SCIENCE CHINA
Earth Sciences

•REVIEW•

December 2020 Vol.63 No.12: 2029–2041
https://doi.org/10.1007/s11430-019-9611-9

Post-collisional mafic magmatism: Record of lithospheric mantle evolution in continental orogenic belt

Wenliang XU[1*], Zifu ZHAO[2,3] & Liqun DAI[2,3]

[1] *College of Earth Sciences, Jilin University, Changchun 130061, China;*
[2] *CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China;*
[3] *Center for Excellence in Comparative Planetology, Chinese Academy of Sciences (CAS), Hefei 230026, China*

Received November 7, 2019; revised March 18, 2020; accepted April 8, 2020; published online May 14, 2020

Abstract In order to better understand the role of post-collisional mafic magmatism at convergent plate boundaries in revealing the earth's evolution, this paper has systematically summarized the research history of post-collisional mafic magmatism, different types of collision and their influence on the nature of orogenic mantle, the concept and implication of post-collisional magmatism, and the relationship between post-collisional mafic magmatism and orogenic mantle evolution and mineralization. Post-collisional mafic igneous rocks are not only the direct records for studying the nature and evolution of orogenic mantle, but also the important carriers for regional mineralization. However, the type and quantity of the crustal materials involved in modifying the overlying lithospheric mantle during collisional orogeny, the process and mechanism of such modification, and the major control factors and mechanism of mafic magmatism-related mineralization during the post-collisional period are the main contents and direction of future researches in this field. Therefore, the study of post-collisional mafic magmatism is of significant implications for developing the theory of plate tectonics.

Keywords Orogenic belt, Types of collision, Post-collisional mafic magmatism, Orogenic mantle evolution, Mineralization

Citation: Xu W, Zhao Z, Dai L. 2020. Post-collisional mafic magmatism: Record of lithospheric mantle evolution in continental orogenic belt. Science China Earth Sciences, 63(12): 2029–2041, https://doi.org/10.1007/s11430-019-9611-9

1. Introduction

The post-collisional geodynamic setting and/or post-collisional magmatism at convergent plate boundaries, as a special tectonic stage in the evolutionary history of the earth, has not been fully integrated in the realm of classical plate tectonics, and even seldom mentioned in mantle plume theory (Liègeois, 1998). However, intense magmatism and accompanied mineralization are often developed during the post-collisional period. Up to now there are still some questions needed to be answered. How to define the post-collisional magmatism? What are the implications of post-collisional igneous rocks for our understanding of earth deep processes, especially the mantle evolutionary history of orogenic belts? What significance do they have in developing the theory of plate tectonics? These questions are still the main subjects of the studies of post-collisional magmatism.

2. Research history of post-collisional magmatism

In terms of the differences in the research contents of post-collisional magmatism at convergent plate boundaries, combined with the advance in global tectonic research and the development of analytical techniques, the research his-

* Corresponding author (email: xuwl@jlu.edu.cn)

tory of post-collisional magmatism can be divided into the following several stages.

(i) Before mid-1980s: It can be called as experimental petrology and petrogenesis stage. The study of post-collisional magmatism mainly focused on the petrogenesis of alkaline igneous rocks and A-type granites at this stage. The formation conditions of alkaline magma and the influence of source heterogeneity on the formation of alkaline magma are main research subjects of high-temperature and high-pressure experimental petrology (e.g., Wendlandt and Eggler, 1980a, 1980b; Yoder, 1986; Clemens et al., 1986).

(ii) Mid-1980s to Late-1990s: It can be called as petro-geochemistry and petrogenesis stage. Whole-rock geochemical data, especially Sr-Nd-Pb isotopic data, was widely used to study the genesis of potassic-ultrapotassic igneous rocks at this stage (Nelson et al., 1986). Besides the timing, geochemical characteristics, classification and genesis of potassic-ultrapotassic magmatism, scientists began to study the nature of their mantle source and their relationship with evolution of orogenic belts (Hawkesworth et al., 1985; Bonin et al., 1987; Liègeois and Black, 1987; Foley et al., 1987; Thompson et al., 1990).

(iii) Late-1990s to Early 21st century: It can be called as the period of the application of multiple isotope systems and the study on the genesis and nature of source region of post-collisional igneous rocks. Since multiple isotopes (mainly the radiogenic Sr-Nd-Pb) were applied on the study of post-collisional igneous rocks after late 1980s, more attentions had been paid to the nature of their source, such as the contribution and effect of the mantle and crustal materials to post-collisional igneous rocks (Bonin, 1996; Lustrino et al., 2000).

(iv) Early 21st century to the present: This period is mainly characterized by the application of *in-situ* mineral element and isotope and whole-rock nontraditional isotope analysis, and studies on the nature of mantle source, dynamics and crust-mantle interaction process. With the development of analytical techniques (e.g., *in-situ* mineral elements and isotopes, Os-Hf-O and nontraditional isotopes), more attentions have been paid to the mantle dynamics (Liu and Fei, 2006; Prelević et al., 2012; Wang et al., 2014; Kubínová et al., 2017), the process and mechanism of crust-mantle interaction (Dai et al., 2011, 2012, 2015a, 2016a; Dai F Q et al., 2016; Zhao et al., 2011, 2013, 2015; Huang et al., 2015), the lithology of mantle source region (Sobolev et al., 2005; Herzberg, 2011; Dai et al., 2014, 2017a, 2018; Dai et al., 2019), and the contributions of different crustal materials to source region (Gao et al., 2008; Liu et al., 2008; Ammannati et al., 2016; Dai et al., 2015b, 2016b, 2017b; Dai et al., 2019; Zhao et al., 2015).

In this regard, the studies of post-collisional magmatism have experienced evolution from experimental petrology and petrogenesis, lithochemistry and geochemistry, through the nature and evolution of magma sources, to lithotectonic probe for deciphering the lithospheric deep processes. This also provides a guidance on the future study of post-collisional magmatism.

3. Collisional types and its influence on the nature of orogenic mantle

The post-collisional magmatism is a term relative to collision and also occurs at convergent plate boundaries. In order to better understand the post-collisional dynamics, the types of collision and its influence on the nature of mantle source should first be understood in the framework of earth evolution and plate tectonics. According to the distinct property of subducted slab, different types of collision have been identified during plate convergence.

3.1 "Arc-continent" collision corresponding to "ocean-ocean" and "ocean-continent " subduction

Island arc is formed during ocean-ocean subduction, such as the Izu-Bonin-Mariana (IBM) arc, which is the result of subduction of the Pacific plate beneath the Philippine plate (Stern et al., 2004; Reagan et al., 2010). With the continuous subduction of the Philippine plate beneath the Eurasia, the IBM arc will collide with the Eurasia continent. Many orogenic belts are formed by ocean-continent subduction and arc-continent collision, such as the Central Asian Orogenic Belt (CAOB) and western Gangdese Orogenic Belt. The former is the result of the Paleo-Asian oceanic plate subduction, where most arc terranes collided with microcontinents in the Paleozoic (Xiao et al., 2003, 2015; Song et al., 2015a). For example, the collision between the Duobaoshan arc and Xing'an Block took place in the late stage of early Carboniferous (Li et al., 2014). The latter was generated by multiple stages of subduction and accretion of the Neo-Tethyan arc beneath the Lhasa Block since Mesozoic, leading to the final collision and amalgamation of the Koshistan terrane with the southern margin of Asian continent (Aitchison et al., 2000; Jagoutz, 2014; Xu et al., 2019).

The mainly geological processes occurred during arc-continent collision contain the lateral accretion of crust, and the magmatism and metamorphism related to collision (Figure 1). For example, the arc-continent collision result in the formation of the CAOB as the largest accretionary orogen on Earth, where syn-collisional magmatism (late Carboniferous garnet-bearing monzogranite at the eastern margin of the Xing'an Block) and high-pressure metamorphism (early Carboniferous blueschist in Nenjiang, Bureau of Geology and Mineral Resources of Heilongjiang Province, 1993) occurred simultaneously. During arc-continent collision, the reworking of juvenile and ancient con-

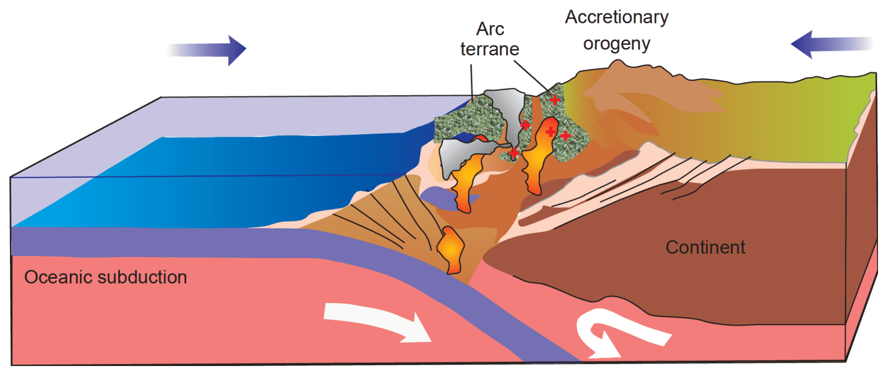

Figure 1 Accretionary (arc-continent collisional) orogeny (revised from Zheng, 2012).

tinental crust and the formation of enriched lithospheric mantle generally occur due to the convergence of juvenile oceanic crust, juvenile and ancient continental crust at this stage (Zhu et al., 2011; Wu and Zheng, 2013).

3.2 "Continent-continent" collision corresponding to "continent-arc-continent" and "continent-continent" subduction

Continent-arc-continent and/or continent-continent collisional orogens are formed with the disappearance of subducting oceanic slab, the closure of ocean and the subsequent arc-continent collision due to the pulling of descending oceanic slab (Yin and Harrison, 2000; Zheng et al., 2013; Song et al., 2014, 2015b; Xu et al., 2019).

In continent-arc-continent collisional orogens (Figure 2), the mainly geological processes contain the lateral accretion of crust during arc-continent collision and subsequent high-pressure (HP) to ultrahigh-pressure (UHP) metamorphism due to continent-continent subduction and collision. Typical examples are the arc-continent collisional orogen (Gangdese belt) formed by the northward subduction of the Neo-Tethyan oceanic plate at the southern margin of the Tibet Plateau since early Mesozoic, and the subsequent continent-arc-continent collisional orogen between the Indian and Asian continents (Yin and Harrison, 2000; Xu et al., 2019). During continent-arc-continent collision, the reworking of juvenile and ancient continental crust, and the formation of enriched lithospheric mantle generally occur (Zhao et al., 2013; Chung et al., 2005). For example, the spatial variation of zircon Hf isotopic compositions in the Mesozoic crust-derived igneous rocks at the southern margin of the Tibet Plateau suggests the reworking of juvenile and ancient continental crust materials (Zhu et al., 2011), whereas the enrichment of incompatible elements in the mantle-derived igneous rocks reveales the contribution of early subducted crustal materials to the formation of enriched mantle source (Chung et al., 2005; Zhao et al., 2009; Zheng, 2012).

In continent-continent collisional orogens (Figure 3), the main geological processes include the HP to UHP metamorphism and the reworking and recycling of ancient continental crustal materials during the subduction and collision between two continents, such as the Qinling-Tongbai-Hong'an-Dabie-Sulu orogenic belt (Xu et al., 1992; Zheng, 2008; Liou et al., 2009; Zheng et al., 2003, 2019a; Wu and Zheng, 2013). During continent-continent subduction and collision, the reworking of ancient crustal materials and the formation of enriched lithospheric mantle generally occur. The Dabie-Sulu orogenic belt was formed by the collision of the South China and North China bolcks, where the UHP metamorphic rocks occurred and were even partially melted during the exhumation of subducted continental crust (Zheng et al., 2011). The generation of felsic veins in UHP metamorphic rocks and syn-exhumation granites are the case in point (Chen et al., 2017; Zhao et al., 2012, 2017a), which suggests the reworking of subducted continental crust materials. The Late Triassic mafic igneous rocks in the Jiaodong Peninsula and southern Liaoning, and the Early Cretaceous mafic igneous rocks in western Shandong are characterized by arc-like trace element distribution patterns and enriched Sr-Nd isotopic compositions, indicating that the enriched mantle source was generated by the modification of the overlying lithospheric mantle peridotite by the subducted continental crust materials (Yang et al., 2005, 2007; Gao et al., 2008; Yang D B et al., 2012; Yang Q L et al., 2012a, 2012b; Zhang et al., 2012; Zhao et al., 2012; Xu et al., 2013a; Dai et al., 2019). In addition, some mantle-derived mafic igneous rocks occurred within the collisional orogenic belt and the margin of overlying continental block, also record the modification of lithospheric mantle by previously subducted paleo-oceanic crust materials (Li et al., 2016, 2018). The mafic magmatic rocks occurred in southern Liaodong Peninsula (Early-Middle Triassic) and the Qinling-Tongbai-Hong'an orogenic belt (Early Cretaceous-Cenozoic) generally display OIB-like trace element distribution patterns and relatively depleted Sr-Nd isotopic compositions, suggesting the modification of overlying mantle by the subducted Paleo-

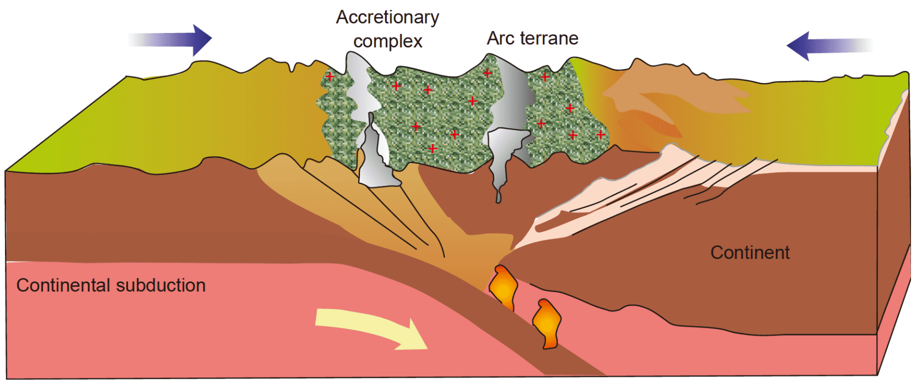

Figure 2 Continent-arc-continent collisional orogeny (revised from Zheng, 2012).

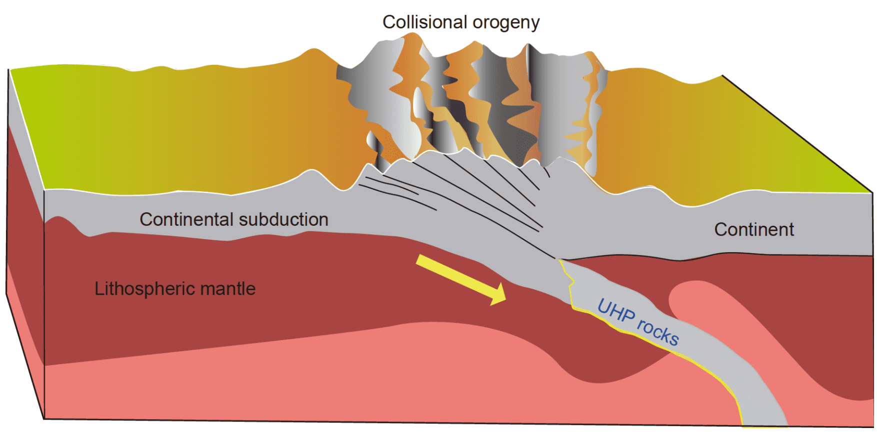

Figure 3 Continent-continent collisional orogeny (revised from Zheng, 2012).

Tethyan oceanic crust which provides the pulling force for the subduction of the South China Bolck (Dai et al., 2015b, 2017b, 2018; Zhao et al., 2015; Fang et al., 2020).

4. The definition, characteristics and time limitation of post-collisional mafic magmatism

4.1 Definition of post-collisional magmatism

The "post-collisional geodynamic setting" and "post-collision magmatism" are relative to collisional orogeny. Therefore, determining the timing of collisional orogeny is the major premise. The basic principle to determine the timing of collisional orogeny is that the geological records generated before and after collision can be used to define the timespan of collisional orogeny. For example, the sedimentation, magmatism and metamorphism during oceanic subduction can be used to constrain the lower limit of collisional orogeny, whereas the magmatism, metamorphism and molasse deposition during collisional orogeny can be used to determine its upper limits (Liègeois, 1998; Zheng and Wu, 2018). In view of the formation time of post-collisional magmatism, the post-collisional event is younger than the collisional orogeny. Furthermore, post-collisional magmatism takes place in a different tectonic setting from the collisional orogeny, but it has inheritance in both texture and composition from the collisional orogen (Zheng et al., 2013, 2019a).

Generally, the collision occurs between two or more continents, which is marked by the occurrence of major thrust faults and HP to UHP metamorphism. However, post-collision usually refers to the period after the transition from a convergent plate boundary to an intracontinent environment, where the major ocean is closed, but still with the occurrence of reactivation along the mega-suture zones, which is essentially indistinguishable from an intraplate setting. The post-collisional setting is a composite tectonic stage that can include many geological events such as large horizontal movements along shear zones, delamination and collapse of orogenic roots, and generation of small oceanic basin, which are generally related to continental rifting (Zheng and Chen, 2017). As these events happen in continuous or episodic extensional regimes, the various types of magmatisms generated in such settings can be referred to as post-collision magmatism (Liègeois, 1998; Bonin, 2004; Zheng and Chen, 2017; Zheng et al., 2019b).

4.2 Use of the term "post-collisional magmatism" and its implication

At present, there are two different expressions for "post-collision magmatism" in the literatures, i.e., Late-collisional magmatism and Post-collisional magmatism. The former refers to the magmatism occurred in the late stage of collision event such as Late Triassic syn-exhumation alkaline magmatism in the Jiaodong Peninsula and southern Liaoning Peninsula (Yang et al., 2005, 2007; Zhao et al., 2012, 2017a). The latter implies the magmatism occurred after collisional orogeny, whose formation time and geodynamical setting are independent of collisional orogeny, but its source region has been affected by collision event such as the Early Cretaceous magmatism in the Dabie-Sulu orogenic belt and its adjacent areas (Yang et al., 2004; Yang D B et al., 2012; Zhao and Zheng, 2009; Zhao et al., 2017b). With respect to potassic-ultrapotassic igneous rocks in the southern Tibet plateau, they have a range of emplacement ages from 48 to 8 Ma (Chung et al., 2005; Zhao et al., 2009). Most of these ages are later than the time span of 55±10 Ma for the collisional orogeny between the Indian and Asian continents (Zhu et al., 2011; Hu et al., 2016; Zheng and Wu, 2018). Thus, the majority of these igneous rocks belong to the product of post-collisional magmatism at 48–44 Ma may be categorized into late-collisional one. Nevertheless, all these potassic-ultra-potassic igneous rocks are the product of extensional tectonism, recording extension of the orogenic lithosphere since the late-collisional stage. In order to avoid confusion, we agree with the suggestion by Liègeois (1998), i.e., distinguishing "post-collisional magmatism" from "late-collisional magmatism".

Recently, Zheng et al. (2019b) proposed that the formation and evolution of a orogenic belt at convergent plate boundary can be subdivided into three stages (Figure 4), i.e., the accretionary orogeny stage related to the subduction of oceanic plate, the collisional orogeny stage related to the collision and amalgamation of continents, and the rifting orogeny or post-collisional stage related to large-scale reactivation of lithosphere along previous compressional orogen at the convergent plate boundary. However, Liègeois (1998) suggested that post-orogenic and anorogenic stage should be classified as the intraplate stage. Indeed, the covergent plate boundaries had become intracontinental environment after the collision between two continents happened. Thus, the post-collisional and post-orogenic should be distinguished when using the terminology of post-collisional magmatism. The former indicates that the magmatism occurs after the collisional period but is genetically related to the collisional event, while the latter refers to the magmatism occurred after either accretionary or collisional orogenic cycle. For the post-collisional magmatisms, they usually formed by rifting orogeny along the fossil suture zone (Zheng and Chen, 2017; Zheng and Zhao, 2017), thus belonging to magmatisms after a cycle of compressional-style orogeny.

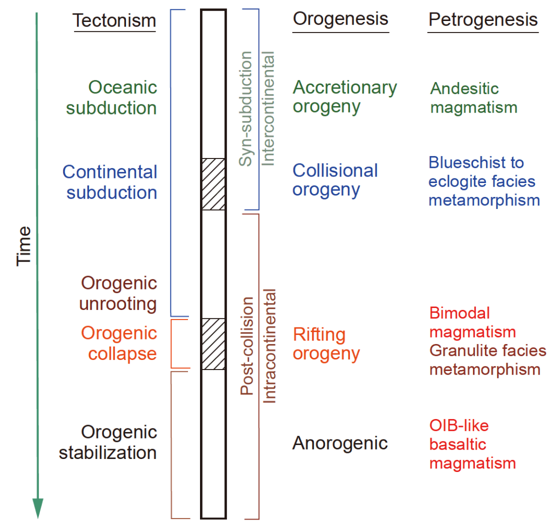

Figure 4 The definition of orogenesis (revised from Zheng et al., 2019b).

4.3 Characteristics of "post-collisional magmatism" and its distinction with "intraplate magmatism"

Post-collisional magmatism usually has the following characteristics (Liègeois, 1998; Bonin, 2004; Zhao and Zheng, 2009; Song et al., 2015b): (1) Post-collisional magmatism is, in volume, mainly potassic and in particular high-K calc-alkaline rocks with subordinate amount of shoshonitic rocks. Strongly peraluminous and alkaline-peralkaline granitoids may be voluminous but are more sporadic. Compared with granitoids, the outcropping of mafic-ultramafic igneous rocks is less, including pyroxenite, gabbro, basalt and mafic dykes; (2) post-collisional magmatism is commonly linked to large-scale horizontal movements along the major shear zones; (3) the source region of post-collisional magmatism has been generated during the preceding subduction and collision period, whether it lies within the crust or lithospheric/asthenospheric mantle. Moreover, this source can contain a large amount of juvenile components, either mantle or newly formed crust of igneous or sedimentary character (Liègeois, 1998; Bonin, 2004). The nature of magma source is mainly related to the types of collision. It is generally difficult to determine the composition of source region, as juvenile mafic lower crust is geochemically and isotopically similar to lithospheric mantle. At present, it is widely accepted that the geochemistry of post-collisional igneous rocks could reflect the composition of their magma source materials. Much less assent exists on the idea that geochemistry can characterize geotectonic setting (Liègeois, 1998).

The intraplate magmatism also occurs within the continent out of orogenic belt such as Cenozoic continental basalts in eastern China. The main marks have been proposed for distinguishing post-collisional magmatic rocks from intaplate magmatic rocks. For example, Liègeois (1998) suggested that distinguishing marks are: (1) Post-collisional magmatism usually ends with silica-oversaturated calc-alkaline igneous rocks, while intraplate magmatism is dominated by silica-undersaturated alkaline igneous rocks; (2) most post-collisional magmatism is related to the large-scale horizontal movement along major shear zones, while the large-scale horizontal movements have already terminated in the intraplate period, heralding the arrival of quieter intraplate period; (3) the transition to intraplate period, where the entire area acquires a unique pole of rotation and constitutes a single plate. This transition marks the end of orogeny. In view of the advances in mordern igneous petrology, the Liègeois (1998)'s suggestions can be reinterpreted as follows: (1) Post-collisional magmatism is characterized by high degree of partial melting to result silica-oversaturated calc-alkaline magmatism, whereas intraplate magmatism is characterized by low degree of partial melting to result in silica-undersaturated alkaline magmatism; (2) post-collisional magmatism dominantly occurs in unstable collisional orogens, whereas intraplate magmatism usually occurs within stable continents; (3) when the continent enters a stable period, the entire area occurs as a whole in petrotectonics (but unnecessarilly constitutes a single plate), but this tectonic transition does not mark the end of rifting orogeny.

The convergent plate boundaries have become intraplate environments since the amalgamation of two continents. Traditionally, the transition from post-collisional to intraplate periods is used to mark the end of an orogenic cycle, but this actually refers to as the end of a Wilson cycle. An orogenic cycle actually is the duration of one of the three types of orogeny (accretionary, collisional, or rifting). Generally, the duration of accretionary orogeny is the longest among the three types of orogeny, whereas that of collisional orogeny is the shortest, and that of rifting orogeny is in between (Zheng and Chen, 2017). The post-collision is after either arc-continent collision or continent-continent collision. For the Wilson cycle, once post-collisional magmatism occurs at a convergent plate boundary, it indicates a failed continental rift there, which is a prelude of continental breakup. If a continental rift could evolve into continental breakup and seafloor spreading, it would be a successful continental rift and thus start a new Wilson cycle (Zheng et al., 2019a). Therefore, the continental collision marks the end of a Wilson cycle (Dewey and Burke, 1974), whereas post-collisional magmatism is a tectonic response to continental rifting along fossil suture zones (Zheng and Chen, 2017).

4.4 Time range of post-collisional magmatism in typical orogenic belts

The determination of the timespan of post-collisional magmatism is the foundation to study the origin of post-collisional magmatism and its relationship to mineralization. According to available results, there are two main views at present. One is that post-collisional magmatism mainly occurs after collision, which is related to extensional tectonism and belongs to the highly evolved product in collisional orogens, its origin is related to rifting orogeny (Zheng and Chen, 2017). When the alkaline magmatism occurs, it marks the beginning of a quiet period of intraplate settings (Liègeois, 1998). The other is that the source compositions of post-collisional igneous rocks are affected by the collisional orogeny, and post-collisional magmatism occurs at some time after the collisional orogeny (Zhao and Zheng, 2009; Zheng et al., 2019a, 2019b). So, what is the time interval between syn-collisional and post-collisional magmatisms? This may be answered by studying the formation and evolution of typical collisonal orogens and associated magmatism.

The Dabie-Sulu orogenic belt is a typical Mesozoic continent-continent collisional orogen in east-central China. Zircon U-Pb dating for UHP metamorphic rocks indicates that the UHP metamorphism occurred at 240–225 Ma (Zheng et al., 2009; Liu and Liou, 2011), marking the peak period of collisional orogeny. Magmatism closely associated with the processes of the subduction and collision includes Early-Middle Triassic diabases at 244–247 Ma in the southern margin of Liaodong peninsula (Fang et al., 2020), and Late Triassic Jiazishan alkaline rocks at 201–220 Ma (Yang et al., 2005; Zhao et al., 2012; Xu et al., 2016) and Mibaishan granites (Zhao et al., 2017a) in the Jiaodong peninsula. According to the emplacement ages of these igneous rocks, the former belongs to syn-subduction magmatism, whereas the latter belongs to syn-exhumation magmatism. The two episodes of magmatism together make syn-collisional magmatism. In this regard, the duration from collision and compression to exhumation and extension in the collisional orogen is about 20–35 Myr, which is the duration of this collisional orogeny. In addition, voluminous Early Cretaceous igneous rocks occur in the Dabie-Sulu orogenic belt and its adjacent areas, which have magma emplacement ages of 145–118 Ma, mainly at 130–120 Ma (Zhao et al., 2017b). The lithochemical and geochemical studies have demonstrated that these mafic and felsic igneous rocks are the products of partial melting of the orogenic lithospheric mantle modified by subducting continental crust-derived material and subducted continental crust itself, respectively (Zhao et al., 2013, 2017b). A few Cretaceous mafic igneous rocks in the Qinling-Tongbai-Hong'an orogenic belt west of the Dabie-Sulu are characterized by OIB-like trace element distribution patterns and depleted radiogenic isotopic compositions, recording recycling of the previously subducted paleo-Tethyan oceanic crust and related crust-mantle interaction (Dai et al., 2015b, 2017a, 2017b, 2018). If all these magmatic rocks are considered as the products of post-collisional magmatism, the time interval between the magmatism and collisional orogeny reaches up to 80–110 Myr.

The Himalayan orogen in the southern Tibetan plateau is a typical Cenozoic continental subduction/collision orogen, which is the result of collision between the Indian and Eurasia continents despite the arc-continent collision in the Mesozoic (Zheng and Wu, 2018; Zheng et al., 2019b). Previously, there is some debate on the timing of continent-continent collision, even the whole Cenozoic was regarded as the age of collisional orogeny. With the development of isotopic dating techniques, it has been recognized that the collisional orogeny occurred in a short period of 55±10 Ma (Zhu et al., 2011; Hu et al., 2016; Zheng and Wu, 2018). The potassic-ultrapotassic magmatism in the southern Tibetan plateau, which is considered the representative of post-collisional magmatism, mainly occurred at 46–8 Ma (Chung et al., 2005; Zhao et al., 2009). These age differences indicate that the post-collisional magmatism in the southern Tibetan plateau happened at 10–50 Myr after the continental collision between India and Asia. The Anatolian orogen, an important part of the Alpine-Himalayan orogenic belt, is the product of arc-continent and continent-continent collision during evolution of the Neo-Tethyan Ocean. In the northwestern Anatolia, the collision between the Kirsehir continent and Anatolian island terrane took place at the Paleocene to Early Eocene, whereas the post-collisional magmatism began at ~54 Ma and continued until the Quaternary (Dilek and Altunkaynak, 2007, 2009; Güraslan and Altunkaynak, 2019). Therefore, the post-collisional magmatism in the Anatolian orogen lasts about 50 Myr since the end of collisional orogeny.

The Central Asian orogenic belt is a typical arc-continent collision accretionary orogen. Its eastern section is commonly called as the Xing-Meng orogen, which is the result of the evolution of the Paleo-Asian Ocean. Based on the timing of syn-collisional granite and late Permian molasse deposition, the finial formation of the Xing-Meng orogen (i.e., the final closure of the Paleo-Asian Ocean) occurred at 250–245 Ma in the Late Permian-Middle Triassic (Li, 2006; Xu et al., 2013b; Song et al., 2015a; Wang et al., 2018). The post-collisional magmatisms can be represented by the alkaline igneous rocks and Late Triassic granitoids (205–230 Ma) distributed in east-west trending in the northern margin of the North China Craton, and the mafic-ultramafic intrusive rocks (210–225 Ma) in the orogen (Wu et al., 2004; Xu et al., 2013b). Therefore, post-collisional magmatisms in the Xing-Meng orogen occurred at 20–45 Myr after the collisional orogeny.

The European Variscan orogenic belt extends from Iberia in the west to Bohemia in the east, including the north-central Pyrenees-Iberian Peninsula, French Massif Central, Vosges-Black Forest Region, Corsica-Sardinia Island, and Bohemian terrane and other regions. The collision of multiple terranes occurred in the Late Silurian to Early Permian, mainly in the Early Carboniferous. Among them, the age of peak metamorphism in the French Massif Central is about 420–400 Ma (Berger et al., 2010) and post-collisional magmatism mainly occurred at 345–300 Ma (Paquette et al., 2003; Faure et al., 2010). However, the ages of UHP metamorphism are 360–353 Ma in the Bohemia Earle and Italian Alps regions (Schmädicke et al., 1995), where post-collisional magmatism mainly occurred at 310–260 Ma (Dallagiovanna et al., 2009; Maino et al., 2012). Despite systematic differences in the ages of metamorphism and magmatism between the western and eastern segments, it appears that the post-collisional magmatisms in the French Massif Central and Bohemia regions occurred at about 40–100 Myr after the collisional orogeny.

The western Gondwana orogenic belt (also known as the Pan-African orogenic belt) formed at 620–580 Ma, whereas the post-collisional magmatism occurred mainly at 580–525 Ma (Araujo et al., 2014), indicating that the post-collisional magmatism in this orogenic belt mainly occurred at about 50 Myr after the collisional orogeny.

In summary, based on the collisional timing of typical orogenic belts and the timing of post-collisional magmatism, we conclude that post-collisional magmatisms in collisional orogens generally occurred at about 20–50 Myr after collisional orogeny, some are even less than 20 Myr or more than 100 Myr. The Dabie-Sulu orogenic belt has the most obvious time interval between collisional orogeny and post-collisional magmatism, making the time interval between Triassic continental collision and Early Cretaceous magmatism very clear (Zhao et al., 2013, 2017b). However, with respect to the continental collision after the closure of the Neo-Tethyan ocean in the southern margin of Eurasia, the time interval between collisional orogeny and post-collisional magmatism is relatively short, sometimes it is difficult to distinguish from each other. In addition, syn-collisional magmatic rocks are mainly emplaced on continental margins above subduction zones, whereas late-collisional and post-collisional magmatic rocks can be emplaced on the continental margins of both sides of plate suture zones.

5. Post-collisional mafic magmatism: Records of the nature and evolution of orogenic mantle

According to the activity and stability of petrotectonic units, lithosphere can be subdivided into cratonic and orogenic units. Orogenic belts, as main sites where tectonic processes occur during the evolution of Earth, record not only the crustal accretion and reworking, but also the formation and evolution of lithospheric mantle. How to understand the nature and evolution of orogenic belts? Whereas post-collisional felsic magmatism records the crustal growth and reworking, post-collisional mafic magmatism reflects the evolution of orogenic mantle (Dilek and Altunkaynak, 2007, 2009; Zhao et al., 2013; Song et al., 2014; Chung et al., 2005; Zheng et al., 2020). Then, what are the factors to influence the nature and evolution of orogenic mantle?

Firstly, the nature of orogenic mantle can be affected by the irregular geometry of subducting slab (tearing, detachment and rolling-back), subduction velocity, polarity and dip angle as well as the composition of the mantle wedge before subduction (Syracuse et al., 2010; Li et al., 2015; Zheng and Chen, 2016). Secondly, orogenic process is the second factor to influence the nature of orogenic mantle. The collisional tectonism in orogens caused the thickening and stacking of lithosphere, resulting in the geochemical heterogeneity of orogenic mantle. The lithospheric uplift, collapse, detachment and rifting occurred successively after collisional orogeny are the main geodynamic mechanisms for the generation of post-collisional magmatism (Zheng and Zhao, 2017; Zheng et al., 2019b, 2020). Thirdly, the formation mechanism of orogenic belts is also a factor to result in the difference in the composition of orogenic mantle. Therefore, it is possible that post-collisional magmatism can be used to understand the dynamic evolution of orogenic lithosphere, which is detailed as follows.

With respect to arc-continent collisional orogens, the mantle wedge beneath active continental margin would be metasomatized by materials derived not only from previously subducted oceanic crust, but also from subsequent subducted continental crust. As a result, the orogenic lithospheric mantle is relatively rich in fluid-mobile elements (Zheng, 2019).This is exemplified by the Mesozoic Gangdese orogen in the southern Tibet (Zhu et al., 2011; Zheng et al., 2019b). With respect to the geochemical enrichment of the mantle wedge beneath the active continental margin, it has experienced at least three stages: (1) The southern margin of the Asian continent was metasomatized by subduction of the Neo-Tethyan oceanic plate in the Mesozoic, generating the Gangdese continental arc; (2) during the Early Cenozoic subduction of the Indian continent, the mantle wedge beneath the continental arc was metasomatized again by fluids from the subducting continental crust, resulting in syn-collisional magmatism at backarc sites; (3) in the post-collisional stage, the previously active continental margin was reactivated to produce post-collisional magmatism (Zheng et al., 2019b). Partial melting of the metasomatic mantle domains beneath the continental arc give rise to mafic igneous rocks, which exhibits arc-like trace element distribution patterns (i.e., enrichment in LILE, LREE and Pb, depletion in HFSE) and depleted-weakly enriched Sr-Nd isotopic compositions.

With respect to continent-continent collisional orogens, the mantle wedge beneath active continental margins would be metasomatized by materials derived not only from previously subducted oceanic crust, but also from subducted continental crust, so that the orogenic lithospheric mantle is also relatively enriched in fluid-mobile elements and metallogenic elements. However, because the lithosphere of such active continental margins was too thick, neither continental arc magmatism nor significant syn-collisional magmatism occurred. This is illustrated by the southern margin of the North China Craton north of the Dabie-Sulu orogenic belt (Zheng, 2008; Zheng et al., 2019a). The magma sources for syn-exhumation and post-collisional magmatism are mainly characterized by geochemical modification of the overlying subcontinental lithospheric mantle by subdcuted ancient continental crust-derived materials. For example, the Early Cretaceous mafic igneous rocks and related mantle-derived xenoliths in the southeastern North China Craton have well revealed the process and mechanism of the lithospheric mantle modification by the subducted continental crust materials (Gao et al., 2008; Zhang et al., 2002; Xu et al., 2013a). These mafic igneous rocks formed by partial melting of such modified mantle display arc-like trace element distribution patterns and relatively enriched Sr-Nd isotopic compositions (Yang D B et al., 2012; Zhao et al., 2013). The subduction of continental crust is usually considered to be pulled by gravity of the preceedingly subducting oceanic crust, so the subducting paleo-oceanic crust should have also influenced the overlying lithospheric mantle above the continental subduction zone. For example, the Early-Middle Triassic mafic dykes in the Liaodong Peninsula and Early Cretaceous diabases in the Tongbai-Hong'an area record the geochemical modification of the orogenic lithospheric mantle by presubducted Paleo-Tethyan oceanic crust materials (Dai et al., 2015b, 2017b; Fang et al., 2020). These mafic igneous rocks formed by partial melting of such modified mantle exhibit OIB-like trace element distribution patterns and relatively depleted Sr-Nd isotopic compositions. Since the lithospheric mantle of continent-continent collisional orogen undergone the later superimposed modification of the subducting continental crust, the post-collisional mafic igneous rocks record relatively little information about the subducting paleo-oceanic crust.

In summary, the composition of orogenic mantle is complex, and it has been varied along with the development from oceanic subduction to continent collision. How to reveal the composition and evolution of orogenic mantle? Geochemistry of mantle-derived post-collisional igneous rocks is still the unique record to explore mantle dynamics in collisional orogens, because they record the mantle composition variations through time, corresponding to syn-collisional and post-collisional geodynamics. Prelević et al. (2012) used the composition of ultrapotassic-mafic igneous rocks to explore the evolution of orogenic lithospheric mantle. The Os-Sr-Mg isotopic compositions of post-collisional ultrapotassic rocks in the southern Tibet plateau have been used to reveal carbonate metasomatism in the lithospheric mantle (Liu et al., 2015). Ammannati et al. (2016) used the olivine trace element abundances in silica-unsaturated ultrapotassic rocks to reveal the occurrence of carbonate metasomatism in the lithospheric mantle. Dai et al. (2017a) used the composition of alkaline basalts in orogens to distinguish differential contributions from carbonate and silicate melts to their mantle sources, likely existing as carbonated peridotite and amphibolite, respectively. Qi et al. (2018) conducted a comparative study of mantle-derived igneous rocks before and after collision in the southern Lhasa terrane. They found that the former is characterized by depleted-weakly enriched Sr-Nd isotopic compositions, indicating its derivation from partial melting of the mantle metasomatized by the subducting Neo-Tethyan oceanic crust-derived materials; the latter has significantly enriched Sr-Nd isotopic compositions, indicating its origination from the mantle metasomatized by the subducting Indian continental crust-derived materials. Despite the fact that the orogenic mantle was geochemically modified by subducting crustal materials has been documented by the studies of post-collisional igneous rocks, the types and quantity of crustal materials contributing to the modification of lithospheric mantle and its process and mechanism are still poorly understood. These issues have become the main subjects to study post-collisional mafic magmatism in the future and are of great significance to develop the plate tectonics theory.

6. Post-collisional mafic magmatism and mineralization

The collisional tectonism caused the thickening and stacking of orogenic lithosphere at convergent plate boundaries. Subsequently, the extension and collapse of orogenic belts would occur due to its instability in gravity and convective thinning at the thermal boundary layer. This is the geodynamic background to result in post-collisional magmatism. At this stage, both granitic magmatism formed by reworking of crustal rocks and mafic-ultramafic magmatism formed by partial melting of the mantle (lithospheric or asthenospheric) can occur (Liègeois, 1998; Bonin, 2004; Zhao and Zheng, 2009; Zheng et al., 2020). The former is mainly related to the formation of porphyry deposits, and the latter is mostly associated with orogenic Cu-Ni sulfide and/or platinum group element deposits (Wu et al., 2004; Xu et al., 2013b; Fiorentini et al., 2018). In addition, there may also exist the genetic connection between the early subduction and metasomatism of oceanic crust and the late post-collisional hydrothermal mineralization (Hou et al., 2015; Zheng et al., 2019b). The early subduction and metasomatism of oceanic crust can preliminarily enrich ore-forming elements in the mantle wedge, and the late post-collisional rifting orogeny can reactivate the pre-enriched metal regions and finally lead to mineralization in collisional orogens (Zheng et al., 2019b). Hou et al. (2015) also suggested that the porphyry copper mineralization in the late post-collisional stage may be related to the early subduction of oceanic crust. Mafic arc magmas are characterized by high oxygen fugacity in closed systems, resulting in the progressive enrichment of Cu and Au in evolved magmas and the finial formation of subduction-type porphyry copper deposits. In contrast, the interaction between mafic arc magmas and their overlying continental crust would happen in open systems, leading to the decrease of magmatic oxygen fugacity and subsequent accumulation of magma sulfide in the juvenile lower crust. Partial melting of the juvenile lower crust enriched in metal sulfide would release Cu to the magmatic system and generate the collision-type porphyry Cu deposits (Zhang and Hou, 2018).

The Late Triassic Hongqiling Cu-Ni sulfide deposit in the southern margin of the Xing-Meng orogen is a typical example of mineralization in collisional orogens. The Cu-Ni sulfide deposit is related to post-collisional Late Triassic mafic-ultramafic magmatism formed in an extensional environment after the final closure of the Paleo-Asian Ocean. The Cu-Ni sulfide mineralization resulted from mafic magma differentiation at deep depth and multiple stages of emplacement at shallow depth (Wu et al., 2004; Xu et al., 2013b). In addition, the occurrence of mantle-derived mafic and alkaline magmatism and their underplating, accumulation and differentiation at the crustal bottom are also the main approaches to transfer the mantle metal and sulfur into the continental crust (Fiorentini et al., 2018). Thus, these mantle-derived igneous rocks at the crustal bottom provide sound material bases for later crustal magmatism and the formation of porphyry copper deposits. The generation of some orogenic gold deposits is just related to post-collisional granitic magmatism (Zhang et al., 2017).

Taken together, it can be concluded that post-collisional magmatism is closely related to regional mineralization. Although it has been documented that ore-forming metals and sulfur can be transported from the mantle to the crust by post-collisional magmatism in collisional orogens, little is known about the way of magma emplacement, and mechanism, rate and dynamics for the migration of metals and volatiles from the locally enriched lithospheric mantle to the bottom of the continental crust (Griffin et al., 2009; Fiorentini et al., 2018). Additionally, how to establish a clear metallogenic theory through the study of post-collisional magmatism, and then applied it to different types of collisional orogens and other tectonic environments? And what are the key controlling factors for orogenic mineralization? These questions have become one of the key issues in studying the relationship between post-collisional magmatism and mineralization in the future, and it will be of great significance for guiding regional ore prospecting.

7. Conclusions

Post-collisional mafic magmatism is an important stage in the evolution of plate subduction and collisional orogeny. Post-collisional mafic magmatism formed in the extension and collapse stage of collisional orogens, and record the evolution of the lithospheric mantle at convergent plate boundaries from the pre-collisional through collisional to post-collisional stages. Thus, it is not only the direct material record to reveal the evolution of orogenic mantle, but also the important carrier for the formation of various mineral resources. However, the type and quantity of crustal materials modifying the overlying mantle wedge, and its modification process and mechanism, as well as the major control factors and formation mechanism of post-collisional mafic magma-related mineralization are the main issues and direction of future studies in this field.

Acknowledgements *We thanks Prof. Yong-Fei Zheng for inviting us to write this article, and three reviewers for their constructive comments and suggestions, which are of great importance to improve the quality of this article. This study was supported by the National Key R&D Program of China (Grant No. 2016YFC0600103) and the National Natural Science Foundation of China (Grant Nos. 91858211 & 41822302).*

References

Aitchison J C, Badengzhu J C, Davis A M, Liu J, Luo H, Malpas J G, McDermid I R C, Wu H, Ziabrev S V, Zhou M. 2000. Remnants of a Cretaceous intra-oceanic subduction system within the Yarlung-Zangbo suture (southern Tibet). Earth Planet Sci Lett, 183: 231–244

Ammannati E, Jacob D E, Avanzinelli R, Foley S F, Conticelli S. 2016. Low Ni olivine in silica-undersaturated ultrapotassic igneous rocks as evidence for carbonate metasomatism in the mantle. Earth Planet Sci Lett, 444: 64–74

Araujo C E G, Rubatto D, Hermann J, Cordani U G, Caby R, Basei M A S. 2014. Ediacaran 2500-km-long synchronous deep continental subduction in the West Gondwana Orogen. Nat Commun, 5: 5198

Berger J, Féménias O, Ohnenstetter D, Bruguier O, Plissart G, Mercier J C C, Demaiffe D. 2010. New occurrence of UHP eclogites in Limousin (French Massif Central): Age, tectonic setting and fluid-rock interactions. Lithos, 118: 365–382

Bonin B. 1996. A-type granite ring-complexes: Mantle origin through crustal filters and the anorthosite-rapakivi magmatism connection. In: Demaiffe D, ed. Petrology and Geochemistry of Magmatic Suite of Rocks in the Continental and Oceanic crusts. Bruxelles: ULB-MRAC. 201–218

Bonin B. 2004. Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review. Lithos, 78: 1–24

Bonin B, Platevoet B, Vialette Y. 1987. The geodynamic significance of alkaline magmatism in the Western Mediterranean compared with West Africa. Geol J, 22: 361–387

Bureau of Geology and Mineral Resources of Heilongjiang Province. 1993. Regional Geology of Heilongjiang Province (in Chinese). Beijing: Geological Publication House

Chen Y X, Zhou K, Gao X Y. 2017. Partial melting of ultrahigh-pressure metamorphic rocks during continental collision: Evidence, time, mechanism, and effect. J Asian Earth Sci, 145: 177–191

Chung S L, Chu M F, Zhang Y, Xie Y, Lo C H, Lee T Y, Lan C Y, Li X, Zhang Q, Wang Y. 2005. Tibetan tectonic evolution inferred from spatial and temporal variations in post-collisional magmatism. Earth-Sci Rev, 68: 173–196

Clemens J D, Holloway J R, White A J R. 1986. Origin of an A-type granite: Experimental constraints. Am Miner, 71: 317–324

Dai F Q, Zhao Z F, Dai L Q, Zheng Y F. 2016. Slab-mantle interaction in the petrogenesis of andesitic magmas: Geochemical evidence from postcollisional intermediate volcanic rocks in the Dabie orogen, China. J Petrol, 57: 1109–1134

Dai F Q, Zhao Z F, Zheng Y F, Sun G C. 2019. The geochemical nature of mantle sources for two types of Cretaceous basaltic rocks from Luxi and Jiaodong in east-central China. Lithos, 344-345: 409–424

Dai L Q, Zhao Z F, Zheng Y F, Li Q L, Yang Y H, Dai M N. 2011. Zircon Hf-O isotope evidence for crust-mantle interaction during continental deep subduction. Earth Planet Sci Lett, 308: 229–244

Dai L Q, Zhao Z F, Zheng Y F, Zhang J. 2012. The nature of orogenic lithospheric mantle: Geochemical constraints from postcollisional mafic-ultramafic rocks in the Dabie orogen. Chem Geol, 334: 99–121

Dai L Q, Zhao Z F, Zheng Y F. 2014. Geochemical insights into the role of metasomatic hornblendite in generating alkali basalts. Geochem Geophys Geosyst, 15: 3762–3779

Dai L Q, Zhao Z F, Zheng Y F, Zhang J. 2015a. Source and magma mixing processes in continental subduction factory: Geochemical evidence from postcollisional mafic igneous rocks in the Dabie orogen. Geochem Geophys Geosyst, 16: 659–680

Dai L Q, Zhao Z F, Zheng Y F. 2015b. Tectonic development from oceanic subduction to continental collision: Geochemical evidence from post-collisional mafic rocks in the Hong'an-Dabie orogens. Gondwana Res, 27: 1236–1254

Dai L Q, Zheng Y F, He H Y, Zhao Z F. 2016a. Postcollisional mafic igneous rocks record recycling of noble gases by deep subduction of the continental crust. Lithos, 252-253: 135–144

Dai L Q, Zheng Y F, Zhao Z F. 2016b. Termination time of peak decratonization in North China: Geochemical evidence from mafic igneous rocks. Lithos, 240-243: 327–336

Dai L Q, Zhao Z F, Zheng Y F, An Y J, Zheng F. 2017a. Geochemical distinction between carbonate and silicate metasomatism in generating the mantle sources of alkali basalts. J Petrol, 58: 863–884

Dai L Q, Zheng F, Zhao Z F, Zheng Y F. 2017b. Recycling of Paleotethyan oceanic crust: Geochemical record from postcollisional mafic igneous rocks in the Tongbai-Hong'an orogens. Geol Soc Am Bull, 129: 179–192

Dai L Q, Zheng F, Zhao Z F, Zheng Y F. 2018. Geochemical insights into the lithology of mantle sources for Cenozoic alkali basalts in West Qinling, China. Lithos, 320-303: 86–98

Dallagiovanna G, Gaggero L, Maino M, Seno S, Tiepolo M. 2009. U-Pb zircon ages for post-Variscan volcanism in the Ligurian Alps (Northern Italy). J Geol Soc, 166: 101–114

Dewey J F, Burke K. 1974. Hot spots and continental break-up: Implications for collisional orogeny. Geology, 2: 57–60

Dilek Y, Altunkaynak Ş. 2007. Cenozoic crustal evolution and mantle dynamics of post-collisional magmatism in Western Anatolia. Int Geol Rev, 49: 431–453

Dilek Y, Altunkaynak Ş. 2009. Geochemical and temporal evolution of Cenozoic magmatism in western Turkey: Mantle response to collision, slab break-off, and lithospheric tearing in an orogenic belt. Geol Soc Lond Spec Publ, 311: 213–233

Fang W, Dai L Q, Zheng Y F, Zhao Z F, Ma L T. 2020. Tectonic transition from oceanic subduction to continental collision: New geochemical evidence from Early-Middle Triassic mafic igneous rocks in southern Liaodong Peninsula, east-central China. Geol Soc Am Bull, doi: 10.1130/B35278.1

Faure M, Cocherie A, Mézème E B, Charles N, Rossi P. 2010. Middle Carboniferous crustal melting in the Variscan Belt: New insights from U-Th-Pbtot. monazite and U-Pb zircon ages of the Montagne Noire Axial Zone (southern French Massif Central). Gondwana Res, 18: 653–673

Fiorentini M L, LaFlamme C, Denyszyn S, Mole D, Maas R, Locmelis M, Caruso S, Bui T H. 2018. Post-collisional alkaline magmatism as gateway for metal and sulfur enrichment of the continental lower crust. Geochim Cosmochim Acta, 223: 175–197

Foley S F, Venturelli G, Green D H, Toscani L. 1987. The ultrapotassic rocks: Characteristics, classification, and constraints for petrogenetic models. Earth-Sci Rev, 24: 81–134

Gao S, Rudnick R L, Xu W L, Yuan H L, Liu Y S, Walker R J, Puchtel I S, Liu X, Huang H, Wang X R, Yang J. 2008. Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton. Earth Planet Sci Lett, 270: 41–53

Griffin W L, O'Reilly S Y, Afonso J C, Begg G C. 2009. The composition and evolution of lithospheric mantle: A re-evaluation and its tectonic implications. J Petrol, 50: 1185–1204

Güraslan I N, Altunkaynak Ş. 2019. Role of mantle and lower continental crust in the genesis of Eocene post-collisional granitoids: Insights from the Topuk pluton (NW Turkey). J Asian Earth Sci, 179: 365–384

Hawkesworth C J, Fraser K J, Rogers N W. 1985. Kimberlites and lamproites: Extreme products of mantle enrichment processes. Trans Geol Soc South Africa, 88: 439–447

Herzberg C. 2011. Identification of source lithology in the Hawaiian and Canary islands: Implications for origins. J Petrol, 52: 113–146

Hou Z, Duan L, Lu Y, Zheng Y, Zhu D, Yang Z, Yang Z, Wang B, Pei Y, Zhao Z, McCuaig T C. 2015. Lithospheric architecture of the Lhasa Terrane and its control on ore deposits in the Himalayan-Tibetan Orogen. Econ Geol, 110: 1541–1575

Hu X M, Garzanti E, Wang J G, Huang W T, An W, Webb A. 2016. The timing of India-Asia collision onset—Facts, theories, controversies. Earth-Sci Rev, 160: 264–299

Huang F, Chen J L, Xu J F, Wang B D, Li J. 2015. Os-Nd-Sr isotopes in Miocene ultrapotassic rocks of southern Tibet: Partial melting of a pyroxenite-bearing lithospheric mantle? Geochim Cosmochim Acta, 163: 279–298

Jagoutz O. 2014. Arc crustal differentiation mechanisms. Earth Planet Sci Lett, 396: 267–277

Kubínová Š, Faryad S W, Verner K, Schmitz M, Holub F. 2017. Ultrapotassic dykes in the Moldanubian Zone and their significance for understanding of the post-collisional mantle dynamics during Variscan orogeny in the Bohemian Massif. Lithos, 272-273: 205–221

Li H Y, Chen R X, Zheng Y F, Hu Z C. 2016. The crust-mantle interaction in continental subduction channels: Zircon evidence from orogenic peridotite in the Sulu orogen. J Geophys Res-Solid Earth, 121: 687–712

Li H Y, Chen R X, Zheng Y F, Hu Z, Xu L. 2018. Crustal metasomatism at the slab-mantle interface in a continental subduction channel: Geochemical evidence from orogenic peridotite in the Sulu orogen. J Geophys Res-Solid Earth, 123: 2174–2198

Li J Y. 2006. Permian geodynamic setting of Northeast China and adjacent regions: Closure of the Paleo-Asian Ocean and subduction of the Paleo-Pacific Plate. J Asian Earth Sci, 26: 207–224

Li Y, Xu W L, Wang F, Tang J, Pei F P, Wang Z J. 2014. Geochronology and geochemistry of late Paleozoic volcanic rocks on the western margin of the Songnen-Zhangguangcai Range Massif, NE China: Implications for the amalgamation history of the Xing'an and Songnen-Zhangguangcai Range massifs. Lithos, 205: 394–410

Li Z H, Liu M Q, Gerya T. 2015. Material transportation and fluid-melt activity in the subduction channel: Numerical modeling. Sci China Earth Sci, 58: 1251–1268

Liègeois J P. 1998. Preface-some words on the post-collisional magmatism. Lithos, 45: 15–17

Liègeois J P, Black R. 1987. Alkaline magmatism subsequent to collision in the Pan-African belt of the Adrar des Iforas (Mali). Geol Soc Lond Spec Publ, 30: 381–401

Liu D, Zhao Z, Zhu D C, Niu Y, Widom E, Teng F Z, DePaolo D J, Ke S, Xu J F, Wang Q, Mo X. 2015. Identifying mantle carbonatite metasomatism through Os-Sr-Mg isotopes in Tibetan ultrapotassic rocks. Earth Planet Sci Lett, 430: 458–469

Liu F L, Liou J G. 2011. Zircon as the best mineral for P-T-time history of UHP metamorphism: A review on mineral inclusions and U-Pb SHRIMP ages of zircons from the Dabie-Sulu UHP rocks. J Asian Earth Sci, 40: 1–39

Liu W, Fei P X. 2006. Methane-rich fluid inclusions from ophiolitic dunite and post-collisional mafic-ultramafic intrusion: The mantle dynamics underneath the Palaeo-Asian Ocean through to the post-collisional period. Earth Planet Sci Lett, 242: 286–301

Liu Y S, Gao S, Kelemen P B, Xu W L. 2008. Recycled crust controls contrasting source compositions of Mesozoic and Cenozoic basalts in the North China Craton. Geochim Cosmochim Acta, 72: 2349–2376

Liou J G, Ernst W G, Zhang R Y, Tsujimori T, Jahn B M. 2009. Ultrahigh-pressure minerals and metamorphic terranes—The view from China. J Asian Earth Sci, 35: 199–231

Lustrino M, Melluso L, Morra V. 2000. The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy). Earth Planet Sci Lett, 180: 259–270

Maino M, Dallagiovanna G, Gaggero L, Seno S, Tiepolo M. 2012. U-Pb zircon geochronological and petrographic constraints on late to post-collisional Variscan magmatism and metamorphism in the Ligurian Alps, Italy. Geol J, 47: 632–652

Nelson D R, McCulloch M T, Sun S S. 1986. The origins of ultrapotassic rocks as inferred from Sr, Nd and Pb isotopes. Geochim Cosmochim Acta, 50: 231–245

Paquette J L, Ménot R P, Pin C, Orsini J B. 2003. Episodic and short-lived granitic pulses in a post-collisional setting: Evidence from precise U-Pb zircon dating through a crustal cross-section in Corsica. Chem Geol, 198: 1–20

Prelević D, Akal C, Foley S F, Romer R L, Stracke A, Van Den Bogaard P. 2012. Ultrapotassic mafic rocks as geochemical proxies for post-collisional dynamics of orogenic lithospheric mantle: The case of southwestern Anatolia, Turkey. J Petrol, 53: 1019–1055

Qi Y, Gou G N, Wang Q, Wyman D A, Jiang Z Q, Li Q L, Zhang L. 2018. Cenozoic mantle composition evolution of southern Tibet indicated by Paleocene (~64 Ma) pseudoleucite phonolitic rocks in central Lhasa terrane. Lithos, 302-303: 178–188

Reagan M K, Ishizuka O, Stern R J, Kelley K A, Ohara Y, Blichert-Toft J, Bloomer S H, Cash J, Fryer P, Hanan B B, Hickey-Vargas R, Ishii T, Kimura J I, Peate D W, Rowe M C, Woods M. 2010. Fore-arc basalts and subduction initiation in the Izu-Bonin-Mariana system. Geochem Geophys Geosyst, 11: Q03X12

Schmädicke E, Mezger K, Cosca M A, Okrusch M. 1995. Variscan Sm-Nd and Ar-Ar ages of eclogite facies rocks from the Erzgebirge, Bohemian Massif. J Metamorph Geol, 13: 537–552

Stern R J, Fouch M J, Klemperer S L. 2004. An overview of the Izu-Bonin-Mariana subduction factory. In: Eiler J, ed. Inside the Subduction Factory. American Geophysical Union. 175–222

Sobolev A V, Hofmann A W, Sobolev S V, Nikogosian I K. 2005. An olivine-free mantle source of Hawaiian shield basalts. Nature, 434: 590–597

Song S, Niu Y, Su L, Zhang C, Zhang L. 2014. Continental orogenesis from ocean subduction, continent collision/subduction, to orogen collapse, and orogen recycling: The example of the North Qaidam UHPM belt, NW China. Earth-Sci Rev, 129: 59–84

Song S, Wang M M, Xu X, Wang C, Niu Y, Allen M B, Su L. 2015a. Ophiolites in the Xing'an-Inner Mongolia accretionary belt of the CAOB: Implications for two cycles of seafloor spreading and accretionary orogenic events. Tectonics, 34: 2221–2248

Song S G, Wang M J, Wang C, Niu Y L. 2015b. Magmatism during continental collision, subduction, exhumation and mountain collapse in

collisional orogenic belts and continental net growth: A perspective. Sci China Earth Sci, 58: 1284–1304
Syracuse E M, van Keken P E, Abers G A. 2010. The global range of subduction zone thermal models. Phys Earth Planet Inter, 183: 73–90
Thompson R N, Leat P T, Dickin A P, Morrison M A, Hendry G L, Gibson S A. 1990. Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: Evidence from Miocene minettes of northwest Colorado, U.S.A. Earth Planet Sci Lett, 98: 139–153
Wang M J, Song S G, Niu Y L, Su L. 2014. Post-collisional magmatism: Consequences of UHPM terrane exhumation and orogen collapse, N. Qaidam UHPM belt, NW China. Lithos, 210: 181–198
Wang Y N, Xu W L, Wang F, Li X B. 2018. New insights on the early Mesozoic evolution of multiple tectonic regimes in the northeastern North China Craton from the detrital zircon provenance of sedimentary strata. Solid Earth, 9: 1375–1397
Wendlandt R F, Eggler D H. 1980a. The origins of potassic magmas; 1, Melting relations in the systems $KAlSiO_4$-Mg_2SiO_4-SiO_2 and $KAlSiO_4$ MgO-SiO_2-CO_2 to 30 kilobars. Am J Sci, 280: 385–420
Wendlandt R F, Eggler D H. 1980b. The origins of potassic magmas; 2, Stability of phlogopite in natural spinel lherzolite and in the system $KAlSiO_4$-MgO-SiO_2-H_2O-CO_2 at high pressures and high temperatures. Am J Sci, 280: 421–458
Windley B F, Alexeiev D, Xiao W, Kröner A, Badarch G. 2007. Tectonic models for accretion of the Central Asian orogenic belt. J Geol Soc, 164: 31–47
Wu F Y, Wilde S A, Zhang G L, Sun D Y. 2004. Geochronology and petrogenesis of the post-orogenic Cu-Ni sulfide-bearing mafic-ultramafic complexes in Jilin Province, NE China. J Asian Earth Sci, 23: 781–797
Wu Y B, Zheng Y F. 2013. Tectonic evolution of a composite collision orogen: An overview on the Qinling-Tongbai-Hong'an-Dabie-Sulu orogenic belt in central China. Gondwana Res, 23: 1402–1428
Xiao W J, Windley B F, Hao J, Zhai M G. 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the Central Asian orogenic belt. Tectonics, 22: 1069
Xiao W J, Windley B F, Sun S, Li J L, Huang B C, Han C M, Yuan C, Sun M, Chen H L. 2015. A tale of amalgamation of three Permo-Triassic collage systems in Central Asia: Oroclines, sutures, and terminal accretion. Annu Rev Earth Planet Sci, 43: 477–507
Xu S T, Okay A I, Ji S Y, Sengor A M C, Su W, Liu Y C, Jiang L L. 1992. Diamond from the Dabie Shan metamorphic rocks and its implication for tectonic setting. Science, 256: 80–82
Xu W L, Zhou Q J, Pei F P, Yang D B, Gao S, Li Q L, Yang Y H. 2013a. Destruction of the North China Craton: Delamination or thermal/Chemical erosion? Mineral chemistry and oxygen isotope insights from websterite xenoliths. Gondwana Res, 23: 119–129
Xu W L, Pei F P, Wang F, Meng E, Ji W Q, Yang D B, Wang W. 2013b. Spatial-temporal relationships of Mesozoic volcanic rocks in NE China: Constraints on tectonic overprinting and transformations between multiple tectonic regimes. J Asian Earth Sci, 74: 167–193
Xu H, Zhang J, Wang Y, Liu W. 2016. Late Triassic alkaline complex in the Sulu UHP terrane: Implications for post-collisional magmatism and subsequent fractional crystallization. Gondwana Res, 35: 390–410
Xu Z Q, Zhao Z B, Ma X X, Chen X J, Ma Y. 2019. From Andean orogen to Gangdese orogen: From ocean-continent subduction to continent-continent collision. Acta Geol Sin-Engl, 93: 1–11
Yang J H, Chung S L, Zhai M G, Zhou X H. 2004. Geochemical and Sr-Nd-Pb isotopic compositions of mafic dikes from the Jiaodong Peninsula, China: Evidence for vein-plus-peridotite melting in the lithospheric mantle. Lithos, 73: 145–160
Yang J H, Chung S L, Wilde S A, Wu F, Chu M F, Lo C H, Fan H R. 2005. Petrogenesis of post-orogenic syenites in the Sulu Orogenic Belt, East China: Geochronological, geochemical and Nd-Sr isotopic evidence. Chem Geol, 214: 99–125
Yang J H, Sun J F, Chen F, Wilde S A, Wu F Y. 2007. Sources and petrogenesis of Late Triassic dolerite dikes in the Liaodong Peninsula: Implications for post-collisional lithosphere thinning of the Eastern North China Craton. J Petrol, 48: 1973–1997
Yang D B, Xu W L, Pei F P, Yang C H, Wang Q H. 2012. Spatial extent of the influence of the deeply subducted South China Block on the southeastern North China Block: Constraints from Sr-Nd-Pb isotopes in Mesozoic mafic igneous rocks. Lithos, 136-139: 246–260
Yang Q L, Zhao Z F, Zheng Y F. 2012a. Modification of subcontinental lithospheric mantle above continental subduction zone: Constraints from geochemistry of Mesozoic gabbroic rocks in southeastern North China. Lithos, 146-147: 164–182
Yang Q L, Zhao Z F, Zheng Y F. 2012b. Slab-mantle interaction in continental subduction channel: Geochemical evidence from Mesozoic gabbroic intrusives in southeastern North China. Lithos, 155: 442–460
Yin A, Harrison T M. 2000. Geologic evolution of the Himalayan-Tibetan Orogen. Annu Rev Earth Planet Sci, 28: 211–280
Yoder H S. 1986. Potassium-rich rocks: Phase analysis and heteromorphic relations. J Petrol, 27: 1215–1228
Zhang H F, Sun M, Zhou X H, Fan W M, Zhai M G, Yin J F. 2002. Mesozoic lithosphere destruction beneath the North China Craton: Evidence from major-, trace-element and Sr-Nd-Pb isotope studies of Fangcheng basalts. Contrib Mineral Petrol, 144: 241–254
Zhang J, Zhao Z F, Zheng Y F, Liu X, Xie L. 2012. Zircon Hf-O isotope and whole-rock geochemical constraints on origin of postcollisional mafic to felsic dykes in the Sulu orogen. Lithos, 136-139: 225–245
Zhang J Y, Ma C Q, Li J W, Pan Y M. 2017. A possible genetic relationship between orogenic gold mineralization and post-collisional magmatism in the eastern Kunlun Orogen, western China. Ore Geol Rev, 81: 342–357
Zhang H R, Hou Z Q. 2018. Metallogenesis within continental collision zones: Comparisons of modern collisional orogens. Sci China Earth Sci, 48: 1629–1654
Zhao Z, Mo X, Dilek Y, Niu Y, DePaolo D J, Robinson P, Zhu D, Sun C, Dong G, Zhou S. 2009. Geochemical and Sr-Nd-Pb-O isotopic compositions of the post-collisional ultrapotassic magmatism in SW Tibet: Petrogenesis and implications for India intra-continental subduction beneath southern Tibet. Lithos, 113: 190–212
Zhao Z F, Zheng Y F. 2009. Remelting of subducted continental lithosphere: Petrogenesis of Mesozoic magmatic rocks in the Dabie-Sulu orogenic belt. Sci China Ser D-Earth Sci, 52: 1295–1318
Zhao Z F, Zheng Y F, Wei C S, Wu F Y. 2011. Origin of postcollisional magmatic rocks in the Dabie orogen: Implications for crust-mantle interaction and crustal architecture. Lithos, 126: 99–114
Zhao Z F, Zheng Y F, Zhang J, Dai L Q, Li Q, Liu X. 2012. Syn-exhumation magmatism during continental collision: Evidence from alkaline intrusives of Triassic age in the Sulu orogen. Chem Geol, 328: 70–88
Zhao Z F, Dai L Q, Zheng Y F. 2013. Postcollisional mafic igneous rocks record crust-mantle interaction during continental deep subduction. Sci Rep, 3: 3413
Zhao Z F, Dai L Q, Zheng Y F. 2015. Two types of the crust-mantle interaction in continental subduction zones. Sci China Earth Sci, 58: 1269–1283
Zhao Z F, Zheng Y F, Chen Y X, Sun G C. 2017a. Partial melting of subducted continental crust: Geochemical evidence from synexhumation granite in the Sulu Orogen. Geol Soc Am Bull, 129: 1692–1707
Zhao Z F, Liu Z B, Chen Q. 2017b. Melting of subducted continental crust: Geochemical evidence from Mesozoic granitoids in the Dabie-Sulu orogenic belt, east-central China. J Asian Earth Sci, 145: 260–277
Zhao Z F, Zheng Y F. 2003. Calculation of oxygen isotope fractionation in magmatic rocks. Chem Geol, 193: 59–80
Zheng Y F. 2008. A perspective view on ultrahigh-pressure metamorphism and continental collision in the Dabie-Sulu orogenic belt. Chin Sci Bull, 53: 3081–3104
Zheng Y F. 2012. Metamorphic chemical geodynamics in continental subduction zones. Chem Geol, 328: 5–48
Zheng Y F. 2019. Subduction zone geochemistry. Geosci Front, 10: 1223–1254

Zheng Y F, Chen R X, Zhao Z F. 2009. Chemical geodynamics of continental subduction-zone metamorphism: Insights from studies of the Chinese Continental Scientific Drilling (CCSD) core samples. Tectonophysics, 475: 327–358

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

Zheng Y F, Xia Q X, Chen R X, Gao X Y. 2011. Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. Earth-Sci Rev, 107: 342–374

Zheng Y F, Xiao W J, Zhao G. 2013. Introduction to tectonics of China. Gondwana Res, 23: 1189–1206

Zheng Y F, Chen Y X. 2016. Continental versus oceanic subduction zones. Natl Sci Rev, 3: 495–519

Zheng Y F, Chen R X. 2017. Regional metamorphism at extreme conditions: Implications for orogeny at convergent plate margins. J Asian Earth Sci, 145: 46–73

Zheng Y F, Zhao Z F. 2017. Introduction to the structures and processes of subduction zones. J Asian Earth Sci, 145: 1–15

Zheng Y F, Wu F Y. 2018. The timing of continental collision between India and Asia. Sci Bull, 63: 1649–1654

Zheng Y F, Zhao Z F, Chen R X. 2019a. Ultrahigh-pressure metamorphic rocks in the Dabie-Sulu orogenic belt: Compositional inheritance and metamorphic modification. Geol Soc Lond Spec Publ, 474: 89–132

Zheng Y F, Mao J W, Chen Y J, Sun W D, Ni P, Yang X Y. 2019b. Hydrothermal ore deposits in collisional orogens. Sci Bull, 64: 205–212

Zheng Y F, Xu Z, Chen L, Dai L Q, Zhao Z F. 2020. Chemical geodynamics of mafic magmatism above subduction zones. J Asian Earth Sci, 104185; doi: 10.1016/j.jseaes.2019.104185

Zhu D C, Zhao Z D, Niu Y, Mo X X, Chung S L, Hou Z Q, Wang L Q, Wu F Y. 2011. The Lhasa Terrane: Record of a microcontinent and its histories of drift and growth. Earth Planet Sci Lett, 301: 241–255

(Responsible editor: Yongfei ZHENG)