokkaido, ilmenite-series gabbroids and granitoids, with Miocene or older ages occur along the N–S trending Hidaka sedimentary and metamorphic zone. The gabbroids have $^{87}Sr/^{86}Sr\textit{I}$ ratios of 0.7030–0.7039, whereas the granitoids have ratios of 0.7046–0.7053 (Shibata and Ishihara, 1979). These rocks are not related to major mineralization, but small Ni–pyrrhotite-bearing graphite deposits are hosted in the gabbroids; their C and S are probably derived from the accreted sediments of Tertiary age (Takahashi and Sasaki, 1983).

The gabbroids and granitoids are equally distributed in central Hokkaido. Thus a large amount of gabbroic magmas intruded from the upper mantle into the suture between NE and SW Hokkaido. The ilmenite-series granitoids were generated within the accretionary complex of the Hidaka Supergroup and its basement, by heat provided by these gabbroids. The granitoids are well exposed and the Horoman peridotite block

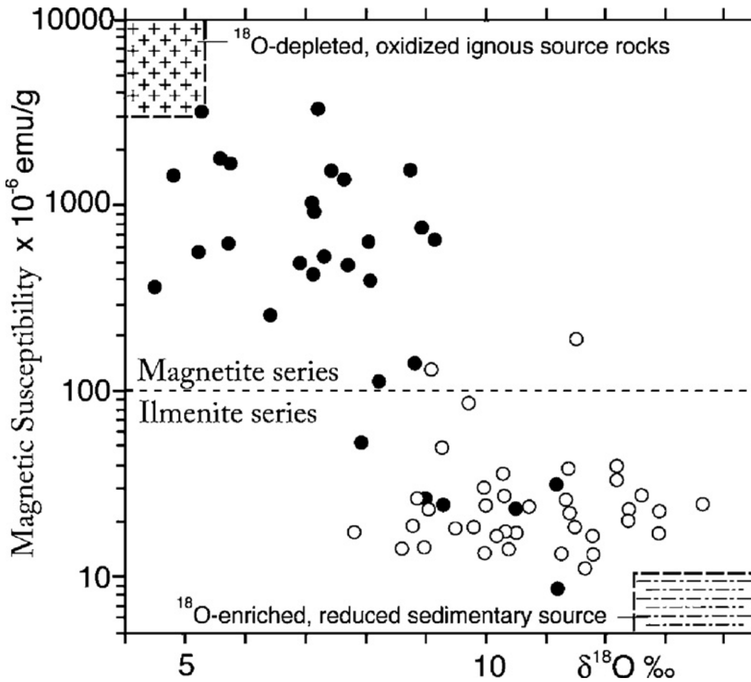

Fig. 4. Magnetic susceptibility vs. whole rock δ^{18}O of Miocene plutonic rocks in Japan. Solid circle, those of the Greentuff Belt; open circle, those of the outer zone of SW Japan and Hidka zone. The original data is from Kanaya and Ishihara (1973), and Ishihra and Matsuhisa (1999, 2005). Conversion from the weight magnetic susceptibility (X_{CGS}) to volume SI unit is expressed as K_{SI}=4 pai p X_{CGS} (Ueno, 1987).

is also exposed in the southwestern part, because of the westward shortening, followed by collision of NE Hokkaido (N. American plate) against SW Hokkaido.

4. Paleogene–Cretaceous paired belts in island-arc settings

4.1. Southwest Japan

Paleogene to Late Cretaceous granitoids occur most widely in the innerzone (north of MTL, Median Tectonic Line; Fig. 5) of SW Japan, and is referred to as the INSW batholith. The southern two-third of the Ryoke and Sanyo belts, consist mostly of ilmenite-series granitoids, but the northern one-third of the Sanin belt is composed generally of magnetite-series granitoids. Hornbelnde–biotite granodiorite is dominant, with local muscovite–biotite granite in the Ryoke metamorphic belt and biotite granite in the Sanyo and Sanin belts. Important W and some Cu skarn and vein deposits are associated with fractionated granites of the Sanyo belt, but no associated mineralization occurs with the Ryoke granitoids.

The granitoids of the Sanin belt are similar in silica variation to those of the Sanyo and Ryoke belts (Fig. 3), but belong to the magnetite series. Leucogranites of this belt are associated with Mo vein and Pb–Zn skarn deposits. Occurrence of magnetite vs. ilmenite-series granitoids is not time- but space-dependent; given the rocks are Late Cretaceous in northern Kyushu but Paleogene in Sanin and Chubu districts. The magnetite series tends to occur along the margin of the marginal basin.

Adakitic quartz diorite and granodiorite scatter as small stocks in the northwest of Kyoto at the northern margin of Sanyo belt (Kiji et al., 2000). Similarly, small mafic adakitic bodies were reported in the Yamizo Mountains, an eastern extension of the Sanyo belt (Takahashi et al., 2005). Adakitic characters of the INSW batholith, if any, may have been erased by mingling with felsic magmas generated in the C-bearing continental crust of the Sanyo and Ryoke belts.

Gabbroids are locally common in the Ryoke metamorphic belt. Mafic enclaves and syn-plutonic dikes are also locally present, especially in the Ryoke belt (Yokoyama, 1984) and Sanin belt (Ishihara and Tani, 2004; Wada et al., 2004). The $^{87}Sr/^{86}SrI$ ratio varies from 0.7050 to 0.7106 in all the granitoids (Shibata and Ishihara, 1979), but δ^{18}O values are consistently low (less than +8‰, Ishihara and Matsuhisa, 2002) in the magnetite series but high (more than +8‰) in the ilmenite series. These data suggest that the ilmenite-series granitoids were formed by oxidized (?) mafic magmas mingled with C-bearing Jurassic accretionary sediments stacked in the Ryoke and Sanyo belts. On the other hand, such magmas had little chance to react with reducing agents of C-poor meta-igneous basement of the Hida massif and also for the extensional tectonic setting of the Saninbelt during the Paleogene.

4.2. Northeast Japan

Late Cretaceous to Early Cretaceous granitoids also occur in NE Japan towards the east of the Tanakura Tectonic Line (Fig. 5), which shows a paired magnetite/ilmenite series belt in a reverse geographical manner. Here, the main Abukuma belt is composed of ilmenite-series granitoids with a narrow zone of magnetite-series granitoids along the eastern rim. Bulk compositions are more mafic than the INSW batholith (Fig. 3). Hornblende–biotite granodiorite and biotite granite are the main facies, but two-mica granite also occurs in limited areas. Gabbroic bodies are often seen floating in the granitoids. The

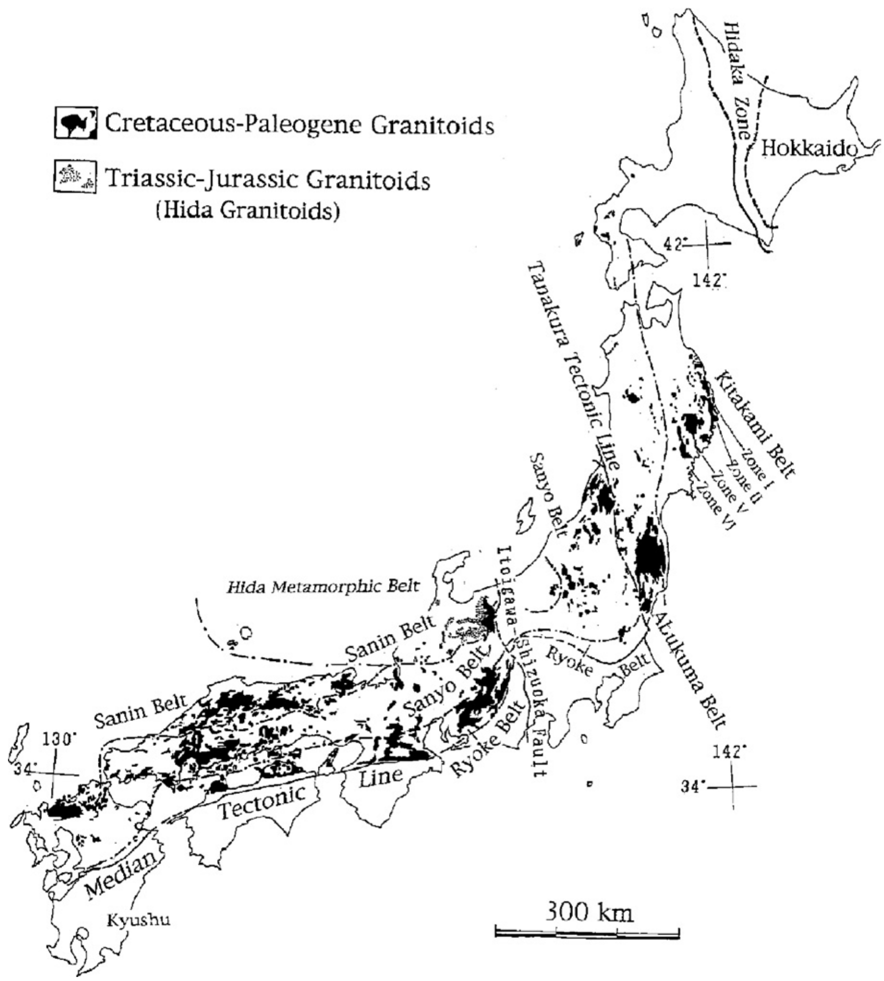

Fig. 5. Distribution of Cretaceous–Paleogene granitoids and the tectonic divisions in Japan. Minor Triassic–Jurassic granitoids in the Hida Belt are also shown.

only sizable ore deposit is scheelite-Cu skarns at Yaguki mine, Fukushima Prefecture.

Towards the north–northeast, Early Cretaceous granitoids occur in the Kitakami Mountains (Fig. 5). They are quartz diorite–tonalitic in the west, granodiorite in the central part, adakitic in the eastern zone (Zone II), and granodiorite and granitic with equivalent effusive facies in the easternmost zone (Zone I). These granitoids become magnetic toward the east, including a strongly magnetic belt in the eastern offshore belt shown clearly in the aeromagnetic map (Makino et al., 1992). Intensive Cu-magnetite skarn and small-scale scheelite-Au veins deposits occur in west-central parts (Ishihara and Murakami, 2004); Mo skarn and veins are present in the eastern zone.

The spatial distribution of magnetic anomalies and metallogenic patterns of northeast Japan is opposite to those of southwest Japan. This led Ishihara (1978) to propose that a subduction setting, similar to that of the present Manila and Philippine Trenches around the Philippines islands, occurred during Cretaceous time in NE Japan. Therefore, the eastern part is the back-arc side, and the Cretaceous volcanic rocks host kuroko-type Taro deposits, the ore deposit typically known in marginal basins.

The initial $^{87}Sr/^{86}Sr\mathit{I}$ ratio of the Abukuma granitoids is low, around 0.70518; these values are higher than that (0.70363–0.70463) of the Kitakami granitoids. The $\delta^{18}O$ values of the Abukuma granitoids are in general higher than +9‰, with the highest value for muscovite–biotite granite (ca. +12‰). In contrast, the $\delta^{18}O$ values of Kitakami granitoids are lower than +10‰ (Ishihara and Matsuhisa, 2004). Igneous sources of intermediate composition plus some sedimentary components are considered as the source rocks of Abukuma granitoids.

In the Kitakami granitoids, the Zone II adakite can be derived from the subducting slab (Tsuchiya and Kanisawa, 1994), while normal calc–alkaline rocks involved melting of the lower crust. The alkaline granitoids were probably derived from metasomatized upper mantle to achieve the highly mafic and potassic compositions. This mixed occurrence of various magma types is characteristic of this terrane and may have been caused by deep N–S faulting prevailing in the Kitakami belt.

5. Cretaceous magnetite series in continental margins

Cretaceous sedimentation in the southern part of the Korean Peninsula and Zhejiang–Fujian coast of South China was followed by intensive effusive and coeval plutonic activities. This zone is also known to contain alkali granitoids (Hong et al., 1996; Qiu et al., 2004), and is different from the Japanese islands. These plutonic rocks including those of the Lower

Yangtze region in China have been defined as the syntexis type of the Late Yanshanian cycle (Xu et al., 1987; Zhu, 1998).

5.1. Korean Peninsula

Korea is essentially Precambrian country intruded by Triassic, Jurassic (traditionally called Daebo) and Cretaceous–Paleogene (traditionally Bulguksa) granitoids. The Imjingan suture, of a fold and thrust belt (Fig. 6), is considered as the eastward extension of the Qinling–Dabie–Sulu fault in China, and formed due to collision of the South China continent against the Korean Peninsula (Yin and Nie, 1993). The Cretaceous–Paleogene granitoids occur as small batholiths and stocks mainly in the Gyeongsang basin, with general younging age eastwards, and partly in small basins developed along left-lateral shear-faults in the Ogcheon belt and around the southwestern tip of the Korean Peninsula (Yeongdong–Gwangju basin).

The granitoids are largely calc–alkaline granodiorite and granite with limited distribution of alkali granitoids (Jwa, 2004). They belong mostly to magnetite series (Jin et al., 2001) and are associated with large base metal and W skarn deposits, particularly around the northern margin of the Gyeongsang basin (Ishihara et al., 1981). The Cretaceous–Paleogene granitoids have average SiO_2 content of 71.1% in the Gyeongsang basin and 72.8% in the Ogcheon belt (Jwa, 1998). Thus the whole rock composition is granitic like those of the Sanin and Sanyo belts (Fig. 3). Jwa (2004) pointed out that the granitoids are characterized by low Sr content and rapidly decreasing Zr with increasing SiO_2, similar to low-temperature I-type granitoids of Chappell et al. (1998, 2004).

Sr and Nd isotopic ratios for the Cretaceous granitoids are quite distinct, depending upon the basement rocks. Those occurring in the main, Gyeongsang basin, show mostly juvenile signatures with $^{87}Sr/^{86}SrI=0.7024$–0.7069 and $\varepsilon_{Nd}=2.5$ to -4.4, and those of the Ogcheon Belt are mostly enriched, with $^{87}Sr/^{86}SrI=0.7122$–0.7226 and $\varepsilon_{Nd}=-13.4$ to -17.6. Those of the Yeongdong–Gwangju are intermediate ($^{87}Sr/^{86}SrI=0.7083$–0.7129 and $\varepsilon_{Nd}=-6.3$ to -15.2; Jwa, 2004). Whole-rock $\delta^{18}O$ values of unaltered Cretaceous granitoids range from +7.1 to +8.3 in granitoids of the main Gyeongsang basin, but are slightly higher (+7.7∼+9.1‰) in the intermontane basins of the Ogcheon belt (Kim et al., 1992).

Gabbroids occur sporadically in the Gyeongsang basin, but the majority is granitic. The granitoids of the Gyeongsang basin are considered to have a mixed source of magma derived from the metasomatized upper mantle and crustal materials. The granitoids outside the basin had much more continental input as indicated isotopically, and thus were probably generated within the older basement below the Cretaceous basin sediments (Jwa, 2004).

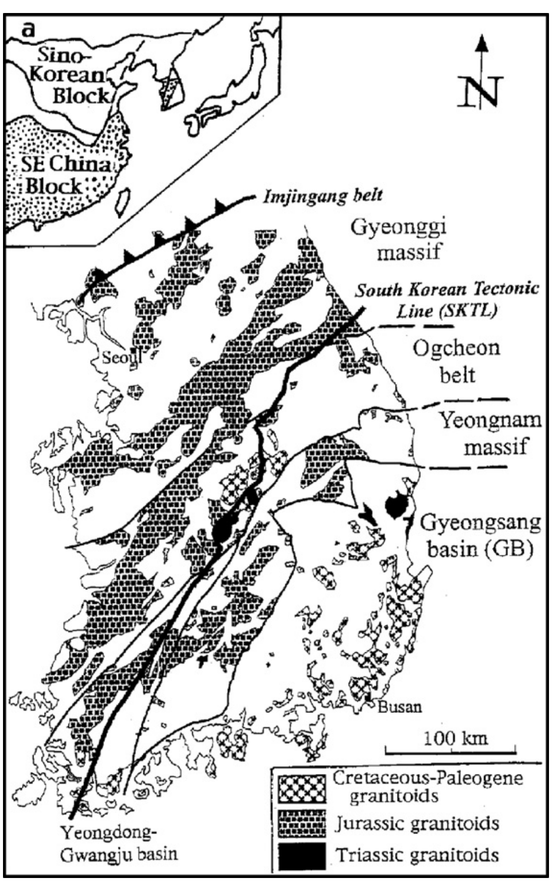

Fig. 6. Phanerozoic granitoids and the tectonic zones of South Korea (adopted from Jwa, 2004).

5.2. Coastal SE China

Cretaceous (or Late Yanshanian) magmatism is widespread along the NNE-trending (1800 km×70 km) coastal belt of Zhejian and Fujian Provinces, SE China, and is bounded to the northwest by the Zhenghe–Dapu left-lateral fault (Fig. 7) and Chengle–Nan'so thrust to the southeast (Chen et al., 2002). The volcanic rocks, abundant in the northern part accumulated up to 2000 m thick, are composed of lava and pyroclastic rocks and subaerial epiclastic deposits. The volcanic rocks include basaltic lavas and ignimbrites implying bimodal volcanism in an extensional tectonic setting during Late Cretaceous (Li, 2002). The Cretaceous granitoids are mostly monzogranite, but include A-type syenogranite (Qiu et al., 2004). The $^{87}Sr/^{86}SrI$ ratios vary from 0.706 to 0.710 (Hong et al., 1998). Weak metallic mineralizations with mainly Pb–Zn veins and some Cu–Mo and Sn deposits are known from this zone (Fig. 7).

Chen et al. (2004) recognized three stages of Cretaceous magmatism in the coastal belt: (1) syn-orogenic (130–110 Ma), (2) post–orogenic (110–99 Ma) and (3) anorogenic (94–81 Ma). They are, therefore, older than the Cretaceous–Paleogene granitoids in the Gyeongsang Basin. The syn-orogenic rocks are composed of high-Al gabbros and gneissic tonalite, trondhjemite and granodiorite (TTG) belonging to medium-K calc–alkaline series with high Sr/Y ratios (adakitic), and are considered to have crystallized in the deep basement (18–24 km based on hornblende geobarometry; Chen et al., 2004). On the contrary, the post- and anorogenic granites are mainly high-K calc–alkaline to shoshonitic with low Sr/Y ratios and are emplaced at shallow levels (6–8 km). High-Al gabbro and TTG magmas were probably generated by dehydration melting of amphibolites, which was formed by thickening of the

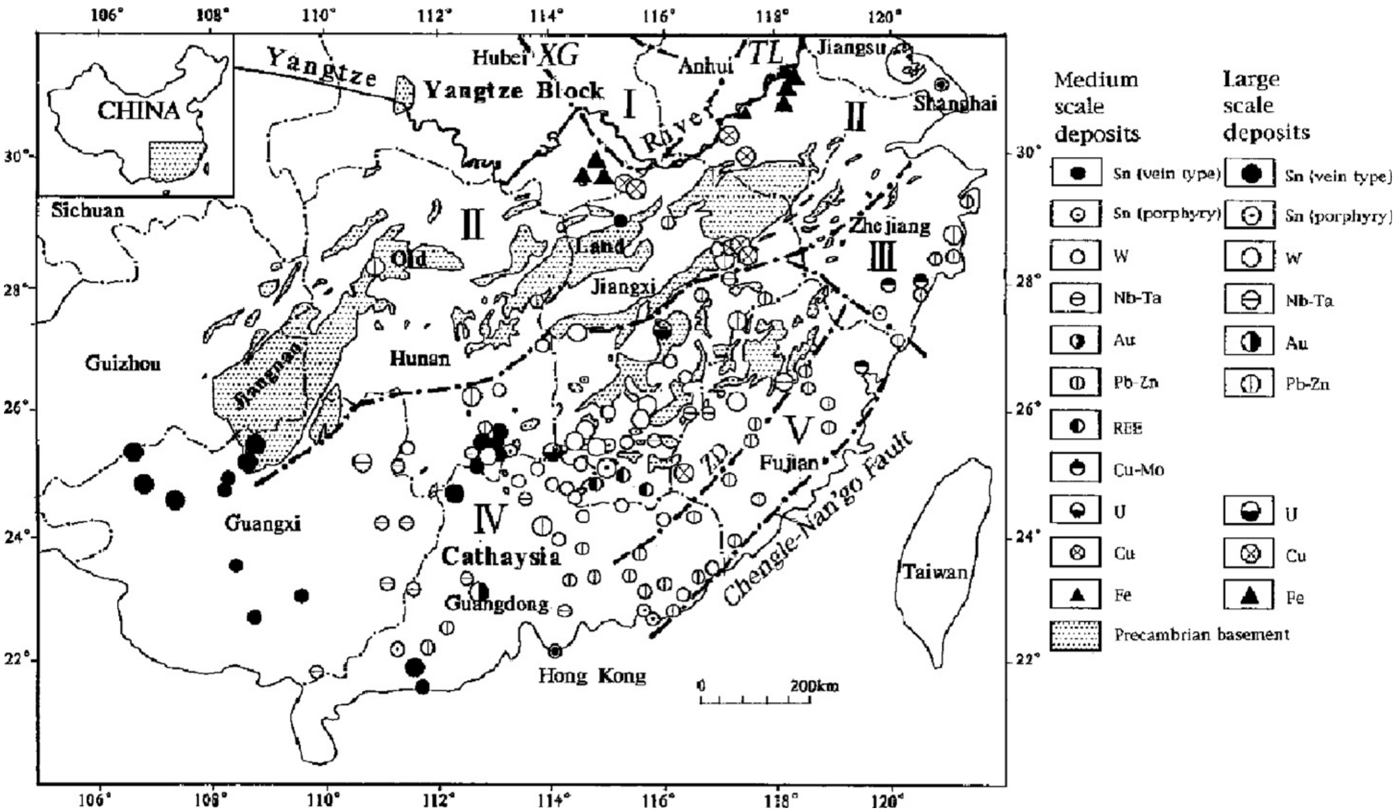

Fig. 7. Precambrian basement, tectonic division and ore deposits of SE China (modified from Hong et al. (1998) and Chen and Jahn (1998)). XG, Xiangfan–Guangji fault; TL, Tanchang–Lujiang fault, ZD, Zehnghe–Dapu fault; I Dabie terrain; II, Yangtze block, III, East Zhejiang volcanic terrain, IV, Cathaysia Interior; V, East Fujian.

lithosphere. Progressive depletion of Ba, Sr, Eu and P from post- to anorogenic granites is interpreted as partial melting of felsic granulites from hydrous to dry conditions (Chen et al., 2004).

Redox state of these granitoids has not been studied in detail, but reconnaissance field measurement by magnetic susceptibility meter by the author in the Fuzhou area indicated high values of magnetic susceptibility. Mineral separate data indicate that most of the major granitoids in the Fuzhou and Suzhou areas contain more than 1000 ppm of magnetite and the Quiqi miarolitic granite contains additional hematite (Hong, 1988; Granite Research Group of Nanling Region, 1989; Zhang et al., 1988), which may have formed during the subsolidus stage. All the granitoids here belong to magnetite series and formed above nickel–nickel oxide (NNO) buffer, but the latest anorogenic Quiqi granite intruded into higher levels and crystallized nearly at the hematite–magnetite (HM) buffer.

5.3. Cretaceous magnetite series in the Lower Yangtze Block

Cretaceous oxidized magmatism occurs in small scale along the lower Yangtze River north of the Jiangnan old land, and is associated with strong magnetite and copper skarn and strata bound mineralization (Fig. 7). High-K diorites are often associated with oxidized Cu, Fe, Au and Mo skarn and porphyry deposits (Zhou, 2005), while high-Na diorites and subvolcanic rocks are related to magnetite skarn deposits (e.g., Ningwu basin, Ishihara et al., 1986). The basement rocks are composed of Proterozoic metamorphic and igneous rocks, which are overlain by Paleozoic marine sedimentary rocks. The Paleozoic rocks have undergone to Caledonian and Hercynian deformation and are covered by Triassic continental sediments including evaporites.

Late–Middle Triassic continental collision led to suturing of the Yangtze Block and Sino-Korean Craton along the Xiangfan–Guangji and Tanglu Faults. After the collision, sedimentary and volcanic basins and centers were developed at the intersection of the NE–SW and E–W-trending faults during Jurassic–Cretaceous, and intruded by many small (~0.2 km^2) plutonic bodies (230 localities) (Zhou, 2005). They have a wide range of composition including gabbro, diorite, quartz diorite, granodiorite, granite, monzonite, syenite, quartz monzonite and quartz syenite, with the SiO_2 contents varying from 48% to 67%. The total alkali contents are high, falling in the shoshonite to high-K series. Their magnetic susceptibility is very high ranging from 23 to 73×10^{-3} SI on unaltered samples from the Ningwu basin (Ishihara et al., 1986).

Hong et al. (1998) summarized $^{87}Sr/^{86}Sr\mathit{I}$ ratios of these plutonic rocks, and found that they mostly fall in the range of 0.706 and 0.708, which is one of the lowest for the southern China granitoids. Ishihara et al. (1986) indicated a time difference, with an early cycle of orthopyroxene-bearing microdiorite with $^{87}Sr/^{86}Sr\mathit{I}$ of 0.7055–0.7056, and a later cycle of pyroxene-bearing hornblende–biotite granodiorite and phonolite with $^{87}Sr/^{86}SrI$ of 0.7062–0.7056. Whole rock $\delta^{18}O$ values of these plutonic rocks vary from +6.4‰ to +8.5‰. These rocks may have originated from mafic lower crust within an extensional tectonic setting.

6. Continental interior ilmenite series

A great majority of the Phanerozoic granitoids in Korea and China is Jurassic in age. They intrude into all the basement units including, from south to north, South China Fold Belt (Cathaysia), Sino-Korean Paraplatform, and Songliao–Xing'an Blocks (Fig. 9). The granitoids in SE China are traditionally divided into transformation type and syntexis type (Zhu, 1998). The syntexis type is best seen in the lower Yangtze River region. The transformation type, which is the major granitic activity in the Nanling Range, is considered as late- and post-tectonic magmatism of the Indosinian orogeny (250–230 Ma; Hua et al., 2005).

6.1. South Korea

The Korean Peninsula, occupying the eastern part of the Sino-Korean Paraplatform, Triassic granitoids occur as small plutons (Fig. 6), while the Jurassic granitoids occur abundantly as batholiths and stocks in the NE-trending Gyeonggi massif, Ogcheon belt and Yeongnam massif (Fig. 6). These granitoids were formed after the collision along the Permo-Triassic Imjingan suture (Yin and Nie, 1993). They are mostly granodiorite to biotite- and/or two mica-granites and are divided into foliated and non-foliated granitoids. The former occurs mostly around ductile shear zones in the Yeongnam massif and the Ogcheon belt and is pre- or syn-tectonic relative to the shearing events (Sagong and Kwon, 2005). Molar $Al_2O_3/CaO+Na_2O+K_2O$ (A/CNK) ratio of the Triassic granitoids are lower than 1.1, while those of the Jurassic and Cretaceous granitoids straddle over 1.05 (Jwa, 2004).

The Jurassic granitoids are generally classified as ilmenite series based on magnetic susceptibility measurements (Jin et al., 2001). Rare magnetite-series granitoids have been observed in small bodies north of Seoul. The Jecheon pluton of the Ogcheon belt also belongs to this series. The Jecheon granite is the first occurrence of biotite granite with pink K–feldspar having adakitic chemistry in the western Pacific rim, and its origin could be explained by recycling of older granitic and metamorphic rocks, which are now seen in the Hidakabelt of central Japan (Ishihara et al., 2005).

In spite of the general ilmenite-series character, the Jurassic granitoids have positive $\delta^{34}S$ values (ca +5‰) as determined from rock-forming sulfides (Ishihara et al., 2000); these values corresponding to those of the magnetite series in the Japanese Islands. Assimilation of sulfate sulfur contained in Paleozoic carbonates of the upper crust was proposed to explain the ^{34}S enrichment of these granitoids (Ishihara et al., 2002). The whole rock $\delta^{18}O$ values of the Jurassic granitoids vary from +7.1 to +10.0‰ (average +8.2‰, $n=20$), which is 1.2‰ higher than that of the Cretaceous granitoids (Kim et al., 1992), and are lower than that (+8.6‰ to +12.0‰) of the Jecheon pluton (Ishihara et al., 2005). Thus, some amount of sedimentary component appears to be included in the Jecheon granitoids.

Triassic granitoids occur as deep-seated stocks in restricted areas of the Ogcheon belt, the Yeongnam massif and the Gyeongsang basin (Fig. 6). They are mostly medium to coarse-grained equigranular hornblende–biotite granodiorite with some K–feldspar megacrysts. They may not be saturated with Zr and shows similarities to high temperature I-type granitoids (Jwa, 2004).

Based on ε_{Nd} and $^{87}Sr/^{86}SrI$ geochemistry, Jwa (2004) proposed a multi-source and mixing model for the genesis of these granitoids. The mantle–crust mixing model could account for the source of the Triassic and Cretaceous granitoids in the Gyeongsang basin, the less enriched Jurassic granitoids in the Yeongnam massif and the Cretaceous granitoids in the Yeongdon–Gwangju basin, whereas the crust/crust mixing produced the more enriched source magmas for the Triassic and the Jurassic granitoids in the Yeongnam massif, the Jurassic granitoids in the Gyeonggi massif and more enriched Cretaceous granitoids in the Yeongdon–Gwangju basin and in the Ogcheon belt.

6.2. Southeast China

Jurassic (or early Yanshanian) granitoids are most widely distributed in SE China (Fig. 8). They intrude into the Precambrian basement (Fig. 7), but mostly into the deformed Paleozoic sedimentary rocks. The Phanerozoic granitic activity is generally classified into early Paleozoic, late Paleozoic, Triassic, Jurassic and Cretaceous. These Phanerozoic granitoids are all monzogranitic based on their average modal plagioclase–K–feldspar–quartz ratios of Nanjing Univ. (1980).

Mo et al. (1980) summarized petrography of 122 Jurassic granitic plutons, and found that the average compositions are granodiorite (14 bodies), biotite monzogranite (100 bodies) and muscovite–biotite syenogranite (5 bodies), and albitized syenogranite (3 bodies). As a whole, the Jurassic granitoids are extremely high in SiO_2 contents (Series I; Fig. 3). Hua et al. (2003) classified the Yanshanian granitoids into S type and Li–F granite. They further subdivided them chronologically into early Yanshanian (ca. 185–170 Ma), middle Yanshanian (150–140 Ma) and late Yanshanian (140–65 Ma).

The early Yanshanian stage includes four types of magmatism: basalt, bimodal volcanics, A-type granite and intraplate high-K calc–alkaline rocks, which are associated with local Pb–Zn, Cu and Au mineralizations. The magmatism is probably caused by extensional thinning of the upper lithosphere and upwelling of mantle materials (Hua et al., 2003). The lithosphere thinning may have accelerated during the middle Yanshanian stage (170–140 Ma), which caused the greatest amount of crustal remelting granitoids in the Nanling Range. The most important lithophile element ore deposits, including W, Sn, Nb–Ta, Bi and Be were formed at the end of this stage. The late Yanshanian stage (140–65 Ma) was characterized by a complete breakup of the lithosphere of SE China, which supplied basaltic mantle materials (Hua et al., 2005).

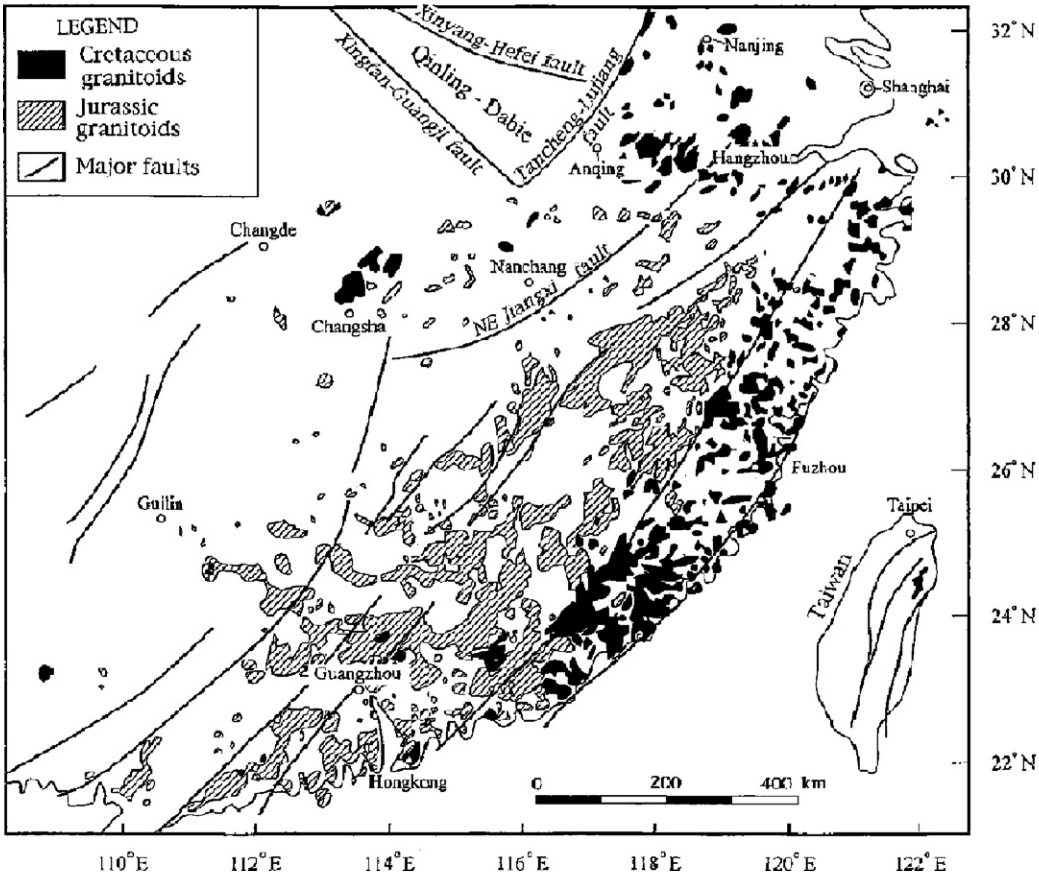

Fig. 8. Distribution of Jurassic and Cretaceous granitoids and major faults in SE China (modified from Li, 2002).

The occurrence of the world famous W(–Sn) deposits (Fig. 7), implies that the middle Yanshanian granitoids are mostly reduced type, substantiating an early reconnaissance measurement of magnetic susceptibility ($0.08–0.10 \times 10^{-6}$ emu/g, Ishihara et al., 1986; Ishihara, unpublished data). Re-examination of published Fe_2O_3 and FeO data of the bulk chemistry showed general low Fe_2O_3/FeO ratios (<0.5) but local oxidized values, and revealed no clear regional variations following NE–SW lineaments (Ishihara and Wang, 1999). Ye et al. (1998), however, reported magnetite-series granites and associated Dexing–Wuyuan porphyry-Cu deposits on the NW side of the NE Jiangxi deep fault (Fig. 8), and magnetite-free, ilmenite-series granites on the SE side of the fault.

The Jurassic granitoids appear to belong to ilmenite series, but rock-forming magnetite has been sometimes reported. Mo et al. (1980) gave an average of 4264 ppm (from 8 plutons) of magnetite for the latest Jurassic granitoids, which may correspond to the few oxidized spots observed on regional analysis of the bulk chemistry (Ishihara and Wang, 1999). Evaluation of redox state of individual plutons is a future task in SE China.

In summarizing the isotopic data, Hong et al. (1998) divided the SE China granitoids into six zones. The most interior of the Hunan–Guangxi intracontinental zone, which includes the western part of Zone IV (Fig.7), is characterized by the highest $^{87}Sr/^{86}Sr$ ratios (>0.720) and $\delta^{18}O$ values (+10‰ to +13‰) of the early Paleozoic to Mesozoic granites, including the Permo-Triassic cordierite-bearing monzogranite. Together with Nd and O isotope data (Hong et al., 1998), the source for these granitoids is considered to be largely continental crust underneath these granites.

The northeastern side of this zone, referred as the Hunan–Jiangxi–Guangdong transitional zone, is the main part of the Jurassic granitoids region. The Phanerozoic granites of the Zone IV (Fig. 7) have $\delta^{18}O$ values of +9‰ to +12‰ and $^{87}Sr/^{86}Sr I$ ratios between 0.720 and 0.708. Their T_{DM} (Nd depleted mantle model age) is greater than 1.8 Ga and are similar to the ages of the metamorphic basement and of inherited zircon in the granites. The granites are considered generated by partial melting of the continental crust (Hong et al., 1998).

6.3. Northeast China

Phanerozoic granitoids occur also to the north of the Sino-Korean Paraplatform, in the Songliao–Xing'an Blocks, which is a part of the Central Asian Orogenic Belt (CAOB, Jahn, 2004), and occupy 50–80% of northeast China (Fig. 9). The basement rocks below the Songliao basin are also composed of granitoids and deformed sedimentary rocks (Wu et al., 2000). Most of these granitoids were traditionally regarded as late Paleozoic ("Hercynian") in age, but recent age determinations have shown younger, mostly Jurassic and Cretaceous ages (Wu et al., 2000,

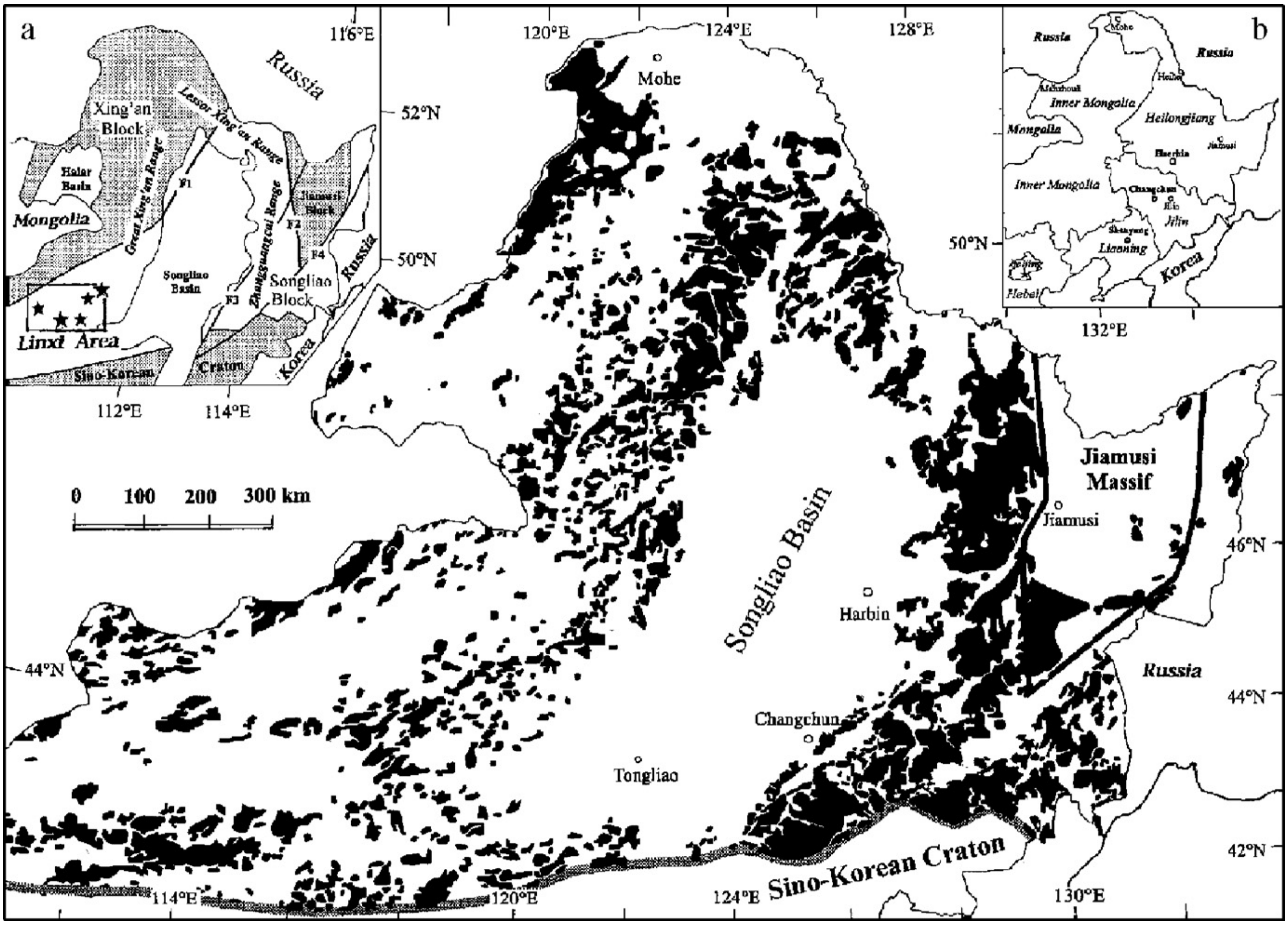

Fig. 9. Geotectonic units and distribution of the Phanerozoic granitoids in NE China (Wu et al., 2000). F1, F2, F3 and F4 represent Nenjiang, Mudanjiang, Jiavi and Dunmi Faults, respectively.

2005), implying wide occurrence of similar age granitic magmatism from SW Japan to NE China through South Korea and North Korea.

Jurassic with minor Triassic granitoids extend widely (ca. 100,000 km^2) in the Songliao Block (Fig. 9) and are composed of granodiorite (minor), monzogranite, syenogranite and K–feldspar granite. Mafic enclaves are rare. Many plutons contain abundant miarolitic cavities and banding of biotite, indicating a high level of intrusion. They can be considered highly fractionated. Arfvedsonite and aegirine–augite are only found in the late alkaline granites (Wu et al., 2000). Cretaceous granitoids of the Songliao Block are also felsic, including granodiorite, monzogranite, syenite and peralkaline granites.

In the Liaodong Peninsula, the Jurassic granitoids (180–153 Ma) are more calcic, consisting of hornblende–biotite tonalite–granodiorite and two-mica monzogranite that have undergone regional ductile deformation. The Cretaceous granitoids, distributed more widely than the Jurassic ones, are undeformed. They consist of a variety of granitoids from granodiorite, monzogranite or syenogranite, K–feldspar granite to alkaline granite (Wu et al., 2005).

The Mesozoic granitoids of NE China appear to have granitic average compositions and are characterized by abundant alkali granites. Reconnaissance measurement of magnetic susceptibility on 98 samples and re-examination of Fe_2O_3/FeO on 88 bulk analyses from the late Paleozoic to Cretaceous granitoids reported in HBGMR (1993) indicate that the granitoids are of the oxidized type rather than the reduced type, although further studies on the opaque mineralogy are required.

The most striking feature discovered in the recent studies in this region is the juvenile nature of the granitoids shown by Sr–Nd isotopes. Leucotonalite similar to those of the Izu–Bonin area has been found (Jahn et al., 2001). Fig. 10 indicates that the most of the granitoids have low $^{87}Sr/^{86}Sr\,I$ ratios (0.705 ± 0.001), positive ε_{Nd} (T) values (+4 to 0) and fairly young T_{DM} model ages (500 to 1300 Ma). Such isotopic features are quite different from those occurring in SE China. Wu et al. (2002) interpret that the granitoids were probably derived by remelting of portions of the juvenile continental crust by basaltic magmas from the upper mantle.

However, to the west of the Songliao basin in the southern part of the Great Xing'an Range of the Inner Mongolia, tin and tin–polymetallic vein deposits occur widely in the Linxi area (Akiyama and Sun, 2001, see insert map a of Fig. 9), which are related to ilmenite-series granitoids (Wang et al., 2001). The K–

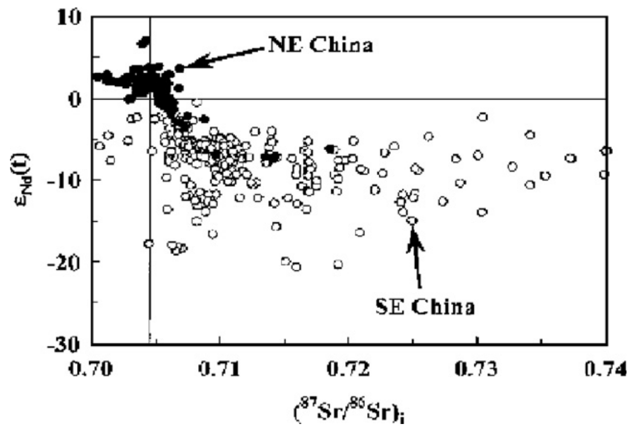

Fig. 10. Sr–Nd isotopic comparison of granites between NE and SE China (Wu et al., 2002).

Ar, Rb–Sr and U–Pb ages of altered minerals are Early Cretaceous varying from 140 to 131 Ma. Tin is a typical recycling element originating from the felsic continental crust. Therefore a variety of granitic magmas may be expected in the Songliao–Xing'an Block, and we need further work on these granitoids.

7. Concluding remarks

The Cenozoic–Mesozoic granitoids of East Asia are reviewed from recent works. They are classified based on their redox state (magnetite/ilmenite series) and bulk composition (granodioritic/granitic). The granodioritic magnetite series occurs in the back-arc side of island arcs (e.g., Greentuff and Kitakami Belts) and intercontinental rupture zones (e.g., Lower Yangtze Block). Here, gabbroic and dioritic rocks occur together with granitoids. This magmatism, forming the root zone for the island-arc andesitic volcanism, is intrinsically an oxidized type due probably to sea-floor alteration of the subducted oceanic plate. Lower crust of these rupture zones might have collapsed by overlying crust delamination, and mafic magmas provided directly from the upper mantle then mingled with crust-generated felsic magmas. This type is lowest in the $\delta^{18}O$ values and $^{87}Sr/^{86}SrI$ ratios (Fig. 11), because of primitive, young igneous source rocks.

The granitic magnetite series occur in ruptured zones along continental margins (e.g., Gyeongsang basin and coastal SE China), and back-arc of island arcs (Sanin Belt). Again mafic magmas were brought up from the upper mantle, but their main role would be providing heat to generate the granitic magmas within continental crust, thus forming abundant felsic magmas. The generated granitic magmas had little interaction with C- and S-bearing reducing materials, due probably to extensional tectonic settings. The nature of the crustal materials, igneous vs. sedimentary, etc is also important in the redox state of the generated magmas (Sato et al., 2004). The $\delta^{18}O$ value gives narrow ranges but the $^{87}Sr/^{86}SrI$ ratio varies greatly depending upon the age and Rb content of the continental crust (Fig. 11).

In order to have the ilmenite-series granitic magmas, involvement of sedimentary rocks is necessary to account for high $\delta^{18}O$ ratios. The involvement through subduction processes (Tatsumi, 2001; Takagi, 2004) may be possible, but magma mingling and assimilation of the C- and S-bearing sediments must have occurred not in the subduction zone but within the crust for the tectonic settings of the ilmenite-series granitoids. They tend to occur in the granitic belts of

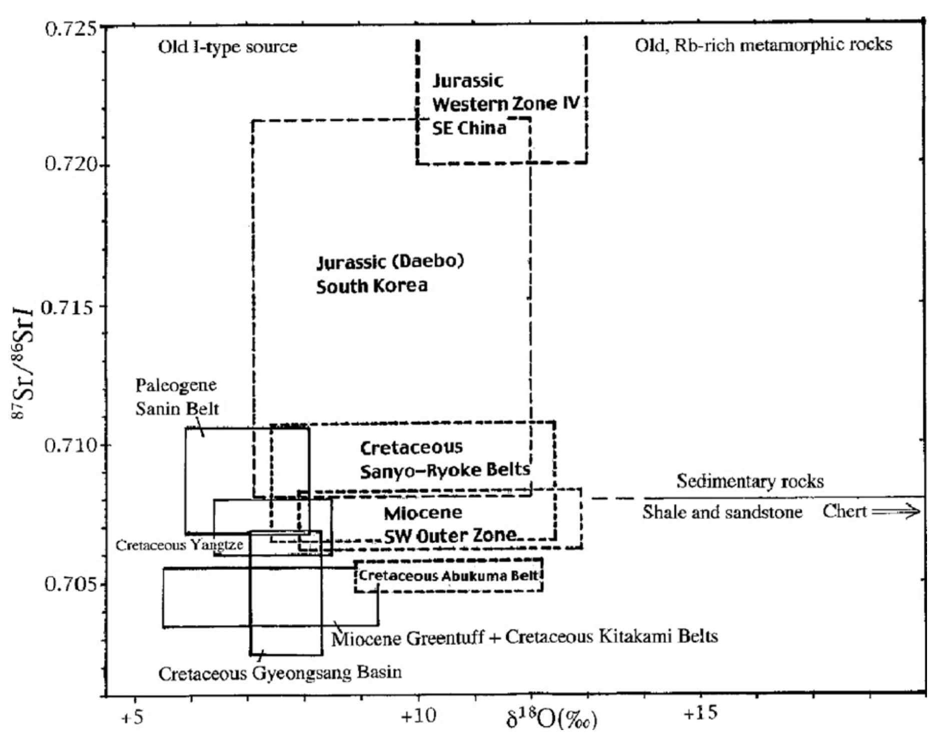

Fig. 11. $\delta^{18}O$ values vs. $^{87}Sr/^{86}SrI$ ratios of the Mesozoic and Cenozoic granitoids in East Asia. Solid boxes, magnetite series; Broke line boxes with gothic letter, ilmenite series. See text for source of the data.

accretionary sedimentary terrains, where the magmas were forced to interact with the accreted sediments due to compressional tectonic setting. Those generated in young island arcs (e.g., Abukuma and Hidaka belts), which had much supply of gabbroic magmas from the upper mantle, have low $^{87}Sr/^{86}SrI$ ratios and high $\delta^{18}O$ values (Fig. 11).

Ilmenite-series granitoids in the continental interiors are characterized by high $^{87}Sr/^{86}SrI$ ratios, implying that the continental crust is composed of old felsic metamorphic and granitic rocks. The mantle heat provided by crust delamination heated up the lower and middle continental crust, producing granitic magmas. The chemical composition and redox state of the granitic magmas would be essentially controlled by those of the original protolith in this kind of granitic magmatism.

One of the central questions on the granitic magmatism in East Asia is the wide range of distribution. Recent finding of Cretaceous granitoids in North China implies more than 1500 km wide of the activities from the SW Japan to the Great Hinggan belt, in which different series of Cretaceous granitoids occur with different tectonic backgrounds. This would imply that the characterization of the granitic magmatism was not time-dependent but strongly space-dependent.

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