Destruction of the North China Craton Induced by Ridge Subductions

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ABSTRACT

The destruction of the North China Craton (NCC) mainly occurred in the Cretaceous and has been attributed to a "top-down" rapid delamination, "bottom-up" long-term thermal/chemical erosions, or hydration by subduction-released fluids. On the basis of the distribution of one Jurassic and two Early Cretaceous adakite belts and the drifting history of the paleo-Pacific Plate, we propose that three ridge subduction events dominated the large-scale decratonization in the NCC. Both physical erosion and magmatism induced by ridge subduction contributed to the destruction of the NCC; the last ridge subduction, at 130 ± 5 Ma, was the key driving force in the final destruction. We present mineralogical, geochemical, and isotopic data in support of the ridge subduction model: flat subduction of a spreading ridge resulted in stronger physical erosion on the thick lithosphere mantle of the NCC. Consequently, slab melting occurred during ridge subduction, forming adakites with mantle Mg isotope compositions, followed by A-type granites as a result of asthenosphere upwelling. Delaminated lower continental crust was also partially melted after reacting with hydrous magmas, as indicated by eclogite xenoliths, resulting in a zircon age spectrum similar to that of the NCC and some adakitic samples with chemical characteristics similar to those of the Dabie adakites. The final decratonization was triggered by the last ridge subduction, with both physical erosion (flat subduction) and thermal erosion (adakitic and A-type magmatisms). Given that ridge subduction has occurred throughout Earth's history, the associated decratonization processes are presumably a common phenomenon that modified the chemical compositions of the continental crust.

Online enhancements: appendix tables.

Introduction

Cratons, the most stable parts of the Earth's lithosphere, have lasted for billions of years. Although the destruction of cratons (i.e., decratonization) is rare (Gao et al. 2004; Menzies et al. 2007; Griffin et al. 2009), determining the mechanism behind decratonization is essential to understanding the highly evolved chemical composition of the continental crust (Gao et al. 2004). The thickness of the North China Craton (NCC) changed dramatically in the Mesozoic, providing the best example of decratonization (Fan and Menzies 1992; Griffin et al. 1992, 1998; Menzies et al. 1993; Gao et al. 2004). Recent studies show that the NCC was finally destroyed in the Early Cretaceous (Xu 2007). The thickness of the NCC was >200 km in the Paleozoic, declined to <60 km in the Early Cretaceous, and then increased back to its current ~80 km (Xu 2001, 2007; Menzies et al. 2007). There are currently three major competing models for the destruction of the NCC: delamination of the eclogitic lower continental crust (Gao et al. 2004) or post-collisional lithosphere (Wu et al. 2002), thermal/

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chemical erosion of the lithospheric mantle (Xu 2001, 2007; Menzies et al. 2007), and hydration induced by Pacific Plate subduction (Niu 2005).

The delamination model is essentially a "top-down" process, proposing that the thickened lower continental crust of the NCC transformed into eclogite, which is denser than the mantle peridotite, and consequently destabilized and delaminated to the convecting mantle. The delaminated lower continental crust was partially melted in the convecting mantle after being heated by the asthenosphere mantle, forming high-Mg adakites through melt-mantle reaction (Gao et al. 2004). This model has been criticized mainly for two reasons. First, the delaminated lower continental crust should have disturbed the asthenospheric mantle, presumably so that A-type granites and other asthenosphere-derived or induced magmas could form shortly before adakite. This is not observed in the NCC. Second, magmatism lasted from the Jurassic to the Cenozoic (Zhou and Armstrong 1982; Guo et al. 2005; Wu et al. 2005; Xu 2007, 2009*b*), with adakitic rocks formed in three episodes, which is again difficult to explain feasibly in the delamination model (Menzies et al. 2007).

The thermal/chemical-erosion model consists essentially of prolonged melt-rock reactions (Xu 2001, 2007), which is a plausible explanation of the protracted switch in the source regions of volcanic rocks from enriched (enriched layers in the keel, the thick cratonic lithospheric mantle) to depleted (sublithosphere asthenosphere) over about 100 m.yr. in eastern China (Menzies et al. 2007; Xu 2007). This "bottom-up" process, however, requires vast volumes of mafic melt over a long period of time, which have yet to be resolved (Menzies et al. 2007). Considering that the Kaapvaal craton is stable even though it has been overriding the African superplume (Ni et al. 2002; Wang and Wen 2007) for more than 200 m.yr. (Burke et al. 2008), simple melt-rock interaction cannot convincingly explain the destruction of the NCC.

The hydration model involves a process that "transformed" the basal portion of the lithosphere through addition of water released from the subducted oceanic lithosphere occurring along the Pacific Rim (Niu 2005). Recent studies, however, show low water contents in the Cenozoic lithosphere mantle beneath the eastern NCC (Xia et al. 2010), implying that either the wet portion was removed or the mantle was not hydrated at all. Nevertheless, most cratons in the world are very stable, though surrounded by orogenic belts; i.e., they have experienced plate subduction and collisions. Decratonization is far less common than plate subduction. Moreover, because subduction has occurred several times from three directions surrounding the NCC since the Paleozoic (Li et al. 1993; Xiao et al. 2003; Zheng et al. 2003), a simple hydration model cannot feasibly be used to interpret why the NCC was destroyed in the Cretaceous (Xu 2007).

Moreover, the last two models pay little attention to the wide distribution of adakites in the NCC, which is one of the most distinctive features accompanying its decratonization (Gao et al. 2004). Adakite is a type of intermediate magma with high Sr and low heavy rare earth–element (REE) and Y concentrations, distributed mainly along convergent margins (Drummond et al. 1996; Yogodzinski et al. 2001; Benoit et al. 2002; Cole et al. 2006). Adakites are originally referred to volcanic rocks with major components from slab melts usually associated with subduction of oceanic crust younger than 25 Ma (Kay 1978; Defant and Drummond 1990). In addition to slab melting, there are several other mechanisms proposed for the formation of adakite or adakitic rocks, which include partial melting of the lower continental crust (Yumul et al. 2000; Chung et al. 2003; Gao et al. 2004; Zellmer 2009; Zellmer et al. 2012), underplated new crust (Petford and Atherton 1996), and fractional crystallization of normal arc magmas (Castillo et al. 1999; Castillo 2006; Macpherson et al. 2006; Richards and Kerrich 2007; Rodríguez et al. 2007; Richards 2011). Recent studies have proposed that slab melts can be discriminated from lower continental crust melt through chemical characteristics (Liu et al. 2010*a*; Ling et al. 2011*b*; Sun et al. 2011, 2012). In addition to adakite, A-type granites are also commonly associated with ridge subductions, as a result of slab window and slab rollback processes after ridge subduction (Benoit et al. 2002; Li et al. 2012).

Given that adakitic rocks are usually found near convergent margins, the formation of adakitic rocks and their relation to the decratonization of the NCC need to be addressed. We studied the geochemical characteristics of adakites and eclogitic xenoliths hosted within adakites from the Xu-Huai region and Mg isotopes for adakites from the Dabie Mountains and the Lower Yangtze River Belt (LYRB). Our results, together with previously published data, support the hypothesis that the decratonization was triggered by ridge subduction events.

Geological Background and Samples

The Xu-Huai region is located in the southeastern part of the NCC, ca. 100 km west of the Tan-Lu fault and ca. 300 km north of the Dabie orogenic belt (Xu et al. 2006*b*; fig. 1). The Neoproterozoic and Paleozoic strata in this region had been deformed and formed the Xu-Huai nappe structure (Wang et al. 1998; fig. 1). There are primarily three Mesozoic intrusive bodies emplaced into the Late Permian strata in which eclogite and garnet-clinopyroxenite xenoliths have been found: from north to south, the Liguo, Banjing, and Jiagou intrusions, which follow a northeasterly trend roughly parallel with the Tan-Lu fault (Xu et al. 2006*a*, 2009*a*). The Liguo intrusion is composed of

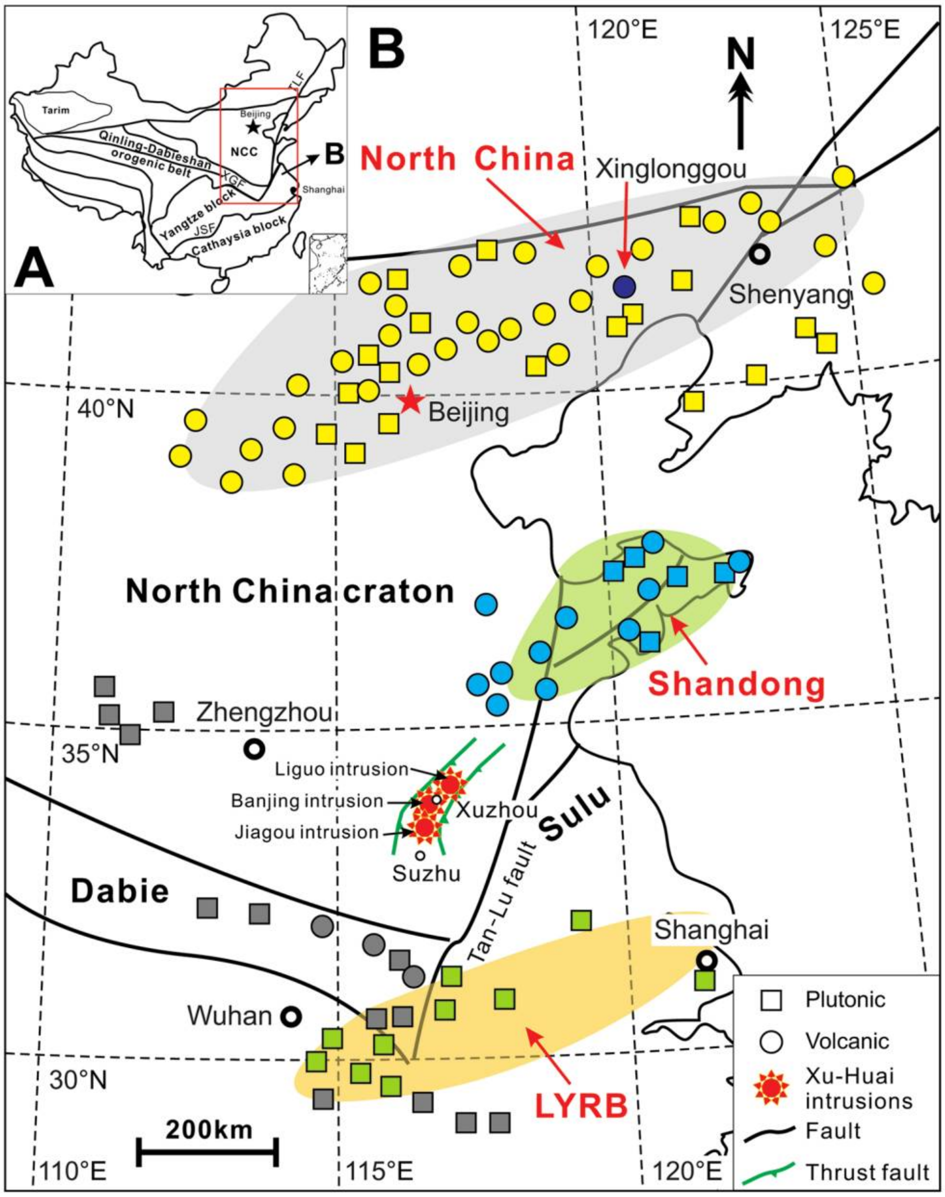

Figure 1. Sketch map of eastern China, showing the distribution of Late Mesozoic adakites, modified after Zhang et al. (2001). Three belts of Mesozoic adakites are distributed in eastern China: the Jurassic adakite belt along the northern margin of the North China Craton (NCC) and Early Cretaceous adakite belts along the Shandong Peninsula and the Xu-Huai region (~130 Ma) and the Lower Yangtze River Belt (LYRB; ~140 Ma). Also plotted are three Cretaceous intrusions (Liguo, Banjing, and Jiagou) in the Xu-Huai region, northern Jiangsu and Anhui Provinces, where eclogitic xenoliths were sampled and analyzed in this study. A series of thrust faults were developed there, forming arc-shaped structures (Xu et al. 1987). Squares represent plutonic (intrusive) rocks, while the circles represent volcanic (extrusive) rocks, both of which are shown in different colors in the three adakite belts. JSF = Jianshan-Shaoxing Fault; TLF = Tan-Lu Fault; XGF = Xiangfan-Guangji Fault.

dioritic and syenite-dioritic porphyries with Cu mineralization; the Banjing intrusion consists of gabbro-dioritic, monzodioritic, and granodioritic porphyries; and the Jiagou intrusion is mainly monzodioritic porphyry (Xu et al. 2009*a*).

In this study, adakite samples from the Liguo (34°33.68′N, 117°16.98′E), Banjing (34°09.31′N, 117°03.03′E), and Jiagou (33°51.95′N, 117°01.05′E) intrusions were collected for mineralogical, geochemical, and geochronological studies. Xenoliths within these adakite samples consist of garnet, clinopyroxene, quartz, and rutile, with minor amphibole (Xu et al. 2006*a*, 2009*a*). Clinopyroxene in the eclogite xenoliths is omphacite containing 2.69%–3.90% Na_2O and a 19–29 mol% jadeite component, while clinopyroxene in the garnet-clinopyroxenite xenoliths is augite with 1.96% Na_2O and a 13 mol% jadeite component (Xu et al. 2006*a*). The garnet clinopyroxenite xenoliths also contain minor plagioclase (Xu et al. 2009*a*), indicating that these xenoliths were formed at low pressures, under conditions that were drier than subducted oceanic crust, or a combination of both. Magnesium isotopes of adakitic samples from the Dabie Mountains and the LYRB were also analyzed. Samples from the Dabie Mountains have been studied by previous authors (Wang et al. 2007*a*). EGB-1 and YFD-6 are granite porphyries collected from Egongbao and Yunfengding, respectively, and FZL-3 is monzonitic granite collected from Fuziling. Detailed sample descriptions of EGB-1 and FZL-3 can be found in Wang et al. (2007*a*). Samples from the LYRB were collected as part of this study from Jiguanshan (JGS-1), Shangyaopu (SYP-1, SYP-2, and SYP-3), and Tongguanshan (TGS-1). JGS-1 is diorite, while SYP-1, SYP-2, SYP-3, and TGS-1 are all granodiorites.

Analytical Methods

Sample Preparation. Fresh rock samples were ground to <200 mesh with a Retsch Rotor Beater Mill SR 300 for analyses of major and trace elements. Lithium borate glass disks of whole-rock powder with sample/flux ratios of 1 : 8 and 1 : 3 were fused for major-element analysis by x-ray fluorescence (XRF) and trace-element analysis using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), respectively.

Zircons were separated from samples by traditional heavy-liquid and magnetic-separation techniques, handpicked under a binocular microscope, mounted with epoxy resin, and polished down to near half sections to expose internal structures for secondary ion mass spectrometry (SIMS) U-Pb dating. Cathodoluminescence images were used to inspect the zircon morphology before U-Pb dating.

Major and Trace Elements, Zircon and U-Pb Dating, and Electron Microprobe Analysis. Analyses of major and trace elements were performed at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Major elements were determined by Rigaku 100e XRF, with analytical precisions better than 1% for major elements (Ma et al. 2007). Trace elements were analyzed by Perkin-Elmer ELAN 6000 ICP-MS with the solution method or by Agilent 7500a ICP-MS coupled with a RESOlution M-50 laser ablation using glass fusion method (Liang et al. 2009; Tu et al. 2011). Analytical precisions for trace elements by the solution and glass fusion methods are both better than 5% (Liu et al. 1996; Tu et al. 2011).

Zircon U-Pb dating was performed at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, in Beijing, with a Cameca IMS 1280 SIMS, following the procedures reported by Li et al. (2009). Temora was used as an external standard. The ellipsoidal spot was ~20–30 μm in size. The O_2^- primary ion beam was accelerated at -13 kV with an intensity of ~10 nA, and positive secondary ions were extracted with a 10-kV potential.

Major-element analyses for minerals in xenoliths were conducted through JEOL JXA-8100 electron microprobe analysis (EMPA) at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The accelerating voltage was 15.0 kV. The beam current was 30 nA, and the spot diameter was 1–2 μm. Both silicates and pure oxides were used as standards. The *P-T* conditions for xenoliths were calculated on the basis of the EMPA results.

Magnesium Isotopes. Magnesium isotopic analyses were carried out at the Isotope Laboratory of the University of Arkansas, Fayetteville. Chemical procedures and instrumental analyses followed those reported in previous studies (Teng et al. 2007, 2010; Yang et al. 2009; Li et al. 2010; Liu et al. 2010*b*). All chemical procedures were performed in a class 10,000 clean laboratory, equipped with a class 100 laminar-flow exhaust hood (Li et al. 2010). Optima-grade acids or distilled acids and Milli-Q water with a resistivity of 18.2 MΩ-cm were used throughout the chemical procedures (Teng et al. 2007; Li et al. 2010).

In order to obtain at least 10 μg of Mg in solution for multicollector (MC) ICP-MS analysis (Teng et al. 2010), approximately 2–20 mg of whole-rock powder, depending on the Mg content, was dissolved in Savillex screw-top beakers with a mixture of concentrated HNO_3-HF (1 : 3, v/v), a mixture of concentrated HNO_3-HCl (1 : 3, v/v), and concentrated HNO_3 in turn. Magnesium was separated by cation-exchange column chemistry using columns filled with Bio-Rad AG50W-X8 resin (200–400 mesh) and eluted with 1N HNO_3 (Teng et al. 2007; Li et al. 2010). The column chemistry procedure was conducted twice successively, to ensure recovery of a pure Mg solution. The purified Mg solutions were introduced to the plasma by a quartz cyclonic spray chamber, and Mg isotope ratios were determined by a Nu Plasma MC-ICP-MS in a low-resolution mode with the sample-standard bracketing technique, in which ^{26}Mg, ^{25}Mg, and ^{24}Mg isotopes were measured simultaneously in three separate Faraday cups: H5, Ax, and L4, respectively (Teng et al. 2010). Magnesium ratio measurements for all sample solutions were repeated four times within a session (Liu et al. 2010*b*). The Mg isotopic results are reported in standard δ notation in parts per thousand (permil) relative to DSM3 (Galy et al. 2003). Precision and accuracy of analyses in this laboratory were evaluated by full-procedural repeated analyses of samples and standards with different matrixes, including a synthetic multielement standard solution (IL-Mg-1, concentration ratios of Mg : Fe : Al : Ca : Na : K : Ti = 1 : 1 : 1 : 1 : 1 : 1 : 0.1), pure Mg Cambridge-1 standard solution, rocks, minerals, and seawater (Teng et al. 2007, 2010; Li et al. 2010). In this study, a seawater sample from southwestern Hawaii was also analyzed to test precision and accuracy. The duplicate (repeated measurement of a different aliquot of the same Mg cut) and replicate (repeated column chemistry and measurement) analyses of Hawaii seawater yielded an average $\delta^{26}Mg = -0.87 \pm 0.03$ (2 SD, $n = 5$; table A3, available in the online edition or from the *Journal of Geology* office), which is consistent with that of global seawater (Ling et al. 2011*a*).

Results

Major- and trace-element results of Xu-Huai adakites are reported in table A1, available in the online edition or from the *Journal of Geology* office. These samples have typical geochemical characteristics of adakite, with intermediate-acidic SiO_2 contents between 55.77% and 61.50%, relatively high MgO from 2.02% to 5.89%, Al_2O_3 from 13.13% to 15.83%, high Sr concentration (278–1151 ppm), low Y (7.30–15.0 ppm) and Yb (0.68–1.39 ppm) concentrations, and relatively high Sr/Y, from 23.1 to 79.4. Zircon U-Pb dating results of two eclogitic xenolith samples in adakites from the Xu-Huai region are reported in table A2, available in the online edition or from the *Journal of Geology* office. The ages of xenoliths can be mainly classified into three groups: 126–158, 1400–2100, and 2200–2550 Ma (fig. 2). The Th/U ratios of these groups of zircons are in the ranges 0.06–1.31, 0.02–2.16, and 0.35–2.60, respectively. The zircon of adakites from the Xu-Huai region also yielded three groups of U-Pb ages: 125–148, 1330–2000, and 2220–2620 Ma (fig. 3), with Th/U of 0.04–1.49, 0.01–1.58, and 0.04–3.52, respectively. Magnesium isotopic compositions of adakites from the LYRB and the Dabie orogen are reported in table A3. The Lower Yangtze River adakites have homogeneous mantle-like magnesium isotopic compositions with $\delta^{26}Mg$ ranging from $-0.29‰ \pm 0.08‰$ to $-0.21‰ \pm 0.08‰$, whereas adakites from the Dabie orogen have heterogeneous Mg isotopic compositions heavier than that of the mantle, with $\delta^{26}Mg$ from $-0.16‰ \pm 0.06‰$ to $-0.06‰ \pm 0.07‰$. The $\delta^{26}Mg$ of Dabie adakites correlates positively with 1/MgO (fig. 4).

Slab Melting versus Lower Continental Crust Melting

Eastern China is a unique place, with abundant adakitic rocks distributed far from modern and ancient subduction zones (Zhang et al. 2001, 2007; Xu et al. 2002; Wang et al. 2007*b*). Three adakite belts have been recognized (fig. 1), with ages of 140 ± 5 Ma (Early Cretaceous) along the LYRB (Xu et al. 2002; Wang et al. 2006; Ling et al. 2009; Liu et al. 2010*a*), 130 ± 5 Ma (Early Cretaceous) along the Shandong Peninsula and Xu-Huai region (Y. G. Xu et al. 2004; W. L. Xu et al. 2006*a*, 2009*a*), and 170 ± 5 Ma (Jurassic) along the northern margin of NCC (Gao et al. 2004; Yang and Li 2008), from south to north. Various models have been proposed for the origin of these adakites, including partial melting of either delaminated or thickened lower continental crust (Xu et al. 2002; Gao et al. 2004; Wang et al. 2007*b*) and partial melting of oceanic crust (Ling et al. 2009; Liu et al. 2010*a*).

Here we show that some sets of adakitic rocks from eastern China have geochemical indices consistent with partial melts of oceanic slab, while others are consistent with partial melts of lower continental crust, although the fields of slab and continental crust partial melts overlap each other slightly at the low-Sr/Y, low-La/Yb end (fig. 5). Partial melts from oceanic slab and lower continental crust can be distinguished with a Sr/Y-versus-$(La/Yb)_N$ diagram (Liu et al. 2010*a*), because oceanic crust has a $(La/Yb)_N$ ratio considerably lower than

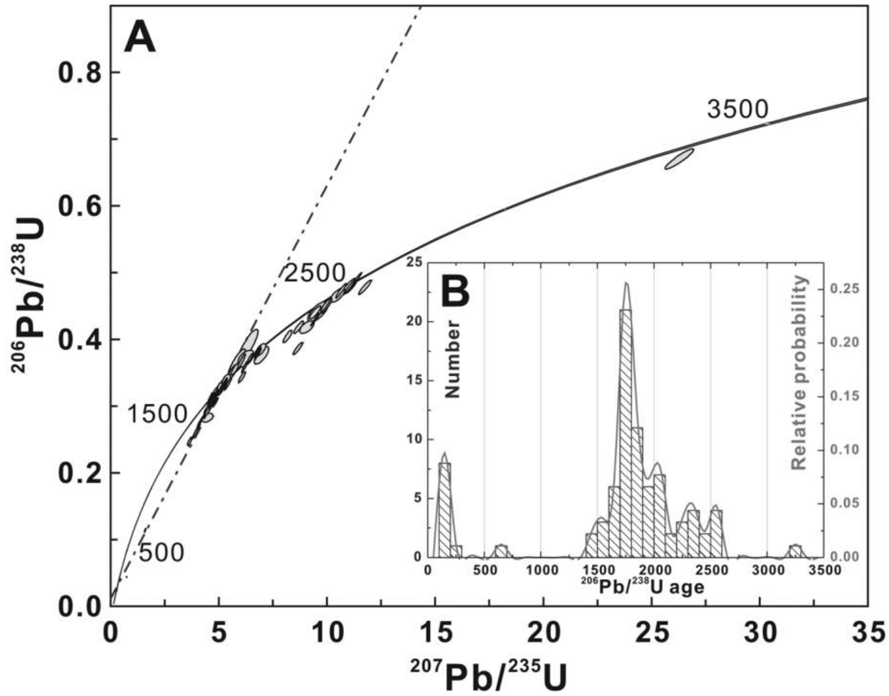

Figure 2. *A*, Zircon U-Pb concordia diagram of two eclogitic xenolith samples (total of 81 zircon grains) from the Xu-Huai region. *B*, Histogram of zircon U-Pb ages. The ages define three groups. The magmatic age of about 130 Ma represents the age of the host adakite. Inherited zircons of 1400–2100 and 2200–2550 Ma are typical North China Craton ages (Chen et al. 2003; Zheng et al. 2004). The younger group of inherited zircons has Th/U ratios ranging from 0.06 to 1.31, indicating both magmatic and metamorphic origins. The older group has Th/U ratios higher than 0.2, suggesting predominantly magmatic origins. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

that of the lower continental crust (Sun and McDonough 1989; Rudnick and Gao 2003; Sun et al. 2008). All adakites from the circum-Pacific margins (GEOROC 2010), which are predominantly partial melts of subducted slab (Kay 1978; Defant and Drummond 1990; Drummond et al. 1996), fall together in a vertically distributed low-La/Yb field, consistent with the light REE–depleted characteristics of mid-ocean ridge basalt (MORB). The high Sr/Y ratio might result from the retention of Y by garnet in subducted slabs, the absence of plagioclase and the addition of Sr during sea-floor alteration, and dehydration during subduction. Adakites from the Xinglonggou region in the NCC, the LYRB, and the Xu-Huai region and some from the Shandong Peninsula fall predominately in the field defined by adakites from the circum-Pacific margins, indicating that all of these adakites have major components from oceanic slab-derived partial melts. By contrast, Dabie adakites form a field with high $(La/Yb)_N$ and have positive correlation between $(La/Yb)_N$ and Sr/Y (fig. 5), consistent with their origin as partial melts of lower continental crust. This is also supported by the REE pattern and trace-element spidergram (fig. 6). Some of the adakites from the Shandong Peninsula also plot in the same field (fig. 5). Interestingly, adakite samples from the southern Tibetan Plateau (formed 30–15 Ma; Chung et al. 2003, 2009) plot between the fields defined by the circum-Pacific and Dabie adakites. These adakites were also attributed to partial melting of the lower continental crust (Chung et al. 2003). We argue that subducted oceanic slab still existed under the southern Tibetan Plateau when these adakites formed (fig. 5).

Magnesium isotopes provide additional constraints on the origin of the Lower Yangtze River and Dabie adakites. Magnesium isotopic compositions of the Lower Yangtze River adakites, unlike those of the Dabie adakites, fall in the mantle field. The positive correlation between the δ^{26}Mg and the 1/MgO of the Dabie adakites suggests mixing between mantle and crustal materials, which is consistent with partial melting of delaminated lower continental crust triggered by asthenosphere upwelling and thus with addition of mantle materials

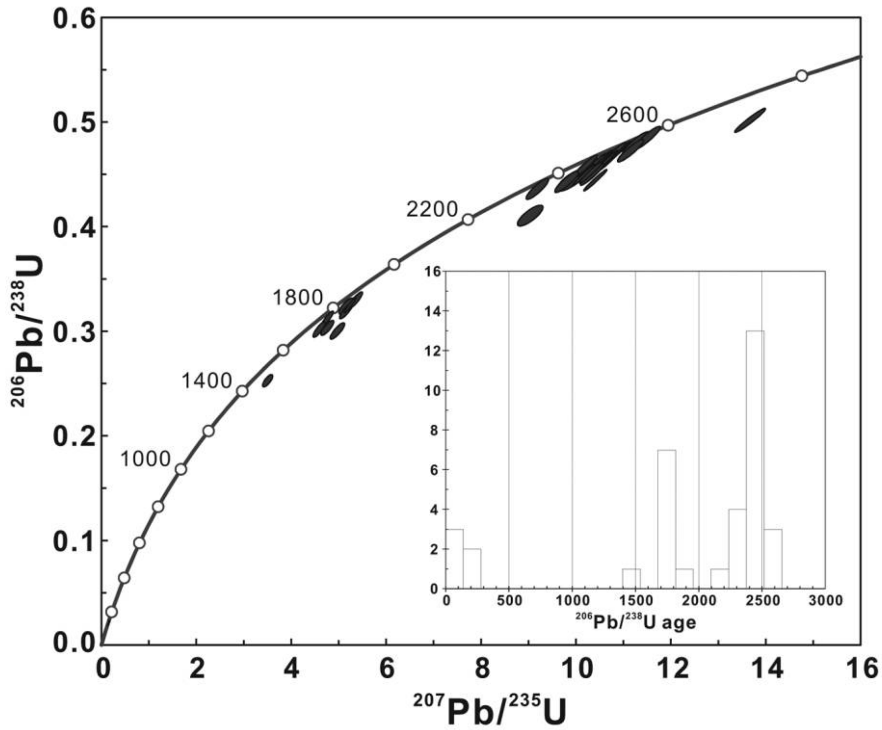

Figure 3. Zircon U-Pb concordia diagram and histogram of adakites from the Xu-Huai region. Like those of zircons in xenoliths, the ages can also be classified into three groups. Ages of 125–148 Ma represent the formation of adakites. The other two groups are typical inherited zircon ages in the North China Craton: 1330–2000 and 2220–2620 Ma. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

to lower continental crust melts (Ling et al. 2011*b*). In contrast, the Lower Yangtze River adakites do not display any correlation between $\delta^{26}Mg$ and 1/MgO: all plot in the mantle value. Because Mg isotope fractionation during magma differentiation is limited (Teng et al. 2007, 2010; Li et al. 2010; Liu et al. 2010*b*), the original melt of the Lower Yangtze River adakites may have an Mg isotopic composition similar to that of the mantle. Note that the Mg isotope composition of MORB is similar to that of the mantle (Teng et al. 2010). By contrast, the lower continental crust may have a Mg isotopic composition different from that of the mantle, as indicated by our Dabie adakite samples. Therefore, the mantle-like Mg isotopic composition of Lower Yangtze River samples is compatible with slab melting (Ling et al. 2009, 2011*b*; Liu et al. 2010*a*).

In previous studies, the Xu-Huai adakites were attributed to partial melting of the lower continental crust on the basis of lower-crustal xenoliths (Xu et al. 2006*a*, 2009*a*). Most of the xenoliths from the Xu-Huai adakites are garnet clinopyroxenite, with minor eclogite, which is different from those of subducted oceanic crust. These xenoliths have zircon age spectra typical of the NCC, with major peaks at 2.5 and 1.8 Ga (fig. 2; Chen et al. 2003), which was taken as the key evidence in favor of their lower-crustal origin and the delamination model (Xu et al. 2006*a*, 2009*a*).

Delaminated lower continental crust may be partially melted in the convecting mantle after being heated by the asthenosphere mantle. The *P*-*T* conditions of the asthenosphere, however, are not commonly recorded in the Xu-Huai xenoliths. The peak metamorphic *P* and *T* of these xenoliths have been estimated to be >15 kbar and 800°–1060°C (Xu et al. 2006*a*) or ~27 kbar and 750°–950°C, respectively (this study, fig. 7). The estimated *P*-*T* conditions for the xenoliths were calculated on the basis of several geobarometers and geothermometers (Ellis and Green 1979; Mercier 1980; Powell 1985; Krogh 1988). These *P*-*T* conditions are above (to the right of) those for the solidus of wet basalt but far below (to the left of) those for the solidus of dry basalt (fig. 7). Therefore, these xenoliths might have experienced partial melting, but only in wet conditions. Moreover, the lower continental crust of cratons is usually dry (Rudnick and Gao 2003; Menzies et al. 2007). The mineral assemblage of the Xu-Huai

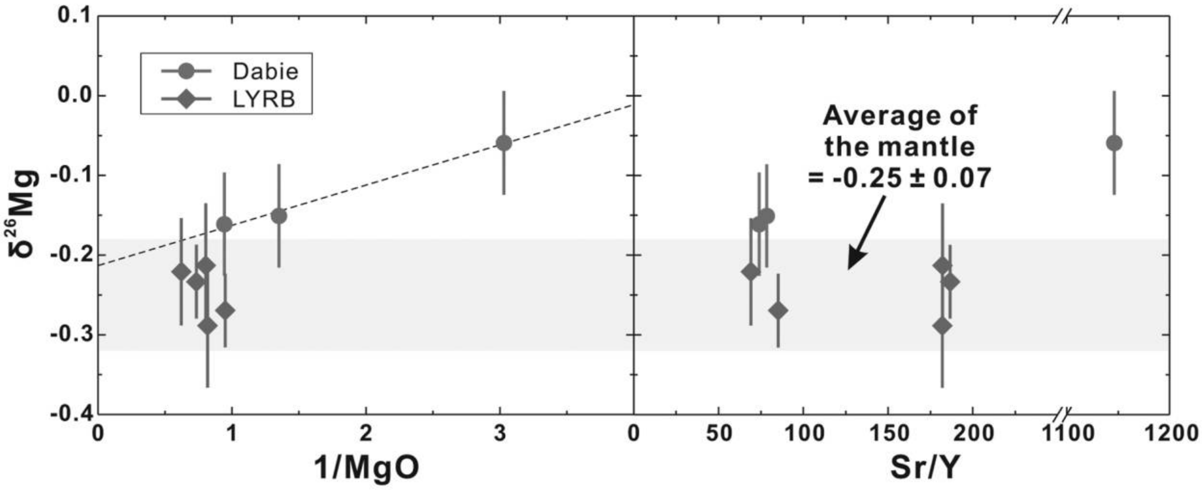

Figure 4. δ^{26}Mg versus 1/MgO and δ^{26}Mg versus Sr/Y diagrams for adakites from the Dabie Mountains and the Lower Yangtze River Belt (LYRB). Data are reported in table A3, available in the online edition or from the *Journal of Geology* office. Dabie adakite samples show a positive correlation between Mg isotope and 1/MgO, which can be best interpreted as indicating mixing between the mantle and the lower continental crust. See text for details. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

xenoliths shows low water contents. In this case, the xenoliths are not likely to initiate partial melting under the recorded *P*-*T* conditions (fig. 7); i.e., these xenoliths are not likely to be the main source of the host adakitic rocks. This is supported by the reactive rims of amphibole (with volatile components ranging from 1.1% to 4.5%) surrounding most of the xenoliths, which indicate that the host adakitic melt was wet, and these dry xenoliths are not in equilibrium with the wet melt. Adakite magma formed under "wet" conditions is consistent with our interpretation from geochemical data (fig. 5) that the petrogenesis of the Xu-Huai adakites involved partial melts of subducted oceanic slab.

The identical zircon age spectra of xenoliths with clear NCC affinity, however, suggest the same degree of partial melting of lower continental crust. Also of note is that rutile exsolutions in several garnet grains from some xenoliths (fig. 8) and aluminum-rich titanite exsolutions in clinopyroxene were used to argue that some of the xenoliths had been subjected to high- to ultrahigh-pressure metamorphism (Xu et al. 2006*a*). Nevertheless, the rare occurrence of primary amphibole in the xenoliths reported by previous authors (Xu et al. 2006*a*, 2009*a*) would suggest that only a very small amount of water was present. In fact, the lower-crustal rocks are usually at granulite facies, which may be transformed into eclogite facies through addition of fluids under appropriate *P*-*T* conditions (John et al. 2004). Addition of water from a subducted oceanic slab (Niu 2005) may have contributed to the eclogitization and subsequent partial melting of the NCC lower continental crust. These plausibly explain the fact that adakites from the Xu-Huai region and the Shandong Peninsula show geochemical and petrologic evidence for both slab and lower continental crust melts.

Ridge Subduction

Ridge subduction was a common phenomenon along the margins of the Pacific Plate and other convergent margins (Uyeda and Miyashiro 1974; Kinoshita 1995, 2002; Maruyama et al. 1997; Kim et al. 2005; Cole et al. 2006; Espurt et al. 2008; Cole and Stewart 2009; Ling et al. 2009; Tang et al. 2010). It is presumably a general process in the Earth's history, because when oceans close, all the ocean ridges must be consumed along convergent margins.

Ridge subduction is generally inferred to result in flat slabs that can extend several hundreds of kilometers or more inboard from the subduction zone beneath the overriding continent (Espurt et al. 2008). Subduction of ridges with axes perpendicular to the subduction zone can form linearly distributed adakites commonly associated with Cu-Au porphyry deposits (Cooke et al. 2005; Sun et al. 2010, 2011). This provides the best explanation for the three linearly distributed late Mesozoic adakite belts in eastern China that are situated far from the current subduction zone. The first ridge subduction occurred near the northern margin of the NCC in

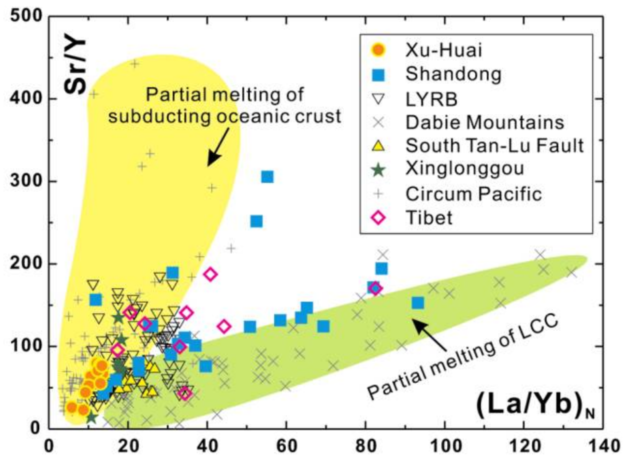

Figure 5. Sr/Y versus $(La/Yb)_N$ diagram discriminating adakites of different origin. $(La/Yb)_N$ ratios are chondrite-normalized values (Sun and McDonough 1989). Circum-Pacific data are compiled from the adakite data of GEOROC (2010), which represent the typical origin of partial melting of subducted young oceanic crust. Adakites from the Dabie Mountains and the South Tan-Lu fault originated from partial melting of lower continental crust (LCC; Wang et al. 2007*a*; Huang et al. 2008; Liu et al. 2010*a*). Adakites of Xinglonggou in the North China Craton and Xu-Huai adakite indicate major components from subducting oceanic crust (table A1, available in the online edition or from the *Journal of Geology* office). Shandong adakite indicates diverse origins (Xu et al. 2004), similar to adakite of Tibet (Chung et al. 2003). Several samples from Luzon that formed through partial melting of a subducted back-arc basin plot slightly offset from the field defined by circum-Pacific adakites. LYRB = Lower Yangtze River Belt.

the Jurassic, the second formed the LYRB in the Early Cretaceous (140 ± 5 Ma; Ling et al. 2009), and the third formed the Shandong Peninsula and the Xu-Huai belts at 130 ± 5 Ma.

Ridge Subduction along the Northern Margin of the NCC. The widely distributed mid-Jurassic granites in the Okcheon, Gyeonggi, and Yeongnam regions in South Korea (200 km long and >150 km wide) were attributed to ridge subduction by Uyeda and Miyashiro (1974). This was supported by later studies (Maruyama et al. 1997; Kim et al. 2005). It has been proposed that subduction of the Farallon-Izanagi ridge under the Korean Peninsula caused large-scale magmatism in the Korean Peninsula until around 165 Ma, with the main magmatic period between 175 and 166 Ma (Kim et al. 2005). According to published data, many of the Jurassic granites in the Korean Peninsula are adakitic or A-type diorite/granites. Therefore, the Jurassic adakitic belt along the northern margin of the NCC (fig. 1) may extend farther east to the large-scale magmatic belt in Korea. In the Sr/Y-versus-$(La/Yb)_N$ diagram (fig. 5), most of the Jurassic adakites fall in the circum-Pacific field, with several in the overlap region between the circum-Pacific and Dabie adakite fields. The best explanation for such large-scale magmatism of these chemical characteristics is ridge subduction. More-detailed work is needed to better constrain the process of the ridge subduction and understand why so few Cu-Au porphyry deposits have been discovered along this belt. A likely reason for the lack of Cu is that most of these adakitic rocks are deep intrusive rocks that have not experienced further Cu enrichment at shallow depths (Sun et al. 2004, 2007*a*) or that the shallow porphyries have been eroded.

Ridge Subduction along the Lower Yangtze River. The adakite belt along the Lower Yangtze River is considered a result of a ridge subduction that occurred at 140 ± 5 Ma (Ling et al. 2009), on the

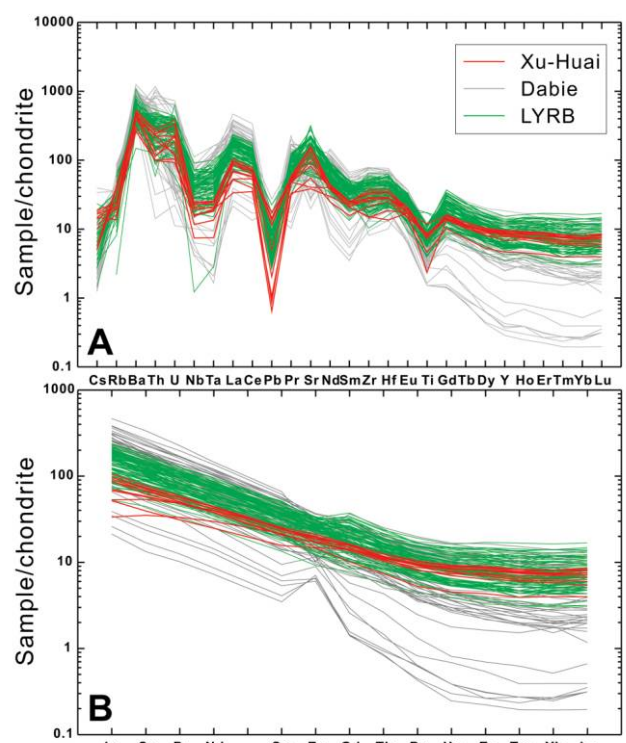

Figure 6. Chondrite normalized spidergram (*A*) and rare earth element pattern (*B*) of adakites from Xu-Huai region (data in this study), compared with those from the Dabie orogen and the Lower Yangtze River Belt (LYRB; data from Ling et al. 2009, 2011*b* and references therein). Xu-Huai adakites are similar to those from the LYRB, with affinity of slab melting, but distinct from those from the Dabie orogen, with lower continental crust origin. Chondrite values are from Sun and McDonough (1989).

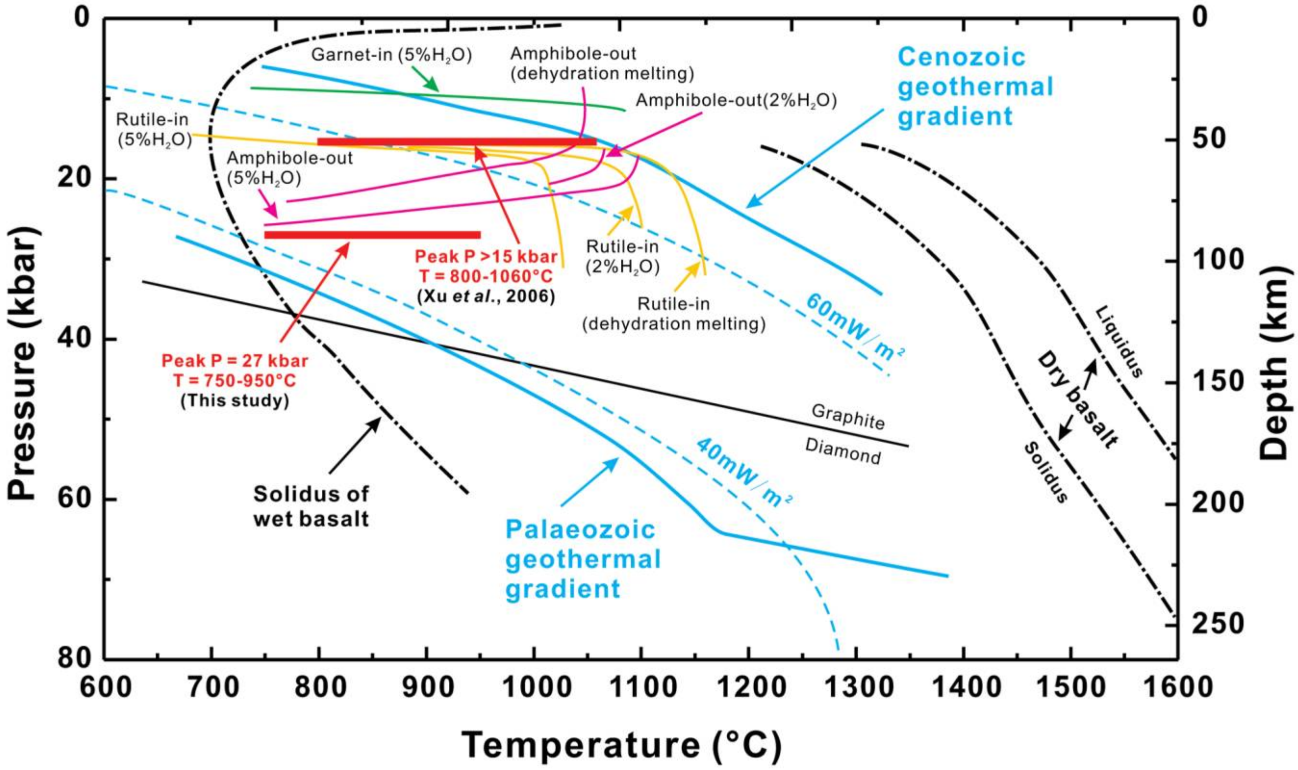

Figure 7. Pressure-temperature (*P-T*) diagram showing the metamorphic condition of eclogitic xenoliths, as well as wet- and dry-solidus lines; typical geothermal gradients are after Xu (2001). The *P-T* boundaries of garnet, amphibole, and rutile are after Xiong et al. (2005). The *P* and *T* of peak metamorphism of the xenoliths are estimated to be >15 kbar and 800°–1060°C, respectively, based on a 19–29 mol% jadeite component in omphacite (Xu et al. 2006*a*), or 27 kbar and 750°–950°C, using different conventional geobarometers and geothermometers (this study). Solidus and liquidus lines of dry basalt are from Yaxley (2000). The solidus of wet basalt is from Lee and King (2010), indicating that water content dramatically decreases the temperatures of partial melting. For *P-T* calculation, single-clinopyroxene thermobarometry (Mercier 1980) yielded $P = 27$ kbar, $T = 758$°C. A *P* value of 27 kbar was then used to calculate temperature in the following garnet-clinopyroxene thermometers: (1) Ellis and Green (1979): $T = 965$°C, (2) Powell (1985): T = 940°C; (3) Krogh (1988): $T = 885$°C. In summary, the *T* is between 750° and 950°C.

basis of the distribution of adakite, A-type granites, and Cu-Au deposits as well as the drifting history of the Pacific and Izanagi Plates (Maruyama et al. 1997; Koppers et al. 2001; Sun et al. 2007*b*). Dabie adakites, located to the northwest of the Lower Yangtze River farther from the subduction zone, were formed through partial melting of the lower continental crust (Wang et al. 2007*a*; Huang et al. 2008) delaminated by ridge subduction (Ling et al. 2011*b*).

Ridge Subduction along the Shandong Peninsula and in the Xu-Huai Region. The Xu-Huai adakites are spatially associated with arc-shaped nappe structures in the Xu-Huai region (fig. 1). They are spatially associated with the Cretaceous Shandong adakite belt, with identical formation ages of 130 ± 5 Ma (figs. 1, 3; table A2). Shandong adakites fall in both the slab and lower continental crust partial-melt fields defined by circum-Pacific and Dabie Mountain samples, respectively (fig. 5). In addition to adakites, there is an A-type granite belt about 500 km long, formed about 10 m.yr. after the adakite event along the Shandong Peninsula and the Xu-Huai region (Wang et al. 1995).

The Shandong Peninsula is separated from the Xu-Huai region and the NCC by the Tan-Lu fault. Previous studies suggested that the total offset along the Tan-Lu fault was more than 550 km (Zhu et al. 2005) or even 1000–1500 km (Xu et al. 1987) from the Triassic to the present day. We estimate the displacement of the Shandong Peninsula since the Cretaceous at about 100–200 km.

With the offset of the Tan-Lu wrench fault (Xu

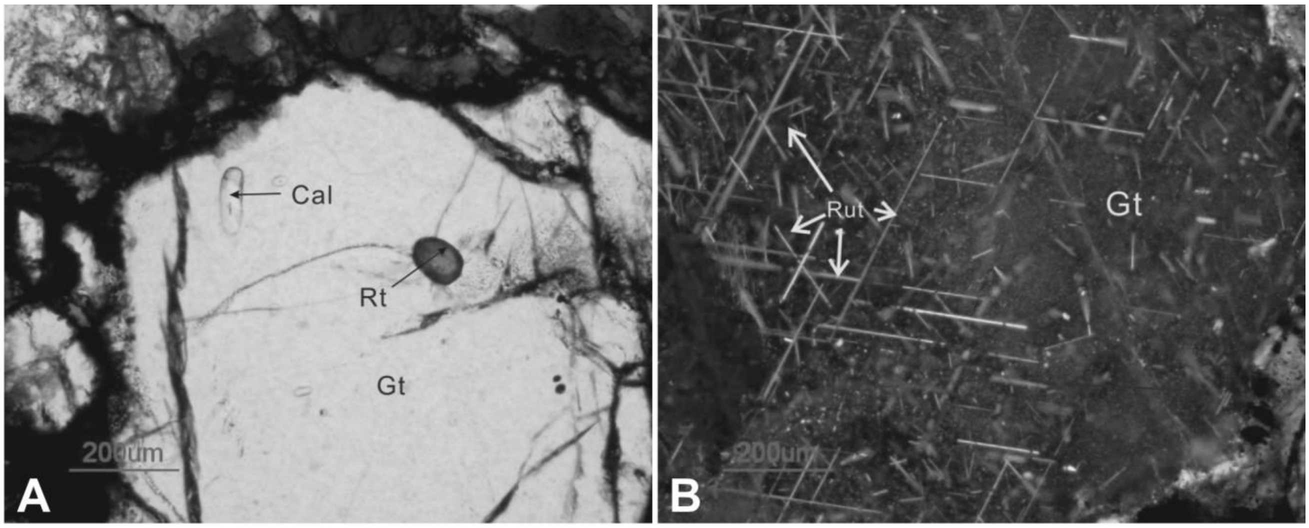

Figure 8. Photomicrographs of garnet (Gt) with calcite (Cal) and rutile (Rt) inclusions (*A*) and rutile (Rut) exsolutions (*B*) in eclogitic xenoliths from Jiagou in the Xu-Huai region, indicating ultrahigh pressures. See the text for details. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

et al. 1987) taken into account, the Shandong Peninsula was located along strike with the Xu-Huai adakites. Considering that the northwestward drifting of the Izanagi Plate was faster than the southwestward drifting of the Pacific Plate in the Early Cretaceous, the ridge between these two plates moved northward and probably shifted from the LYRB to the Shandong Peninsula in about 10 m.yr. (Sun et al. 2007*b*), which is compatible with the ages of the two adakite belts.

The Ridge Subduction Model. All the phenomena mentioned above can be interpreted by a ridge subduction model. Adakites were formed by partial melting of the subducting slab and probably also delaminated lower continental crust. A-type granites may form as a result of slab window and slab rollback processes after ridge subduction (Benoit et al. 2002; Li et al. 2012). All these magmatisms provide strong chemical erosion agents.

Shandong Peninsula is well known for the Sulu ultrahigh-pressure metamorphic belt, which is the eastern part of the Triassic Dabie-Sulu orogenic belt. The continental crust and lithospheric mantle there thickened during the Triassic collision between the North and South China Blocks, so that this region was more resistant to flat subduction, i.e., to stronger interactions, and thus was more likely to be delaminated during ridge subduction. Destruction of the lithospheric mantle led to partial melting of the lower continental crust as a result of hydration and basal heating from the asthenosphere. Therefore, the Shandong adakite belt consists of both slab and lower continental crust partial melts.

Similar to the wide distribution of A-type granites in the Shandong Peninsula and the Xu-Huai region, abundant Late Mesozoic A-type granites in the eastern part of the NCC formed after the adakitic rocks. For example, in the LYRB, A-type granites (Fan et al. 2008; Li et al. 2011) formed about 15 m.yr. later than adakitic rocks in the same region (Wang et al. 2006; Xie et al. 2009) and associated mineralization (Sun et al. 2003; Mao et al. 2006; Xie et al. 2007). A similar pattern is found in Jurassic granites in the Korean Peninsula (Kim et al. 2005). All these are consistent with the ridge subduction model.

Decratonization Induced by Ridge Subduction. It is now generally accepted that the Early Cretaceous was an important period of lithospheric thinning in the NCC (Zhang et al. 2002, 2003; Menzies et al. 2007), as indicated by the so-called great igneous event (Wu et al. 2005). Remarkably, the geochemical compositions of mafic rocks in eastern China changed from enriched to depleted (Xu 2001; Yang et al. 2003). The first Cretaceous basalt with depleted Nd isotope compositions in the NCC was formed at about 120 Ma (Xu 2001). Consistently, mantle peridotite xenoliths hosted in Cenozoic basalts also show depleted isotopic signatures (Fan et al. 2000; Xu 2001). These events coincide with the ridge subduction along the Shandong Peninsula, implying that the decratonization of the NCC was induced by the last ridge subduction, which occurred at ~130 Ma.

The flat subduction of a spreading ridge is inferred to have resulted in stronger physical subduction-related erosion. The lithospheric mantle of the central eastern NCC was first physically destroyed during the ridge subduction, then thermally eroded by adakitic magmas and eroded by upwelling asthenosphere and A-type magmas at about 130–120 Ma. The evolvement of enriched metasome horizons of the mantle keel (Xu 2001) might then explain the enriched isotopic characteristics of adakites and A-type granites in the NCC.

We propose that ridge subduction events in the late Mesozoic were responsible for the destruction of the NCC. The final decratonization was induced by the ridge subduction at 130 ± 5 Ma along the Shandong Peninsula, pointing toward the center of the NCC. The other two ridge subductions, along the LYRB at 140 ± 5 Ma and along the northern margin of the NCC at 170 ± 5 Ma (fig. 1), also contributed to the destruction of the NCC but affected only the southern and northern margins, respectively.

Previous studies proposed that the drifting direction of the Pacific Plate changed suddenly by about 80°, from southwestward to northwestward, at about 120–125 Ma, likely as a result of the onset of the Ontong Java large igneous province (Sun et al. 2007*b*), although this scenario is still not well agreed on (Li and Li 2007; Wessel and Kroenke 2008). Nevertheless, the oldest part of the West Pacific oceanic crust is Jurassic and is located in the south (near Ontong Java); the crust becomes younger to the north (e.g., Seton et al. 2012). Such an age distribution of oceanic crust is consistent with a southward drifting; at the least, a Pacific spreading ridge was located in the north. Moreover, Wessel and Kroenke (2008) also showed the bending of the Skatsky Rise. To us, the best explanation of this bending is a major change in drifting direction. After this transition, the Pacific and Izanagi Plates drifted in roughly the same direction. Consequently, the ridge between these two plates gradually stopped growing and moved quickly farther north. No major ridge subduction after the Late Cretaceous has been recognized in eastern China.

Conclusion

Ridge subduction events in the late Mesozoic are interpreted as being responsible for the destruction of the NCC. The main decratonization was induced by the ridge subduction at 130 ± 5 Ma along the Shandong Peninsula and in the Xu-Huai region. Ridge subduction at 140 ± 5 Ma along the LYRB may have also contributed to the destruction of the NCC but affected only the south margin, and the Jurassic ridge subduction along the northern margin of the NCC at 170 ± 5 Ma presumably mainly influenced the north margin.

Adakites formed during these ridge subductions consist of both slab and lower continental crust melts. Some of the lower continental crust may have been delaminated down to the asthenosphere, as indicated by rutile exsolutions in garnet, whereas the majority of lower-crust xenoliths from the Xu-Huai region are dry and in disequilibrium with the host wet adakitic magmas.

Ridge subduction is inevitable during the closure of an ocean, such that it has occurred continuously through Earth's history. Therefore, decratonization has presumably occurred periodically, transforming margins of cratons into orogenic belts and shaping the chemical compositions of the continental crust, although less commonly under preexisting cratons.

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