International Geology Review, Vol. 49, 2007, p. 14–29.
Copyright © 2007 by V. H. Winston & Son, Inc. All rights reserved.

Dabieshan UHP Metamorphic Terrane: Sr-Nd-Pb Isotopic Constraint to Pre-metamorphic Subduction Polarity

BOR-MING JAHN[1]

Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei 11529, Taiwan

AND BIN CHEN

Department of Geology, Peking University, Beijing 100871, China

Abstract

The Qinling-Dabie orogen in east-central China was produced by Triassic collision between two Precambrian cratons. The traditional view about the pre-collisional plate movement is that the South China Block (SCB = Yangtze craton) underwent northerly subduction beneath the North China Block (NCB = Sino-Korean craton). In this paper, we use the Sr-Nd-Pb isotopic tracer technique to test the validity of this view. In all published models, ultrahigh-pressure and high-pressure metamorphic rocks and subjacent "basement" gneisses of Dabieshan are considered to be the deeply subducted, then exhumed crustal slices of the South China Block. Cretaceous igneous rocks, including granitic batholiths generated by partial melting of the Yangtze middle to lower crust and mafic rocks derived from the subjacent upper mantle, should carry the isotopic signatures of the SCB lithosphere. However, Sr-Nd-Pb isotopic tracer analyses indicate that the Cretaceous granitoids and mafic-ultramafic rocks of Dabieshan have an NCB isotopic signature; hence the subducted lithosphere has little resemblance to the Yangtze craton. We conclude that an opposite polarity of the Triassic subduction is more likely, namely that the NCB plate was subducted southward beneath the SCB plate. A new tectonic model is presented, and we suggest that the plate boundary is located in the southern margin of the Dabieshan.

Introduction

THE CONTINENTAL ORIGIN of eclogites from the ultrahigh-pressure metamorphic (UHPM) terranes of China (Dabie and Su-Lu) is well established by several lines of evidence including field, petrologic, geochemical, and isotopic arguments (e.g., Wang and Liou, 1991; Li et al., 1993; Yui et al., 1995; Ernst and Liou, 1995; Cong et al., 1996; Liou et al., 1996; Jahn, 1998; Jahn et al., 2003, 2005; Rumble et al., 2003; Zheng et al., 2003). Their occurrence implies a deep subduction of continental rocks to mantle depths, which, in turn, may have a direct consequence of crust-mantle interaction and continental recycling in a dynamic earth.

Geochemical and Sr-Nd isotopic analyses on post-orogenic mafic and ultramafic rocks (gabbro and pyroxenite) from the Northern Dabie Complex (NDC) have revealed that these mantle-derived rocks carry an astonishing isotopic signature of the continental crust. This led Jahn et al. (1999) to propose a model of crust-mantle interaction and production of mafic magmas by the melting of such a modified mantle source. The interaction was envisaged to take place between the upper mantle peridotite (asthenosphere) and deeply subducted continental rocks, presumably lower-crustal granulites of the Precambrian craton. Partial melting of such metasomatized mantle produced the basic magmas in response to the same thermal pulse that triggered the production of massive Cretaceous granitic and syenitic intrusions and the resetting of isotopic clocks in UHP metamorphic rocks. We call attention to the fact that such characteristic mafic-ultramafic intrusions are not limited to the NDC; they also occur in other parts of Dabieshan, including the North Huaiyang Belt (Wang et al., 2005) and the Southern Dabie UHP terrane, such as in the Bixiling Complex. Jahn et al. (1999) also advocated that digestion of deeply subducted continental blocks in the upper mantle represents an efficient way of crustal recycling when dealing with the problem of continental growth and destruction. Remnants of the subducted continental slabs in the upper mantle between the Moho and 110 km depth

[1]Corresponding author; email: jahn@earth.sinica.edu.tw

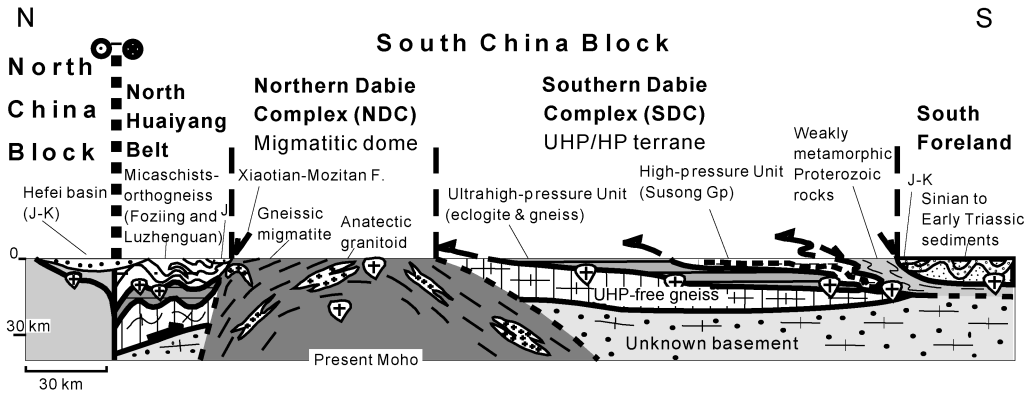


FIG. 1. Crustal-scale cross-section showing the surface geology and lithotectonic units of Dabieshan (adopted from Faure et al., 1999).

appear to be revealed by seismic tomography (Xu et al., 2001).

The tectonic evolution of the Dabie orogen has been controversial. While most agree that the UHP terrane (Southern Dabie Complex) represents a "thin" slice exhumed from great depths (≥ 100 km), the tectonic affinity of the orogen and the pre-metamorphic subduction polarity are still debatable (Jahn et al., 2001, 2003; Zhao et al., 2003, 2005). In traditional tectonic models, the bulk of the Dabieshan is considered as part of the Yangtze craton, which was presumably subducted northward beneath the Sino-Korean craton. However, northward subduction models cannot explain the Sr-Nd-Pb isotopic systematics in post-orogenic, late Mesozoic magmatic rocks emplaced in the same orogen. It is well known that mafic magmas provide information about the characteristics of their upper mantle source(s), whereas granitic magmas reveal their source characteristics of lower to middle crustal levels. In this paper, we analyzed isotopic bulk-rock compositions of Cretaceous mafic to granitic rocks in order to characterize the "source rocks" beneath Dabieshan. In so doing, we unraveled the possible genetic relationship between different terranes and lithologic units, and concluded that the source rocks were isotopically distinguished from the Yangtze craton. This casts doubt about the traditional view of northward subduction polarity and tectonic evolution of the Dabie orogen. We suggest that the Dabie orogen was more logically produced by a southerly subduction of the NCB, and that the Triassic plate boundary was located along the southern margin of the Dabieshan.

General Geological Setting of the Dabie Orogen and Tectonic Interpretation

The general geological setting of the Dabie orogen can be understood by studying a crustal-scale cross-section of the Dabieshan given by Faure et al. (1999), which illustrates the present distribution of lithotectonic units (Fig. 1). According to the current tectonic division, the North China Block is separated from the Dabieshan by a strike-slip fault hidden underneath the Hefei Basin. The North Huaiyang Belt (Foziling and Luzhenguan groups) is characterized by low-grade metamorphic rocks (mica schists) with minor amphibolite-facies rocks. They were intruded by Cretaceous granitoids and rare mafic-ultramafic rocks. In addition, an upper Mesozoic volcanisedimentary sequence occurs extensively in this belt. Detailed geochemical and Sr-Nd-Pb isotopic studies of volcanic rocks from this belt and the adjacent Northern Dabie Complex were recently carried out by Fan et al. (2004) and Wang et al. (2005). The North Huaiyang Belt is in fault contact (Xiaotian-Mozitan fault) with the Northern Dabie Complex, which is a high-temperature gneiss terrane considered as the core complex of a migmatite dome formed after the exhumation of the UHP metamorphic slice (Faure et al., 1999). The NDC is also characterized by extensive emplacement of granitoid batholiths as well as Cretaceous mafic-ultramafic intrusions. Recently, relicts of Triassic eclogites have been identified in the northern margin of NDC (Xu et al., 2000, 2005a; Liu et al., 2005).

South of the migmatite dome is the Southern Dabie Complex, which includes the celebrated

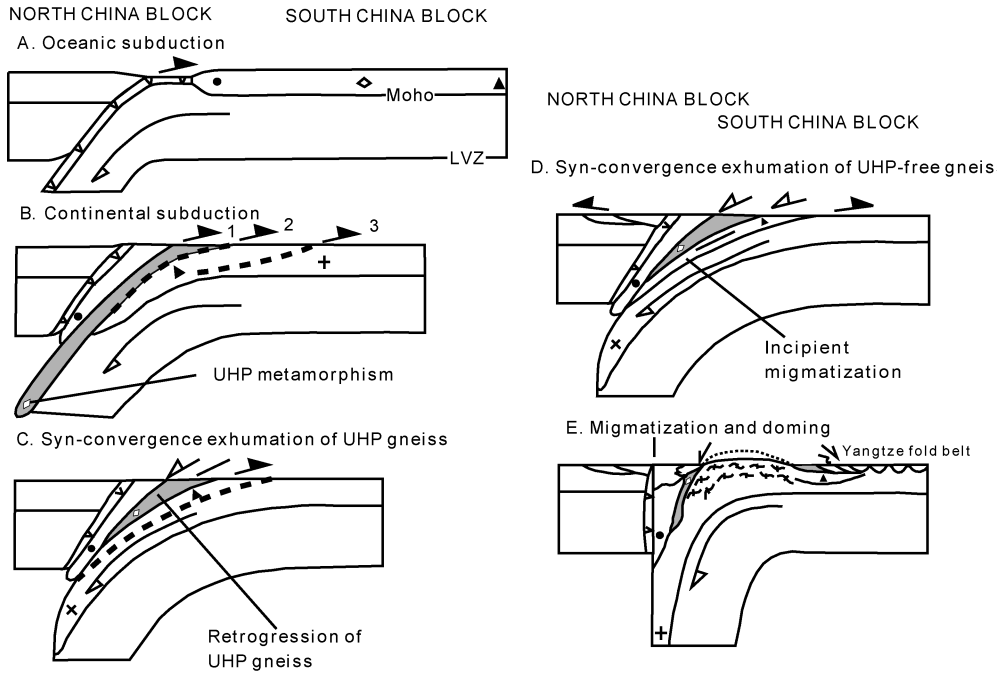


FIG. 2. The tectonic model of Faure et al. (1999) is used to illustrate the genetic relation between subducted and then exhumed crustal slices and subjacent mantle lithosphere. Partial melts formed within the Dabieshan should bear the isotopic signatures of the subducted lithosphere.

UHP-HP metamorphic rocks. Structural analyses and seismic reflection and refraction studies suggest that the UHP-HP metamorphic unit formed as a thin slice resting upon unknown basement gneisses (e.g., Faure et al., 1999; Hacker et al., 2000; Liu et al., 2003; Dong et al., 2004). The UHP unit comprises quartzofeldspathic gneisses, eclogite blocks and lenses, and supracrustal rocks including metaclastic rocks and marbles. The HP unit (the Susong Group) is made up mainly of metasedimentary rocks of greenschist to amphibolite facies. Lenses of glaucophane schist also occur. The unit may be separated into three zones. According to Wang et al. (1996), the lithological types in the northern zone include magnetite-bearing sandstone with thin layers of mica schist and granitic gneiss. The middle zone consists of marble, quartzite, garnet-biotite gneiss, and meta-phosphorite, whereas in the south zone, kyanite-bearing quartzite, chlorite-sericite schist, greenschist, and biotite gneiss are the main constituents. The Susong Group has undergone multi-stage metamorphism and deformation (Jiang et al., 2003). Zircon U-Pb dating revealed that a monzogranitic gneiss has an age of about 2.0 Ga, and a muscovite-plagioclase gneiss has 741 ± 7 Ma. In addition, an Ar-Ar age of 228 ± 1 Ma was obtained for a quartz amphibolite (Jiang et al., 2003). The Susong Group is fault-bounded against the uppermost Proterozoic (Sinian) to Lower Triassic sediments of the Yangtze craton.

From the distribution of lithological assemblages, it is clear that the metamorphic temperature of the Dabieshan decreases toward the south. Nevertheless, the entire region was later affected by massive emplacement of Cretaceous granitoid batholiths and subordinate mafic-ultramafic intrusions.

The above geological setting has been invariably interpreted as the result of northerly subduction of the SCB beneath the NCB, followed by exhumation of UHP-HP metamorphic rocks during the interval 240–210 Ma. The Triassic tectonic evolution can be represented by a model proposed by Faure et al. (1999; Fig. 2). In Figure 2, the subduction of the Yangtze craton is depicted such that, following oceanic subduction (Fig. 2A), different crustal segments were subducted to different depths (Figs. 2B and 2C), with some reaching mantle depths and

UHP metamorphic conditions. Moreover, some segments underwent synconvergence exhumation (Figs. 2C and 2D). Incipient migmatization was hypothesized to take place during the late stage of plate convergence (Fig. 2D), but the full-scale migmatization and doming took place in the final stage of exhumation (Fig. 2E). According to such tectonic evolution, the exhumed crustal segments are entirely of Yangtze affinity, and the ensemble is in fault contact with the NCB.

If the above scenario is correct, then the post-tectonic magmatic rocks emplaced in the Dabieshan would be expected to bear the isotopic signatures of the South China Block. We now present the available Sr-Nd-Pb isotopic data to show that the subducted continental lithosphere was not of the Yangtze, but rather of NCB affinity.

Lithological and Geochemical Characteristics of the Gneisses and Cretaceous Intrusions

The migmatite terrane of the Northern Dabie Complex (Fig. 1) was variously presented as an upper part of the subducted plate (Maruyama et al., 1994; Ernst and Liou, 1995), a high-temperature part of a vertical extrusion complex which includes UHP and HP rocks (Hacker et al., 1996), a high-temperature metamorphic terrane formed in the hanging wall of the North China craton, intruded by crustal melts and mafic-ultramafic rocks (R. Y. Zhang et al., 1996a), a magmatic complex created during Cretaceous N-S extension (Hacker et al., 1998), a migmatitic dome (= core complex) formed by decompressional partial melting of the exhuming slice, soon after the plate collision but not in the Cretaceous (Faure et al., 1999), or as an asymmetric Cordilleran-type extensional complex (i.e., a core complex) formed in the Cretaceous (Hacker et al., 1995; Ratschbacher et al., 2000).

The Northern Dabie Complex consists dominantly of granitic gneisses and subordinate migmatite, amphibolite, garnet granulite, marble, and some conspicuous trains of mafic-ultramafic rocks. The presence of mafic granulites at several localities suggests that the NDC underwent granulite-facies metamorphism that was strongly overprinted by amphibolite-facies assemblages and a later thermal event when massive Cretaceous granites were emplaced. Some granulites (e.g., from Luotian and Huangtuling) may represent late Archean to early Proterozoic crustal relics that survived the later tectonic evolution (Chen et al., 1996; Ge et al., 2001; Xia et al., 2003).

The granitic gneisses of the NDC cover a wide range of chemical compositions (SiO_2 = 53–80%). Gray gneisses with TTG compositions dominate over granitic gneisses (Zheng et al., 1999). In the TAS diagram of Middlemost (1994), the gneisses plot in the fields following the subalkaline trend of intrusive rocks.

Quartzofeldspathic gneisses of the South Dabieshan UHP-HP terranes have been separated into paragneiss and orthogneiss based on their mineral assemblages (R. Y. Zhang et al, 1996b). The paragneisses (Pl + Qtz + Phe + Bt + Ep ± Gt ± Ttn ± Rt) are intimately associated with eclogites, typically interlayered with marble, phengitic schists, and jadeitic quartzite, and are considered to have undergone UHP metamorphism. The orthogneisses (Pl + Kf + Qtz + mica + Ep ± Grt ± Ttn ± Am) are granitic and trondhjemitic; they are distinguished from paragneisses by the absence of rutile and presence of K-feldspar. Zircon dating revealed that most protoliths of the gneisses were formed in the late Proterozoic (~700–800 Ma), but a few, such as those at Shuanghe, have definitely older late Archean ages (Liou et al., 1997; Chavagnac, 2001; Chen et al., 2002). Together with granulites from the Luotian gneiss dome and trondjemitic gneisses and metapelites of the Kongling group (zircon ages up to 3.2 Ga; Qiu et al., 2000), these rocks have been considered by many workers to represent the only known relics of Archean rocks in the Yangtze craton.

The entire metamorphic complex of the Dabieshan was intruded by mafic to granitic rocks during the Cretaceous. The granitic intrusions and the coeval mafic-ultramafic rocks were emplaced indiscriminately in all the tectonic units of Dabieshan. However, trains of mafic stocks, plugs, and dikes, and massive granitoid batholiths seem to be most visible in the migmatite dome. The Cretaceous granitic intrusions encompass a wide spectrum of rock types including monzonite, quartz monzonite, syenite, and granite. They plot in the mid-alkaline field in the TAS diagram, and form a roughly continuous trend with alkali gabbros of Dabieshan (Chen et al., 2001). In the North Huaiyang Belt, intrusions are dominated by trace element–rich syenitic magmas (Zhou et al., 1995a). In parallel, volcanic rocks are also composed of trace element–rich lamprophyres, trachyandesites, and trachydacites (Fan et al., 2004; Wang et al., 2005). Overall, the Cretaceous granitoids have geochemical composi-

tions indicative of an origin from enriched sources. They are not crustal melts produced in a continental collision zone, but are liquids formed in extensional zones with significant input from metasomatized mantle.

Sr-Nd-Pb Isotopic Signatures of Gneisses and Cretaceous Mafic and Granitic Intrusions

Isotope tracer techniques are a powerful tool for the study of petrogenesis and tectonic terrane identification. Because NCB and SCB have distinctive crustal ages and tectonic evolutions (e.g., Chen and Jahn, 1998; Wu et al., 2005), rocks derived from the two cratons should possess their individual, characteristic isotopic signatures. The Sr-Nd-Pb isotopic data used in the present analysis are from our own work and literature sources. The principal isotopic signatures are described as follows.

Nd-Sr isotopic compositions of the Dabie-Sulu terrane (Figs. 3A and 3B): Figure 3A shows that at 220 Ma all granitic gneisses have evolved to negative ε_{Nd} values. However, the data sets for the UHP (SDC) and high-T migmatite terranes (NDC) can easily be distinguished, with moderately negative $\varepsilon_{Nd}(T)$ values of –2 to –13 (except one) for the UHP and highly negative $\varepsilon_{Nd}(T)$ values of –11 to –23 (except Huangtuling) for the migmatite terranes. The SDC gneisses have more dispersed $^{87}Sr/^{86}Sr$ ratios (= I_{Sr}), up to 0.740, whereas the NDC gneisses are more restricted in the range of 0.706 to 0.715. The gneisses at the Shuanghe locality are evidently extraordinary in all aspects with regard to other gneisses of the SDC. They have the lowest ε_{Nd}(220 Ma) values (–26), the highest T_{DM} model ages (3.3 Ga), and the oldest zircon ages (late Archean) among the SDC gneisses (Chavagnac et al., 2001). A granulite from the village of Huangtuling, near Yingshan, has a very low ε_{Nd}(220 Ma) value of –30, very high $^{87}Sr/^{86}Sr$ (220 Ma) of 0.742, and an Archean T_{DM} age of 2.99 Ga (Jahn, unpubl. data). Together with some known Archean zircon ages for granulites from the same region, it indicates a presence of late Archean relics in Dabieshan.

The granitic gneisses of the Su-Lu UHP terrane seem to differ from those of the Dabie UHP terrane (SDC) in terms of their lower range of $\varepsilon_{Nd}(T)$ values, but are similar in the wide range of Sr isotope compositions. At 120 Ma (Fig. 3B), the mantle-derived Cretaceous mafic/ultramafic rocks are characterized by highly negative $\varepsilon_{Nd}(T)$ of –15 to –20 and high I_{Sr} (0.706–0.710). The isotope signature was taken to imply a metasomatized mantle presumably produced by interaction of subducted lower crust with mantle peridotites (Jahn et al., 1999). However, this interpretation is not unique, and we will discuss this point in the next section. The coeval but much more voluminous granitic intrusions are shown to have isotopic compositions remarkably similar to both the mafic rocks and NDC granitic gneisses. The Cretaceous granitoids were emplaced in all tectonic units of the Dabieshan (North Huaiyang, NDC, SDC, and Susong Group), yet their isotopic compositions are conspicuously uniform.

Pb isotopic compositions of the Dabie-Sulu terrane (Figs. 4A and 4B): Based on literature data (e.g., compilations of L. G. Zhang, 1995; Chen and Jahn, 1999; Zhang et al., 2002a), the Pb isotope fields for Mesozoic granitoids of the NCB are clearly distinguished from those of the Yangtze craton, even though overlap is present. However, the data for Cretaceous granitoids from the Dabieshan and Su-Lu terranes show Pb isotopic compositions similar to those of the NCB, but very different from the Yangtze craton. This is astonishing if the Cretaceous granitoids were derived by partial melting of the Yangtze basement rocks.

Nd-Sr-Pb isotopic compositions of Cretaceous magmatic rocks from NCB (Figs. 5 and 6): Figure 5 illustrates that Cretaceous magmatic rocks of basic to acidic compositions from the NCB have a characteristic range of Nd and Sr isotopic compositions. The great majority of data fall in the range of the Dabieshan rocks. Note that ε_{Nd}(120 Ma) values for the NCB rocks vary from –8 to –22, excluding a few outliers from the Jaiodong Peninsula. Figure 6 shows that recent Pb isotope analyses on Cretaceous magmatic rocks from the NCB (Zhang et al., 2002a; Chen et al., 2004; Xu et al., 2004) fall within the fields earlier established by M. Zhang et al. (1995) for the Mesozoic granitoids of NCB.

We now summarize the key geochemical and isotopic constraints to the tectonic evolution of the entire Dabie orogen as follows:

1. The Sr-Nd isotope data indicate that the Cretaceous mafic-ultramafic rocks in the Dabieshan were derived from a metasomatized mantle source with an EM1 signature. Additional data reported most recently by Wang et al. (2005) confirm this point.

2. The Cretaceous granitoids (felsic volcanics included) have Sr-Nd isotopic and elemental characteristics similar to the mafic-ultramafic rocks, suggesting their possible genetic relationship. The

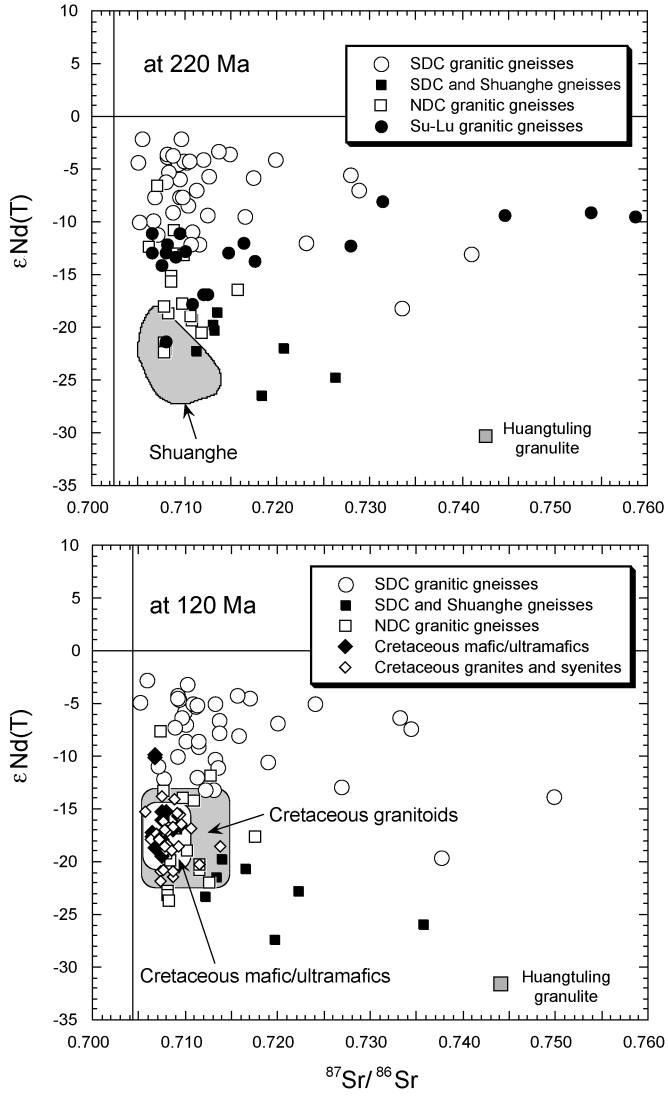


FIG. 3. A. Plot of $\varepsilon_{Nd}(T)$ vs. $^{87}Sr/^{86}Sr$ ratios, recalculated at 220 Ma, for granitic gneisses from the Southern and Northern Dabie Complex, and the Su-Lu terrane. The Shuanghe gneisses and Huangtuling granulite are exceptions. B. Plot of $\varepsilon_{Nd}(T)$ vs. $^{87}Sr/^{86}Sr$ ratios, recalculated at 120 Ma, for the granitic gneisses from the SDC and NDC, and Cretaceous mafic/ultramafic and granitic rocks. Note the similarity between the Cretaceous mafic/ultramafic rocks, Cretaceous granites/syenites, and the Neoproterozoic NDC gneisses. Data sources: Ames et al. (1996), Zheng et al. (2000), Chavagnac et al. (2001), Chen et al. (2001), and Jahn (unpubl.).

isotopic signature is "typical" of the lower continental crust of moderately depleted granulite-facies rocks. This is also supported by the available Pb isotopic data (L. G. Zhang, 1995; Zhou et al., 1995b; Chen and Jahn, 1999; Zhang et al., 2002a).

3. Recent isotopic investigations on Cretaceous mafic and felsic volcanic rocks from various regions in the eastern part of the NCB reveal that these rocks also have Nd and Pb isotopic signatures very similar to contemporaneous intrusions in the Dabie-

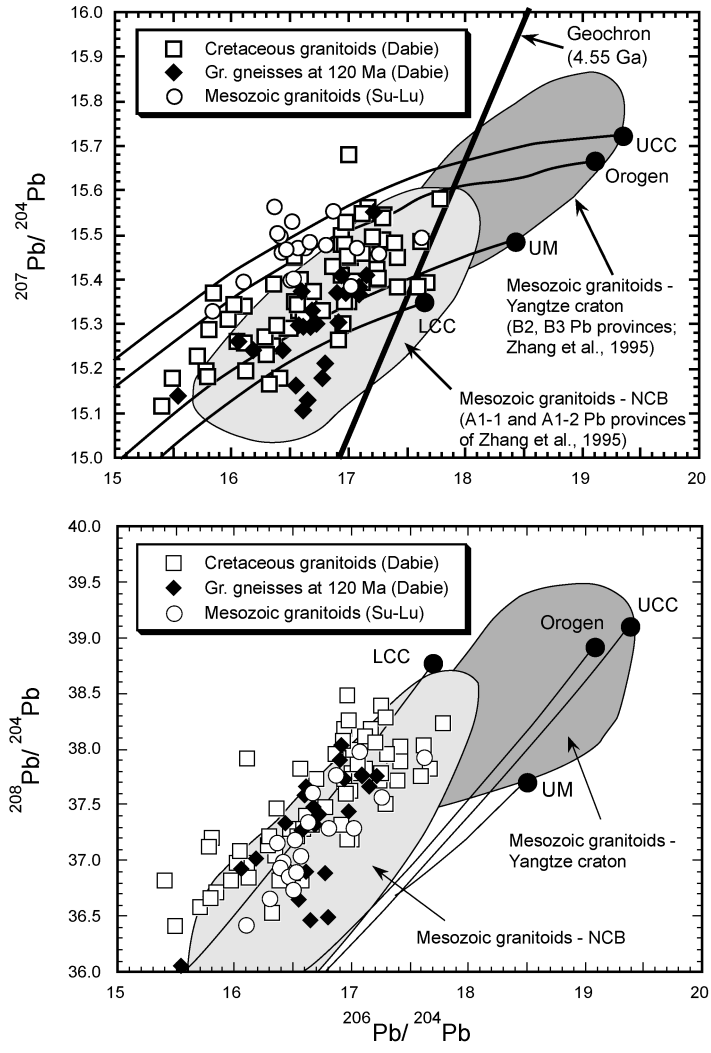


FIG. 4. A. Plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ ratios for Cretaceous granitoids and granitic gneisses of the Dabieshan, and Mesozoic granitoids of the Su-Lu terrane. The distinctive isotope fields for the Yangtze craton and the NCB is clearly shown despite a small area of overlap. Most Cretaceous granitoids and gneisses (calculated at 120 Ma) show their close affinity with the NCB, and are completely distinguished from the Yangtze craton. B. Plot of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ ratios for Cretaceous granitoids and granitic gneisses of the Dabieshan, and Mesozoic granitoids of the Su-Lu terrane. Data sources: Zhang et al. (1995) and references therein, and Zhou et al. (1995b).

shan (Figs. 4 and 5). By contrast, Chen and Jahn (1998) reviewed the Nd isotopic data of Paleozoic to Cretaceous (450–90 Ma) igneous rocks from the SCB, and concluded that the initial εNd values ranged from 0 to –15, except for two cases (Fig. 7). This range is significantly different from that of Cretaceous magmatic rocks from Dabieshan (–13 to –22). Recent Pb isotope analyses have reinforced the observation of such a distinctive isotope evolution (Fig. 6).

4. The quartzofeldspathic gneisses of the NDC and SDC are distinguished both in terms of isotopic and trace-element compositions. Sr-Nd-Pb isotopic data indicate that the SDC gneisses had no role in

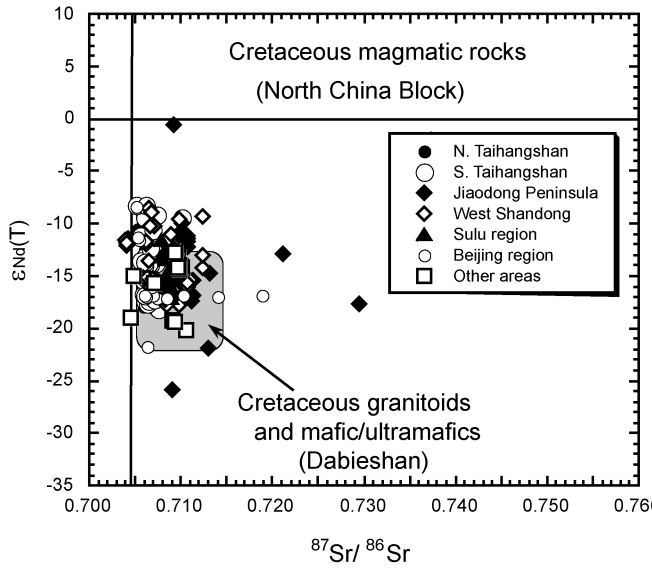


FIG. 5. Plot of $\varepsilon_{Nd}(T)$ vs. $^{87}Sr/^{86}Sr$ ratios for Cretaceous magmatic rocks emplaced in the North China craton. The Dabieshan field is shown for comparison. Data sources: Huang and Wu (1990), Qiu et al. (1996, 1997), Li et al. (2000), Xu and Xu (2000), Shao et al. (2001), and Chen et al. (2002, 2003, 2004).

the genesis of post-orogenic granitoids, but the data allow the Neoproterozoic NDC gneisses to have been a source for the Cretaceous granitoids.

Discussion and Tectonic Implications

The grossly similar Nd-Sr-Pb isotopic signature between Cretaceous mafic-ultramafic rocks, Cretaceous granitic rocks, and the NDC gneisses is intriguing. The derivation of mafic and ultramafic rocks from a metasomatized mantle is beyond doubt. However, the precise metasomatic processes are not well understood. Jahn et al. (1999) proposed that the process occurred in the post-collisional epoch, and that metasomatism resulted from interaction between hot asthenosphere and "trapped" lower continental crust after most subducted continental slices were exhumed. Implicitly, the lower crust dominated the Sr-Nd-Pb isotope budget for both the mafic liquids produced from the mantle and the granitic rocks formed by melting of the lower crust. Although this interpretation may be feasible for a terrane with deep subduction of continental blocks, it becomes difficult to explain the similar isotopic signature observed for the contemporaneous rocks widely emplaced in other parts of the North China Block.

Moreover, a comparison of chemical composition between the NDC gneisses and Cretaceous granitoids poses another problem. Petrological experiments indicate that melting of felsic gneisses under lower-crustal conditions would produce liquids of silica-rich granitic composition, and in no way could syenitic liquids be formed (Litvinovsky et al., 2000). The occurrence of syenitic and monzonitic rocks in the North Huaiyang Belt and NDC probably indicate an important input of the mantle (Litvinovsky et al., 2001). Besides, high Sr-Ba concentrations in the Cretaceous granitoids cannot be explained by melting of ordinary felsic gneisses. Consequently, in addition to the NDC gneisses, an input from metasomatized mantle is required for the production of the Cretaceous granitoids.

Many recent studies have established metasomatized mantle underneath the North China craton, at least for the region east of the well-known North-South Gravity Lineament (NSGL) that runs from the Great Xing'an Range to Taihangshan. Since the late Mesozoic, this region has been tectonically active, with development of rifted sedimentary basins, high heat flow (50-105 mW/m^2) and seismic activity, and widespread volcanism and granitoid intrusion (Chen et al., 1991). Mantle xenolith studies have revealed that this region has had a thin lithosphere (~80 km)

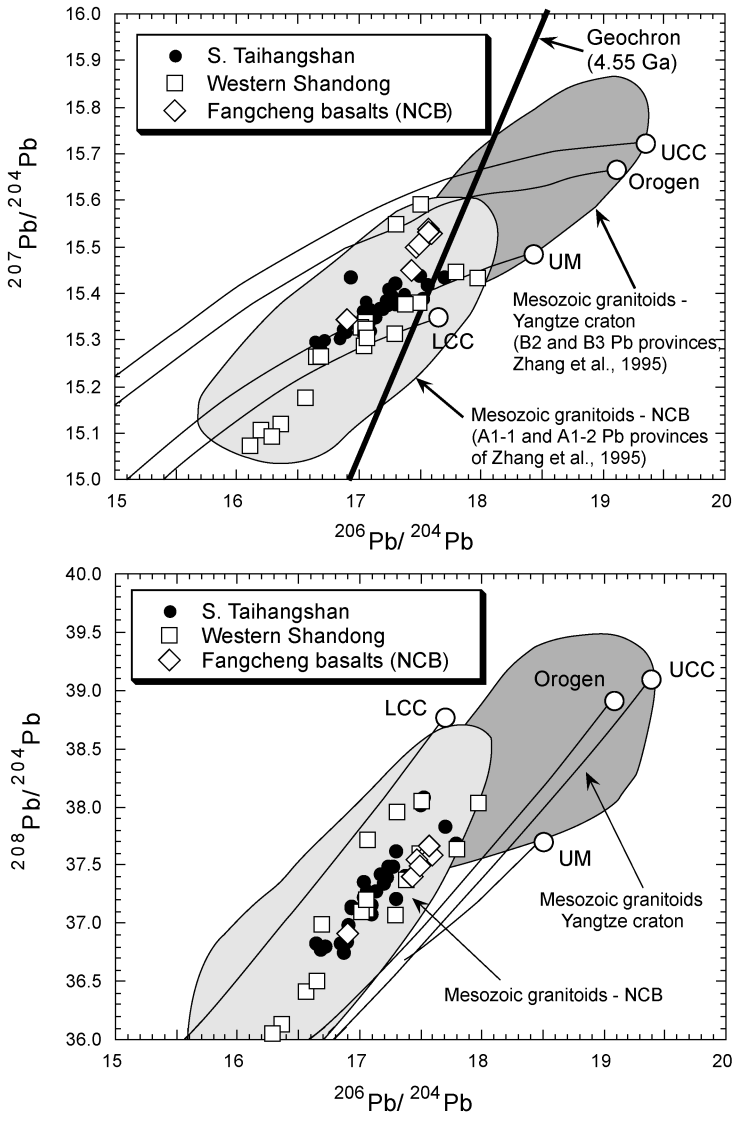


FIG. 6. Plots of recently published Pb isotopic data for Mesozoic igneous rocks from three regions of the North China craton. The data points in the (A) $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and (B) $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plots fall in the envelopes defined for the NCB by earlier analyses. Data source: Zhang et al. (2002a, 2002b), Chen et al. (2004), and Xu et al. (2004).

since the Tertiary, but its thickness was inferred to be ~200 km prior to the Ordovician time (Menzies et al., 1993; Menzies and Xu, 1998; Griffin et al., 1998; Fan et al., 2000). A loss of >120 km of Archean lithosphere is established, although the mechanism for its removal (or replacement) is still debated (e.g., Xu, 2001). Although Cenozoic basaltic liquids were produced mainly from the "newly replaced" oceanic-type (OIB) asthenosphere (Song et al., 1990; Zhi et al., 1990; Basu et al., 1991; Tatsumoto et al., 1992), Cretaceous volcanism probably tapped an early Precambrian metasome horizon (= EM1). According to Menzies and Xu (1998), the metasome horizon was located at 80 to 120 km

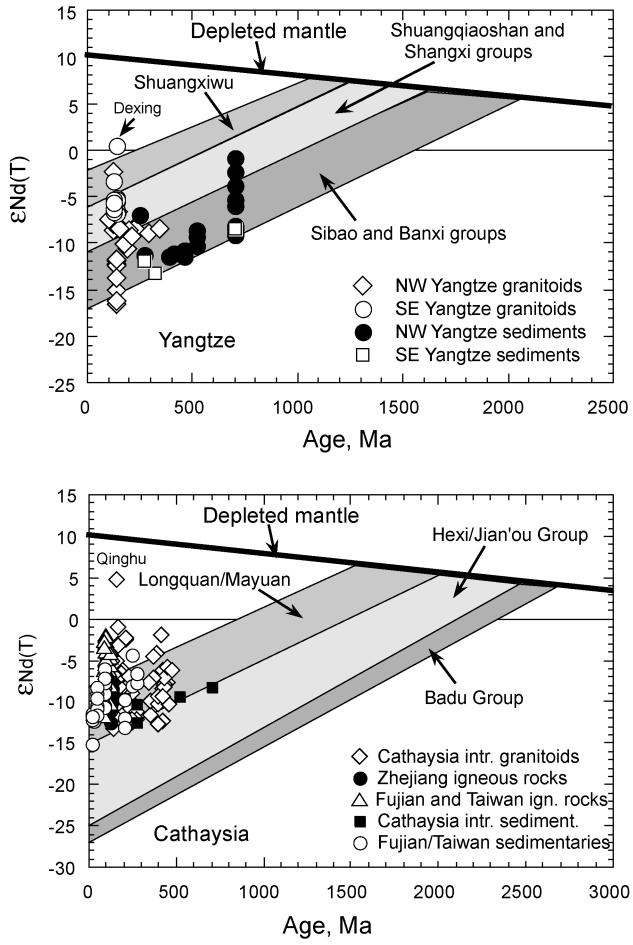


FIG. 7. Plot of $\varepsilon_{Nd}(T)$ vs. age for Phanerozoic granitic rocks of the South China Block (Yangtze and Cathaysia) according to the compilation of Chen and Jahn (1998). Note that none of the values are lower than –15. The three points apparently with ≤ –15 were, in fact, for rocks from the Dabieshan, because the Dabie terrane was considered as part of the Yangtze craton at the time of compilation.

depth, but it disappeared by the end of the Paleozoic. The isotopic data for Cretaceous magmatic rocks suggest that the metasome horizon must have survived at least until the Cretaceous, a scenario depicted earlier by Menzies et al. (1993) and later by Xu (2001). In Northeast China, the potassic volcanic rocks were derived from the melting of a mixed mantle source involving asthenosphere and old metasomatized subcontinental lithosphere (M. Zhang et al., 1995, 1998). Therefore, the metasomatized mantle with EM1 signature evidently has survived into the Cenozoic.

If the lower crust and the upper mantle sources of Cretaceous magmatic rocks in the Dabieshan are identical to that of the NCB, then it implies that the continental lithosphere underneath the Dabieshan is the same as that underneath the NCB. Consequently, the Dabie terrane must have a tectonic affinity with the NCB, but not SCB. In this case, the traditionally accepted view that the Yangtze craton subducted beneath the Sino-Korean craton can no longer hold. The subduction polarity could just be the opposite.

A proposed tectonic model

We now present our model for the tectonic evolution of the Dabieshan. In Figure 8A, the continental lithosphere of the NCB was subducted southward

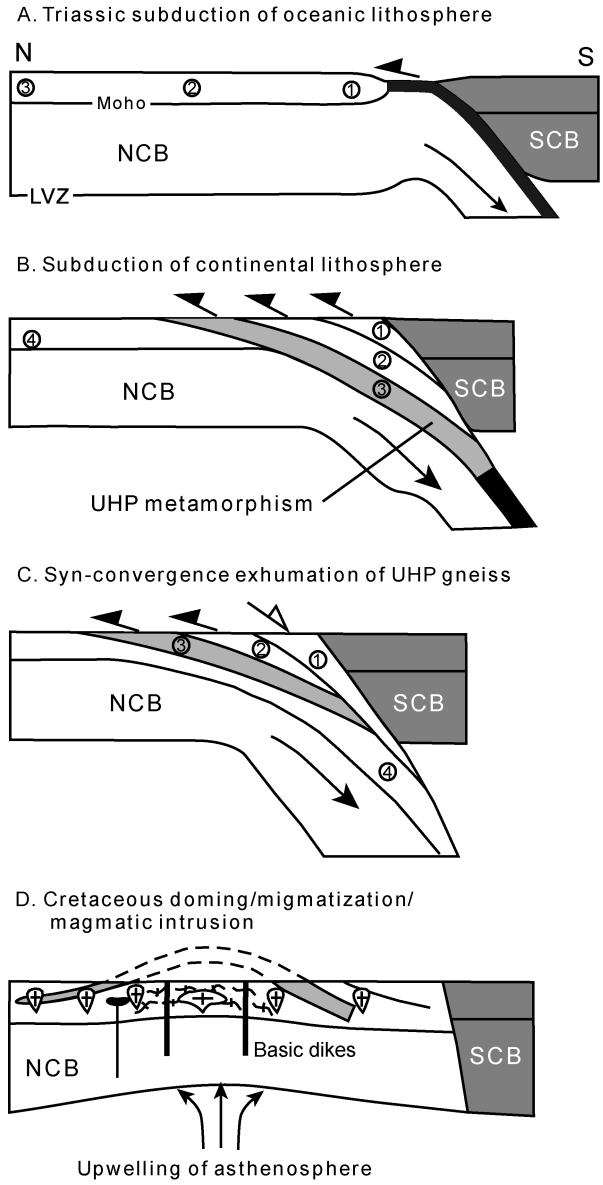


FIG. 8. A proposed tectonic model showing southerly subduction of the NCB.

beneath the SCB lithosphere following the consumption of the oceanic lithosphere. As in many models (e.g., Faure et al., 1999), the subducting continental crust was not integrally conducted to mantle depth; it was subducted in several crustal slices in sequence (Fig. 8B). To be consistent with the observed regional metamorphic zoning, the frontal and upper part of the continental crust was only barely subducted (= weakly metamorphosed Proterozoic rocks; Fig. 1), but the crustal slices behind were subducted to progressively greater depths until the subduction ceased as a result of the delamination of the oceanic lithosphere. Some intermediate slices could have been exhumed during the convergent process (Fig. 8C). Immediately after the cessation of subduction, the deeply subducted slice

of UHP gneisses was exhumed, mainly propelled by its buoyancy because the bulk of the UHP gneisses was still of light continental crust despite the association of eclogite blocks and lenses that comprise about 5% of the total UHP terrane.

The subsequent doming and erosion in the northern Dabieshan contributed to the apparent splitting of the UHP slice (Fig. 8D). However, it is not yet determined when the doming took place, either in the Late Triassic (about 200 Ma) soon after the exhumation, or in Cretaceous in concert with the emplacement of massive granitoids and subordinate mafic intrusions (Ratschbacher et al., 2000). In any case, the process of doming and splitting of the UHP slice is consistent with the recent discovery of UHP eclogites in the northern Dabieshan (Xu et al., 2000, 2005a; Liu et al., 2005), which has effectively erased the long doubt about the possible occurrence of UHP eclogites in such high-temperature terranes as the NDC.

With regard to the plate boundary, we propose that it is located along the southern margin of the Dabieshan. One may wonder why the area to the south of this boundary in the Yangtze craton does not show any features characteristic of an active margin, such as calc-alkaline volcanism and related arc deposits. Indeed, this is puzzling, and we do not have an answer to this question. However, the same question may be posed to the conventional tectonic models in which the plate boundary is placed on the northern margin of Dabieshan. There, no products of arc magmatism directly related to the pre-Triassic subduction have been identified. Despite the weakness of the present new model, we could adequately interpret the isotope signatures of the post-tectonic Cretaceous magmatic rocks, which clearly bear a genetic relation with the NCB lithosphere. The signatures are sufficiently different from those recorded in the Cretaceous rocks from the northern margin of the Yangtze craton (Chen and Jahn, 1998; Chen et al., 2001).

Comment on the models of Li and Yan (2003) and Wang et al. (2005)

Li and Yan (2003) presented a "wedge model" in an attempt to reconcile the dilemma between the conventional tectonic models of northerly subduction of the Yangtze craton and the NCB isotopic signatures of Cretaceous magmatic rocks of the Dabieshan. These authors are fully aware of the fact that the isotopic compositions of the Cretaceous rocks are characteristic of the NCB. They adopted the original idea of Li (1994) about the NCB-SCB mantle lithospheric boundary, which is different from that observed in the upper crustal rocks. Li (1994) placed the boundary along the line between Nanjing and Shanghai, and considered that the area to the east of the Tanlu fault, now transposed along with the Su-Lu UHP terrane to the north, was underlain by the NCB mantle. This hypothesis was supported by Chung (1999).

With some modifications, Li and Yan (2003) later proposed that the exhumed slice of UHP-HP rocks of Yangtze affinity was delaminated (separated) from the underlying mafic lower crust and lithospheric mantle, and the NCB lithosphere wedged into the space created by the crustal delamination. The resultant lithospheric cross-section resembles a large crocodile swallowing an oversized animal. The fatal point of this model is that the wedging was produced by continuous compression after exhumation of the UHP-HP rocks. This process is very difficult to envision; the exhumation of these rocks commonly implies that the tectonic regime changed from compressive to extensional, hence a continuous squeezing and wedging seems unlikely to occur.

More recently, Wang et al. (2005) presented a variant of the Li and Yan (2003) model. They also attempted to reconcile the apparent Yangtze surface geology and the NCB isotopic signatures of the Cretaceous basic-intermediate rocks of the Dabieshan. They called for a tectonic decoupling between the surface geology and upper mantle soon after the UHP-HP rocks were exhumed. However, it is not clear how the NCB crust gave way to the northward advancing Yangtze crust represented by the Northern Dabie Complex.

Epilogue

We have presented the rationale of our approach and strong isotopic constraints regarding the tectonic evolution of the Dabieshan. The tectonic affinity of this orogen has long been disputed. The isotopic tracer technique has rarely been employed in tectonic models of the Dabieshan in the past. Although our southward subduction model encounters certain problems, we nevertheless emphasize that the tectonic issue is not yet settled. Some of the commonly mentioned arguments in favor of the northward subduction of the SCB, including the foreland fold-and-thrust belt on the Yangtze craton, northward increase of metamorphic pressure conditions, position of the plate suture, position of the

accretionary wedge and arc, etc., are still debatable. They can even be circumvented because all these features could be interpreted otherwise using a different tectonic model. Moreover, ages of 700–800 Ma have been commonly obtained for granitic gneisses of the UHP terrane; the ages were invariably and correctly interpreted as the formation time of their protoliths. These ages have been taken as a strong argument for the Dabieshan to be of Yangtze affinity because this age range is rare in the NCB, whereas it is very common in the SCB. Once again, this is not proven. If the UHP rocks of the Dabieshan were indeed of NCB origin, then the NCB is no longer deprived of Neoproterozoic rocks. In any case, this paper is intended to shed light on an unresolved tectonic problem involving a fantastic terrane that deserves further investigation.

Acknowledgments

This paper is dedicated to J. G. (Louie) Liou on the occasion of his retirement from Stanford University. Louie is a life-long close friend of the senior author (BmJ) and a constant inspiring figure for his scientific career. Louie has made "Dabieshan" a household term and a celebrated hotspot for investigation of deep-crustal processes. Lothar Ratschbacher provided a substantive, critical assessment of an earlier version of this paper, and the present manuscript has benefitted from critical reviews by J. G. Liou. The research was supported by grants of the National Science Council of Taiwan to Bor-ming Jahn (NSC 93-2116-M-001-022, NSC 94-2116-M-001-008), and of the Natural Science Foundation of China to Bin Chen (NSFC grant No. 40372033).

REFERENCES

Ames, L., Zhou, G., and Xiong, B., 1996, Geochronology and isotopic character of high-pressure metamorphism with implications for collision of the Sino-Korean and Yangtze cratons, central China: Tectonics, v. 15, p. 472–489.

Basu, A. R., Wang, J. W., Huang, W. K., Xie, G. H., and Tatsumoto, M., 1991, Major element, REE, and Pb, Nd, and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: Implications for origin from suboceanic-type mantle reservoirs: Earth and Planetray Science Letters, v. 105, p. 149–169.

Chavagnac, V., Jahn, B. M., Villa, I. M., Whitehouse, M. J., and Liu, D. Y., 2001, Multichronometric evidence for an in-situ origin of the ultrahigh-pressure metamorphic terrane of Dabieshan, China: The Journal of Geology, v. 109, p. 633–646.

Chen, B., Jahn, B. M., Arakawa, Y., and Zhai, M. G., 2004, Petrogenesis of the Mesozoic intrusive complexes from the southern Taihang orogen, North China craton: Elemental and Sr-Nd-Pb isotopic constraints: Contributions to Mineralogy and Petrology, v. 148, p. 489–501.

Chen, B., Jahn, B. M. and Wei, C., 2002, Petrogenesis of Mesozoic granitoids in the Dabie UHP complex, Central China: Trace element and Nd-Sr isotope evidence: Lithos, v. 60, p. 67–88.

Chen, B., Zhai, M. G. and Jahn, B.M., 2003, Sr-Nd isotopic characteristics of the Mesozoic magmatism in the Taihang-Yanshan orogen, North China craton, and implications for Archaean lithosphere thinning: Journal of the Geological Society, London, v. 160, p. 963–970.

Chen, D. G., Deloule, E. and Xia, Q. K., 2002, Metamorphic zircon from Shuanghe ultrahigh pressure eclogite, Dabieshan: Ion microprobe and internal micro-structure study: Acta Petrological Sinica, v. 18, p. 369–377.

Chen, G. Y., Song, Z. H., An, C. Q., Cheng, L. H., Zhuang, Z., Fu, Z. W., Lu, Z. L. and Hu, Z. F., 1991, Three-dimensional crustal and upper mantle structure of the North China region: Acta Geophysica Sinica, v. 34, p. 172–181 (in Chinese).

Chen, J. F. and Jahn, B. M., 1998, Crustal evolution of southeastern China: Nd and Sr isotopic evidence: Tectonophysics, v. 284, p. 101–133.

Chen, J. F., Jahn, B. M., 1999, Nd-Sr-Pb isotope tracer study and crustal evolution of southeastern China, *in* Zheng, Y. F., ed., Chemical geodynamics: Beijing, China, Science Publishing House, p. 262–287 (in Chinese).

Chen, J. F., Yan, J., Xie, Z., and Xing, F., 2001, Nd and Sr isotopic compositions of igneous rocks from the Lower Yangtze Region in eastern China: Constraints on sources: Physics and Chemistry of the Earth, v. 26, p. 719–731.

Chen, N. S., You, Z. D., Suo, S. T., Yang, Y., and Li, H. M., 1996, Zircon U-Pb ages of granulites and deformed granites from Dabieshan: Chinese Science Bulletin, v. 41, p. 1009–1012 (in Chinese).

Chung, S. L., 1999, Trace element and isotope characteristics of Cenozoic basalts around the Tanlu fault with implications for the eastern plate boundary between North and South China: The Journal of Geology, v. 107, p. 301–312.

Cong, B., Zhang, R., Liou, J. G., Ye, K., and Wang, Q., 1996, Metamorphic evolution of UHPM rocks, *in* in Cong Bolin, ed., Ultrahigh-pressure metamorphic rocks in the Dabieshan-Sulu region of China: Beijing, China/Dordrecht, The Netherlands: Science Publishing House/Kluwer Academic Publishing, p. 128–160.

Dong, S. W., Gao, R., Cong, B. L., Zhao, Z. Y., Liu, X. C., Li, S. Z., Li, Q. S., and Huang, D. D., 2004, Crustal

structure of the southern Dabie ultrahigh-pressure orogen and Yangtze foreland from deep seismic reflection profiling: Terra Nova, v. 16, p. 319–324.

Ernst, W. G., and Liou, J. G., 1995. Contrasting plate tectonic styles of the Qinling-Dabie-Sulu and Franciscan metamorphic belts: Geology, v. 23, p. 353–356.

Fan, W. M., Guo, F., Wang, Y. J., and Zhang, M., 2004, Late Mesozoic volcanism in the northern Huaiyang tectono-magmatic belt, central China: Partial melts from a lithospheric mantle with subducted continental crust relicts beneath the Dabie orogen?: Chemical Geology, v. 209, p. 27–48.

Fan, W. M., Zhang, H. F., Baker, J., Jarvis, K. E., Mason, P. R. D., and Menzies, M. A., 2000, On and off the North China Craton: Where is the Archaean keel?: Journal of Petrology, v. 41, p. 933–950.

Faure, M., Lin, W., Shu, L., Sun, Y., and Schärer, U., 1999, Tectonics of the Dabieshan (eastern China) and possible exhumation mechanism of ultrahigh-pressure rocks: Terra Nova, v. 11, p. 251–258.

Ge, N. J., Li, H. Y., Qin, L. P., Hou, Z. H., and Bo, L., 2001, Sr-Nd-Pb isotope geochemistry of granulites and TTG gneisses from Dabieshan: Acta Geologica Sinica, v. 75, p. 379–384 (in Chinese with English abstract).

Griffin, W. L., Zhang, A. D., O'Reilly, S. Y., and Ryan, G., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton, *in* Flower, M., Chung, S. L., Lo, C. H., and Lee, T. Y., eds., Mantle dynamics and plate interaction in east Asia: AGU Geodynamics Series, no. 27, p. 107–126.

Hacker, B. R., Ratschbacher, L., and Webb, L., 2000. Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic–early Jurassic tectonic unroofing. Journal of Geophysical Research, v. 105 (B6), p. 13,339–13,364.

Hacker, B. R., Ratschbacher, L., Webb, L., and Dong S., 1995, What brought them up? Exhumation of the Dabie Shan ultrahigh-pressure rocks: Geology, v. 23, p. 743–746.

Hacker, B. R., Ratschbacher, L., Webb, L., Ireland, T., Walker, D., and Dong, S. W., 1998, U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinling-Dabie orogen, China: Earth and Planetary Science Letters, v. 161, p. 215–230.

Hacker, B. R., Wang, X., Eide, E. A., and Ratschbacher, L., 1996, The Qinling-Dabie ultrahigh-pressure collisional orogen, *in* Yin, A., and Harrison, M. T., eds., Tectonic evolution of Asia: Cambridge, UK, Cambridge University Press, p. 345–370.

Huang, X., and Wu, L. R., 1990, Nd-Sr isotopes of granitoids from Shanxi province and their significance of tectonic evolution: Acta Petrological Sinica, v. 2, p. 1–11.

Jahn, B. M., 1998, Geochemical and isotopic characteristics of UHP eclogites and ultramafic rocks of the Dabie orogen: Implications for continental subduction and collisional tectonics, *in* Hacker, B., and Liou, J. G., eds., When continents collide: Geodynamics and geochemistry of ultrahigh-pressure rocks: Dordrecht, The Netherlands: Kluwer Academic Publishers, p. 203–239.

Jahn, B. M., Chen, B., Li, H. Y., and Potel, S., 2001, Continental subduction and mantle metasomatism: Consequence on the Cretaceous magmatism and implications for the architecture of the Dabie Orogen, *in* Ogasawara, Y., Maruyama, S., and Liou, J. G., eds., UHPM Workshop 2001, Waseda University: Tokyo, Japan, Waseda University, p. 147–154.

Jahn, B. M., Liu, X. C., Yui, T. F., Morin, N., and Bouhnik-Le Coz, M., 2005, High-pressure/ultrahigh-pressure eclogites from the Hong'an Block, east-central China: Geochemical characterization, isotope disequilibrium, and geochronological controversy: Contributions to Mineralogy and Petrology, v. 149, p. 499–526.

Jahn, B. M., Rumble, D., and Liou, J. G., 2003, Geochemistry and isotope tracer study of UHP metamorphic rocks, *in* Carswell, D. A., and Compagnoni, R., eds., Ultrahigh pressure metamorphism: EMU Notes in Mineralogy Series, p. 365–414.

Jahn, B. M., Wu, F., Lo, C. H., and Tsai, C. H., 1999, Crust-mantle interaction induced by deep subduction of the continental crust: Geochemical and Sr-Nd isotopic evidence from post-collisional mafic-ultramafic intrusions of the northern Dabie complex, central China: Chemical Geology, v. 157, p. 119–146.

Jiang, L. L., Wu, W. P., Liu, Y. C. and Li, H. M., 2003, U-Pb zircon and Ar-Ar hornblende ages of the Susong complex of the southern Dabie orogen and their geological implication: Acta Petrologica Sinica, v. 19, p. 497–505.

Li, S., Xiao, Y., Liou, D., Chen, Y., Ge, N., Zhang, Z., Sun, S., Cong, B., Zhang, R., Hart, S., and Wang, S., 1993, Collision of the N China and Yangtze blocks and formation of coesite-bearing eclogite: Timing and processes: Chemical Geology, v. 109, p. 89–111.

Li, S. G., and Yan, W., 2003, Decoupling of surface and subsurface sutures in the Dabie Orogen and a continent-collisional lithospheric-wedging model: Sr-Nd-Pb isotopic evidence of Mesozoic igneous rocks in eastern China: Chinese Science Bulletin, v. 48, p. 831–838.

Li, W. P., Lu, F. X., Sun, S. P., and Li, J. Z., 2000, Petrogenesis and tectonic setting of the volcanic rocks of Donglingtai Formation, western Beijing: Acta Petrologica Sinica, v. 16, p. 345–352.

Li, Z. X., 1994, Collision between the North and South China Blocks: A crustal-detachment model for suturing in the region east of the Tanlu Fault: Geology, v. 22, p. 739–742.

Liou, J. G., Zhang, R. Y., and Jahn, B. M., 1997, Petrology, geochemistry and isotope data on a ultrahigh-pressure jadeite quartzite from Shuanghe, Dabie Mountains, east-central China. Lithos, v. 41, p. 59–78.

Liou, J. G., Zhang, R. Y., Wang, X. M., Eide, E. A., Ernst, W. G., and Maruyama, S., 1996, Metamorphism and teconics of high-P and ultrahigh-P belts in the Dabie-Sulu region, eastern central China, *in* Harrison, M. T., and Yin, A., eds., The tectonic development of Asia: Cambridge, UK, Cambridge University Press, p. 300–344.

Litvinovsky, B. A., Jahn, B. M., Zanvilevich, A. N., Saunders, A., Poulain, S., Kuzmin, D. V., and Titov, A. V., 2001, Petrogenesis of syenite-granite suites from the Bryansky complex (Transbaikalia, Russia): implications for the origin of A-type granitoids magmas. Chemical Geology, v. 189, p. 105–133.

Litvinovsky, B. A., Steele, I. M., and Wickham, S. M. 2000. Silicic magma formation in overthickened crust: Melting of charnockite and leucogranite at 15, 20 and 25 kbar: Journal of Petrology, v. 41, p. 717–737.

Liu, F. T., Xu, P. F., Liu, J. S., Yin, Z. X., Chun, K. Y., Zhang, X. K., Zhang, C. K., and Zhao, J. R., 2003, The crustal velocity structure of the continental deep subduction belt: Study on the eastern Dabie Orogen by seismic wide-angle reflection/refraction: Chinese Journal of Geophysics, v. 46, p. 366–372.

Liu, Y. C., Li, S. G., Xu, S. T., Jahn, B. M., Zheng, Y. F., Zhang, Z. Q., Jiang, L. L., Chen, G. B., and Wu, W. P., 2005, Geochemistry and geochronology of eclogites from northern Dabie Mountains, central China: Journal of Asian Earth Sciences, v. 25, p. 431–443.

Maruyama, S., Liou, J. G., and Zhang, R., 1994, Tectonic evolution of the ultrahigh-pressure (UHP) and high-pressure (HP) metamorphic belts from central China: The Island Arc, v. 3, p. 112–121.

Menzies, M. A., Fan, W. M., and Zhang, M., 1993, Paleozoic and Cenozoic lithoprobes and the loss of >120 km of Archaean lithosphere, Sino-Korean craton, China, *in* Princhard, H. M., Alabaster, T., Harris, N. B. W., and Neary, C. R., eds., Magmatic processes and plate tectonics: Geological Society, London, Special Publications, v. 76, p. 71–78.

Menzies, M. A. and Xu, Y. G., 1998, Geodynamics of the North China craton *in* Flower, M., Chung, S. L., Lo, C. H., and Lee, T. Y., eds., Mantle dynamics and plate interaction in east Asia: American Geophysical Union, Geodynamics Series, no. 27, p. 155–165.

Middlemost, E. A. K., 1994, Naming materials in the magma/igneous rock system: Earth Science Review, v. 37, p. 215–224.

Qiu, J. S., Wang, D. Z., Zhou, J. C., and Zeng, J. H., 1996, Geology, geochemistry and genesis of the Mesozoic shoshonitic volcanic rocks in Shandong Province: Earth Sciences, v. 21, p. 546–552.

Qiu, J. S., Wang, D. Z., Zeng, J.C. and McInnes, B. J. A., 1997, Study on trace element and Nd-Sr isotopic geochemistry of the Mesozoic K-rich volcanic rocks and lamprophyres in western Shandong: Geological Journal of China Universities, v. 3, p. 384–395.

Qiu, Y. M., Gao, S., McNaughton, N. J., Groves, D. I., and Ling, W., 2000, First evidence of >3.2 Ga continental crust in the Yangtze craton of south China and its implications for Archean crustal evolution and Phanerozoic tectonics: Geology, v. 28, p. 11–14.

Ratschbacher, L., Hacker, B. R., Webb, L. E., McWilliams, M., Ireland, T., Dong, S. W., Calvert, A., Chateigner, D., and Wenk, H. R., 2000, Exhumation of the ultrahigh-pressure continental crust in east central China: Cretaceous and Cenozoic unroofing and the Tan-Lu fault: Journal of Geophysical Research, v. 105, p. 13,303–13,338.

Rumble, D., Liou, J. G., and Jahn, B. M., 2003, Continental crust subduction and ultrahigh pressure metamorphism, *in* Rudnick, R. L., ed., Treatise of geochemistry, volume 3. The crust: Amsterdam, The Netherlands, Elsevier/Pergamon, p. 293–319.

Shao, J., Li, X. H., Zhang, L. Q., Mu, B. L., and Liu, Y. L., 2001, Geochemical constraints on the petrogenesis of the Mesozoic bimodal dyke swarm in Nankou-Guyaju, Beijing: Geochimica, v. 30, p. 517–524.

Song, Y., Frey, F. A., and Zhi, X. C., 1990, Isotopic characteristics of Hannuoba basalts, eastern China: Implications for their petrogenesis and the composition of subcontinental mantle: Chemical Geology, v. 85, p. 35–52.

Tatsumoto, M., Basu, A. R., Huang, W. K., Wang, J. W., and Xie, G. H., 1992, Sr, Nd, and Pb isotopes of ultramafic xenoliths in volcanic rocks of Eastern China: Enriched components EMI and EMII in subcontinental lithosphere: Earth and Planetary Science Letters, v. 113, p. 107–128.

Wang, Q. C., Zhai, M. G., and Cong, B. L., 1996, Regional geology, *in* Cong, B. L., ed., Ultrahigh-pressure metamorphic rocks in the Dabieshan-Sulu region of China: Beijing, China/Dordrecht, The Netherlands, Science Publishing House and Kluwer Academic Publishers, p. 8–26.

Wang, X. M., and Liou, J. G., 1991, Regional ultrahigh-pressure coesite-bearing eclogitic terrane in central China: Evidence from country rocks, gneiss, marble, and metapelite: Geology, v. 19, p. 933–936.

Wang, Y., Fan, W., Peng, T., Zhang, H., and Guo, F., 2005, Nature of the Mesozoic lithospheric mantle and tectonic decoupling beneath the Dabie orogen, Central China: Evidence from $^{40}Ar/^{39}Ar$ geochronology, elemental and Sr-Nd-Pb isotopic compositions of early Cretaceous mafic igneous rocks: Chemical Geology, v. 220, p. 165–189.

Wu, F. Y., Zhao, G. C., Wilde, S. A., and Sun, D. Y., 2005, Nd isotopic constraints on crustal formation in the North China Craton: Journal of Asian Earth Sciences, v. 24, p. 523–545.

Xia, Q. K., Zheng, Y. F., Ge, N. J., and Deloule, E., 2003, U-Pb ages and oxygen isotope compositions of zircons from gneiss of Huangtuling, northern Dabie: Old

protolith and multi-stage evolution: Acta Petrologica Sinica, v. 19, p. 506–512.

Xu, H. and Xu, G. P., 2000, Geochemical characteristics of the lamprophyres from Jiadong: Implications for petrogenesis: Acta Petrologica et Mineralogica, v. 19, p. 36–43.

Xu, P. F., Liu, F. T., Wang, Q. C., Cong, B. L., and Chen, H., 2001. Slab-like high velocity anomaly in the uppermost mantle beneath the Dabie-Sulu orogen: Geophysical Research Letters, v. 28, p. 1847–1850.

Xu, S. T., Liu, Y. C., Chen, G. B., Ji, S. Y., Ni, P., and Xiao, W. S., 2005a, Microdiamonds, their classification and tectonic implications for the host eclogites from the Dabie and Su-Lu regions in central eastern China: Mineralogical Magazine, v. 69, p. 511–522.

Xu, S. T., Liu, Y. C., Chen, G. B., and Wu, W. P., 2005b, Architecture and kinematics of the Dabie orogen, Central Eastern China: Acta Geologica Sinica, v. 79, p. 356–371.

Xu, S. T., Shu, W., Liu, Y. C., Wang, R. C., Jiang, L. L., and Wu, W. P., 2000, Discovery of eclogites and its petrography in the Northern Dabie Mountains: Chinese Science Bulletin, v. 45, p. 273–278.

Xu, Y. G., 2001, Thermo-tectonic destruction of the Archaean lithospheric keel beneath the Sino-Korean Craton in China: Evidence, timing and mechanism: Physics and Chemistry of the Earth (A), v. 26, p. 747–757.

Xu, Y.G., Huang, X.L., Ma, J. L., Wang, Y. B., Iizuka, Y., Xu, J. F., Wang, Q., and Wu, X. Y., 2004, Crust-mantle interaction during the tectono-thermal reactivation of the North China Craton: Constraints from SHRIMP zircon U-Pb chronology and geochemistry of Mesozoic plutons from western Shandong: Contributions to Mineralogy and Petrology, v. 147, p. 750–767.

Yui, T. F., Rumble, D., and Lo, C. H., 1995, Unusually low $\delta^{18}O$ ultrahigh-pressure metamorphic rocks from the Sulu terrain, eastern China: Geochimica et Cosmochimica Acta, v. 59, p. 2859–2864.

Zhang, H., Gao, S., Zhong, Z., Zhang, B., Zhang, L., and Hu, S., 2002a, Geochemical and Sr-Nd-Pb isotopic compositions of Cretaceous granitoids: constraints on tectonic framework and crustal structure of the Dabieshan ultrahigh-pressure metamorphic belt, China: Chemical Geology, v. 186, p. 281–299.

Zhang, H. F., Sun, M., Zhou, X. H., Fan, W. M., Zhai, M. G. and Yin, J. F., 2002b, Mesozoic lithosphere destruction beneath the North China Craton: Evidence from major-, trace-element, and Sr-Nd-Pb isotope studies of Fangcheng basalts: Contributions to Mineralogy and Petrology, v. 144, p. 241–253.

Zhang, L. G., 1995, Geology of East Asian lithospheric—isotope geochemistry and dynamics of the upper mantle, basement, and granitic rocks: Beijing, China, Science Publishing House, 252 p. (in Chinese, with English abstract).

Zhang, M., Suddaby, P., Thompson, R. N., Thirlwall, M. F., and Menzies, M. A., 1995, Potassic rocks in NE China: Geochemical constraints on mantle source and magma genesis: Journal of Petrology, v. 36, p. 1275–1303.

Zhang, M., Zhou, X. H., and Zhang, J. B., 1998, Nature of the lithospheric mantle beneath NE China: Evidence from potassic volcanic rocks and mantle xenoliths, *in* Flower, M., Chung, S. L., Lo, C. H., and Lee, T. Y., eds., Mantle dynamics and plate interaction in east Asia: American Geophysical Union, Geodynamics Series, no. 27, p. 197–220.

Zhang, R. Y., Liou, J. G., and Tsai, C. H., 1996a, Petrogenesis of a high-temperature metamorphic terrane: A new tectonic interpretation for the north Dabieshan, central China: Journal of Metamorphic Geology, v. 14, p. 319–333.

Zhang, R. Y., Liou, J. G., and Ye, K., 1996b, Petrography of UHPM rocks and their country rock gneisses, *in* Cong Bolin, ed., Ultrahigh-pressure metamorphic rocks in the Dabieshan-Sulu region of China: Beijing, China/Dordrecht, The Netherlands, Science Publishing House/Kluwer Academic Publishers, p. 49–68.

Zhao, Z. Y., Fang, A. M., and Yu, L. J., 2003, High- to ultrahigh-pressure (UHP) ductile shear zones in the Sulu UHP metamorphic belt, China: Implications for continental subduction and exhumation: Terra Nova, v. 15, p. 322–329.

Zhao, Z. Y., Fang, A. M. and Yu, L. J., 2005, Reply to "Discussion of the paper: 'High- to ultrahigh-pressure (UHP) ductile shear zones in the Sulu UHP metamorphic belt, China: Implications for continental subduction and exhumation' by Zhao et al.": Terra Nova, v. 17, p. 89–93.

Zheng, Y. F., Fu, B., Gong, B., and Li L., 2003. Stable isotope geochemistry of ultrahigh pressure metamorphic rocks from the Dabie-Sulu orogen in China: Implications for geodynamics and fluid regime. Earth Science Reviews, v. 62, p. 105–161.

Zheng, X. S., Jin, C. W., Zhai, M. G., and Shi, Y. H., 1999, Petrochemistry and tectonic background of the grey gneisses in north Dabie terrane: Acta Petrologica Sinica, v. 15, p. 350–358.

Zheng, X. S., Jin, C. W., Zhai, M. G., and Shi, Y. H., 2000, Approach to the source of the gray gneisses in north Dabie terrain: Sr and Nd isochron age and isotope compositions: Acta Petrologica Sinica, v. 16, p. 194–198.

Zhi, X. C., Song, Y., Frey, F. A., Feng, J., and Zhai, M. G., 1990. Geochemistry of Hannuoba basalts, eastern China: Constraints on the origin of continental alkalic and tholeiitic basalt: Chemical Geology, v. 88, p. 1–33.

Zhou, T. X., Chen, J. F., and Zhang, X., 1995a, Geochemical study of the granite-syenite belt in the N. Huaiyang region and its tectonic significance. Geological Review, v. 41, p. 144–151.

Zhou, T. X., Li, X., Zhang X., Wei, G., Pan, G., and Chen, J., 1995b, A lead isotopic study of alkali intrusion in the N. Huaiyang region: Journal of China University of Science and Technology, v. 25, p. 467–473.