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Postcollisional mafic igneous rocks record crust-mantle interaction during continental deep subduction

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Findings of coesite and microdiamond in metamorphic rocks of supracrustal protolith led to the recognition of continental subduction to mantle depths. The crust-mantle interaction is expected to take place during subduction of the continental crust beneath the subcontinental lithospheric mantle wedge. This is recorded by postcollisional mafic igneous rocks in the Dabie-Sulu orogenic belt and its adjacent continental margin in the North China Block. These rocks exhibit the geochemical inheritance of whole-rock trace elements and Sr-Nd-Pb isotopes as well as zircon U-Pb ages and Hf-O isotopes from felsic melts derived from the subducted continental crust. Reaction of such melts with the overlying wedge peridotite would transfer the crustal signatures to the mantle sources for postcollisional mafic magmatism. Therefore, postcollisional mafic igneous rocks above continental subduction zones are an analog to arc volcanics above oceanic subduction zones, providing an additional laboratory for the study of crust-mantle interaction at convergent plate margins.

S ubduction of oceanic crust is an important mechanism for exchanging mass and energy between the mantle and the crust. Recycling of the oceanic crust into the asthenospheric mantle is accepted as the basic mechanism for mantle heterogeneity[1,2]. It has been a paradigm that the subduction of oceanic crust and subsequent crust-mantle interaction produce the mantle source of arc volcanics at convergent plate margins[3,4]. Subduction-zone fluids have played a substantial role in transferring typical slab-derived signatures from oceanic basalt and seafloor sediment to the mantle wedge. Ultramafic metasomes could have formed as a transitional lithology at the slab-mantle interface in oceanic subduction channel.

Continental crust can also be subducted to mantle depths, experiencing ultrahigh-pressure (UHP) metamorphism and then exhumed back to crustal levels[5,6]. While orogenic peridotites record the crust-mantle interaction in continental subduction channel[7,8], it is intriguing whether recycling of subducted continental crust is recorded by mafic magmatism above continental subduction zones. If it does, what is the mechanism of crust-mantle interaction and where is its final product? These issues remain poorly understood, but have important implications for chemical geodynamics of subduction zones.

So far no syn-subduction arc magmatism has been identified above continental subduction zones[8,9]. Nevertheless, postcollisional igneous rocks are common in continental collision orogens and their adjacent margin of overlying continental blocks[10–13]. Insights into the origin of these rocks, especially mafic igneous rocks, are crucial to understanding of the reworking and recycling of subducted continental crust. This is highlighted by an integrated study of geochronology and geochemistry for postcollisional mafic igneous rocks in the Dabie-Sulu orogenic belt and the southeastern edge of the North China Block in east-central China. We propose a novel model of petrogenesis to account for the physicochemical processes that generate their mantle sources at the slab-mantle interface in continental subduction channel. This provides a tectonic framework for the crust-mantle interaction during continental collision and consequent mafic magmatism in collisional orogens.

Results

Postcollisional igneous rocks are widespread in the Dabie-Sulu orogenic belt (Supplementary Fig. 1), which was built by the Triassic subduction of the South China Block beneath the North China Block in east-central China[14,15]. They primarily consist of granitoids, with sporadic occurrences of small plutons and dykes in mafic to ultramafic lithologies; volcanic rocks only occur in the northern part of the orogenic belt[10,16]. They also occur in the southeastern margin of the North China Block (hereafter SE North China) close to the Dabie-Sulu orogenic

belt, primarily consisting of granitoids with minor volumes of gabbros and basalts[12,17–19]. Overall, the postcollisional mafic igneous rocks in east-central China mainly occur in the forms of gabbros and basalts, with small amount of pyroxenites and hornblendites.

Zircon U-Pb geochronological studies have demonstrated that these mafic igneous rocks in east-central China were mainly emplaced in the Early Cretaceous (Fig. 1a). Their ages of 110 to 140 Ma are clearly the product of postcollisional magmatism[10]. Only a small gabbro pluton in the easternmost Sulu orogen has late Triassic ages of 201 to 213 Ma (Fig. 1a), corresponding to the synexhumation magmatism[20]. A few relict zircon cores of Triassic and Neoproterozoic U-Pb ages have been identified in the Dabie postcollisional mafic-ultramafic rocks (Fig. 1a).

In response to their variable rock types, the postcollisional mafic igneous rocks in east-central China show a wide variation in major element compositions. They have variable $Na_2O + K_2O$ contents of 0.27 to 8.68 wt.% and SiO_2 contents of 40.15 to 57.30 wt.% (Supplementary Fig. 2), with Mg# values of 35.9 to 87.0 (Supplementary Table). Zircon O isotope analyses yield a large $\delta^{18}O$ range from 2.0 to 7.5‰ (Fig. 1b), most of which are deviated from typical values of $5.3 \pm 0.3‰$ for the normal mantle[21]. More important is that these mafic rocks are characterized by arc-like patterns of trace element distribution (Fig. 2) such as enrichment of LILE (large ion lithophile elements) and LREE (light rare earth elements) but depletion of HFSE (high field strength elements). They exhibit variably high initial $^{87}Sr/^{86}Sr$ isotope ratios of 0.7040 to 0.7112 and negative $\varepsilon_{Nd}(t)$ values of −21.2 to −2.3 for whole-rock (Fig. 3) and negative $\varepsilon_{Hf}(t)$ values of −39.7 to −0.7 for zircon (Supplementary Fig. 3). Their initial Pb isotope ratios are also variable from 15.906 to 18.256 for $^{206}Pb/^{204}Pb$, 15.078 to 15.634 for $^{207}Pb/^{204}Pb$, and 36.249 to 38.170 for $^{208}Pb/^{204}Pb$ (Supplementary Fig. 4). Such radiogenic isotope compositions are usually viewed as isotopically enriched in mantle geochemistry. Taken together, these trace element and radiogenic isotope compositions are normally regarded as continental crust-like in geochemistry, and they are common in many mafic igneous rocks in continental collision orogens.

Discussion

The continental crust-like geochemical compositions for the postcollisional mafic igneous rocks in east-central China provide a challenge to their petrogenesis. Because of their mafic lithochemistry, they are certainly originated from partial melting of ultramafic mantle lithology[22]. Because of their enrichment in radiogenic isotopes, they are not derived from the normal asthenospheric mantle that is isotopically depleted as recorded by normal mid-ocean ridge basalts (MORB)[23]. Because of their enrichment in melt-mobile incompatible LILE and LREE, on the other hand, they are not derived from the refractory subcontinental lithospheric mantle (SCLM)[24]. In this regard, it is intriguing how the continental crust-like geochemical signatures are transferred to these mafic rocks.

There are two possibilities for this transfer: (1) crustal contamination during ascent of the normal mantle-derived mafic magma en route the continental crust; (2) source mixing before partial melting for mafic magmatism. It is well established that mantle-derived magma is mafic in lithochemistry, whereas the continental crust is felsic in average[25]. There are a series of differences in trace element, radiogenic and stable isotope compositions between the mantle and the continental crust. If mafic magmas could be contaminated by the continental crust during their ascent, they would exhibit synchronous changes in major-trace element and radiogenic isotope compositions. However, there are no correlations between whole-rock Sr-Nd isotope compositions and Mg# values for the postcollisional mafic igneous rocks (Supplementary Fig. 5). Therefore, these continental crust-like geochemical compositions would have inherited from their mantle sources.

In light of the arc-like trace element distribution patterns, enriched Sr-Nd-Hf isotope compositions and abnormal $\delta^{18}O$ values for these mafic rocks, their mantle sources are neither the depleted MORB mantle nor the refractory SCLM. In particular, low $\delta^{18}O$ values and relict zircon cores of Neoproterozoic U-Pb ages occur in some samples (Fig. 1), which are diagnostic features of the subducted continental crust of the South China Block[14]. In this regard, their mantle sources would contain crustal components of the subducted continental crust. Therefore, the source mixing is responsible for these geochemical features. In this regard, fertile and enriched mantle sources were generated by the source mixing between the overlying SCLM wedge peridotite and the subducted continental crust. Continental basement granite and cover sediment are potential candidates for the sources of crustal components in continental subduction channel.

The origin of crustal components in the mantle sources can be deciphered by linking such trace element ratios as $(La/Yb)_N$, Ba/Th and Sr/Rb to initial Sr and Nd isotope ratios (Fig. 4). Because adakitic rocks are typically of high $(La/Yb)_N$ ratios due to plagioclase breakdown during crustal anatexis at mantle depths[26], partial melting of the basement granite tends to yield higher $(La/Yb)_N$ melts than those derived from partial melting of the cover sediment. On the other hand, Ba tends to be enriched in metasediment after metamorphic dehydration whereas Rb is liberated by breakdown of muscovite in
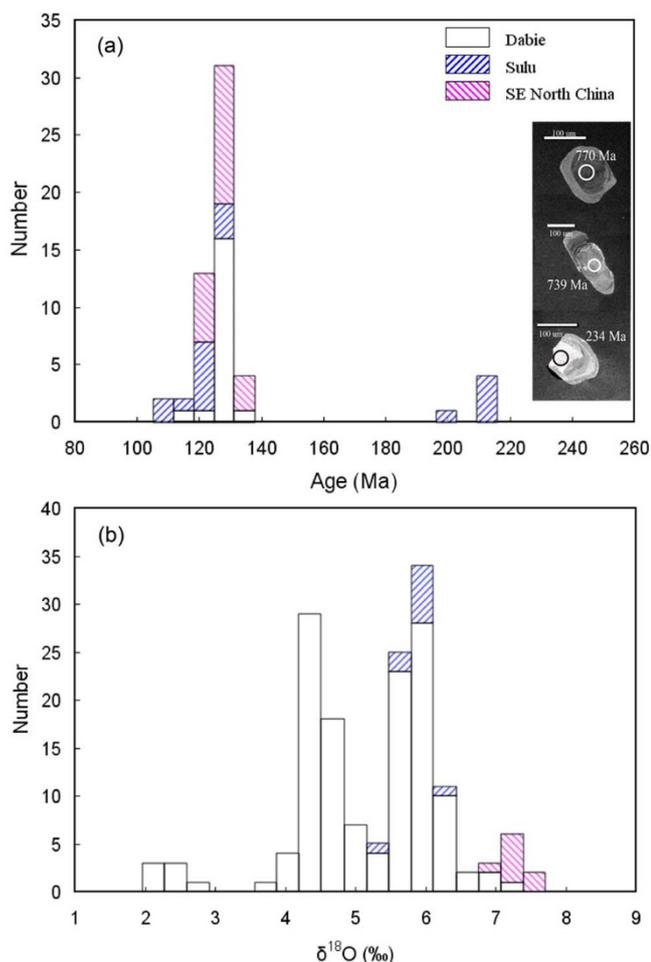
Figure 1 | Histograms of ages (a) and zircon $\delta^{18}O$ values (b) for Mesozoic mafic igneous rocks in the Dabie-Sulu orogenic belt and its adjacent areas in the southeastern margin of the North China Block. A few zircon cores of Neoproterorozoic and Triassic U-Pb ages are present as relicts in voluminous synmagmatic zircon grains of Early Cretaceous U-Pb ages (insert in Fig. 1a).
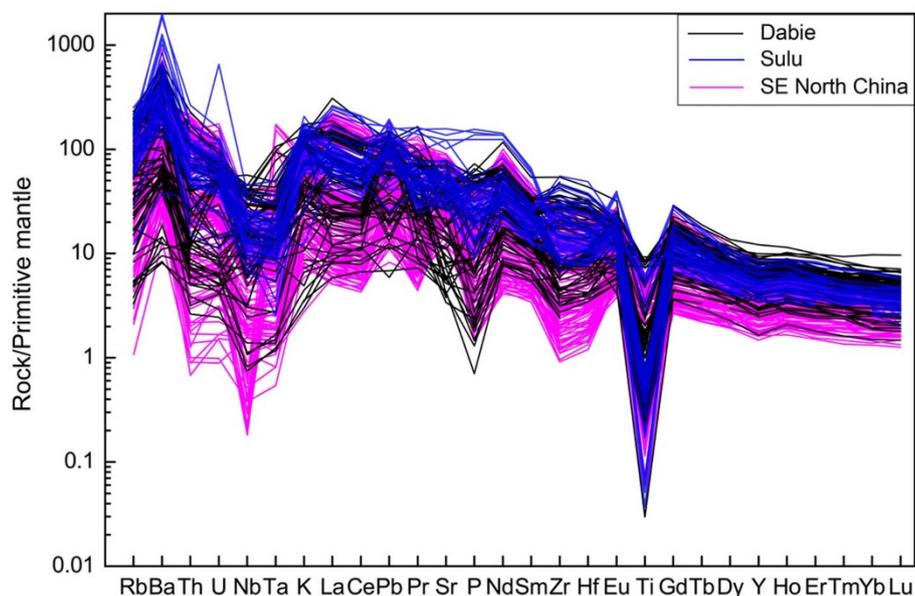
Figure 2 | Primitive mantle-normalized trace element patterns for postcollisional mafic igneous rocks in east-central China. The primitive mantle trace element contents are from Ref. 36.

metagranite during partial melting[27]. As a consequence, the metasediment-derived melt is characterized by high Ba/Th and Sr/Rb ratios but low $(La/Yb)_N$ ratios (Fig. 2a and 2b), whereas the metagranite-derived melt is characterized by low Ba/Th and Sr/Rb ratios but high $(La/Yb)_N$ ratios. Because the low $(La/Yb)_N$ ratios are associated with high $\varepsilon_{Nd}(t)$ values but low $(^{87}Sr/^{86}Sr)_i$ ratios (Fig. 2c and 2d), the metasediment would be derived from weathering of the juvenile arc crust. Because the high $(La/Yb)_N$ ratios are associated with low $\varepsilon_{Nd}(t)$ values but high $(^{87}Sr/^{86}Sr)_i$ ratios (Fig. 2c and 2d), the metagranite is of relatively ancient age. These inferences are consistent with the geochemical features of UHP metamorphic rocks in the Dabie-Sulu orogenic belt[10].

The characteristic geochronological and geochemical features for the postcollisional mafic igneous rocks in east-central China indicate involvement of the subducted continental crust in their mantle sources. It is thus intriguing how the crustal components were incorporated into the mantle sources in the continental collision orogen. Geochemical studies of orogenic peridotites in the Dabie−Sulu orogenic belt have provided important clues to this issue. These orogenic peridotites exhibit zircon U-Pb geochronological evidence

for reaction of the SCLM wedge peridotite with felsic melts derived from the subducted continental crust during the continental collision[7,8]. In addition, their geochemical compositions are generally similar to those of postcollisional mafic igneous rocks, exhibiting arc-like trace element distribution patterns and enriched Sr-Nd isotope compositions. These geochemical anomalies are well accounted for by melt-peridotite reaction in continental subduction channel during continental collision[8]. Therefore, these orogenic peridotites are an analogue to the mantle sources of postcollisional mafic igneous rocks. In other words, the fertile and enriched mantle sources for these mafic rocks would be generated by the same tectonic mechanism.

The postcollisional mafic igneous rocks in east-central China exhibit arc-like trace element distribution patterns, enriched Sr-Nd-Hf isotope compositions, and anomalous zircon $\delta^{18}O$ values. In particular, low $\delta^{18}O$ values and zircon relics of Neoproterozoic and Triassic U-Pb ages are the characteristic features that distinguish the subducted continental crust from the overlying craton lithosphere. Like arc magmatism, the subducted crust-derived signature is firstly incorporated into the wedge peridotite in the form of ultramafic metasomes, and then transferred to mafic magmas by partial melting. Such two-stage processes are substantial to petrogenesis of super-subduction-zone magmatism.

With respect to the crust-mantle interaction during continental collision and its derived mafic magmatism in the postcollisional stage, a series of physicochemical processes are possibly operated in continental subduction channel. These can be generalized by a SARSH model in the following five steps. (1) Subduction (S): the continental crust was subducted beneath the SCLM to depths of >100 km (Fig. 5a). (2) Anatexis (A): anatexis of the subducted continental crust took place due to heating by the overlying SCLM wedge, producing felsic melts that are enriched in LILE and LREE but depleted in HFSE[28]. (3) Reaction (R): the felsic melts would react with the overlying SCLM wedge peridotite, generating fertile and enriched metasomes of ultramafic composition due to preferential partition of melt-mobile incompartible trace elements into the felsic melts. As a consequence, non-peridotite mantle lithology, such as pyroxenite and hornblendite, would be produced by the melt-peridotite reaction at the slab-mantle interface overlying the continental subduction channel. (4) Storage (S): the fertile and enriched metasomes would be stored in orogenic lithospheric mantle for a few to
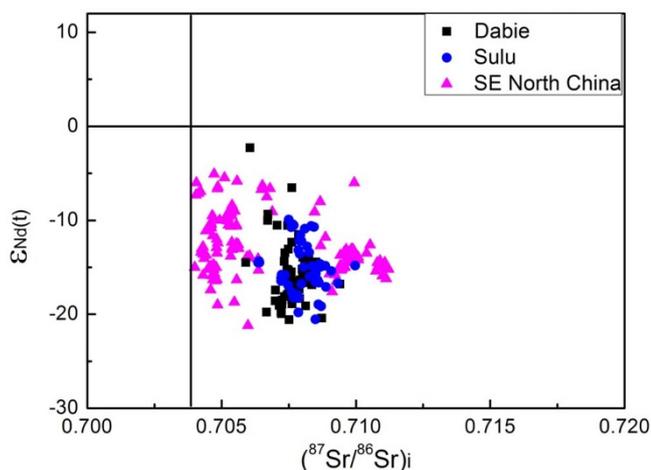
Figure 3 | Initial $^{87}Sr/^{86}Sr$ ratios vs. $\varepsilon_{Nd}(t)$ values for postcollisional mafic igneous rocks in east-central China.
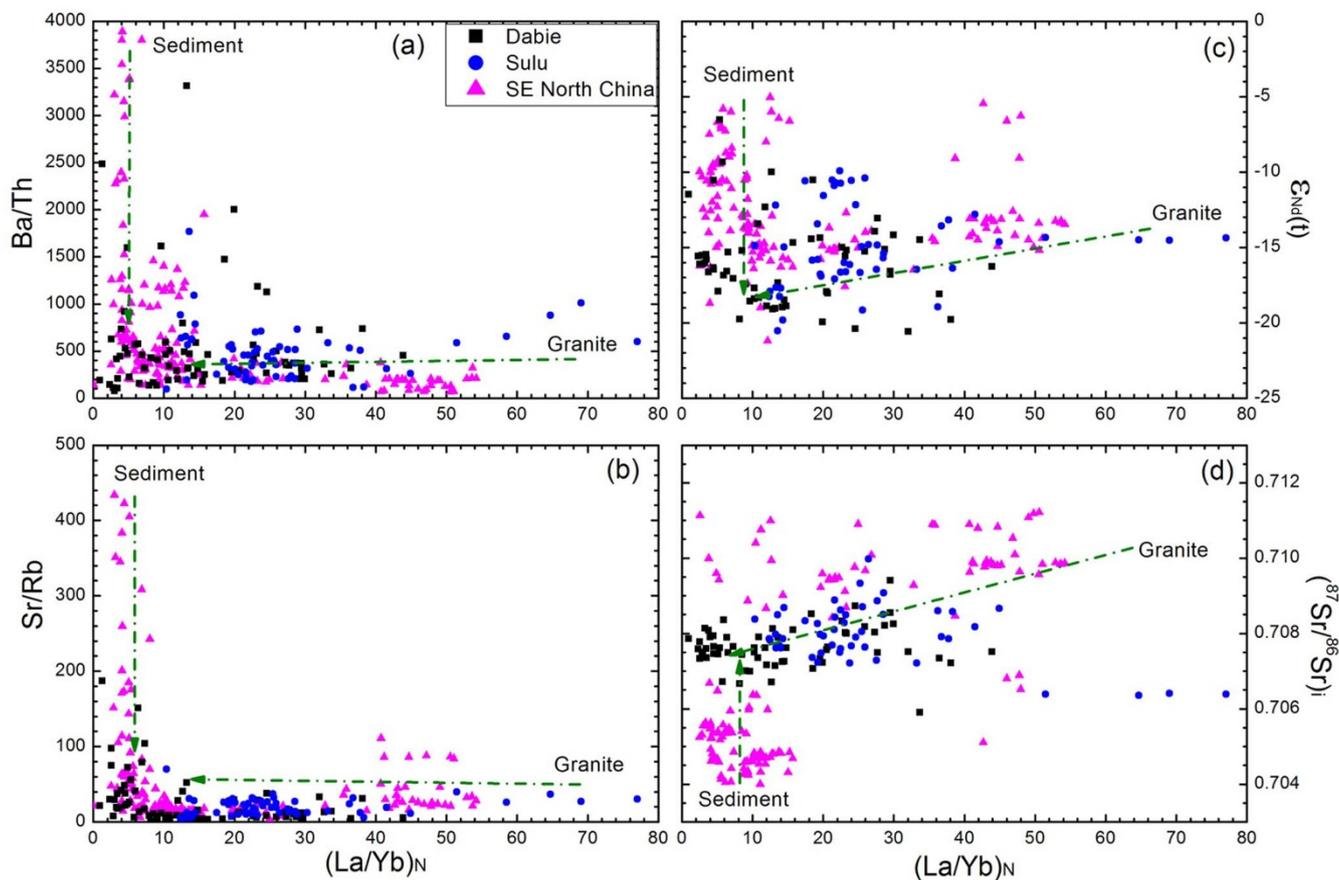
Figure 4 | Plots of whole-rock Ba/Th and Sr/Rb ratios as well as initial Nd-Sr isotope ratios against (La/Yb)$_N$ ratios for postcollisional mafic igneous rocks in east-central China.

tens of million years. (5) Heating (H): the metasomes become partially melted due to heating at the base of collisional orogen (Fig. 5b), giving rise to the postcollisional mafic igneous rocks with arc-like trace element distribution patterns. The above fives steps can be outlined in two stages. The first stage is the generation of ultramafic metasomes by the melt-peridotite reaction, which is the basic mechanism for the crust-mantle interaction in continental subduction zones. The second stage is the postcollisional mafic magmatism in collisional orogens and their adjacent margins of the overlying continental blocks, which provides petrological and geochemical records of the crust-mantle interaction during continental collision.

There are many possible mechanisms responsible for heating at the base of collisonal orogens, such as the upwelling of the asthenospheric mantle due to collapse or delamination of orogenic lithospheric roots[29,30]. If the upwelling asthenospheric mantle itself becomes partially melted, the mafic product would be not only depleted in radiogenic isotope compositions, but also exhibit the MORB-like patterns of trace element distribution[31,32]. However, it is not the case for the postcollisional mafic igneous rocks in the Dabie-Sulu orogenic belt. In this regard, a direct contribution of material from the depleted MORB mantle can be excluded.

With respect to the formation of UHP metamorphic rocks in the Dabie-Sulu orogenic belt, it is well established that the continental collision occurred in the Triassic[14]. The crust-mantle interaction via the melt-peridotite reaction would also take place in this period. On the other hand, the postcollisional mafic magmatism in east-central China occurred in the Early Cretaceous. There is a temporal interval of 80–100 Myr between the two tectonic events. This points to the timescale of 80–100 Myr for the storage of metasomes in the orogenic lithospheric mantle. A possible explanation is that the metasomes were located above the thermal boundary between the

lithospheric and asthenospheric mantles during the Late Triassic to Late Jurassic. As such, they were thermally isolated from the convective asthenospheric mantle, and thus did not become partially melted before heating in the Early Cretaceous. During the Early Cretaceous, the western subduction of the Pacific plate led to thinning of the continental lithosphere of eastern China[33,34]. Rollback of the subducting Pacific slab in this period may be a first-order geodynamic mechanism not only for partial melting of the metasomes but also for extensive magmatism of Early Cretaceous in eastern China.

We have presented a tectonic framework for the crust-mantle interaction during continental subduction and thus for the petrogenesis of postcollisional mafic igneous rocks in continental collision orogens. Reaction of the felsic melts derived from subducted continental crust with the overlying SCLM wedge peridotite overlying the continental subduction channel is proposed as the key process for the crust-mantle interaction and the diagnostic geochemistry of postcollisional mafic rocks in collisonal orogens. The continental crust-like geochemical composition of postcollisional mafic igneous rocks is principally inherited from the felsic melts because melt-mobile incompatible trace elements are imparted to the mantle sources through the melt-peridotite reaction during continental collision. Therefore, postcollisional mafic igneous rocks above continental subduction zones are an analog to arc volcanics above oceanic subduction zones not only in the action of subduction-zone fluids at the slab-mantle interface but also in the recycling of crustal components in mantle geochemistry. Nevertheless, there are three aspects of differences between the two types of supersubduction-zone mafic magmatism: (a) the nature and composition of mantle wedge and subducted crust; (b) the property and composition of metasomatic fluid, and (c) the timescale of metasome storage above the subduction channel.
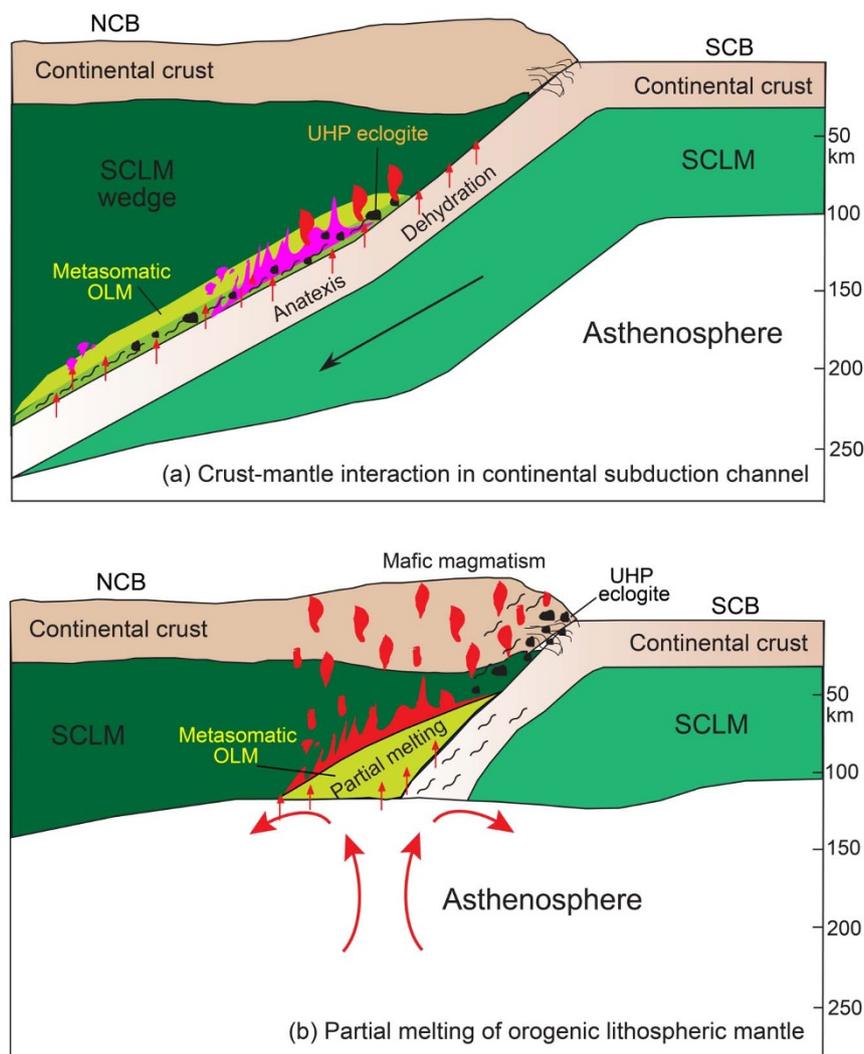
Figure 5 | **Schematic cartoon showing crust-mantle interaction and production of postcollisional mafic igneous rocks in continental collision zone.** (a) Reaction of the overlying SCLM wedge peridotite with felsic melts derived from the subducted continental crust during the Triassic continental collision in east-central China, generating the metasomes in orogenic lithospheric mantle domains overlying the continental subduction channel. (b) Partial melting of the fertile and enriched SCLM domains in the Early Cretaceous, giving rise to postcollisional mafic igneous rocks. Abbreviations of petrotectonic units: SCB = the South China Block, NCB = the North China Block, UHP = ultrahigh-pressure, SCLM = subcontinental lithopsheric mantle, OLM = orogenic lithospheric mantle.

Methods

In order to recognize the crust-mantle interaction and chemical geodynamics in continental collision zones, we have performed a comprehensive compilation of geochronological and geochemical data for postcollisional mafic igneous rocks in the Dabie-Sulu orogenic belt and its adjacent southeastern edge of the North China Block (Supplementary Table). The data are primarily composed of zircon U-Pb ages, whole-rock major-trace elements and Sr-Nd-Pb isotopes, and zircon Hf and O isotopes.

The postcollisional mafic igneous rocks of interest have continental crust-like geochemical compositions such as arc-like trace element distribution patterns and enriched Sr-Nd-Hf isotope compositions. Such compositions are similar not only to those of coeval igneous rocks in the North China Block[35] but also to those of UHP metaigneous rocks in the Dabie-Sulu orogenic belt[10]. This suggests that these geochemical compositions are not diagnostic features that distinguish the subducted South China Block from the obducted North China Block. Nevertheless, low $\delta^{18}O$ values and zircon relics of Neoproterozoic and Triassic U-Pb ages are the characteristic features that distinguish the subducted continental crust from the overlying cratonic lithosphere (Fig. 1). Therefore, we have found the robust evidence for the recycling of subducted continental crust during continental deep subduction.

Furthermore, the crustal components incorporated into the mantle source of these postcollisional igneous rocks have been identified by linking some trace element ratios and Sr-Nd isotopes (Fig. 4). They are primarily composed of basement granite and cover sediment of the subducted continental crust. These two components exhibit a series of differences in element abundances and isotope compositions, which are transferred to the mantle sources via the melt-peridotite reaction in continental subduction channel. Consequently, these geochemical signatures are inherited by the

postcollisional mafic igneous rocks. Based on these results, we propose a tectonic framework for the crust-mantle interaction during continental deep subduction and the petrogenesis of the postcollisional mafic igneous rocks in continental collision zones.

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Z.F.Z., L.Q.D. and Y.F.Z. contributed equally to idea development and data compilation. Z.F.Z. wrote the main text.

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