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Compositional variation of the late Cretaceous–Paleogene plutons from southwest Japan and its implication for ore genesis and continental growth

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ABSTRACT

During the late Cretaceous–Paleogene period, the fluids liberated from the subducting slab along Japanese-arc subduction zone could have triggered the partial melting of the mantle wedge, whose composition was similar to the fertile primitive mantle. Underplating of the produced basaltic magmas beneath the continental crust could further facilitate the partial melting of the lower continental crusts. The primary magmas produced by the mixing of resultant partial melts underwent various degrees of fractional crystallization processes to produce the late Cretaceous–Paleogene plutons in southwest Japan, and have contributed to the growth of continental crust with new, non-recycled materials during the Phanerozoic.

The factor analysis of chemical data from ore-barren Ryoke and W–Sn-ore-rich Sanyo plutonic rocks identifies three major groups of elements: the mafic group (Al, Fe, Mg, Mn, Ca, Sr, Zn, Co, V, P, Cu, Ni, and Cr); the felsic group (Si, K, Rb, Cs, Tl, Pb, Y, Nb, Ta, Hf, Ge, Sn, W, Th, U, and HREE); and the LREE + Zr group (Ba, La, Ce, Pr, Nd, Eu, Zr, and Hf). Mafic group and felsic group elements are inversely correlated. The concentrations of LREE + Zr group elements increase first, then, decrease with increasing SiO_2 content. Therefore, the high silica samples of the Ryoke + Sanyo belts are low in LREE + Zr group elements. In the Ryoke samples Mo behaves like Zr, which results in the lowest Mo content in the Ryoke samples with high silica. The high Mo and Si contents in some Sanyo samples suggest that the zircon-compatible Mo^{4+} may be converted to incompatible Mo^{6+} under a relatively high oxygen fugacity condition at the late stage of magmatic differentiation. W and Sn behave as the felsic group elements in the Ryoke + Sanyo samples. Thus, their concentrations are high in the high silica granitoids, especially rock samples from the Sanyo belt, which are often associated with W–Sn ores. The factor analysis of the Sanin plutonic samples indicates that W still belongs to the felsic group, but Sn no longer correlates with W and behaves more like Zr due to the conversion of incompatible Sn^{2+} to zircon-compatible Sn^{4+} under a relatively high oxygen fugacity condition in the Sanin belt. Therefore, Sn content is low in high silica granitoids from Sanin belt. The high silica Sanin samples are often enriched in Mo, again suggesting the conversion of zircon-compatible Mo^{4+} into incompatible Mo^{6+} in the magmas of those samples. The high Mo granitoids from the Sanin belt are probable source rocks for the associated Mo ores in the area.

1. Introduction

Japanese island arc mainly consists of the late Paleozoic to Cenozoic accretionary complexes, which resulted from the orogens related to the subduction of oceanic crust (Isozaki, 1996; Isozaki et al., 2010). The accretionary complexes contain Precambrian metamorphosed sediments and re-melted crustal materials (Jahn, 2010) and/or other components derived from the partial melts of oceanic crust and upper mantle (Maruyama, 1997; Togashi et al., 2000; Nakajima et al., 2004). The present study focuses on the compositional variation of the late Cretaceous–Paleogene plutons and the related ore formation processes in southwest (SW) Japan.

As shown in Fig. 1, the late Cretaceous–Paleogene plutons from SW Japan (above the Median Tectonic Line) are divided into three major belts: the ore-barren Ryoke belt (110–70 Ma); W–Sn-ore-rich Sanyo belt (110–70 Ma); and Mo-ore-rich Sanin belt (85–30 Ma; Ishihara, 1978). The plutons consist mainly of granite, granodiorite with some quartz diorite, diorite, and gabbro. We loosely call a pluton granitic when $SiO_2 > 52\%$; otherwise, it is considered gabbroic. Plutonic rocks from the Ryoke and Sanyo belts are characterized by their systematically high $\delta^{18}O$ values as compared with those from Sanin belt at a given SiO_2 content (Fig. 2a; data from Ishihara and Matsuhisa, 2002). This is probably an

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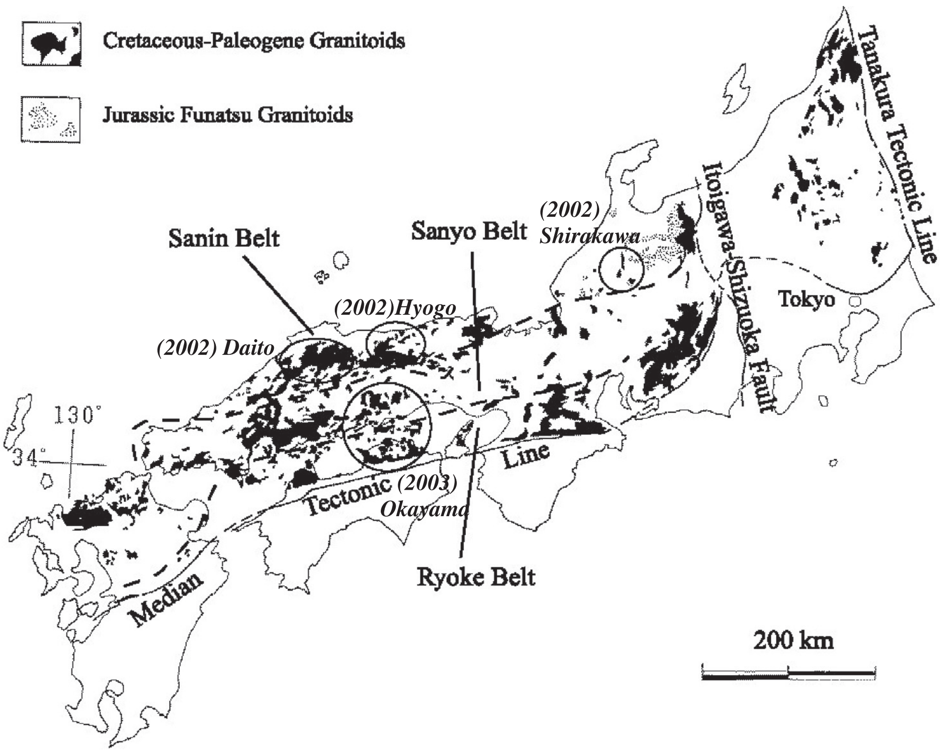

Fig. 1. The areas of Ryoke, Sanyo, and Sanin belts in SW Japan delineated roughly by dashed lines (adopted from Ishihara, 1978).

indication of greater incorporation of continental crust material (with high $\delta^{18}O$ values) for the former than the latter during the formation process of primary magmas. In Fig. 2a, a few samples with very low $\delta^{18}O$ (outside of ovals) may be caused by the exchange with meteoric water. A few Sanin samples fall within the upper oval of Ryoke + Sanyo field and vice versa, indicating some degree of inter-fingering across the belt boundary. The increase in the value of $\delta^{18}O$ with increasing SiO_2 content in each oval may represent the effect of fractional crystallization (removal of mafic minerals with lower $\delta^{18}O$ values causes the residual magma to become higher in $\delta^{18}O$). Sanin samples are mostly high in magnetic susceptibility due to the presence of magnetite ($FeO{\cdot}Fe_2O_3$) and thus are called the magnetite series rocks; Ryoke + Sanyo samples are mostly low in magnetic susceptibility and are called the ilmenite ($FeO{\cdot}TiO_2$) series rocks (Kanaya and Ishihara, 1973; Ishihara, 1977). Sanin rocks were probably formed under higher oxygen fugacity conditions than the Ryoke + Sanyo rocks. The $\delta^{34}S$ values for bulk rocks and sulfide ores from Ryoke + Sanyo belts tend to be more negative (−11‰ to +3‰), while those from Sanin belt are more positive (−2‰ to +10‰; Sasaki and Ishihara, 1979; Ishihara and Sasaki, 2002). The low oxygen fugacity and low $\delta^{34}S$ in Ryoke + Sanyo belts may result from the incorporation of some isotopically light biogenic sulfur and carbon from source rocks of sedimentary origin into their primary magmas (Ishihara and Sasaki, 2002).

The Sr and Nd isotopic ratios for rock samples are often expressed in the initial $^{87}Sr/^{86}Sr$ ratio (I_{Sr}) and the initial $^{143}Nd/^{144}Nd$ ratio (I_{Nd}) at the time of sample formation, and the epsilon notations of ε_{Sr} and ε_{Sr}. For example,

$$I_{Sr} = (^{87}Sr/^{86}Sr)_t = (^{87}Sr/^{86}Sr)_p - (^{87}Rb/^{86}Sr)_p[\exp(\lambda t) - 1]$$

and $\varepsilon_{Sr} = [(^{87}Sr/^{86}Sr)_t/(^{87}Sr/^{86}Sr)_{CHUR,t} - 1] \times 10^4$

Here, t represents the age of sample; p is the present (i.e. $t = 0$); and λ is the decay constant of $^{87}Rb = 1.42 \times 10^{-11}$ year^{-1}. The reference material CHUR is the Chondritic Uniform Reservoir (Faure and Mensing, 2005). For I_{Nd} and ε_{Nd}, one just replaces $^{87}Sr/^{86}Sr$ with $^{143}Nd/^{144}Nd$, $^{87}Rb/^{86}Sr$ with $^{147}Sm/^{144}Nd$ in the above equations, and λ for $^{147}Sm = 6.54 \times 10^{-12}$ year^{-1}.

As shown by Kagami et al. (1992), the majority of the Ryoke + Sanyo samples have narrow ranges in their initial ε_{Sr} and ε_{Nd} values, and those values are almost constant as SiO_2 content increases (the oval RS in Fig. 2b and d), although their formation age varies from 72 to 93 Ma. The implication is that plutonic rocks from the Ryoke + Sanyo belts might evolve from primary magmas that were produced at different times and places from the upper mantle whose composition is rather uniform with regard to $\delta^{18}O$, ε_{Sr}, and ε_{Nd} values in SW Japan. During magmatic differentiation, ε_{Sr}, and ε_{Nd} values stay more or less constant, while $\delta^{18}O$ increases with SiO_2 content through fractional crystallization (Fig. 2a and d). It is hard to produce these features by a simple two-end-member mixing of gabbroic magma (high in ε_{Nd} and low in ε_{Sr} and $\delta^{18}O$) and granitic melt (low in ε_{Nd} and high in ε_{Sr} and $\delta^{18}O$). Nakajima et al. (2004) confirmed that the ε_{Sr} values are near constant (mostly 40–50) as SiO_2 content increases (similar to Fig. 2b) for additional Ryoke plutonic samples (71–86 Ma), including gabbroic cumulates and dykes/pillows, and granites. The close spatial and temporal association of gabbroic and granitic plutons from Ryoke belt points to the importance of magmatic differentiation for their genesis (Nakajima et al., 2004).

The Sanin belt has two distinct primary magmas (the ovals S1 and S2 in Fig. 2b and d). Again, the respective ε_{Sr} and ε_{Nd} values for S1 and S2 are near constant as SiO_2 content increases, suggesting the independent magmatic differentiation for S1 and S2 groups. The formation ages of S1 are around 65 Ma; and of S2 65–75 Ma (Kagami et al. (1992). The ε_{Sr} and ε_{Nd} values for the Sanin rocks, especially the S1 samples, are close to those of the CHUR (Fig. 2c). Samples 26–30 (following the sample assignment by Kagami et al., 1992) are in the transition zone (the oval T in