“Petrogenesis of post-orogenic syenites in the Sulu Orogenic Belt, east China: Geochronological, geochemical and Nd–Sr isotopic evidence” – Reply

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The Jiazishan alkaline complex is located in the Sulu Orogenic Belt, eastern China (Fig. 1). On the basis of detailed geochemical and Sr–Nd isotopic analyses we concluded that the Late Triassic (215–200 Ma) Jiazishan rocks were generated from a mafic magma derived from metasomatized lithospheric mantle – the subducted Yangtze lithosphere (Yang et al., 2005a). Following Bonin (1990) and Bonin et al. (1998), we also suggested that the Jiazishan intrusive suite belongs to the post-orogenic group of alkaline rocks. This represents a geodynamic transition from convergence to extension, and was the result of convective removal of the lower lithospheric mantle (Yang et al., 2005a). Xie et al. (2006) disagree with our conclusions and argue that (1) the source of the Jiazishan complex is not the subducted Yangtze plate, but the overlying North China plate and

(2) the Jiazishan pluton is a break-off related complex, and not a post-orogenic syenite in the common meaning of that term. Their comment provides us with an opportunity to further discuss the source and the geodynamic setting of the Jiazishan complex, to carefully review more recent literature regarding the collision between the North China (NCC) and Yangtze (YC) cratons and the exhumation of the Ultrahigh-Pressure Metamorphic (UHPM) rocks that resulted from this, and to re-examine geochemical and isotopic data of Phanerozoic mafic rocks in the NCC and YC that can be used to constrain the nature of the subcontinental lithospheric mantle beneath the Sulu Orogenic Belt.

In their comment, Xie et al. (2006) suggest that in the Late Mesozoic (160–120 Ma), lithospheric mantle domains beneath the NCC and YC have EM1- and EM2-type Sr–Nd–Pb isotopic compositions, respectively. They selectively emphasize that the Pb isotopic compositions of the Jiazishan complex are similar to those of Early Cretaceous mafic rocks from the NCC, but different from those of Early Cretaceous mafic rocks

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Fig. 1. Location maps showing position of the Jiazishan Complex in eastern China: (a) relation to the Dabie–Sulu ultrahigh pressure metamorphic belt and (b) position within the Jiaodong Peninsula.

from the YC, and thus conclude that the parental magma was derived from a NCC lithospheric mantle source. In fact, there are complications in Pb isotopic compositions between the Early Cretaceous mafic rocks from the NCC and YC (Fig. 2), and a key question we would like to address here is when and how the Pb-isotopic variations between the NCC and YC lithospheric mantle were formed.

Xie et al. (2006) attribute the more radiogenic Pb isotopic ratios (e.g., $^{206}\text{Pb}/^{204}\text{Pb}$ up to 17.59) observed in the Early Cretaceous Fangcheng basalts (Fig. 2) which erupted along the southern margin of the NCC (Zhang et al., 2002) to the involvement of subducted

Yangtze lithosphere. If this is the case, there should be a progressive westward change in Pb isotopic compositions for the Early Cretaceous mafic rocks emplaced in regions extending from the Sulu Orogenic Belt to the NCC. However, no such variation is observed. Early Cretaceous mafic dikes from the Jiaodong Peninsula have EM2-type geochemical and Sr and Nd isotopic compositions (Yang et al., 2004, 2005b; Guo et al., 2004) that are comparable to the Fangcheng basalts. Yang et al. (2004) proposed that the Jiaodong mafic dikes were derived from a vein-plus-peridotite source, while Guo et al. (2004) interpreted the source to be subducted lithospheric

Fig. 2. Pb isotopic ratios of the Jiazishan alkaline rocks, compared with those of Early Cretaceous basalts and mafic rocks from the North China and Yangtze cratons, Jiaodong Peninsula and Dabie Orogenic Belt, and those of Cenozoic basalts from the North China Craton. Data for Jiazishan rocks are from Xie et al. (2006); Fangcheng basalts are from Zhang et al. (2002); Taihangshan and Jinan gabbros are from Zhang et al. (2004); Yangtze mafic rocks are from Yan et al. (2003); Jiaodong mafic dikes are from Yang et al. (2004); Dabie mafic rocks are from Huang et al. (2003); Cenozoic basalts from Chung (1999, and references therein).

mantle. $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic ratios of these Jiaodong dikes increase from 16.74–17.21 to 17.06–17.44, and then to 17.48–18.03, changing with distance away from the Sulu Orogenic Belt (Fig. 1b). In addition, the high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (max. 18.03) overlap with those of the asthenosphere- or juvenile lithospheric mantle-derived Cenozoic basalts emplaced in the NCC (Fig. 2). Thus, Yang et al. (2004) suggested that the Pb-isotopic differences observed in the NCC Early Cretaceous mafic rocks are not related to the subducted Yangtze lithosphere, but result from the contribution made by the ascended asthenospheric mantle following Late Mesozoic lithospheric thinning (200–120 Ma).

In addition, Xie et al. (2006) argue that the Early Cretaceous basalts and mafic rocks from the Dabie terrain and YC have EM2-like Sr and Nd isotopic compositions, due also to involvement of the subducted Yangtze lithosphere. However, Pb isotopic compositions of the Dabie mafic rocks show EM1-like isotopic signatures ($^{206}\text{Pb}/^{204}\text{Pb}$ up to 16.97, Huang et al., 2003) (Fig. 2), much lower than those of subducted Yangtze materials ($^{206}\text{Pb}/^{204}\text{Pb} > 17.50$) proposed by Xie et al. (2006). Huang et al. (2003) interpreted these mafic rocks as resulting from interaction between depleted asthenosphere- and old enriched lithospheric mantle-derived magmas and the lower crust, owing to delamination of

lithosphere and resultant magma underplating following the NCC–YC collision.

Therefore, we suggest that the variation in Pb isotopic compositions of the Early Cretaceous mafic rocks between the NCC and YC is not due to the involvement of subducted Yangtze lithosphere, but essentially caused by upwelling of asthenospheric mantle following delamination of lower crustal materials during the Late Triassic (<200 Ma) and Early Cretaceous (~120 Ma) (Gao et al., 2004). Studies have repeatedly shown that the lithospheric mantle domains beneath the eastern North China and Yangtze cratons have been largely destroyed and/or replaced, with most of them being removed in the Late Mesozoic (NCC: Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Zhang et al., 2002; Yang et al., 2003; Wilde et al., 2003; Wu et al., 2003; Gao et al., 2004; YC: Xu et al., 2000; Zhou and Li, 2000; Xu et al., 2002). Thus, we conclude that the differences in Pb isotopic compositions of Early Cretaceous mafic rocks and basalts cannot be used to constrain the source of the earlier Late Triassic alkaline rocks.

As the asthenospheric mantle has a more radiogenic Pb isotopic composition (Zindler and Hart, 1986), the pre-Late Triassic lithospheric mantle domains beneath the NCC and YC should have had less radiogenic Pb

isotopic ratios before being affected by Late Mesozoic mantle metasomatism. This is evidenced by the Paleozoic kimberlites and lamproites from the YC, which have enriched Sr and Nd isotopic compositions (Zhang et al., 2001) that indicates an ancient lithospheric mantle with less radiogenic Pb isotopes beneath the YC. In addition, zircon U–Pb dating studies suggest that the Dabie–Sulu UHPM eclogites have ancient protolith ages from Archean to Neoproterozoic (Zheng et al., 2003, and references therein). Therefore, it is reasonable to obtain low Pb isotopic ratios from the ancient subducted lithospheric mantle in the Jiazishan complex.

Xie et al. (2006) argue that the Jiazishan alkaline complex is a break-off related complex, but is not post-orogenic in the common meaning of this term; they also favor the usage of a term “syn-exhumation” magmatism as proposed by Zheng et al. (2003). We do not wish to discuss such terms in this paper, since playing with semantics adds nothing to understanding the true nature of the processes involved. Instead, we prefer to follow Bonin who has already discussed these issues in detail. Bonin (1990) and Bonin et al. (1998) proposed that alkaline granitoids post-dating a major orogenic episode can be divided into two groups, i.e., post-orogenic (PO) and anorogenic (EA) granitoids (Bonin, 1990). The former group is characterized by Mg/Mn-rich mafic minerals, high Ba and Sr abundances and crustal Sr isotopic signatures, whereas the latter are characterized by Fe-rich mafic mineral assemblages, low Ba and Sr abundances and lower Sr isotopic ratios. The overall geochemical features of the Jiazishan intrusive suite (Yang et al., 2005a) are similar to those of the former group. In addition, the age of the Jiazishan magmatism (215–200 Ma) apparently post-dates the UHPM event from 244 to 226 Ma (Liu et al., 2004; Wan et al., 2005) that constrains the timing of the continental collision between the NCC and YC.

Geochronology of the UHPM and their country rocks identifies three stages of exhumation of the deeply-subducted slab: (1) initial rapid uplift and cooling subsequent to the peak UHPM event (240–220 Ma), (2) slow uplift and cooling (220–200 Ma), and (3) rapid uplift and cooling (190–175 Ma) (Li et al., 2000). Recently, detailed zircon and monazite SHRIMP U–Pb dating and inferred P–T paths of metamorphic rocks show that the UHPM occurred between 244 and 226 Ma, followed by retrogressive metamorphism (221–218 Ma) during exhumation to at least mid-crustal level (Liu et al., 2004; Wan et al., 2005). All these data indicate that the protoliths of the UHPM rocks were subducted to mantle depths in the Early–Middle Triassic (before ~226 Ma) and rapidly exhumed to mid-crustal

levels by ~218 Ma. The ‘slab break-off’ model is commonly used to explain the initial stage of rapid exhumation of the UHPM rocks (at about 244–226 Ma), as proposed by Davies and von Blanckenburg (1995) and Ernst and Liou (1995).

In the slab break-off model, resultant upwelling of the asthenosphere may heat up the overlying lithosphere and lead to melting of the metasomatized and hydrated portions of the lithospheric mantle, which would result in alkaline to ultrapotassic magmas by small degrees of melting or calc–alkaline magmas by larger degrees of melting (Davies and von Blanckenburg, 1995). This, moreover, requires the break-off to occur at shallow depths, thus causing significant thermal perturbation capable of melting metasomatized/hydrated peridotite that has a solidus temperature of ~1100 °C at 80 km depth (Davies and von Blanckenburg, 1995). In the Sulu Orogenic Belt, where continental subduction went down to >200 km (Ye et al., 2000), slab break-off occurring at such great depth would have led to negligible thermal perturbation in the overriding lithosphere and hence no magmatism (Davies and von Blanckenburg, 1995). We emphasize again that zircon SHRIMP U–Pb and mineral $^{40}\text{Ar}/^{39}\text{Ar}$ age data (Yang et al., 2005a; Guo et al., 2005) suggest that the Jiazishan alkaline complex was emplaced at 215–200 Ma, apparently postdating the rapid exhumation of the UHPM rocks (244–226 Ma; Liu et al., 2004; Wan et al., 2005) that best constrains the timing of slab break-off in the region. Furthermore, it seems unlikely that slab break-off would produce only a single point of magmatism, since the Jiazishan complex is acknowledged by Xie et al. (2006) as being the only known alkaline complex that is associated with the collision between the Yangtze and North China cratons.

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