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大陆板片–地幔相互作用:来自大别造山带碰撞后安山质火山岩的地球化学证据

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摘 要: 俯冲到地幔深度的地壳物质不可避免地在板片－地幔界面与地幔楔发生相互作用,由此形成的超镁铁质交代岩就是造山带镁铁质火成岩的地幔源区.因此,造山带镁铁质火成岩为研究俯冲地壳物质再循环和壳－幔相互作用提供了重要研究对象.为了揭示俯冲陆壳物质再循环的机制和过程,对大别造山带碰撞后安山质火山岩开展了元素和同位素地球化学研究.这些安山质火山岩的SIMS锆石U-Pb年龄为124±3～130±2 Ma,表明其形成于早白垩世.此外,残留锆石的U-Pb年龄为中新元古代和三叠纪,分别对应于大别－苏鲁造山带超高压变火成岩的原岩年龄和变质年龄.它们具有岛弧型微量元素特征、富集的Sr-Nd-Hf同位素组成,以及变化的且大多不同于正常地幔的锆石$\delta^{18}O$值.这些元素和同位素特征指示,这些安山质火山岩是交代富集的造山带岩石圈地幔部分熔融的产物.在三叠纪华南陆块俯冲于华北陆块之下的过程中,俯冲华南陆壳来源的长英质熔体交代了上覆华北岩石圈地幔楔橄榄岩,大陆俯冲隧道内的熔体－橄榄岩反应产生了富沃、富集的镁铁质地幔交代岩.这种地幔交代岩在早白垩世发生部分熔融,就形成了所观察到的安山质火山岩.因此,碰撞造山带镁铁质岩浆岩的地幔源区是通过大陆俯冲隧道内板片－地幔相互作用形成的,而加入地幔楔中长英质熔体的比例决定了这些镁铁质岩浆岩的岩石化学和地球化学成分.

关键词: 安山岩;碰撞造山带;板片－地幔相互作用;熔体－橄榄岩反应;俯冲隧道;地球化学.

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Continental Slab-Mantle Interaction: Geochemical Evidence from Post-Collisional Andesitic Rocks in the Dabie Orogen

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Abstract: Crustal material subducted to mantle depths inevitably interacted with the mantle wedge at the slab-mantle interface. This may generate a variety of ultramafic metasomatites that served as the mantle source of mafic igneous rocks in collisional orogens. Therefore, mafic igneous rocks in collisional orogens are the important target to study the recycling of subdcuted crustal materials and its associated crust-mantle interaction. In order to decipher the mechanism and processes of the recycling of

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subducted continental crustal materials, a combined study of element and isotope geochemistry was performed for post-collisional andesitic volcanics from the Dabie orogen, China. SIMS zircon U-Pb ages for these volcanic rocks are 124±3 to 130±2 Ma, indicating that they formed at Early Cretaceous. In addition, the relict zircons have Middle Neoproterozoic and Triassic U-Pb ages, respectively, corresponding to the ages of protolith formation and ultrahigh-pressure metamorphism (UHP) for UHP metaigenous rocks in the Dabie-Sulu orogenic belt. They have island-arc basalts (IAB)-like trace-element patterns, enriched Sr-Nd-Hf isotope compositions, and variable zircon $\delta^{18}O$ values mostly different from the normal mantle. These element and isotope features indicate that the post-collisional andesitic volcanics are the products of partial melting of metasomatically enriched orogenic lithospheric mantle. During the Triassic subduction of the South China block (SCB) beneath the North China block (NCB), the overlying NCB lithospheric mantle wedge peridotite was metasomatized by felsic melts originated from the subdcuted SCB continental crust, the melt-peridotite reaction in the continental subduction channel generated fertile and enriched metasomatites of mafic composition. Partial melting of such metasomatites in the Early Cretaceous gave rise to these andesitic volcanics. Therefore, the mantle sources for post-collisional mafic igneous rocks in collisional orogens would be generated by the slab-mantle interaction in continental subduction channel, and the lithochemical and geochemical composition of these mafic rocks is dictated by the proportion of felsic melts incorporating into the mantle wedge.

Key words: andesitic rocks; collisional orogens; slab-mantle interaction; melt-peridotite reaction; subduction channel; geochemistry.

板块俯冲是地壳物质再循环进入地幔的重要途径,再循环的地壳物质对地幔的地球化学和岩石学性质产生了巨大的影响(Zindler and Hart,1986;Hofmann,1997;Zheng,2019).大洋和大陆板块均可以俯冲进入地幔,俯冲带既包括大洋俯冲带,也包括大陆俯冲带(Zheng *et al.*,2015).俯冲隧道是指汇聚板块边缘下伏俯冲板片与上覆板片之间的自由空间及其中发生运动的物质(Cloos and Shreve,1988a,1988b),是俯冲板片与上覆地幔楔发生物理化学相互作用的重要场所(Zheng,2012).造山带不同阶段产生的镁铁质岩浆岩为认识地壳物质再循环及其壳幔作用提供了重要的岩石学和地球化学记录(Zheng and Zhao,2017).

现代大洋俯冲带之上的弧岩浆岩是研究俯冲洋壳物质再循环及其壳幔相互作用的重要载体.大洋板片在俯冲过程中经历变质脱水甚至部分熔融,由此释放熔流体交代上覆地幔楔橄榄岩并引起其发生部分熔融,从而产生大洋弧玄武岩或大陆弧安山岩(Hawkesworth *et al.*,1991;Peacock,1993;Tatsumi and Eggins,1995),这是大洋俯冲带弧火山岩的经典成因模型.一般来说,当大洋板片俯冲到80～200 km的弧下深度时,变玄武质洋壳和上覆沉积物可能会发生部分熔融,其中的石榴石和金红石保持稳定,形成不同成分的含水长英质熔体,它们富集轻稀土元素(LREE)和大离子亲石元素(LILE)、亏损重稀土元素(HREE)和高场强元素(HFSE).这些熔体交代上覆地幔楔并发生熔体－橄榄岩反应,可以形成贫橄榄石但富含辉石或者角闪石的地幔交代岩,它们在岩石化学成分上可以是超镁铁质或者镁铁质的.超镁铁质交代岩部分熔融形成玄武质熔体,镁铁质交代岩部分熔融则形成安山质熔体,因此这些地幔交代岩分别成为大洋弧玄武岩和大陆弧安山岩的地幔源区(Chen and Zhao,2017;Zheng,2019).当残留洋壳进一步俯冲到>200 km的弧后深度时,其中的金红石不再保持稳定,所产生的长英质熔体也就不再亏损HFSE,由此形成的地幔交代岩在主要元素组成上为超镁铁质,在微量元素组成上不再亏损HFSE(Zheng,2012,2019).这就产生了洋岛玄武岩(OIB)的地幔源区,由此部分熔融能够形成在微量元素分布上与OIB类似的大陆玄武岩(Zhang *et al.*,2009;Wang *et al.*,2011;Xu *et al.*,2012;Xu and Zheng,2017;Zheng *et al.*,2018).

20世纪末期在变质的大陆地壳岩石中发现了柯石英和金刚石等超高压变质矿物(Chopin,1984;Xu *et al.*,1992),指示大陆地壳可以俯冲到至少80 km的弧下深度,俯冲带壳幔相互作用研究目前已经从大洋俯冲带拓展到大陆俯冲带(Zheng,2012;Zhao *et al.*,2013;赵子福等,2015;Zheng and Chen,2016;Zheng and Zhao,2017).与大洋俯冲带不同,由于低的热梯度,大陆地壳俯冲过程中通常不发育同俯冲弧岩浆岩(Zheng and Chen,2016).然而,在深俯冲大陆地壳折返和碰撞后强烈的裂熔造山作用改造过程中,造山带内部和仰冲板块边缘可以形成广泛分布的岩浆岩(Zheng and Chen,2016;Zhao *et al.*,2017a,2017b).这些岩浆岩特别是镁铁质岩浆岩,为认识俯冲陆壳物质再循环及其壳幔相互作用

提供了极好的研究对象(Dai *et al.*，2011，2012；Zhao *et al.*，2013；赵子福等，2015).

位于中国中东部的大别－苏鲁造山带是三叠纪时期华南陆块俯冲于华北陆块之下形成的，该造山带出露有世界上规模最大、保存最好的不同类型超高压变质岩(Zheng *et al.*，2003，2019).通过对该造山带内部和仰冲板块边缘(华北东南缘)同折返(晚三叠世)和碰撞后(晚侏罗世、早白垩世)花岗岩和镁铁质岩浆岩的研究，已经识别出俯冲华南陆壳物质再造和再循环的鉴定性年代学和地球化学证据(Zhao and Zheng，2009；Zhang *et al.*，2010，2012；Dai *et al.*，2011，2012，2016，2017a；Yang *et al.*，2012a，2012b；Zhao *et al.*，2012，2013，2017a，2017b；赵子福等，2015).为了进一步认识大陆俯冲带壳幔相互作用的化学地球动力学机制和过程，Dai *et al.*(2016)对大别造山带北淮阳带碰撞后安山质火山岩进行了系统的年代学和地球化学研究，为认识俯冲华南陆壳物质再循环及其壳幔相互作用提供了地球化学证据.

1　安山岩成因模型

安山岩广泛出露于汇聚板块边界，是大陆弧最为常见的岩石类型，表明其成因与板块俯冲有关(Chen *et al.*，2014；Gómez-Tuena *et al.*，2014；Straub *et al.*，2014；Chen and Zhao，2017).另一方面，大陆地壳平均成分也为安山质(Rudnick and Gao，2014).大陆地壳整体上是地幔部分熔融的产物，与亏损地幔(DM)形成互补的地球化学储库(Hofmann，1988).但是，地幔部分熔融的产物通常为玄武质，这与大陆地壳平均成分为安山质不匹配.因此，揭示俯冲带安山岩的成因对于理解大陆地壳的形成和地壳－地幔的分异历史具有重要的意义.

目前提出的安山岩成因模型主要有：(1)玄武质岩浆输入；(2)安山质岩浆输入.玄武质岩浆输入模型认为，初始岩浆成分为玄武质，安山岩是通过一系列壳内过程(例如，分离结晶/同化混染、岩浆混合)形成的(Hildreth and Moorbath，1988；Lee *et al.*，2007；Reubi and Blundy，2009).在这些过程中产生的镁铁质－超镁铁质堆晶体/残留体下沉返回地幔就可以平衡大陆地壳的安山质成分(Lee，2014).安山质岩浆输入模型认为，安山质熔体可以在弧下地幔直接产生，其产生机制一般包括以下3种机制：(1)含水地幔橄榄岩部分熔融(Hirose，1997)；(2)俯冲板片的部分熔融及其熔体－橄榄岩反应(Kelemen *et al.*，2007)；(3)俯冲沉积物底辟至地幔楔上部后发生部分熔融并与橄榄岩反应(Hacker *et al.*，2011).但是无论哪种机制，它们都是只强调主要元素、微量元素或者放射成因同位素，基本上没有将这3组地球化学变量综合起来考虑(Chen and Zhao，2017).

不同于安山质岩浆输入模型关注壳下过程，玄武质岩浆输入模型强调壳内过程产生大陆弧安山岩，夸大了同化混染效应.不管哪种模型，安山岩成因中均含有一定的地壳组分，但是这些地壳组分是如何加入到岩浆源区的是一个亟待解决的问题.在安山质岩浆输入模型中，地壳组分加入可以通过俯冲板片析出流体交代上覆地幔楔橄榄岩来实现(Zheng *et al.*，2015).如果是这样的话，俯冲隧道内板片－地幔相互作用是形成安山质岩浆源区的关键过程.据此，Chen *et al.*(2014)和Chen and Zhao(2017)提出长江中下游早白垩世安山岩来自富集富沃的地幔源区，该地幔源区是俯冲洋壳衍生的长英质熔体交代地幔楔橄榄岩形成的，与大洋弧玄武岩地幔源区相比，这个地幔源区中加入了相对多的长英质熔体.

2　大别造山带碰撞后安山质火山岩

尽管安山岩是大陆弧最重要的火山岩类型，它们也可以出现在大陆碰撞造山带，如喜马拉雅造山带、大别造山带(Fan *et al.*，2004；Niu *et al.*，2013).在大别造山带北淮阳地区分布有碰撞后早白垩世安山质火山岩，岩石类型包括玄武粗面安山岩、安山岩、粗面岩和英安岩.Dai *et al.*(2016)对这些火山岩进行了系统的同位素年代学和地球化学研究.同岩浆锆石的SIMS U-Pb年龄为124±3～130±2 Ma，表明它们形成于早白垩世；残留锆石核具有新元古代(656±9～828±12 Ma)和三叠纪(212±3～237±4 Ma)U-Pb年龄(图1b).这些火山岩具有变化的SiO_2(50.28%～63.86%)，Na_2O+K_2O(4.99%～8.46%)(图2a)，CaO(2.17%～7.01%)，MgO(1.18%～4.65%)，$(Fe_2O_3)_T$(3.60%～8.53%)，Al_2O_3(12.92%～18.95%)含量以及$Mg^{\#}$(32.4～63.6).它们具有岛弧型微量元素分布特征(图2c，2d)，即富集LREE[$(La/Yb)_N$=10.3～42.0)]和LILE(例如Rb、Ba和K)、亏损HFSE(例如Nb、Ta、P和Ti)；富集的Sr-Nd-Hf同位素组成，即高的$(^{87}Sr/^{86}Sr)_i$比值(0.707 5到0.711 0)以及负的$\varepsilon_{Nd}(t)$值(－23.1～－15.0)(图2b)和$\varepsilon_{Hf}(t)$值(－29.8～－18.3).锆石原位Hf-O同位素分析得到，同岩浆锆

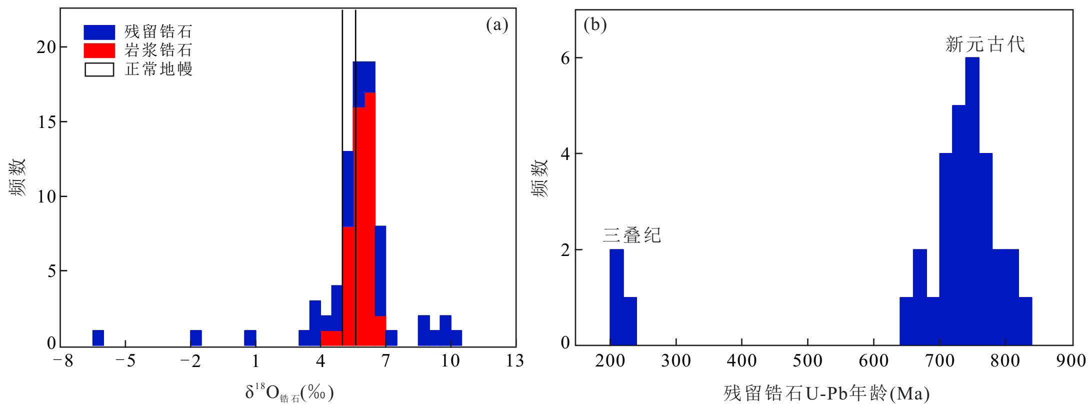

图 1　大别造山带碰撞后安山质火山岩锆石 $\delta^{18}O$ 值(a)和残留锆石 U-Pb 年龄(b)统计图

Fig.1　Histograms of zircon $\delta^{18}O$ values (a) and relict zircon U-Pb ages (b) for post-collisional andesitic rocks in the Dabie orogen

据 Dai *et al*.(2016);正常地幔锆石 $\delta^{18}O$ 为 5.3‰±0.3‰(Valley *et al*., 1998)

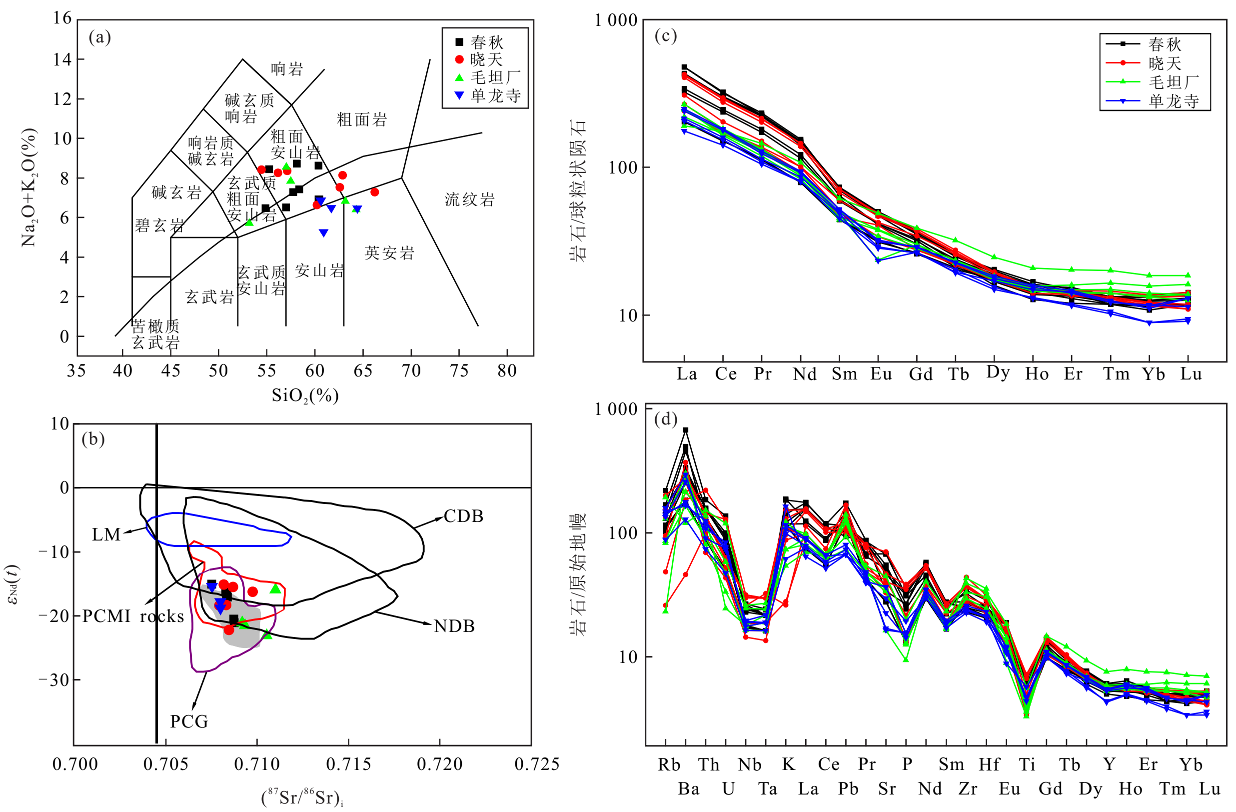

图 2　大别造山带碰撞后安山质火山岩全岩 Na_2O+K_2O-SiO_2(TAS)图(a)、Sr-Nd 同位素组成图(b)、稀土(c)和微量元素(d)分布图

Fig.2　Plots of whole-rock Na_2O+K_2O-SiO_2 (TAS) (a), Sr-Nd isotope compositions (b), REE (c) and trace element (d) distribution patterns for post-collisional andesitic rocks in the Dabie orogen

据 Dai *et al*.,(2016);LM.华北岩石圈地幔;CDB.中大别超高压变质岩;NDB.北大别超高压变质岩;PCMI.大别造山带碰撞后镁铁质－超镁铁质侵入岩;PCG.大别造山带碰撞后花岗岩

石 $\varepsilon_{Hf}(t)$ 值为－31.0～－17.8,$\delta^{18}O$ 值为 4.4‰～6.8‰(图 1a);残留锆石核具有变化的 Hf-O 同位素组成,其 $\varepsilon_{Hf}(t)$ 值为－23.6～－1.3,$\delta^{18}O$ 值为－6.5‰～10.1‰(图 1a).

大别造山带北淮阳安山质火山岩形成于早白垩世,明显晚于三叠纪大陆碰撞的时间,因此属于碰撞后岩浆活动的产物.尽管这些火山岩主微量元素含量具有较大的变化范围,但有些样品具有低的

SiO_2含量(最低值为 50.28 %)、高的 Mg#(最高值为 63.6),高的 Cr 和 Ni 含量(最高值分别为 500×10^{-6} 和 132×10^{-6}),表明它们来自镁铁质－超镁铁质地幔岩石的部分熔融.然而,它们又具有类似于大陆地壳的元素和地球化学特征,如岛弧型微量元素分布特征、富集的 Sr-Nd-Hf 同位素组成以及许多异于正常地幔锆石的 $\delta^{18}O$ 值(图 1).上述地球化学特征表明它们的形成过程中有地壳物质的加入.这些火山岩全岩 Sr-Nd 同位素组成与 SiO_2含量之间没有相关性(Dai *et al*.,2016),排除了岩浆上升过程中地壳物质混染的可能性.因此,它们的地球化学特征继承自地幔源区.结合三叠纪华南陆块俯冲到华北陆块之下的构造体制以及这些火山岩形成于早白垩世碰撞后环境,该地幔源区可能是三叠纪华南陆块俯冲过程中,在大陆俯冲隧道内通过板片－地幔相互作用形成的.这一点也得到了残留锆石 U-Pb 年龄和 O 同位素组成的证实.这些火山岩含有丰富的残留锆石,其新元古代和三叠纪 U-Pb 年龄分别对应于大别－苏鲁造山带超高压变火成岩的原岩年龄和变质年龄(Zheng *et al*.,2003,2009).另外,部分同岩浆锆石和残留锆石具有低于正常地幔的 $\delta^{18}O$ 值(图 1).新元古代 U-Pb 年龄和 ^{18}O 亏损是区分俯冲华南陆块与上覆华北陆块的典型标志(Zheng and Hermann,2014).因此,大别造山带碰撞后安山质火山岩是俯冲华南陆壳物质再循环及其壳幔相互作用的产物.

大别造山带也发育早白垩世碰撞后镁铁质－超镁铁质侵入岩,它们是富沃富集造山带岩石圈地幔部分熔融的产物,该地幔源区是三叠纪大陆碰撞过程中,上覆华北岩石圈地幔(SCLM)楔橄榄岩与俯冲华南陆壳衍生的长英质熔体反应形成的(Zhao *et al*.,2013;赵子福等,2015).除主量元素成分的差别外,与这些镁铁质－超镁铁质侵入岩相比,北淮阳安山质火山岩含有更多的残留锆石,具有更为富集的 Sr-Nd-Hf 同位素组成(Dai *et al*.,2016),表明在形成安山岩地幔源区的过程中加入了更多的俯冲再循环地壳物质.就这些碰撞后幔源岩浆岩的成因而言,Dai *et al*.(2016)采用 SARSH 模型来解释(图 3):(1)俯冲(S),华南陆壳三叠纪俯冲到华北岩石圈地幔之下;(2)深熔(A),俯冲华南陆壳发生深熔作用,形成的长英质熔体富集 LILE 和 LREE 但亏损 HFSE 和 HREE;(3)反应(R),这些长英质熔体与上覆华北岩石圈地幔楔橄榄岩反应,形成富沃富集的镁铁质－超镁铁质交代岩;(4)储存(S),这些富沃富集的交代岩储存在造山带岩石圈地幔中约 100 Ma;(5)加热(H),由于裂熔造山作用和软流圈地幔上涌,加热地幔交代岩发生部分熔融,产生了大别造山带碰撞后安山质火山岩和镁铁质－超镁铁质侵入岩.三叠纪大陆俯冲隧道内的熔体－橄榄岩反应形成了不均一的地幔交代岩,这种不均一性是由于加入的壳源长英质熔体比例不同,并最终传递到这些碰撞后镁铁质火成岩中(Zheng *et al*.,2015;Chen and Zhao,2017).

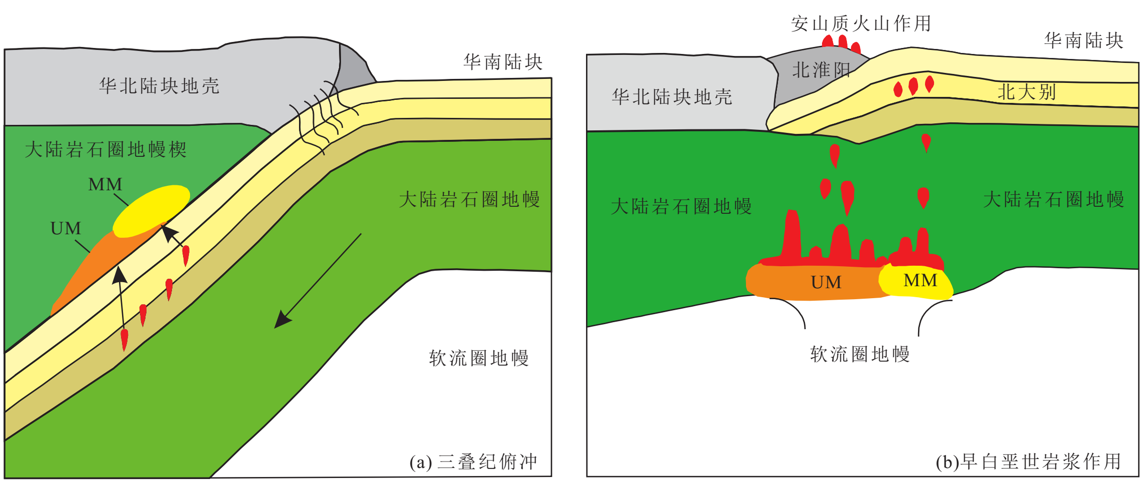

图 3　大陆俯冲隧道板片－地幔相互作用和大别造山带碰撞后安山质火山作用示意

Fig.3　Schematic cartoons illustrating the slab-mantle interaction in continental subduction channel and the post-collisional andesitic volcanism in the Dabie orogen, East-Central China

a.三叠纪,俯冲华南陆壳衍生的长英质熔体与上覆华北岩石圈地幔楔橄榄岩反应,产生镁铁质－超镁铁质地幔交代岩;b.早白垩世,这些交代岩发生部分熔融,形成碰撞后安山质火山岩和镁铁质－超镁铁质侵入岩;UM.超镁铁质交代岩,MM.镁铁质交代岩.据 Dai *et al*.(2016)

3 大陆俯冲带壳幔相互作用

俯冲带镁铁质岩浆岩的地幔源区通常是受到俯冲板片来源流体交代作用所形成的地幔楔，其中含有富化富集的交代岩.这包括一系列地质过程，如俯冲板片变质脱水/部分熔融、地幔楔流体交代作用、富化富集地幔交代岩储存，幔源岩浆上升过程中的分异演化等(Zheng *et al.*, 2015).俯冲隧道中板片－地幔相互作用的性质直接决定了所产生的地幔交代岩的性质.在现代和古老的汇聚板块边界，地幔交代岩在不同阶段部分熔融产生的镁铁质熔体具有不同的地球化学特征，这主要取决于地幔交代岩中地幔和地壳端元的元素和同位素组成以及加入的地壳衍生物质比例.

与洋壳富水相比，陆壳相对较“干”.因此传统观点认为，在陆壳俯冲过程中难以释放出足够的流体交代上覆地幔楔，大陆俯冲带通常不发育同俯冲岛弧型岩浆岩(Rumble *et al.*, 2003; Zheng *et al.*, 2003).然而最近的研究发现，大陆地壳俯冲/折返过程中存在明显的流体活动(Zheng *et al.*, 2009, 2011; Zheng and Hermann, 2014).这表明，大陆俯冲带由于地温梯度较低，俯冲陆壳在弧前深度(<80 km)可能没有显著脱水，而在弧下深度(80～200 km)才经历显著脱水甚至部分熔融，但是由于上覆大陆岩石圈地幔楔温度较低也未能产生同俯冲弧岩浆作用(Zheng *et al.*, 2016).不过，这些流体不仅可以在俯冲陆壳内部流动引起角闪岩相退变质和形成各种成分的脉体，而且可以交代上覆地幔楔橄榄岩.因此，大陆地壳深俯冲不但能够引起超高压变质作用，而且能在大陆俯冲隧道内发生壳幔相互作用(Zheng, 2012).俯冲陆壳岩石在超高压变质和早期折返阶段可能发生部分熔融(Zheng *et al.*, 2011)，产生的长英质熔体富集LILE和LREE、亏损HFSE(Zhao *et al.*, 2012, 2017a).这些长英质熔体在大陆俯冲隧道内会与上覆大陆岩石圈地幔楔橄榄岩发生反应，产生富含辉石的橄榄岩、辉石岩甚至是角闪石岩.这些地幔交代岩发生部分熔融可以形成大陆造山带同折返和碰撞后镁铁质火成岩(Zhao *et al.*, 2013; 赵子福等, 2015; Dai *et al.*, 2016).这些镁铁质火成岩的地幔源区是俯冲陆壳衍生的长英质熔体与相对古老的大陆岩石圈地幔楔橄榄岩反应形成的，因此通常具有岛弧型微量元素分布特征和相对富集的放射成因同位素组成.

大陆地壳由于密度相对较低，不容易直接俯冲进入地幔.然而，大洋地壳由于榴辉岩相变质而密度相对较高，能够重力拖曳大陆地壳俯冲进入地幔深度并发生超高压变质作用.一般认为，大陆地壳之所以能够俯冲是因为受到了先前俯冲大洋地壳的重力牵引.大洋俯冲带和大陆俯冲带在结构和组成上存在明显不同(Zheng and Chen, 2016)，这些差异必然导致俯冲带地幔交代岩在地球化学和岩石学性质上的不同，并最终体现在造山带幔源岩浆岩中.与此相对应，在大陆碰撞造山带出露有两种不同类型的碰撞后镁铁质岩浆岩(赵子福等, 2015).第一类具有岛弧型微量元素分布特征和富集的Sr-Nd-Hf同位素组成，它们是上覆古老岩石圈地幔与俯冲陆壳衍生的长英质熔体反应形成的地幔交代岩部分熔融的产物(Dai *et al.*, 2011, 2012, 2019; Zhao *et al.*, 2013).第二类具有OIB型微量元素分布特征和相对亏损的Sr-Nd-Hf同位素组成，它们是先前俯冲古洋壳衍生的长英质熔体与上覆亏损地幔反应形成的地幔交代岩部分熔融的产物(Dai *et al.*, 2014, 2015, 2017b, 2017c).因此，大陆俯冲带存在两种不同类型的板片－地幔相互作用(赵子福等, 2015; Dai *et al.*, 2019).造山带不同阶段的镁铁质岩浆岩为认识俯冲带壳幔相互作用提供了重要的岩石学和地球化学记录.

4 结语

板块俯冲是地壳物质再循环进入地幔的重要途径，俯冲带是发生壳幔相互作用的理想场所.俯冲带壳幔相互作用可以通过不同的方式进行，并形成不同性质的地幔交代岩.大陆深俯冲过程不仅可以产生超高压变质岩，而且能够发生壳幔相互作用，从而对地幔的地球化学和岩石学性质产生影响.在大陆板块汇聚过程中的不同阶段，先前俯冲洋壳和随后俯冲的陆壳物质均可以再循环进入地幔.俯冲隧道内的熔体－橄榄岩反应是大陆俯冲带壳幔相互作用的物理化学机制.大陆俯冲带存在两种类型的板片－地幔相互作用，产生了地球化学特征截然不同的两类造山带碰撞后镁铁质火成岩的地幔源区.因此，造山带碰撞后镁铁质火成岩为研究俯冲带壳幔相互作用提供了一个大陆岩浆岩对象.

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