Chinese Science Bulletin 2003 Vol. 48 No.8 831—838

Decoupling of surface and subsurface sutures in the Dabie orogen and a continent-collisional lithospheric-wedging model: Sr-Nd-Pb isotopic evidences of Mesozoic igneous rocks in eastern China

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Abstract **There are significant differences of Nd and Pb isotopic compositions between Mesozoic mafic igneous rocks from the North China Block (NCB) and the South China Block (SCB). Mesozoic mantle-derived igneous rocks from the North China Block have very low ε_{Nd} values (- 15 to - 21), and $^{206}Pb/^{204}Pb$ ratios (< 17.9), while those in the SCB are characterized by ε_{Nd} > - 10 and $^{206}Pb/^{204}Pb$ > 18.3. The very low ε_{Nd} values (- 16 to - 20) and $^{206}Pb/^{204}Pb$ ratios (< 17.3) of the early Cretaceous mafic-ultramafic intrusions developed in the north part of the Dabie orogen (NDZ) suggest that the deep lithosphere underneath the NDZ belongs to the NCB but not the SCB. Therefore, although the surface suture between the NCB and SCB is located on the north side of the NDZ, the subsurface suture between the NCB and SCB should be located to the south side of the NDZ. This is consistent with the previous suggestion that the subsurface suture in the Sulu terrane east of the Tanlu fault was the south displacement, but contradictory to northward continental subduction of the SCB. A continent-collisional lithospheric-wedging model can interpret the decoupling of the surface and subsurface sutures in the Dabie-Sulu orogen. After slab break-off, the continuing convergence of two continental blocks must increase the compression force acting on the suture zone, which might induce the lithosphere splitting of SCB. Thus, the lower crust and lithospheric mantle on the south margin of the NCB can wedge into the north margin of the lithosphere of the SCB along the Dabie-Sulu collision zone. This process caused the overthrust of the mid-upper continental crust with exhumed ultrahigh pressure metamorphic (UHPM) rocks and underthrust of the deep lithosphere of the SCB. It could be an important mechanism responsible for the second rapid cooling and uplifting of the UHPM rocks and lithospheric delamination as well as the corresponding magmatism in Jurassic in the Dabie orogen. The southward movement of subsurface suture in the Dabie-Sulu orogen may also provide a tectonic setting in depth for the large-scale Mesozoic magmatic-metallogenesis along the middle-lower reaches of the Yangtse River in eastern China.**

Keywords: Dabie orogen, post-collisional tectonics, Mesozoic mafic igneous rocks in eastern China, Sr-Nd-Pb isotopic geochemistry.

DOI: 10.1360/01wd0554

Based on the distribution of UHPM rocks on the surface in Sulu terrane, the surface suture between the NCB and SCB should be located along the Wulian fault (see Fig. 1, S1). However, based on the aeromagnetic data of eastern China, Li[1] first indicated that the subsurface suture between the NCB and SCB in the region east of the Tan-Lu fault should be located to the east of Nanjing City (see Fig. 1, S2), which south displaced about 400 km from the surface suture. This is contradictory with the northward subduction of the continental crust of the SCB. Li[1] proposed a crust detachment model for suturing to interpret such decoupling between the surface suture and subsurface suture.

In a geochemical study of Cenozoic basalts in eastern China, Chung observed that the Sr-Nd-Pb isotopic features of Cenozoic basalts in the Liuhe area north of the Nanjing (see Fig. 1) are similar to those of Cenozoic basalts in the NCB, but different from those in the SCB[2]. Based on this observation, Chung suggests that the lithospheric mantle underneath the Liuhe area belongs to the NCB and the subsurface suture between the NCB and SCB in the region east of the Tan-Lu fault should be located to the south of the Liuhe area[2], which supports the assumption proposed by Li[1].

Obviously, the decoupling of the surface and subsurface sutures in the region east of the Tan-Lu fault observed by Li[1] and Chung[2] provides a new constraint on the tectonics in the Dabie-Sulu orogen. However, the following questions still remain: (1) Location of the subsurface suture in the region west of the Tan-Lu fault is still unknown; (2) some questions concerning the crustal detachment model, such as when and where did the crustal detachment take place need more constraints and comprehensive discussion; and (3) the geological implication of the south displacement of the subsurface suture for magmatism in the Dabie-Sulu orogen and adjacent area has not been discussed.

These questions are keys to understanding of the tectonic process resulting in such decoupling between the surface suture and subsurface suture, its motion forces and geological implications. Synthesizing the published Sr-Nd-Pb isotopic data of Mesozoic mantle-derived rocks in eastern China including the Dabie orogen, this paper will identify the location of the subsurface suture between the NCB and SCB in the region west of the Tan-Lu fault and give a comprehensive discussion on the above questions.

1 Data source

Almost all studies of Mesozoic mafic igneous rocks in eastern China concluded that their magmata were derived from enriched lithospheric mantle or plus some

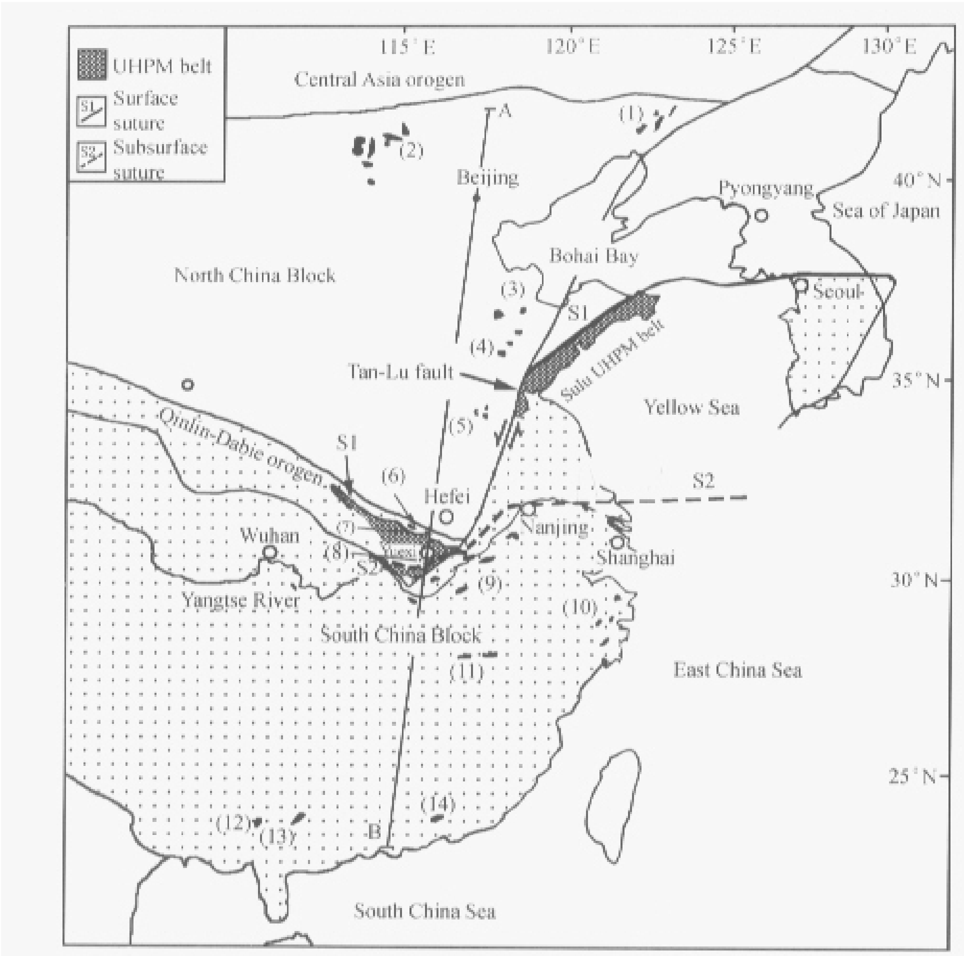

Fig. 1. Tectonic sketch map of the North and South China blocks (after Chung, 1999)[2]. Black areas (locations 1—14) indicate outcrops of Mesozoic mafic igneous rocks emplaced in the regions west of the Tan-Lu fault, which Sr-Nd-Pb isotopic data have been reported. S1 and S2 mark the surface and subsurface sutures between the North and South China blocks, respectively. A Nd isotope cross section along AB direction is drawn in Fig. 4. Sample locations: 1, Liaoxi-Jibei; 2, Hannuoba, Hebei Province; 3, Jinan, Zouping; 4, Luxi; 5, Xuzhou-Suzhou; 6, Beihuaiyang; 7, Zhujiapu; 8, Zhongguan, Yuxi; 9, Middle-lower reaches of Yangtse River; 10, Coast area of Zhejiang Province; 11, Shangrao-Guangfeng; 12, Guidongnan; 13, Western Guangdong; 14, Shantou, Guangdong Province.

lower crustal compositions[3—19]. Therefore, the Sr-Nd-Pb isotopic compositions of the mafic igneous rocks from the NCB, SCB and Dabie orogen can indicate the geochemical features of their lithospheric mantle and lower crust.

The data used in this paper are Sr-Nd-Pb isotopic data of Mesozoic igneous rocks including pyroxenite, gabbro, basalt, minor shoshonit and mafic granulite nodule formed during magma underplating in the Mesozoic time from the NCB, SCB and Dabie orogen[3—19]. The distribution of these rocks in eastern China is shown in Fig. 1. Most of them were formed in the early Cretaceous (130—110 Ma), and a few of them were formed in the Jurassic (190—160 Ma). In order to compare each other, the data collected in different laboratories were adjusted relative to the standard values: NBS-987 $^{87}Sr/^{86}Sr$ = 0.710250; BCR-1 $^{143}Nd/^{144}Nd$ = 0.512630; NBS-981 $^{207}Pb/^{206}Pb$ = 0.9142 ± 0.0015. The normalized Sr-Nd isotopic data were calculated back to their formation ages to obtain their initial isotopic ratios which are plotted on the Sr-Nd isotopic diagram (Fig. 2). The Pb isotopic data have not been calculated back to their formation ages because of the absence of U/Pb ratios for most of the samples. However, U-Pb isotopic study of the Zhujiapu pyroxenite-gabbro shows that both the μ values and ages of such mafic igneous rocks are low enough so that their age corrections are very small and cannot influence our discussion[11].

2 Difference in Sr-Nd-Pb isotopic compositions of Mesozoic mafic igneous rocks in the NCB and the SCB

Fig. 2 shows that Mesozoic mafic igneous rocks from the NCB and the SCB have similar Sr isotopic compositions, but different ε_{Nd} values. The lowest ε_{Nd} values of the samples from the NCB range from –15 to

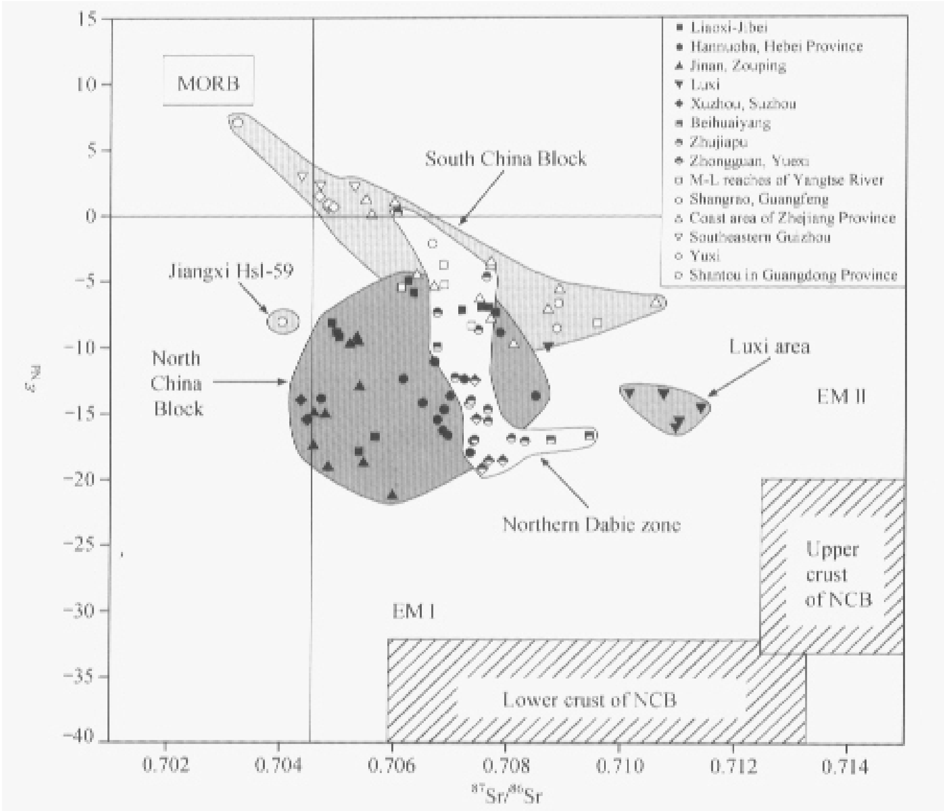

Fig. 2. $\varepsilon_{\mathrm{Nd}}$ versus $^{87}Sr/^{86}Sr$ plot of Mesozoic mafic igneous rocks from the NCB, SCB and Dabie orogen. All data plotted on this plot are initial isotopic ratios corresponding to their formation times. Data are collected from refs. [3—10] and [12—20]. The upper and lower crustal fields of the North China Block are from ref. [4]. MORB field is from ref. [22].

–21, while the lowest $\varepsilon_{\mathrm{Nd}}$ values of the samples from the SCB are higher than –10. The samples with $\varepsilon_{\mathrm{Nd}} > 0$ are from the south part of the SCB, while the samples from the north part (i.e. Yangtse craton) of the SCB have similar $\varepsilon_{\mathrm{Nd}}$ values with the lowest $\varepsilon_{\mathrm{Nd}}$ ranging from –9.2 to –9.8. This difference reflects the different Nd isotopic compositions of the enriched components of their magma sources. Fig. 2 also shows that the Sr-Nd isotopic compositions of the most of Mesozoic mafic rocks from the SCB display a mixing trend between the depleted mantle and EM Ⅱ component except one sample (Hsl-59). By contrast, the Sr-Nd isotopic compositions of the most of Mesozoic mafic rocks from the NCB, except a minor K-rich volcanic rocks or lamproites in the Luxi area, could be a mixing result between a depleted or less depleted mantle and EM Ⅰ component. The K-rich volcanic rocks with EM Ⅱ feature in the Luxi area may reflect that this source was metasomatized by fluid derived from a subducting plate[8]. The overlap of these two isotope provinces for Mesozoic mafic igneous rocks from the NCB and the SCB in Fig. 2 seemingly indicate that the depleted mantle source was shared by all Mesozoic mafic igneous rocks in eastern China. This isotopic feature has also been observed in Cenozoic basalt in eastern China. Cenozoic basalts from the NCB commonly show an EM Ⅰ type isotopic feature marked by relatively low $\varepsilon_{\mathrm{Nd}}$ and $^{206}Pb/^{204}Pb$ ratios, while Cenozoic basalts from the SCB have EM Ⅰ type isotope signature with relatively high $\varepsilon_{\mathrm{Nd}}$ and $^{206}Pb/^{204}Pb$ ratios[2]. The overlap of these two isotopic provinces for Cenozoic basalts in eastern China is most likely representative of the depleted mantle source shared by Cenozoic basalts over eastern China[2]. Actually, a part of Cenozoic basalts from the NCB also displays an EM Ⅱ feature[21].

Two possible interpretations for the Sr-Nd isotopic features of Mesozoic mafic igneous rocks in eastern China have been proposed: (1) These Mesozoic mafic magmas were derived from the enriched lithospheric mantle with EM Ⅰ or EM Ⅱ features respectively[5,6]. The much lower $\varepsilon_{\mathrm{Nd}}$ values of Mesozoic mafic rocks from the NCB may reflect the stronger enrichment or older enriched time of their lithospheric mantle source than those in the SCB; (2) the EM Ⅰ and EM Ⅱ features of Mesozoic mafic rocks in eastern China are results of mantle-crust interaction[3,4]. Therefore, they reflect composite characteristics of deep continental lithosphere including lithospheric mantle and lower crust of the NCB and the SCB. Because of much wider distribution of the Archean rocks in the NCB than that in the SCB, the much lower ε_{Nd} of Mesozoic mafic rocks in the NCB may reflect the older ages of lower crust in the NCB than that in the SCB. Although we prefer the second interpretation, evaluating the two interpretations is not the aim of this paper. However, the common point of the two interpretations is that the ε_{Nd} difference between Mesozoic mafic rocks from the NCB and the SCB reflects the difference of Nd isotopic compositions of the deep lithosphere between the two continental blocks. Whether the deep lithosphere includes lower crust does not influence the discussion in this paper. Therefore, the abrupt change zone of ε_{Nd} values of Mesozoic mafic igneous rocks in eastern China should be the boundary or suture location of the deep lithosphere between the NCB and the SCB.

Although the published Pb isotopic data of Mesozoic mafic igneous rocks in eastern China are much less than the Sr-Nd isotopic data of them, the samples with Pb isotopic data were collected from the most of areas in the NCB and the SCB, such as the north area and middle area in the NCB and north area and eastern area in the SCB. The available Pb isotopic data show the significant difference of Pb isotopic compositions between Mesozoic mafic rocks from the NCB and the SCB. Fig. 2 shows that Mesozoic mafic igneous rocks from the NCB have an EM Ⅰ type isotope signature with significantly lower radiogenic Pb ($^{206}Pb/^{204}Pb < 17.9$), while Mesozoic mafic igneous rocks from the SCB display an EM Ⅱ type isotope affinity marked by relatively high radiogenic Pb ($^{206}Pb/^{204}Pb > 18.0$). This is very similar to that displayed by the Pb isotopic data of Cenozoic basalts in eastern China[2]. Hence, the Pb isotopic ratios of Mesozoic mafic igneous rocks from the Dabie orogen can also be used to identify whether the lithospheric nature of their magma source is similar to the NCB or SCB.

3 Location of subsurface suture in Dabie orogen to the west of Tan-Lu fault

It is, in general, accepted that the Dabie orogen can be subdivided into four metamorphic zones from north to south: (1) Beihuaiyang greenschist-amphibolite facies zone (Beihuaiyang zone); (2) northern Dabie complex zone (NDZ); (3) southern Dabie UHPM zone (SDZ); and (4) Hongan-Susong high-pressure metamorphic (HPM) zone. Obviously, the SDZ and Hongan-Susong HPM zone are parts of the subducted continental crust of the SCB. Abundant geological and geochemical studies[23], especially the discovery of Triassic eclogites in the NDZ[24,25], document that the NDZ is also a part of subducted continental crust of the SCB. In contrast, the Paleozoic island arc volcanic rocks were observed in the Beihuaiyang zone[23]. Therefore, many of researchers believe that the surface suture between the NCB and the SCB should be located on the north side of the NDZ[23].

Post-collisional gabbro-pyroxenite intrusions were broadly developed in the north part of the Dabie Mountains including the Beihuaiyang zone and the north Dabie complex zone. Their U-Pb zircon ages range from 120 to 130 Ma[23,24]. The Sr-Nd isotopic data of the most of them, such as the Shanqilihe and Wangjiachong gabbros in the Beihuaiyang zone, the Zhujiapu, Tongjiachong and Renjiawan pyroxenites in the north part of the NDZ and Zhongguan gabbro-pyroxenite on the south margin of the NDZ, have been reported[3,4]. Fig. 2 shows that the Sr-Nd isotopic compositions of the early Cretaceous mafic-ultramafic intrusions in the Dabie orogen display a mixing trend between depleted mantle and EM Ⅰ component with very low ε_{Nd} values (–16 to –19), which are very similar to those of Mesozoic mafic igneous rocks in the NCB. Huang et al. (2002) have published U-Pb isotopic data of Zhujiapu pyroxenite-gabbro samples from the NDZ[11]. Although Zhujiapu pyroxenite-gabbro has relatively high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios, their low radiogenic Pb ($^{206}Pb/^{204}Pb < 17.3$) is similar to those of Mesozoic mafic igneous rock in the NCB (Fig. 3). Their relatively high $^{207}Pb/^{204}Pb$ and Th/U ratios may be related to the LOMU component in their magma source[11]. These Sr-Nd-Pb isotopic observations suggest that the deep lithosphere underneath the NDZ should be a part of the lithosphere of the NCB.

When projecting all Nd isotopic data of Mesozoic mafic igneous rocks on a section across the eastern China from north to south (Fig. 4), we observed that the ε_{Nd} values on this section abruptly change at the point located in between the NDZ and the north side of the Yangtse River. It is indicated that the subsurface suture between the NCB and the SCB in the Dabie orogen should be located to the south side of the NDZ. Therefore, although the exact location of the subsurface suture cannot be well defined because of the absence of Nd isotopic data of Mesozoic mafic igneous rocks from the southern Dabie zone, the subsurface suture in the Dabie orogen no doubt south displaced 50 km at least relative to the surface suture.

4 A continent-collisional lithospheric-wedging model for interpretation of the decoupling between the surface and subsurface sutures in the Dabie-Sulu orogen

Our observations provide strong evidence for the existence of the decoupling between the surface suture and the subsurface suture in the Dabie orogen west of the Tan-Lu fault. It is suggested that the detachment between subducted upper and lower continental crusts proposed by Li[1] is not a special tectonic process in the region east of the Tan-Lu fault, but a common tectonic process in the whole Dabie-Sulu orogen. A continent-collisional lithospheric-wedging model can interpret the decoupling between the subsurface and surface sutures in the whole

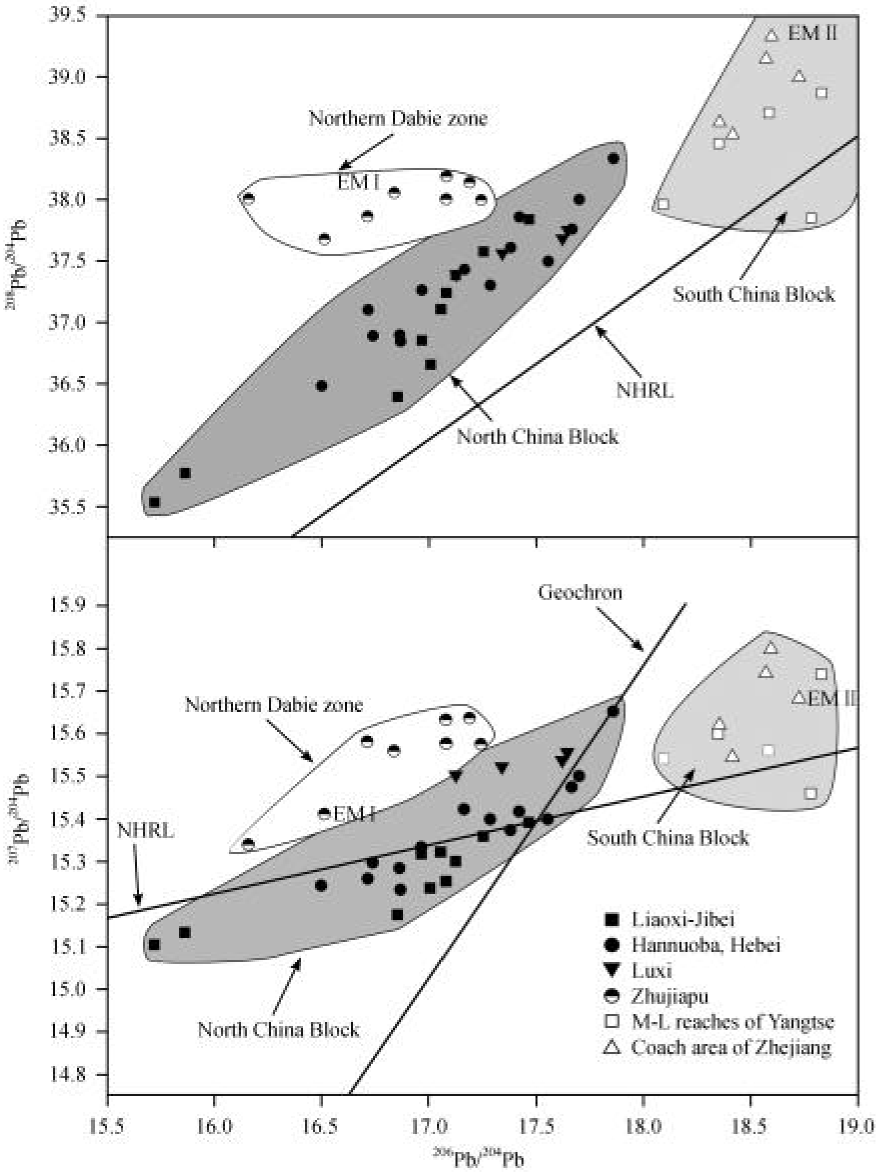

Fig. 3. Plots of $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ of Mesozoic mafic igneous rocks from the NCB, SCB and Dabie orogen. Locations of EM Ⅰ and EM Ⅱ components and the Northern Hemisphere reference line (NHRL) as well as Geochron are from ref. [22]. Data are collected from refs. [5, 8, 10—13, 16].

Dabie-Sulu orogen. This model is similar to the crustal-detachment model for suturing suggested by Li[1], but gives some new constraints as follows:

(1) The HPM and UHPM rocks have been exhumed on the surface overlying above the lithosphere of the NCB. Hence, the detachment of the subducted continental crust of the SCB must occur after that time when UHPM rocks were uplifted to the middle or upper crust level, but did not occur during the continental subduction time. The cooling *T-t* path of UHPM rocks from the Dabie orogen has revealed that the UHPM rocks experienced the first rapid cooling event from 226 to 219 Ma, which was cooled down to 500℃ corresponding to middle crust level[28]. This first rapid cooling time of the UHPM rocks is consistent with the U-Pb zircon ages (220—210 Ma) of the syncollisional granites from the Qinling-Dabie orogen[29,30]. This time consistence suggests that the first rapid cooling and uplifting of UHPM rocks in the Dabie orogen might be caused by break-off of the subducted plate[31]. Therefore, the detachment of the subducted continental crust of the SCB should occur after the later Triassic.

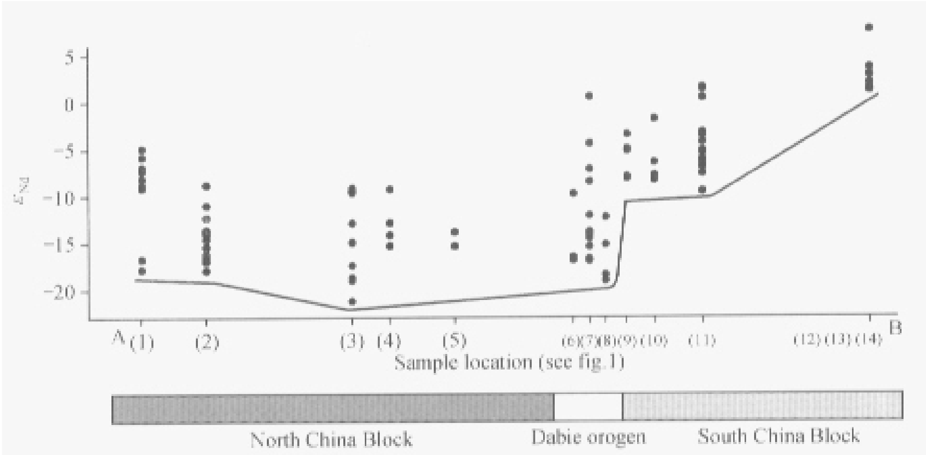

Fig. 4. A Nd isotope cross section along AB direction in eastern China (see Fig. 1) showing the abrupt change of the ε_{Nd} values of the deep lithosphere at a point located in between the NDZ and north side of the Yangtse River. The ε_{Nd} values are initial values corresponding to the formation times of Mesozoic mafic igneous rocks.

(2) The south displacement of the subsurface suture in the Dabie orogen is revealed based on the isotopic data of the early Cretaceous mafic igneous rocks, hence, the south displacement event of the subsurface suture should occur before the early Cretaceous. In addition, Fig. 2 shows that the subsurface suture in the region east of the Tan-Lu fault displaced about 150 km to the north relative to the subsurface suture in the region (Dabie orogen) west of the Tan-Lu fault. Obviously, this displacement is the result of the left-lateral slip of the Tan-Lu fault, which occurred in the early Cretaceous[32,33]. Therefore, the decoupling between the surface and subsurface sutures in the Dabie-Sulu orogen should occur before the early Cretaceous.

(3) Petrological and U-Pb isotope geochemical studies suggest that the eclogite and gray gneisses in the NDZ have lower-middle crustal features[26,34]. Since the northern Dabie metamorphic complex, as a part of subducted continental crust of SCB, is located to the north of the subsurface suture in the Dabie orogen, it should be an overthrust crust overlying above the lithosphere of NCB. Therefore, the detachment in the continental lithosphere of SCB could occur at the main thrust fault separating the exhumed continental crust and unexhumed high dense mafic lower crust and lithospheric mantle.

Based on the above reasons, we suggest a continent-collisional lithospheric-wedging model to interpret the south displacement of the subsurface suture in the Dabie-Sulu orogen. After break-off of the subducted plate and the initial exhumation of UHPM rocks from the mantle depth to mid-crust level, the convergence between the NCB and the SCB continued. Such continuing convergence after slab break-off has been observed in Alps[31] and Himalaya[35] belts, and results in a very highly compressional regime in the collision zone. In this condition, the lithosphere of the SCB was finally splitted and the south margin of the NCB wedged into the lithosphere of the SCB along the Dabie-Sulu orogen. This process induced the overthrust of the mid-upper continental crust with exhumed UHPM rocks and the underthrust of the subducted mafic lower crust (eclogite) and lithospheric mantle of the SCB. The underthrust lithosphere of the SCB may be finally delaminated, so that the subsurface suture between the NCB and the SCB was moved to the south relative to the surface suture. In the meantime, the upper crust on the south margin of the NCB was detached with the lower crust and was pushed to the north by the overthrust subducted continental crust of the SCB. This tectonic process resulted in the Jurassic foreland basin (Hefei Basin). A series of south dipping Jurassic thrust faults and the increase of sedimentary thickness in the late Jurassic in the Hefei Basin support this point[36]. We suggest that similar to continental subduction and slab break-off, lithospheric-wedging is an important step in the evolution of Dabie-Sulu orogen.

5 Tectonic implications

The observation of south displacement of the subsurface suture in the Dabie orogen and post-collisional lithospheric-weding model suggested in this paper can help us to understand the mechanism of the second rapid cooling and uplifting of UHPM rocks and lithospheric delamination during the Jurassic (180—170 Ma) in the Dabie orogen, as well as the tectonic setting of the large-scale Mesozoic magmatic-metallogenesis event occuring along the middle-lower reaches of the Yangtse River in eastern China.

First, according to the lithospheric wedging model, the overthrust of the detached subducted continental crust and the delamination of underthrust lithosphere of the SCB (see Fig. 5) can cause rapid uplift of the UHPM rocks, which had been uplifted to the middle crust level by the first rapid uplifting event. This process may uplift the

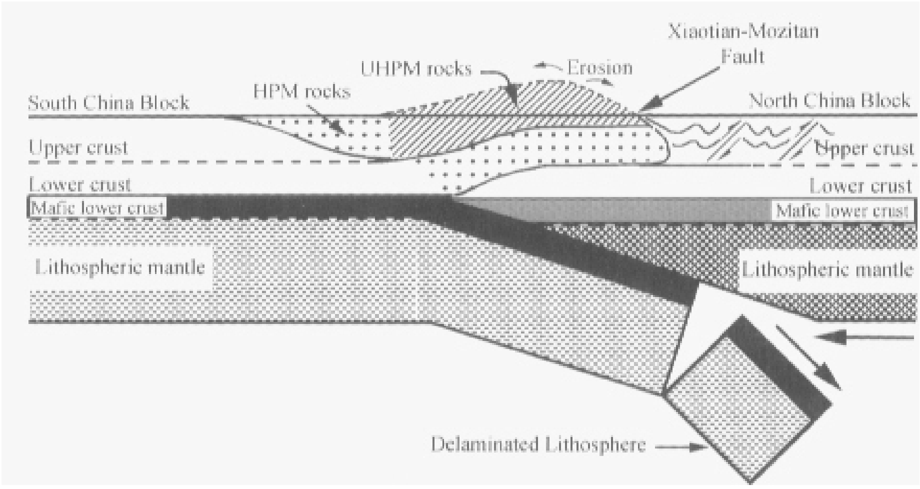

Fig. 5. Post-collisional lithospheric-weding model of the Dabie orogen. The south margin of the NCB wedged into the lithosphere of the SCB along the Dabie-Sulu collision zone resulting in the detachment of the subducted crust and lithospheric mantle of the SCB in Jurassic.

UHPM rocks to the upper crustal level in the Jurassic (180—170 Ma)[28], and then some of them may be exhumed on the surface by erosion in the middle-late Jurassic[37]. The delamination of the mafic lower crust (eclogite) and lithospheric mantle may disturb the asthenosphere and induce the magmatism. The magmatic event during 170—160 Ma in the NDZ may be the result of such lithospheric delamination.

In addition, Fig. 1 shows that the subsurface suture in the region west of the Tan-Lu fault is located to the south of the NDZ, which is close to the Yangtse River. The subsurface suture in the region east of the Tan-Lu fault can be subdivided into two sections. Li identified that the east section of the subsurface suture is located to the east of Nanjing City along the Yangtse River. Although the west section close to the Tan-Lu fault has not been constrained yet, however, it should be connected with the subsurface suture in the Dabie orogen and Nanjing City respectively. Therefore, we suppose that the subsurface suture close to the Tan-Lu fault could be northeast striking dragged by the Tan-Lu fault (see Fig. 1). It is interesting to note that the subsurface suture between the NCB and the SCB in eastern China is very close to and parallel with the Mesozoic magmatic-Fe-Cu metallogenetic belt developed along the middle-lower reaches of the Yangtse River (see Fig. 1). Obviously, the deep subsurface suture zone underneath the Yangtse River in eastern China was a tectonic weak zone after the Jurassic. Hence, a large-scale lithospheric extension could occur in this tectonic weak zone, which was driven by the strike-slip of the Tan-Lu fault in the early Cretaceous. This extension may induce the mantle upwelling and a large-scale magmatism and related Fe-Cu metallogenesis[41,42]. The coupling between the suture zone and post-collisional extension zone in the collisional orogen suggests that the location and striking of lithospheric extension is controlled by the preexisting structure in this zone.

Acknowledgements The authors thank Chang Yinfo for stimulating discussion when this paper was in preparation and Li, Z. -X. for his constructive comments. This work was supported by the Major State Basic Research Program (Grant No. G1999075503), the National Natural Science Foundation of China (Grant No. 49873006) and the Chinese Academy of Sciences (Grant No. KZCXZ-107).

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(Received September 6, 2002)