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# The origin of arc basalts: New advances and remaining questions

Yigang XU[1,2*], Qiang WANG[1,2,3], Gongjian TANG[1,3], Jun WANG[1], Hongyan LI[1], Jinsheng ZHOU[1], Qiwei LI[1], Yue QI[1], Pingping LIU[4], Lin MA[1] & Jingjing FAN[1]

[1] *State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China;*
[2] *College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China;*
[3] *CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China;*
[4] *School of Earth and Space Sciences, Peking University, Beijing 100871, China*

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**Abstract** Whether arc magmatism occurs above oceanic subduction zones is the forefront of studies on convergent plate margins. The most important petrologic issue related to the evolution of arc systems is the origin of arc magmatism, among which arc basalts are the most important one because they provide insights into mantle enrichment mechanism and crust-mantle interaction at oceanic subduction zones. Fluids or melts released either by dehydration or by melting of subducting oceanic slab infiltrate and metasomatize the overlying mantle wedge at varying depth, leading to the formation of source regions of arc basalts. Such processes make most of arc basalts commonly enriched in large ion lithosphile elements and light rare earth elements, but depleted in high-field strength elements and heavy rare earth elements. Small amounts of arc basalts are characterized by relatively high Nb contents or by Nb enrichment. Rare basalts with compositions similar to ocean island basalts or mid-ocean ridge basalt also occur in arc systems. For these peculiar rocks, it remains debated whether their source is affected by subduction-related components. During their ascent and before their eruption, arc basaltic magmas are subjected to crystal fractionation, mixing and crustal contamination. In addition to the contribution of subducting slab components to the mantle source of arc basalts, the materials above the subducting slab at forearc depths would have been transported either by drag or by subduction erosion into the subarc mantle and into the source of arc magmas. Heats and materials brought by corner flows also play important roles in the generation of arc basalts. Despite the important progresses made in recent studies of arc basalts, further efforts are needed to investigate subarc mantle metasomatism, material recycling, the formation of arc magma sources, geodynamic mechanism in generating arc basalts, and their implicationd s for the initiation of plate tectonics on Earth.

**Keywords** Arc basalt, Petrogenesis, Slab-mantle wedge interaction, Subarc mantle metasomatism, Subduction zone

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## 1. Introduction

One of the most important achievements of the modern plate tectonics theory is the generation of arc magmatism by subduction of oceanic plate (Frisch et al., 2011). However, arc magmatism occurs in only about half of the circum-Pacific subduction zone, thereby raising the question as to how arc magmatism is generated along oceanic subduction zones, which represents one of the forefronts of studies on convergent plate margins. The most important petrologic issue related to the evolution of arc systems is the origin of arc magmatic assemblages which include basalt, andesite, dacite and rhyolite (Ringwood, 1974). The pioneering study on arc magmatic systems can be traced back to the end of 19th century. For instance, at that time, boninite, which is closely

* Corresponding author (email: yigangxu@gig.ac.cn)

related to intra-oceanic arc system, has already been identified, defined and described (Kikuchi, 1888, 1890). As early as in the early 20th century, researches have been carried out for igneous petrology of the Japanese island, and Tomita (1935) had discovered Cenozoic low-Si alkaline volcanics in the areas surrounding the Sea of Japan and named them as circum-Japan Sea province of alkaline rocks. One of the most important progresses in petrologic studies in the last century was the finding that basalt is derived from partial melting of the upper mantle (Kushiro, 1959, 1968; Green and Ringwood, 1969). Kuno (1960) found the lateral variation in the nature of Japanese arc volcanism: tholeiite occurs mainly in the side towards the Pacific Ocean, whereas alkali basalt occurs mainly in the side towards the Japan Sea, and he proposed that the former came from the shallower mantle than the latter. Since 1960's, the application of high-pressure and high-temperature piston cylinder apparatus to the geological field greatly improved the study on the origin of arc basalts, and subsequent experiments approved the Kuno's model (Yoder and Tilley, 1962; Kushiro, 1968). Based on the inversion calculation of primary basalts from Japanese island and experimental petrology study, Tatsumi et al. (1983) proposed that the formation depth of tholeiite, high-Al basalt and alkali basalts are 35, 45–50 and 50–70 km, respectively, and suggested that basaltic melts are generated at temperatures greater than 1300°C. Meanwhile, the role of water in the genesis of arc basalts is also demonstrated: water can not only lower significantly the solidus temperature of mantle peridotites, but also change melt's composition (Kushiro, 1968; Grove et al., 2012).

A general consensus is that the formation of arc basalts is closely related to the thermal evolution and the metasomatism of the subarc mantle wedge by fluids/melts ultimately derived from the downgoing plate. Nevertheless, debates persist regarding the formation mechanism of arc basalts. Some researchers proposed that arc basalts are derived via partial melting from the subarc mantle wedge metasomatized by fluids released from the downgoing oceanic crust (Gill, 1981; Tatsumi et al., 1986; Tatsumi, 1989; Hawkesworth et al., 1993; Ulmer and Trommsdorff, 1995; Grove et al., 2002), whereas others thought that high-Nb or Nb-rich basalts are generated by partial melting of the mantle wedge metasomatized by subducting slab-derived melts (e.g., Defant and Drummond, 1990; Defant and Kepezhinskas, 2001; Defant et al., 2002). As the most important rock type of the arc system, arc basalts capture a great wealth of information regarding enrichment and dynamic processes in the mantle underneath oceanic subduction zones and thus represents unique lithoprobe into the important processes such as mantle metasomatism, chemical recycling and deep geodynamic processes (Zheng et al., 2020). This paper reviews major progresses and existing issues regarding genesis of arc basalt, and then identifies some of research opportunities in the future.

## 2. Arc types and related basalts

Volcanic arcs are classified into intra-oceanic arc and continental arc based on the locations of arc magma. Intra-oceanic arc occurs where an oceanic lithosphere is subducted beneath another ocean lithosphere to create a volcanic island arc system built on oceanic crust (Frisch et al., 2011) (Figure 1). Examples for Cenozoic intra-oceanic arc systems mainly occur in the northern and western margins of the Pacific circum, including Aleutian, Izu-Bonin-Marinana (IBM), Philippine-Luzon, Banda, Vanuatu, Fiji-Tonga-Kermadec, and the Lesser Antilles and South Sandwich in the Atlantic (Figure 1). Nevertheless, recent studies suggest that the upper plate in oceanic arc system may contain continental fragments (e.g., Wu et al., 2019). Continental arc occurs where an oceanic lithosphere is subducted beneath a continental lithosphere, whose basement is mainly composed of continental crust (Si-Al materials) (Frisch et al., 2011). Typical continental arcs occur at the western margin of the North and South American, and the Sunda arc in the northeastern margin of the Indian Ocean, where oceanic lithosphere is subducted beneath continental lithosphere without a marine basin behind the volcanic arc; rather, the arc is built directly on the adjacent continent. Continental margin island arc is developed when it is separated from continent by formation of a marine basin due to back-arc spreading induced by oceanic plate subduction. Examples for Cenozoic continental margin island arcs include the Kuril, and Japanese-Rykyu arcs in the northwestern margin of the Pacific circum (Figure 1).

Three principal types of arc basalts can be distinguished: tholeiitic (low-K) basalt, calc-alkaline basalt and shoshonite (Figure 2). Different types of arc basalts show distinct mineralogical and geochemical characteristics. In addition, three types of arc systems (intra-oceanic, continental arcs and continental margin island arcs) show different rock assemblages, geochemical features and petrogenesis.

### 2.1 Intra-oceanic arc basalts and associated rock assemblages

Intra-oceanic arc rocks include predominant basalts, and subordinate andesites and dacites, and some peculiar rocks such as high-Mg andesites and adakites (Kelemen et al., 2003). Basalts in the intra-oceanic arcs are mainly tholeiitic and calc-alkaline basalts, although minor shoshonitic basalts are also present (e.g., Hochstaedter et al., 2000; Ishizuka et al., 2003; Tatsumi et al., 2008; Stern, 2010). Tholeiitic basalts mainly occur at fore-arc and back-arc settings, with type examples in the IBM (Ishizuka et al., 2006, 2009; Reagan et

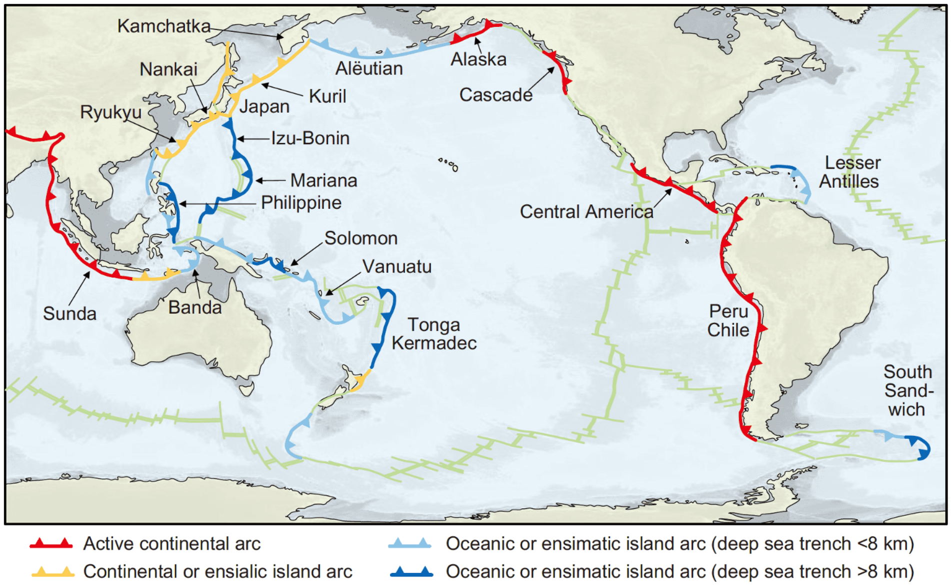


**Figure 1** Active convergentplate margins on Earthcharacterized by intra-oceanic arcs, continental arcs and continental margin island arcs (modified from Frisch et al. (2011)).

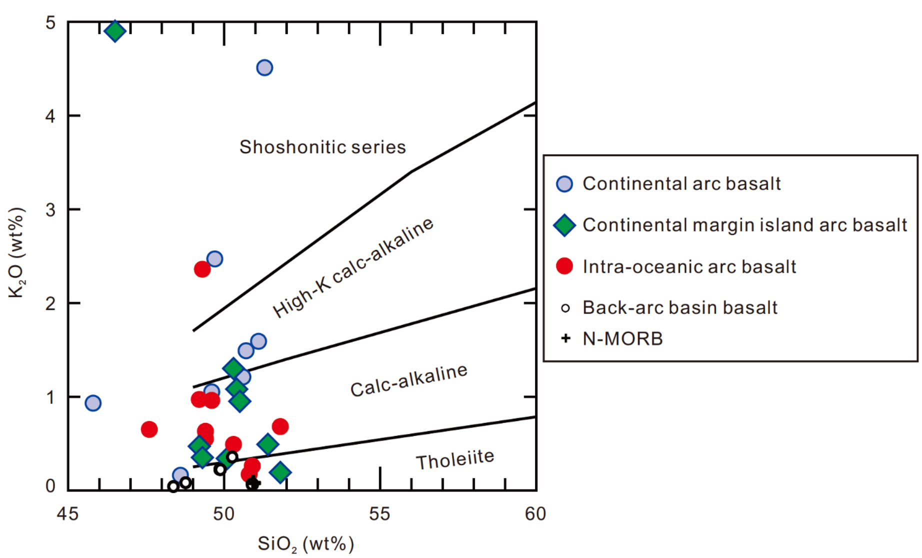


**Figure 2** $SiO_2$-$K_2O$ diagram for basalts from the typical intra-oceanic arcs, continental arcs and continental margin island arcs on Earth (Schmidt and Jagoutz, 2017), which shows that these arc basalts are mainly tholeiitic and calc-alkaline, and a small amount of them are shoshonitic. All samples are selected and re-calculated to represent primitive magmas (Schmidt and Jagoutz, 2017).

al., 2010).

Tholeiitic basalts generally show an aphyric texture and rarely a porphyritic texture, and their phenocrysts include olivine, plagioclase and augite, with minor orthopyroxene and magnetite. Although enriched in large ion lithophile elements (LILEs) and depleted in high field-strength elements (HFSEs), tholeiitic basalts show weakly fractionated rare earth elements (REE) patterns and weak enrichment of light REE (LREE), and thus do not show a typical arc signature. Except for Nb-Ta depletions and weak LILE enrichment, the spidergram of intra-oceanic tholeiitic basalts show a smooth distribution pattern (Figure 3a and 3b). The origin of tholeiitic basalts in intra-oceanic arc is generally attributed to melting of the mantle wedge above subducting slab in conjunction with variable additions of a hydrous slab component (Kelemen et al., 2003; Reagan et al., 2010).

Calc-alkaline basalts generally occur at mature intra-oceanic arc, such as Vanuatu and Solomon arcs (Peate et al., 1997; Schuth et al., 2009; Beaumais et al., 2016). Sometimes they have high $Al_2O_3$ contents and can be classified as high-Al basalts (Stern, 2010). They generally show porphyritic texture, with phenocrysts of plagioclase, olivine, augite, magnetite, and occasional amphibole. Calc-alkaline basalts show similar geochemical characteristics to tholeiitic basalts, but with much stronger enrichment in LILEs and LREE, and

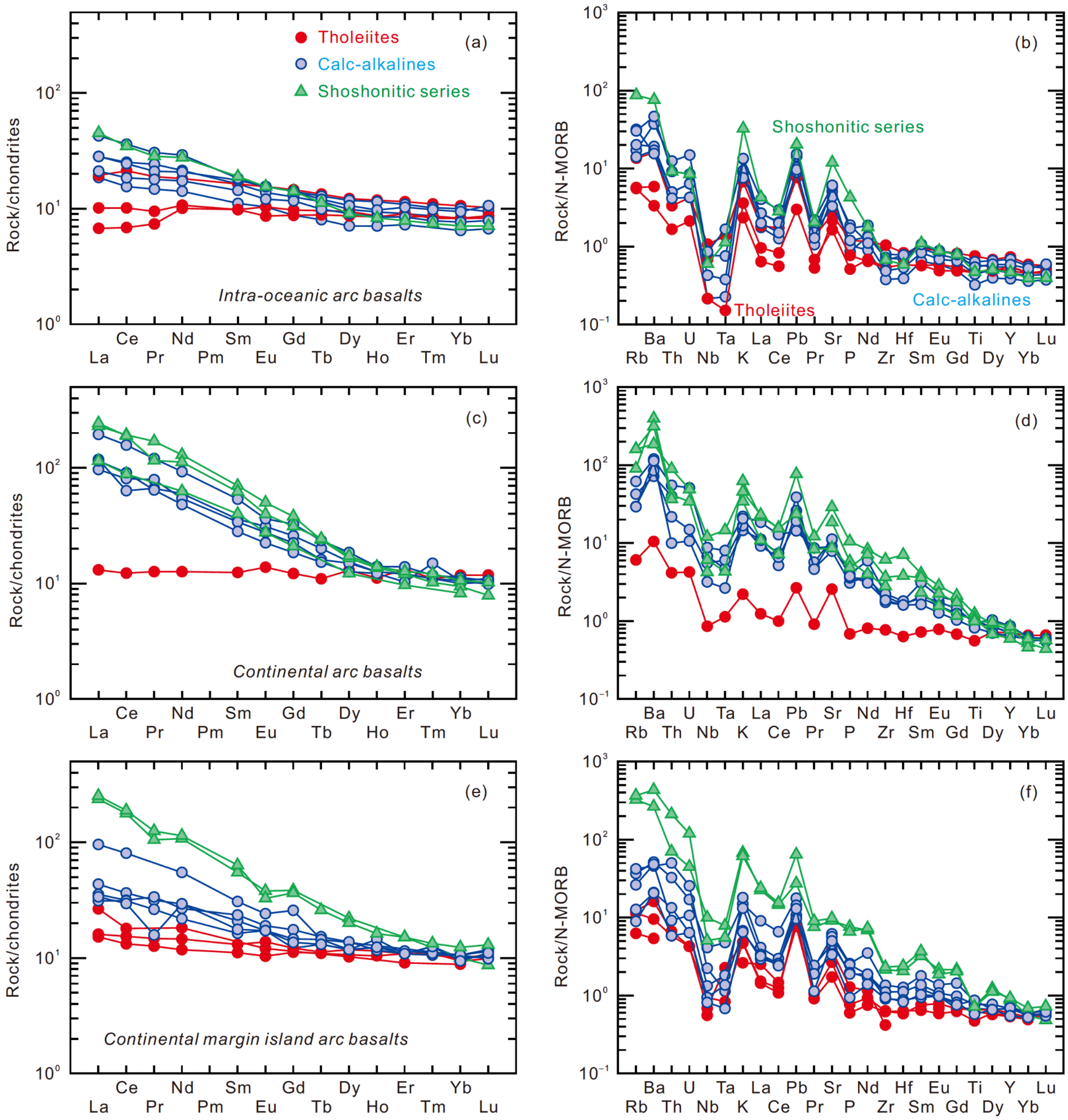


**Figure 3** Chondrite and N-MORB normalized trace element patterns of primitive arc melts from worldwide arcs. Data are from Schmidt and Jagoutz (2017) and normalizing values are from Sun and McDonough (1989). Intra-oceanic arcs: Bismark, Fijia, Aleutian, Izu-Bonin-Marinana, Kermadec, Lesser Antilles, Palau, Solomon, and Vanuatu. Continental arcs: Andes, Central American, Mexico, Cascade and Sunda. Continental margin island arcs: Japan, Kuril, Kamchatka and New Zealand.

with larger geochemical variations (Figure 3a and 3b). Most calc-alkaline basalts show slightly enriched Nd-Hf isotopic compositions relative to mid-oceanic ridge basalt (MORB), which might be related to the involvement of the subducted oceanic sediments in their sources (Beaumais et al., 2016). However, at present, it is generally believed that tholeiitic and calc-alkaline basalts have similar petrogenesis, albeit with different degrees of melting in the mantle wedge (Schmidt and Jagoutz, 2017).

Shoshonitic basalts are relatively rare in the intra-oceanic arc, and are largely confined to the locations far from the trench (i.e., rear-arc), with only a few examples at Fiji, Papua New Guinea and Philippine (Müller et al., 2001; Scherbarth and Spry, 2006; Leslie et al., 2009; Wolfe and Cooke, 2011). Their phenocrysts mainly consist of olivine and augite, with minor amphibole, magnetite and plagioclase. Shoshonitic basalts are strongly enriched in LREEs and LILEs with distinct REE fractionation compared with tholeiitic and calc-alkaline basalts (Leslie et al., 2009). Thus, shoshonitic basalts are likely derived from low degree melting of enriched mantle sources metasomatized by subducted oceanic sediments (Leslie et al., 2009).

### 2.2 Continental arc system basalts and associated rock assemblages

During the formation of continental arc system, the continental lithosphere often occurs as a hanging wall due to its low density and high buoyancy. The geometric configuration of such a subduction zone (e.g., Andean-cordillera orogenic belt) is similar to those of an intra-oceanic arc. During the subduction of oceanic lithosphere, owing to the addition of continental materials into the subduction system and relatively thick continental crust and lithosphere, continental arc basalts show slightly different compositions from intra-oceanic arc basalts. In the continental margin arc, there are abundant andesitic rocks with some dacites and rhyolites, and some calc-alkaline basalts, which can be further divided to low-, middle-, and high-K calc-alkaline and shoshonitic compositions and are different from basaltic rocks from the intra-oceanic arc (Wilson, 1989; Winter, 2014). So far, the most of reported continental arc tholeiitic basalts are from the Cascades volcanic arc, western Northern America (Schmidt and Jagoutz, 2017; Mullen et al., 2017). High-Al olivine-bearing tholeiitic basalts have major and trace element compositions similar to MORB (Figure 3e–3f), but display higher $Al_2O_3$ (>17.0 wt%) and CaO and lower $SiO_2$ and $H_2O$ (<0.2 wt% ) contents than MORBs (Bacon et al., 1997; Le Voyer et al., 2010; Sisson and Layne, 1993). They are likely generated by low-degree (6–10%) partial melting of hydrous spinel peridotites (Baker et al., 1994). Calc-alkaline basalts are widespread in continental arcs in the world, with typical examples in the Andean arc and the Cordillera orogenic belt in the west of Northern and Southern America. Continental margin arc tholeiitic basalts have higher incompatible element contents but lower HFSEs than MORBs (Figure 3e–3f). Compared with intra-oceanic arc basalts, the continental margin arc tholeiitic basalts have higher K/Rb and Fe/Mg ratios and more variable $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ and Pb isotope compostions. This is probably related to the introduction of terrigenous sediments, accumulated in or near the trench, to mantle sources of the continental margin arc magmas (Winter, 2014; Zheng et al., 2020). Shoshonitic rocks in continental margin arcs generally occur at the location far away from the trench, and from far to near locations from the trench, shoshonitic, calc-alkaline and tholeiitic rocks are distributed approximately perpendicularly to arc (Morrison, 1980; Bloomer et al., 1989; Lin et al., 1989). In the Andean region, shoshonitic rocks occur after calc-alkaline and tholeiitic rocks, representing the youngest magmatism (Müller et al., 1992; Scherbarth and Spry, 2006; Beccaluva et al., 2013). Sometimes, calc-alkaline and shoshonitic rocks may occur in the same location of a volcanic arc, which was possibly caused by sudden steeping of subducting slab (Morrison, 1980; Beccaluva et al., 2013).

### 2.3 Continental margin island arc basalts and associated rock assemblages

Although continental margin island arc is a part of the continental lithosphere, the thickness of its continental crust is limited. Continental margin island arc volcanic rocks mainly consist of calc-alkaline, and subordinate tholeiitic and shoshonitic rocks (Tatsumi et al., 2008; Shuto et al., 2015; Lai et al., 2017). Furthermore, some special rock assemblages occur in continental arcs, including oceanic island basalt (OIB)-like basalts, Nb-enriched basalts, sanukites and adakites (Kimura and Ariskin, 2014; Hanyu et al., 2002; Tatsumi, 2006). Tholeiitic basalts mainly occur in the intra-oceanic arcs, such as Mariana and Tonga arcs (Ishizuka et al., 2003; Meffre et al., 2012), but they may also occur in some continental margin island arcs, such as Kuril and Japanese arcs (Shuto et al., 2015; Kuritani et al., 2008).

A remarkable feature of continental margin island arcs is the cross-arc variations in geochemical compositions; fore-arc basalts mainly consist of tholeiitic basalts and minor calc-alkaline basalts, while back-arc basalts are mainly composed of calc-alkaline basalts and minor alkaline basalts (Tatsumi et al., 2008). The tholeiitic basalts in continental margin island arc consist of olivine, plagioclase, augite and orthopyroxene. They show typical subduction zone magma geochemical features (Figure 3c and 3d), characterized by weakly REE fractionated and moderately enriched LILE patterns, with negative Nb-Ta and positive Sr-Pb anomalies (Figure 3c and 3d). The tholeiitic basalts in continental margin island arcs are slightly more enriched in LILE and LREE compared with their counterparts in intra-oceanic arcs (Figure 3c and 3d). The alkaline basalts generally occur in the rear-arc of the continental margin island arc, such as in the rear-arc of the NE Japan arc (Shuto et al., 2015). The calc-alkaline basalts from the continental margin island arcs and intra-oceanic arcs show similar geochemical characteristics, but the former have more enriched LREEs and LILEs (Figure 3c and 3d), but lower HFSE than the latter.

Such geochemical difference is not related to subducted slab components, but is likely due to melting degree of the mantle wedge. The frontal-arc magmas are generally generated by higher degrees of melting of the shallower asthenospheric mantle, whereas the rear-arc magmas result from lower degrees of melting of the deeper part of asthenospheric mantle (Shuto et al., 2015). Shoshonitic basalts rarely occur in continental margin island arcs, which mainly consist of augite, orthopyroxene, hornblende, phlogopite and feldspar. These shoshonitic basalts are believed to be mainly from melting of the enriched lithospheric mantle (Elburg and Foden, 1999).

Basaltic rocks from intra-oceanic arc, continental arc and continental margin arc systems exhibit clearly different Sr-Nd isotope compositions (Figure 4): basaltic rocks from in-

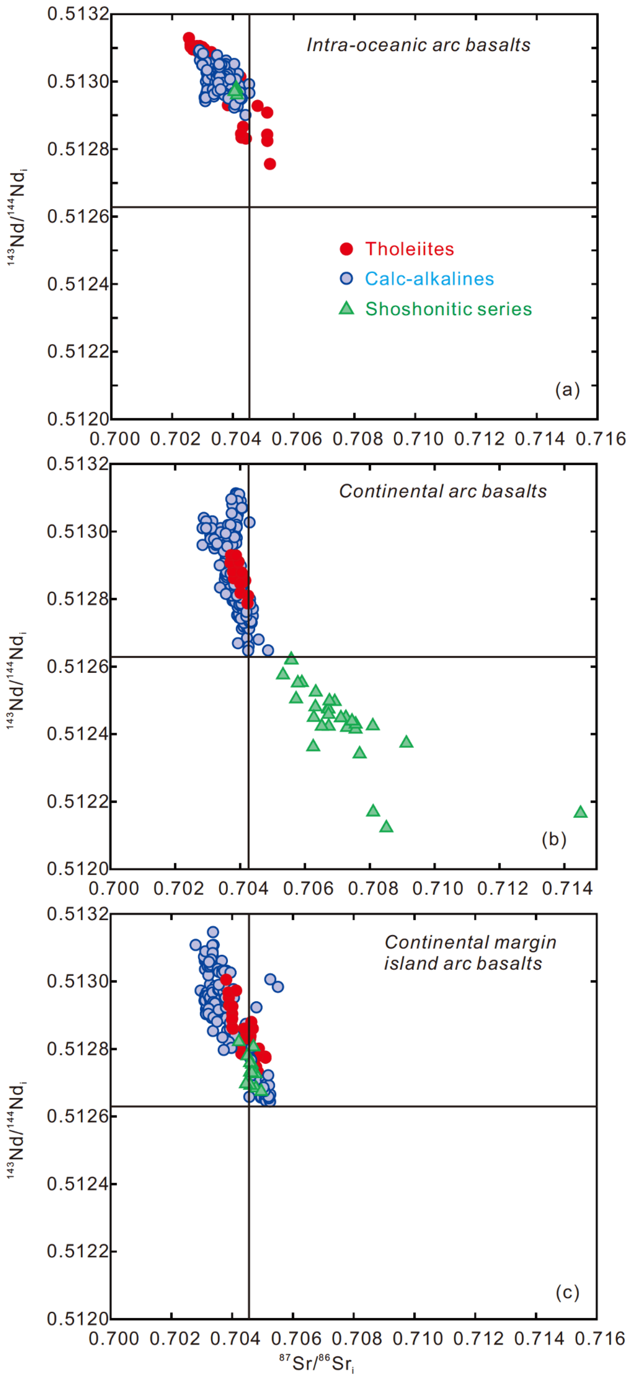


**Figure 4** Sr-Nd isotope plots for the arc basalts from global arcs. Representative arcs are same as in Figure 3. Data are from GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/).

tra-oceanic arcs show depleted Sr-Nd isotope compositions (Figure 4a), whereas those from continental margin island arcs have much larger Sr-Nd isotope variations, ranging from depleted to enriched ones (Figure 4b). In the continental arc system, tholeiitic and calc-alkaline basaltic rocks show slightly depleted Sr-Nd isotope compositions, but shoshonitic rocks have enriched isotope compositions (Figure 4c). From intra-oceanic arc via continental margin island arc to continental arc systems, the Sr-Nd isotope compositions of the basaltic rocks vary from depleted to enriched, and from narrow to wide ranges (Figure 4). Compared with shoshonitic rocks from intra-oceanic and continental margin island arc systems, those from continental arcs are characterized by more enriched Sr-Nd compositions (Figure 4). This reflects that their mantle source either is ancient lithospheric mantle or contains more sediment components (e.g., Carlier et al., 2005; Winter, 2014).

Continental margin island arc and continental arc systems are different in tectonic characteristics and magma types: the former (e.g., Japan and Kurile island arcs) is associated with back-arc extensional basins, and basalts and andesites, whereas the latter (e.g., Andean arc) lacks back-arc extensional processes and is mainly associated with andesites (Frisch et al., 2011). The main factors responsible for above differences include ages of subducted slab, subduction angles and deep geodynamic processes of subduction (Winter, 2014; Frisch et al., 2011; Wang et al., 2020). In the western Pacific Ocean, due to its old age and relatively high density, the oceanic slab is subducted at high angles, and the slab rollback often occurs, triggering back-arc extension and consequently large-scale upwelling of the asthenosphere, leading to the formation of back-arc basins and basalts and andesites in Japan and Kurile island arcs. In contrast, due to its young age and relatively low density, the oceanic slab in the eastern Pacific Ocean is subducted at low angles, which results in a small (or no) asthenospheric wedge, and creates a compressional tectonic setting and the lack of back-arc basins in the hanging wall. In this circumstance, the arc crust is thickened, and magmas generated by partial melting of subducted oceanic slab, melange, or mantle, underwent complex evolutions such as multiple melting, assimilation, storage and homogenization (MASH) processes, forming an Andean type rock assemblage. Nevertheless, the subducting angle may vary with time. In the west Pacific, the subducting slab may have experienced a two-stage evolution from a low angle to a high angle subduction, whereas a three-stage process is proposed for the east Pacific, where subducting angle varied from gentle to steep and to gentle again.

## 3. Some special basaltic rocks in arc systems

### 3.1 High-Nb or Nb-enriched arc basalts

The term of high-Nb arc basalts was firstly proposed by Defant et al. (1991, 1992) when they studied Cenozoic arc basalts in east Pacific. Some absarokites and shoshonites were found in continental arcs such as Baja California, Mexico, Southern Washington Cascades, and Panama. These rocks are characterized by high Nb contents (>20 ppm, 1 ppm=1 μg $g^{-1}$) or negligible Nb anomalies in trace element spiderdiagram (Figure 5) (Defant et al., 1991, 1992), which

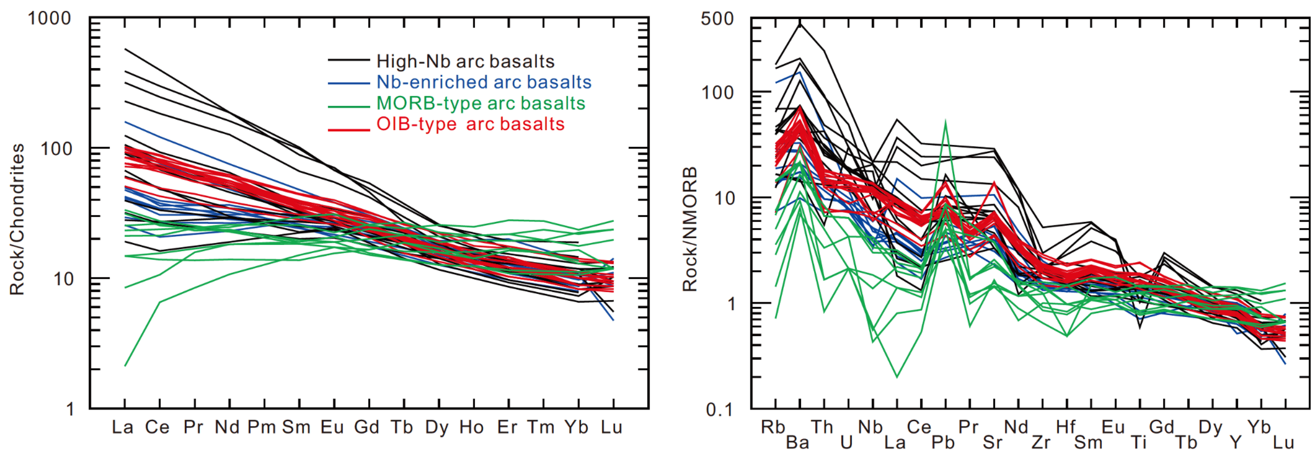


**Figure 5** Rare earth element and trace element patterns of special basalts in arcs in the world. Data sources: high-Nb or Nb-enriched arc basalts (Bourdon et al., 2003; Castillo et al., 2007; Defant et al., 1992; Kepezhinskas and Defant, 1996; Sajona et al., 1996); OIB-type arc basalts (Mullen and Weis, 2013); MORB-type arc basalts (Cole and Stewart, 2009; Sorbadere et al., 2013b); Chondrite and N-MORB normalizing values are from Sun and McDonough (1989).

are different from those "normal arc basalts" with typical low Nb contents or strong depletion in Nb-Ta-Ti (Figure 3). Sajona et al. (1993, 1994, 1996) named the term of "Nb-enriched arc basalts" to denote those rocks with relatively high Nb contents (Nb=7–16 ppm, Na/La>0.5) or negligible Nb anomalies (Figure 5). Nb-enriched arc basalts mainly occur in the Zamboanga peninsula and the Mindanao island of the Philippines arc in west Pacific, and the Ecuador arc of Southern America to the east Pacific (Figure 5) (Beate et al., 2001; Bourdon et al., 2003). High-Nb or Nb-enriched arc basalts are often associated with high-Mg andesites and adakites, and are considered to have been generated by partial melting of slab-derived adakitic melt-metasomatized mantle wedge peridotites (e.g., Sajona et al., 1993, 1996; Defant and Kepezhinskas, 2001; Defant et al., 2002; Wang et al., 2007).

### 3.2 OIB-type arc basalts

OIB-type arc basalts show trace element compositions similar to OIBs; on the one hand, they resemble arc basalts in showing LILE enrichment and strong fractionation between LREE and HREE, but show no obvious depletions in Nb and Ta on the other hand. This type of rock mainly occurs in the following special subduction settings: (1) An arc influenced by a nearby mantle plume, as exemplified by the northern termination of the Tonga Arc (Falloon et al., 2007; Price et al., 2014). The Samoa plume flows westward into the nearby Tonga back-arc region, resulting in the formation of OIB-type basalts with elevated $^3He/^4He$ ratios. (2) A slab window (i.e., active ridge subduction), as represented by the Northern Cordilleran arc (Mullen and Weis, 2013; Thorkelson et al., 2011). Decompression melting is then triggered by upwelling of the hot asthenospheric mantle through the slab window. (3) An abnormally hot subduction zone as exemplified by the Cascades arc (Leeman et al., 2005; Carlson et al., 2018). The young, hot oceanic slab of Juan de Fuca has been completely dehydrated in the forearc region, and the sub-arc mantle wedge is less affected by subduction components. The mantle sources of these OIB-type arc basalts in the above-mentioned Cenozoic subduction zones lack slab-derived hydrous fluids but contain abundant slab-derived hydrous melts. It is commonly believed that the mechanism inducing mantle melting involves decompression upwelling of relatively dry and hot mantle, which is similar to the case of mid-ocean ridges or mantle plumes, so that the generated magmas will not have typical "arc signature" such as HFSE depletions. This explanation has been questioned by Zheng (2019), who suggested that rutile breaks down during melting of subducting slab at >1200°C, generating melts rich in HFSEs. The mantle wedge peridotites metasomatized by such melts are the source of OIB-type arc basalts.

Since OIB-type arc basalts commonly occur in the subduction zones which are associated with hot mantle upwelling, it has been proposed, on the basis of geophysical, geochemical, and laboratory-based studies, that there may be deep-sourced mantle plumes in these subduction zones. However, these views still remain controversial. For example, it is not clear whether the Cascades arc volcanoes and the High Lava Plains volcanic chain were related to the Yellowstone plume (Liu and Stegman, 2012; Kincaid et al., 2013). Some high-Nb or Nb-enriched arc basalts show no obvious negative Nb anomalies or even positive Nb anomalies, similar to OIB. These basalts were thought to be generated by melting of enriched mantle components in the mantle wedge (Castillo et al., 2002), the upwelling asthenospheric mantle through the slab window (Gorring et al., 2003; Thorkelson et al., 2011; Tang et al., 2010), or deep mantle metasomatized by rutile-undersaturated melts derived from subducted oceanic crust (Ringwood, 1990; Zheng et al., 2020).

### 3.3 E-MORB-type basalts

In some fore-arcs (e.g., IBM and Central America arcs), there occur basalts with trace element characteristics similar to those of MORB (DeBari et al., 1999; Reagan et al., 2010; Ishizuka et al., 2011; Shervais et al., 2019; Whattam, 2018). In addition, these MORB-type basalts occasionally occur in island arc settings (e.g., the Vanuatu arc) and are associated with arc basalts (Sorbadere et al., 2013b). Like MORB, these MORB-type arc basalts can also be divided into normal and enriched types, similar to N-MORB and E-MORB, respectively. Specifically, these E-MORB-type arc basalts are characterized by no depletion in HFSE and relatively high Nb contents similar to Nb-enriched basalts (Figure 5). Their mantle source was only metasomatzed by tiny amounts (~0.2 wt%) of subducted oceanic slab-released fluids (Sorbadere et al., 2013a). Moreover, some MORB-type basalts also occur in some special arcs (e.g., Alaska and western America), which are associated with the subduction of spreading oceanic ridge (Cole and Stewart, 2009). The Alaska basalts and the western American show the geochemical characteristics of N-MORB and E-MOR-type basalts, respectively (Cole and Stewart, 2009). The formation of these MORB-type basalts in the subduction zones is related to the strong extension of thin arc crust, e.g., deep faults in the crust, the subduction of spreading mid-oceanic ridge and the extension induced by initial subduction of oceanic crust. The special basalts represent the decompression melting of the upwelling mantle.

### 3.4 High aluminum basalts

Early studies found a large number of high-Al basalts ($Al_2O_3$ >16 wt%) in subduction zones, which have MgO contents usually less than 7 wt%. They are distinguished from tholeiitic basalts by widespread occurrence of anorthite (Kuno, 1960; Himilton, 1964; Crawford et al., 1987). These high Al basalts were initially thought to be generated by very high-degree partial melting of subducted eclogitic slab, but this view was gradually abandoned (Brophy, 1989). It is now generally accepted that high-Al basalts are differentiated products of water-rich (>2 wt%) primitive arc basalts by fractionation of olivine and clinopyroxene without plagioclase (Beard and Lofgren, 1992; Blatter et al., 2013; Melekhova et al., 2015; Pichavant and MacDonald, 2007; Sisson and Grove, 1993; Xie et al., 2016). Parman et al. (2011) compiled the experimental results of fractional crystallization of magma with different water contents, and concluded that the peak in $Al_2O_3$ contents of the differentiated melts is proportional to water contents of magmas. The higher the water content is, the more significantly delayed crystallization of feldspar happens, and the higher the peak $Al_2O_3$ contents of the differentiated melts are. Pichavant and MacDonald (2007) also suggested that the $Al_2O_3$ contents of plagioclase-saturated hydrous basaltic melts (<4 kbar) are positively correlated with the water contents of magma. In addition, the crystallization experiments of hydrous basaltic magmas under different pressures (0.4–0.9 GPa) show that the suppression of plagioclase crystallization under high-pressure conditions favors the formation of low-magnesium, high-Al basalts (Blatter et al., 2013).

## 4. Petrogenesis of arc basalts

Petrogenesis of arc basalts involves mantle source characteristics, partial melting and fractional crystallization processes.

### 4.1 Matasomatism of the sub-arc mantle wedge and formation of basalt source

*4.1.1 Dehydration of subducted slab and fluid metasomatism*

The typical arc basalts commonly exhibit the enrichment in LILEs (e.g., Cs, Rb, K, Ba, Pb and Sr) and LREE, and depletion in HFSEs (e.g., Ta, Nb, Zr and Ti) and HREE (Figure 3). These trace element geochemical characteristics are typical of mantle sources of arc basalts, which are metasomatized by subducted slab-released fluids (e.g., Tatsumi et al., 1986; Tatsumi, 2005; Zheng, 2019). Subducted oceanic slab mainly consists of sedimentary rocks, basalts, gabbros and peridotites, which contain many hydrous minerals with $H_2O$ contents varying from 2.0 to 18.0 wt%, such as mica group (phengite, biotite, and paragonite), amphibole group (richterite, glaucophane, barroisite and pargasite), lawsonite, zoisite, epidote, chloritoid, chlorite, talc, and serpentine (Schmidt and Poli, 2014). These minerals can be subducted to different depths (from 30 to 250 km and even more than 250 km) and undergo dehydration, which generates fluids to metasomatize the overlying mantle wedge to form the source of arc basalts (Tatsumi et al., 1986; Brenan et al., 1995; Keppler, 1996; Schmidt and Poli, 2014; Zheng et al., 2016). Geophysical data revealed that subducted oceanic slab-released fluids entered the mantle wedge and triggered arc magmatism beneath some Cenozoic continental arcs (e.g., Mount Rainier of northern America) (McGary et al., 2014). The experiments on the element distribution between hydrous fluids and eclogite assemblage minerals (garnet, clinopyroxene and rutile) under the conditions of 900–1200°C and 3.0–5.7 GPa suggested that both garnet and pure clinopyroxene cannot lead to the differentiation of HFSEs from LILEs, but 1.5% rutile-bearing eclogites-released fluids can cause selective enrichment in LILEs and depletion in HFSEs in the mantle wedge (Stalder et al., 1998; Foley et al., 2000). Recent studies on non-traditional stable isotope geochemistry provide supporting evidence for the above viewpoints. For example, some basalts from intra-oceanic arc (e.g., Lesser Antilles arc in Central America) have heavy Mg isotope compositions, which probably resulted from metasomatism of slab-derived fluids (Figure 6a; Teng et al., 2016). Arc basalts have variable Li isotope compositions ($\delta^7$Li=−8.4‰ to 11.4‰; Su et al., 2016), most of them are similar to those of MORB. However, the basalts from continental arc (e.g., Central America) and intra-oceanic arc (e.g., Lesser Antilles and IBM) show significantly different Li isotopes, which are attributable to the metasomatism of slab-related melts/fluids, slab dehydration and water-rock interaction (Moriguti and Nakamura, 1998; Chan et al., 2002; Agostini et al., 2008; Bouvier et al., 2008, 2010; Tang et al., 2014). Cenozoic arc basalts have variable B isotope compositions ($\delta^{11}$B=−9‰ to +16‰; De Hoog and Savov, 2017). B isotope fractionation during the subduction of oceanic slab can be interpreted by Rayleigh fractionation. The fluids released from slab are enriched in heavy B isotopes. Thus, slab dehydration decreases the B concentrations and B isotopes in the subducted slab (Figure 6b) (De Hoog and Savov, 2017). Heavy $\delta^{11}$B of arc volcanic rocks can be formed by metasomatism of slab-derived fluids/melts, as well as melting of fluid-modified serpentinized mantle or mélange in the fore-arc (Benton et al., 2004; Savov et al., 2005, 2007; Pabst et al., 2011; Tonarini et al., 2011; Scambelluri and Tonarini, 2012; Spandler and Pirard, 2013; Konrad-Schmolke et al., 2016; Martin et al., 2016; Zhang et al., 2017; Prigent et al., 2018). Traditionally, the formation of mantle source for arc magmas is considered to be related to the processes that slab-released fluids metasomatize the mantle wedge, and slab-released fluid flux gradually decreases with the increasing subducting depth of slab (e.g., Ishikawa and Nakamura, 1994). However, in the Mariana fore-arc of western Pacific Ocean, the subducted oceanic slab has lost 5.5 wt% $H_2O$ beneath the fore-arc (blueschist facies condition) (Schmidt and Poli, 1998), and 13% fore-arc mantle rocks have been serpentinized at the depths of 20–60 km (Savov et al., 2007). These serpentinized mantle rocks can be brought into deep mantle by subduction-slab pull or subduction erosion, and play an important role in the formation of mantle-derived magmas.

#### 4.1.2 *Melting of subducting slab and melt-related metasomatism*

In addition to release fluids, the subducting slab can also melt to generate adakitic melts if the oceanic crust is young and hot enough (Defant and Drummond, 1990; Peacock et al., 1994). Nicholls and Ringwood (1973) were the first to propose that the mantle wedge may be metasomatized by subducting slab-derived melts. Elliott et al. (1997) also proposed that the mantle wedge can be metasomatized by slab melts and considered metasomatized peridotites as a potential source of arc basalts. Experimental petrology and studies of sub-arc mantle peridotite xenoliths suggest that slab melts are more enriched in HFSE than hydrous fluids (e.g., Kepezhinskas et al., 1995, 1997; Keppler, 1996; Defant and Kepezhinskas, 2001), and melt-peridotite reactions can produce an amphibole-, phlogopite- and HFSE-rich mantle source (Kepezhinskas et al., 1997; Wang et al., 2008). On the other hand, subducting slab-derived melts formed outside the rutile stability field are characterized by high HFSEs (e.g., Ringwood, 1990; Zheng, 2019) and the partial melting of the mantle wedge metasomatized by such melts would generate Nb-enriched or high-Nb basalts, as recorded in some Cenozoic arcs (e.g., Philippine, Panama, Baja California and Kamchatka) (e.g., Sajona et al., 1996; Defant and Kepezhinskas, 2001; Aguillón-Robles et al., 2001). The association of Nb-enriched basalt, high-Mg andesite and adakite in these regions is different from basalt-andesite-dacite-rhyolite assemblages formed by melting of fluid-modified mantle wedge (Sajona et al., 1996; Defant and Kepezhinskas, 2001; Defant et al., 2002; Wang et al., 2007). Mo isotopes can efficiently trace the contributions of different types of subducting slab-derived components. Lavas originating from

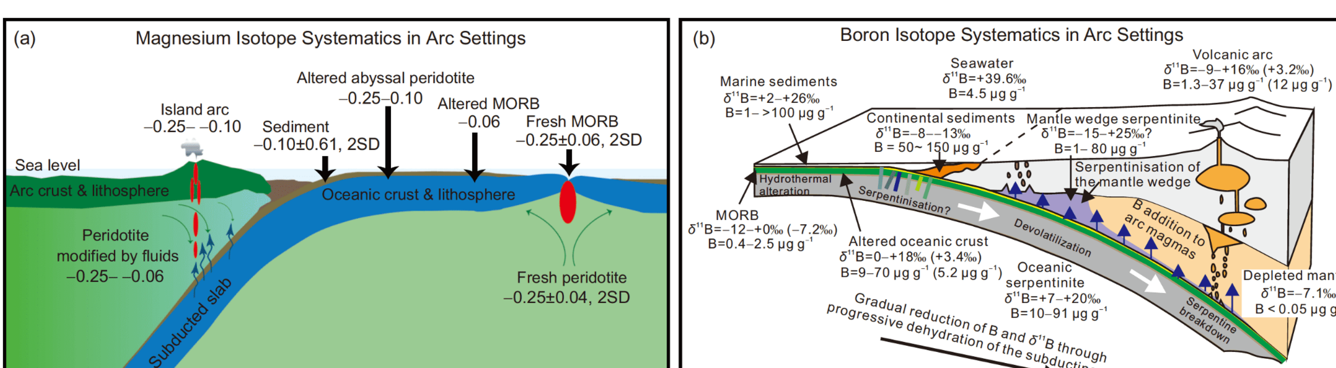


**Figure 6** Diagram showing Mg (a) and B (b) isotope evolution of the intra-oceanic and continental arc basalts (after Teng et al., 2016; De Hoog and Savov, 2017).

the mantle wedge modified by slab fluids have high $\delta^{98}$Mo values (−0.1‰ to +0.24‰), and those originating from the slab melt-modified mantle wedge have low $\delta^{98}$Mo values (−0.72‰ to −0.1‰) (Freymuth et al., 2015; König et al., 2016). In addition, lavas originating from mantle wedge modified by melts of subducted reduced sediments (e.g., black shale) have high $\delta^{98}$Mo values (+0.02‰ to +0.34‰) than those originating from mantle wedge modified by oxidized sediment-derived melts (−0.88‰ to −0.06‰) (Freymuth et al., 2016; Gaschnig et al., 2017).

Partial melting of subducting slab and subsequent melt-peridotite reactions are potentially common in arc system (e.g., Spandler and Pirard, 2013; Kelemen et al., 2014; Schmidt and Jagoutz, 2017; Zheng et al., 2020). Petrology of ophiolite and mantle xenoliths indicates a variety of melt-peridotite reactions (Ertan and Leeman, 1996; Varfalvy et al., 1996; McInnes et al., 2001; Tamura and Arai, 2006; Bénard and Ionov, 2013). Felsic melts are formed by melting of subducting slab in the sub-arc mantle (Rapp and Watson, 1995; Rapp et al., 1999; Hermann and Spandler, 2008; Spandler et al., 2010; Duncan and Dasgupta, 2014; Schmidt, 2015; Sisson and Kelemen, 2018). These melts ascend due to their buoyancy and metasomatize the surrounding mantle peridotites. In addition, mafic magmas, which are derived from the metasomatized mantle, can further react with mantle peridotites during their upward migration (Van den Bleeken et al., 2010, 2011; Lambart et al., 2012; Wang et al., 2013, 2016).

#### *4.1.3 Transfer of slab-derived fluids/melts to the mantle source of arc basalts*

There are three main ways that slab components are transferred to the mantle source of arc basalts (see Spandler and Pirard, 2013 and references therein): (1) Porous flow along the grain boundaries of mantle minerals; (2) Channelled/focused flow through mantle fractures; and (3) Diapiric flow driven by the buoyancy of solid mélanges in subduction channels. The subduction components rise at different rates in these different ways, and the extent to which subduction components and the surrounding mantle peridotite are modified is also different. It is worth noting that a large amount of hydrous metasomatic minerals will be produced during porous flow, which will cause the trace element characteristics of residual fluids to deviate significantly from arc basalts. Therefore, the fluids residual to infiltration reaction are not the main component of source of arc basalts (Pirard and Hermann, 2015). However, the previously formed metasomes can be the source of arc basalts.

### 4.2 Partial melting and thermal structure of the subarc mantle

Partial melting of the mantle requires one of three possible events to occur: an increase in temperature, a decrease in pressure, or an addition of water to the system (Xu, 1999; Niu, 2005). Analyses on phenocryst melt inclusion of global island arc magmas reveal that the water content of island arc magma is ~2–6 wt%, with an average of 3.9±0.4 wt% (Plank et al., 2013), which is much higher than the water content in MORBs. Experimental studies show that the addition of water greatly lowers the solidus of mantle peridotite, and basaltic magma can be generated by partial melting of water-fluxed mantle peridotite under high pressure (>2.5 GPa) or at low pressure but high degree of melting (>25%) (Green, 1973; Gaetani and Grove, 1998; Irving and Green, 2008; Tenner et al., 2012; Green et al., 2014). Therefore, addition of water is the main factor to induce partial melting of the sub-arc mantle.

At present, the solidus temperature of wet peridotite obtained by different experiments varies greatly. At pressure of 3 GPa, the solidus temperature of wet peridotite can be as low as ~800°C (Grove et al., 2006; Till et al., 2012), or as high as 1000–1100°C (Green et al., 2010, 2012). Such considerable solidus temperature difference affects our understanding of arc magma genesis. If the wet solidus is as low as ~800°C, it means that dehydration melting of chloritic peridotite or melting of water-saturated peridotite can take place at the bottom of the mantle wedge (Grove et al., 2009; Till et al., 2012), that is, slab-released water enters the fore-arc mantle and the bottom of the mantle wedge, resulting in the formation of chloritic peridotite, and arc magmas would be formed within the *P-T* area between the dehydration curve of chlorite and the solidus of water-saturated peridotite. However, if the wet solidus is as high as 1000–1100°C, the mantle wedge above the subducting plate will not melt immediately when water is added. Most researchers believed that the subduction components (fluid/melt) derived from the subducing plate need to pass through the wet subsolidus peridotite at the bottom of the mantle wedge, and then enter the core of the mantle wedge, which has high temperature and is the source region of arc basalts (Spandler and Pirard, 2013; Pirard and Hermann, 2015; Prigent et al., 2018). Alternatively, subduction components first metasomatize the peridotite at the bottom of the mantle wedge to form metasomes, which subsequently melt to form basalts (Manning, 2004; Grove et al., 2009; Zheng et al., 2016). Therefore, the generation of island arc magma is not only controlled by dehydration of the subducting plates, but also is closely related to the thermal structure and thermal evolution of the subduction zone (Zheng, 2019). The hydrated peridotite melts only when it is heated at a later stage where the decoupling between the subducting plate and the mantle wedge and the lateral filling of the asthenospheric mantle occur (Manning, 2004; Zheng et al., 2016). Such hydrated metasomatized peridotite can even be stored in the lithospheric mantle without melting during the oceanic subduction, but it melts at the latter extension stage after continental collision (Xu et al., 2004; Zheng et al., 2015).

Some special rock types, such as fore-arc basalt (FAB) and boninite, are generated during subduction initiation. Fore-arc basalts are typical products of decompressional melting of the mantle at the early stage of subduction with almost zero contribution of the subducting plate, whereas the depleted mantle was later metasomatized by fluid or melt derived from the subducting plate, giving rise to the boninite magmatism. Fore-arc basalt and boninite have been regarded as petrological evidence of subduction initiation (Reagan et al., 2010; Xia et al., 2012; Li et al., 2019). Except for the special fore-arc settings, the thermal structure of the mature subduction zone is mainly related to the age of the subducting plate, subduction rate and subduction angle, rate of shear heating in subduction zones and the properties of mantle wedge (Syracuse et al., 2010; Zheng, 2019). In the cold subduction zone, the subducting oceanic crust does not dehydrate significantly when passing through the fore-arc mantle, but it dehydrates extensively at a great subarc depth to metasomatize the overlying mantle wedge, which starts to melt upon heating to form arc basalt (Zheng et al., 2016). In the hot subduction zone, the oceanic crust that already experienced extensive dehydration in the fore-arc mantle does not dehydrate significantly at the sub-arc depth, but the retreat of the subducting plate could induce the lateral flow of the asthenosphere, leading to decoupling between the bottom of the mantle wedge and the plate surface as well as the increase of their temperature (Kincaid and Griffiths, 2003), which could induce melting of the slab at sub-arc depth. The generated melts metasomatize the overlying mantle wedge to form basalts (Zheng, 2019). The corner flow caused by the retreat of subducting oceanic plate and interaction between the hot subarc asthenosphere and the cold mantle wedge play a crucial role in the generation of arc magmas (Hoernle et al., 2008; Turner et al., 2017; Zheng, 2019).

Big data analyses of the global rear-arc volcanic rocks recently reveal that the ambient mantle wedge before metasomatism by subduction components is highly heterogeneous (Turner et al., 2017). After eliminating the possible effects of the subduction inputs, Turner et al. (2017) accounted for the isotopic variations by mixing of two end-member components, one being similar to the depleted MORB mantle source, the other having EMI like isotopic characteristics. They proposed that the enriched component is the ancient continental lithospheric mantle that was metasomatized by low degree melts of the asthenosphere. This lithospheric mantle component was transported to the subarc asthenospheric mantle by the corner flow of the asthenospheric mantle wedge. Similarly, pyroxenites formed from early arc magmas in the lithospheric mantle can interact with late arc magma derived from the asthenosphere (Carlson et al., 2018; Hickey-Vargas et al., 2016). In fact, in addition to the material contribution, the heat brought by the corner flow of subarc asthenospheric mantle plays a significant role in the generation of arc magmas (Figure 7). Moreover, the complexity of sub-arc (vertical or parallel trench) corner flow of the asthenospheric mantle wedge will cause material flows at different directions in the sub-arc mantle and consequently change the composition of the sub-arc mantle source (e.g., Hoernle et al., 2008).

Foden et al. (2018) found that the Fe isotope composition of global basalt-andesite samples from the intra-oceanic arc and continental arc was negatively correlated with the thermal parameters of the arc (the product of plate age and vertical subduction rate, which is a parameter used to characterize the relationship between subduction plate temperature and its geometry; Kirby et al., 1996): the subarc mantle with high thermal parameter has a stronger corner flow and experienced greater melt extraction, resulting in loss of heavy Fe isotopes. Diffusion-induced kinetic fractionation also contributes significantly to the enrichment of light isotopes. The Fe isotopic variation of these rocks was mainly subjected to partial melting and fractional crystallization. Their primitive magmas are enriched in light Fe isotopes, which is due to the source depletion and subduction related metasomatism. In addition to the above-mentioned dynamic mechanisms, processes such as retreat, tearing, detachment/delamination of the subducting plate, subduction of spreading ridge, aseismic ridge or oceanic plateau, and subduction erosion also play roles in the generation of arc magmas (Wang et al., 2020; and references therein).

A diapir model of island arc magma genesis was proposed on the basis of recent experiments and numerical simulations. During subduction, mechanical mixing of altered oceanic crust, sediment, serpentinized peridotite and mantle wedge peridotite occurs at the slab-mantle wedge interface (i.e., subduction channel), resulting in the formation of mélange (Hall and Kincaid, 2001; Gerya and Yuen, 2003; Zhu et al., 2009). The mélange could rise into the core of the hot mantle wedge as diapirs due to its buoyancy, and then melts partially to form arc magmas (Behn et al., 2011; Marschall and Schumacher, 2012). Such mélange melts have geochemical characteristics akin to those natural arc magmas (Castro et al., 2010; Behn et al., 2011; Marschall and Schumacher, 2012; Nielsen and Marschall, 2017; Codillo et al., 2018; Cruz-Uribe et al., 2018). Partial melting of sediment-dominated mélange forms calc-alkaline basaltic andesite-andesite sequences (Cruz-Uribe et al., 2018; Codillo et al., 2018), whereas partial melting of serpentinite-dominated mélange produces tholeiitic basalts (Codillo et al., 2018). Nevertheless, it remains unclear how the mélange diapir enters the interior of the relatively cold mantle wedge.

Previous studies have suggested that partial melts of subducting plates could metasomatize the mantle wedge peridotite to form orthopyroxene-rich pyroxenite or websterite

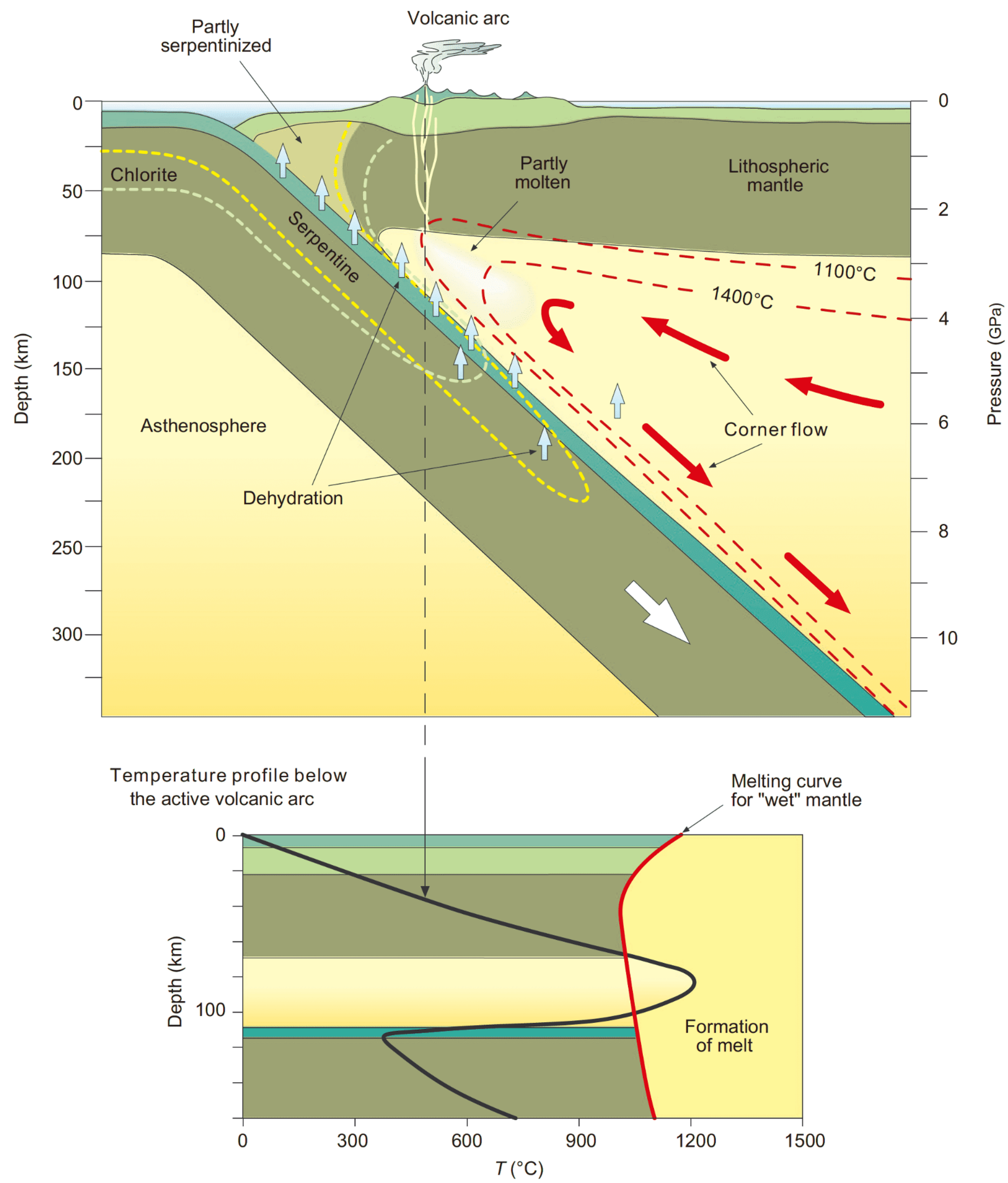


**Figure 7** Melting processes below volcanic arcs (Stern, 2000; Frisch et al., 2011). Dewatering from the subduction zone causes formation of serpentine in the lithospheric mantle of the upper plate and melts in the hot asthenospheric wedge at greater depths.

(Ertan and Leeman, 1996; Varfalvy et al., 1996; Tamura and Arai, 2006), and these pyroxenites are more prone to partial melting than peridotite. Therefore, under the same P-T conditions, partial melting of pyroxenite would produce more melts (Pertermann and Hirschmann, 2003; Hirschmann et al., 2003; Lambart et al., 2009) which will react with the surrounding mantle peridotite to form clinopyroxene or amphibole veins (Pilet et al., 2008; Lambart et al., 2012) or Si-undersaturated basaltic magmas with high $CaO/Al_2O_3$ (>1) (Médard et al., 2006; Sorbadere et al., 2013a).

## 4.3 Evolution and eruption of arc basaltic magmas

Determining primitive magma compositions is of critical importance in basalt studies (Schmidt and Jagoutz, 2017; Zheng et al., 2020). In general, the composition of primary basalts is in equilibrium with mantle peridotite in which olivines have Fo ($Mg/(Mg^{+}Fe^{2+})$) values of 0.87–0.91 and Ni contents of 2000–4000 ppm (Korenaga and Kelemen, 2000). Thus, primitive magma compositions can be obtained using the Fe-Mg exchange coefficient that is equal to 0.3 (Roeder and Emslie, 1970). Samples that have $Mg^{\#}$ of 0.65–0.75 and Ni contents of 150–500 ppm can be considered as primitive magmas. Moreover, the primitive magmas with $SiO_2$ of 49 wt% commonly have MgO≥9 wt%. Compared with these characteristics, most erupted arc basalts have been modified subsequently by differentiation processes. The separation of early crystallized crystals from arc basaltic magmas can occur easily because of low viscosity and high magmatic $H_2O$ content (Plank et al., 2013). Because only a small proportion of arc basalts have an ability to ascend to the surface, the scale of arc basalts is much smaller than those of mid-ocean ridges, ocean islands, and continental flood basalts (Rogers, 2015). High magmatic water content also results in the distinct evolution path of arc basalts. Plagioclase appearance is suppressed in $H_2O$-rich arc magmas (Sisson and Grove, 1993), whereas crystallization of Fe-Ti oxides is promoted by high oxygen fugacity, leading to continuous depletion of FeO in evolved melts, i.e., calc-alkaline magma series (Arculus, 2003; Zimmer et al., 2010). Under some circumstances, such as in the Izu-Bonin-Mariana arc, multiple stages of crystallization have been recognized by Fe isotope studies that olivine and pyroxene crystallized early and magnetite and sulfide precipitated subsequently (Williams et al., 2018). Unlike ocean island $H_2O$-poor, tholeiitic basalts, the evolution of arc basalts is sensitive to pressure (Cashman and Edmonds, 2019). For example, during the path of isobaric cooling under high pressure, change in melt composition is controlled by crystallization of mafic minerals, resulting in strong decrease in MgO and increase in $Al_2O_3$, but minor increase in $K_2O$ (Figure 8a and 8b). The MgO content in melts in which plagioclase saturates has a clear correlation with pressure, as evidenced by the maximum $Al_2O_3$ content in melts (Figure 8b). A rapid steepening of the MgO–$K_2O$ curve indicates an increase in bulk crystallinity. In contrast, isothermal decompression produces a different compositional trend that MgO content increases initially due to decompression-driven melting of clinopyroxene, followed by a rapid increase in $K_2O$ and decreases in $Al_2O_3$. It records extensive decompression-driven crystallization of plagioclase (Figure 8c and 8d). In addition, liquid lines of descent also change after degassing during magma ascent (Blundy et al., 2006).

Unlike viscous silicic magmas that can produce explosive eruptions, arc basalts commonly occur as effusive volcanism, particularly in high-pressure submarine settings (Branney and Acocella, 2015). However, explosive basaltic eruptions have also been observed in the Rota-1 volcano, Marianas arc (Chadwick et al., 2008). The influence of water on arc basalt eruptions has received great attention, but more and more studies began to emphasize the role of $CO_2$ in magma dynamics of arc basalts (Collins et al., 2009; Blundy et al., 2010; Caricchi et al., 2018). It is difficult for a basalt batch to ascend to the surface directly from source, and most arc basalts will form magma reservoirs in shallow crust before eruption (Cashman and Edmonds, 2019). However, there are exceptions that eruptions were connected with the mantle directly (Ruprecht and Plank, 2013). With the development of microanalytical methods, quantitative constraints of time scales concerning the dynamics of basaltic magmas will be critical in future studies (e.g., Lynn et al., 2018; Ruth et al., 2018).

## 5. Remaining questions and new perspectives

Despite many important achievements made in recent years

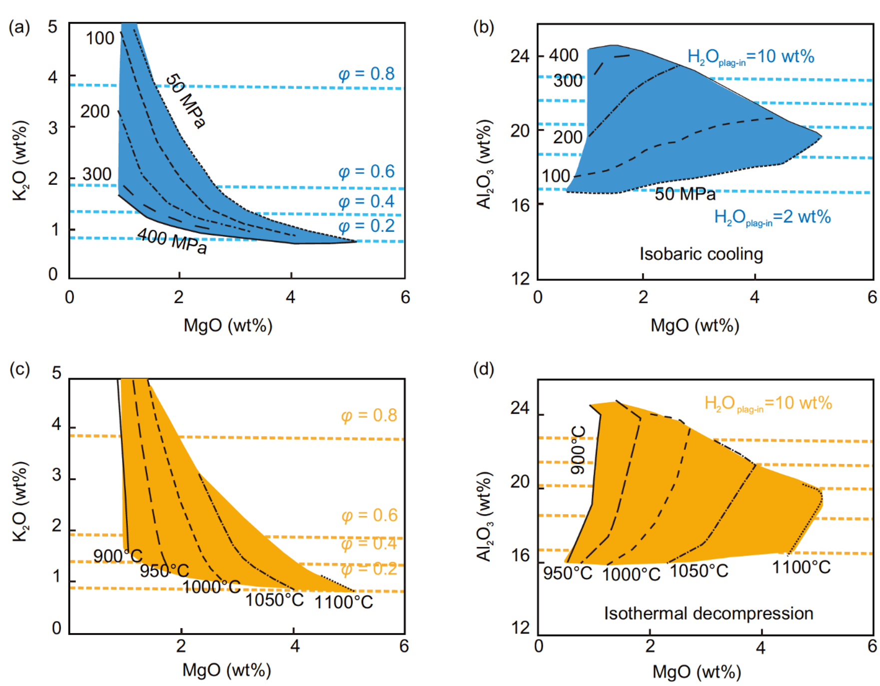


**Figure 8** Evolution of $H_2O$-rich arc basalts (Cashman and Edmonds, 2019). (a) and (b) Evolution of melt composition during isobaric cooling. (c) and (d) Evolution of melt composition during isothermal decompression. The bulk composition for the 1974 Fuego eruption ($H_2O$=4.5 wt%; $fO_2$ of NNO) was used as the starting composition. Compositional evolution determined from rhyolite-MELTS, with the pressure range of 400–50 MPa and the temperature range of 1100–900. The compositional range covers most of the observed melt compositions at Fuego. The compositional space may arise within a complex magmatic system.

on arc basalt genesis, a number of scientific questions are needed to be answered. Four directions require particular attentions in the future.

### 5.1 Sub-arc mantle metasomatism and formation of arc magma source

As discussed previously, the sub-arc mantle wedge is metasomatized by fluids/melts released from downgoing plate either by dehydration or melting, leading to the formation of the source of arc basalts. In actual, subducting plate is compositionally complex, including, in addition to basaltic oceanic crust, overlying pelagic sediments (and carbonates and terrestrial sediments) and underlying oceanic lithospheric mantle. In addition, sediments in accretionary prism and those above the downgoing plate can also be transported to the deep part of mantle wedges through subduction, drag or subduction erosion. Meanwhile, the subducting plate itself may be water-bearing, or become enriched in water due to epidotization, serpentinization and amphibolization, and consequently can carry huge amount of water into deep mantle. Therefore, due to the complexity of origin of fluid or melt and their compositions, the sub-arc mantle metasomatism would be more complex than previously imagined. For example, how the enriched mantle source of shoshonitic or Si-undersaturated potassic rocks formed remains hotly debated. It is suggested that K is largely retained in phengite during progressive metamorphism of sediment-bearing oceanic plate to eclogite facies, and the release of appreciated amount of K into the mantle wedge takes place only when phengite breaks down and starts to melt. In the later scenario, metasomatism of the sub-arc mantle results in formation of K-rich source for potassic volcanics (Schmidt, 1996, 2015; Conticelli et al., 2009; Spandler and Pirard, 2013). Alternatively, it has been proposed, based on melting experiments involving mixture made of peridotite and hydrous sediments, which sediment-derived Si-rich melts, when reacted with peridotites, would evolve to potassic basaltic melts similar to those occurring in subduction zones (Mallik et al., 2015, 2016). Both opinions emphasize sediments as the main source of K, but they are different in the way of participating in the evolution of arc magmatism.

The products of interaction between mantle peridotites and melts are dependent on melt composition, melt/peridotite ratio, and temperature and pressure conditions. When peridotites are reacted with Si-saturated or high $\alpha SiO_2$ magmas, the reaction can be described as the following equation (Johnston and Wyllie, 1989; Rapp et al., 1999; Lambart et al., 2012; Mallik and Dasgupta, 2012; Wang et al., 2016, 2019):

Melt 1+olivine=orthopyroxene+Al-rich phase±melt 2;

The reaction involving low $\alpha SiO_2$ magma is as follows (Morgan and Liang, 2003; Beck et al., 2006; Tursack and Liang, 2012; Lambart et al., 2012; Saper and Liang, 2014):

Melt 1+orthopyroxene=olivine+Al-rich phase+clinopyroxene+melt 2;

The reaction is as follows when all orthopyroxene is consumed:

Melt 1+olivine=clinopyroxene+Al-rich phase±melt 2;

where the extent of reaction depends on melt/peridotite ratio (i.e., Rapp et al., 1999). When melt/peridotite ratio is low, the reaction results in metasomatism of small amount of peridotites; when it is high, residual melts formed after the reaction can erupt to the surface to form arc magmatism. Depending on the composition of initial reactive melts, resultant melts include high-$Mg^{\#}$ andesite and dacite, boninite, alkali basalts, tholeiitic basalt and ultrapotassic rocks (Carroll and Wyllie, 1989; Lambart et al., 2012; Mallik and Dasgupta, 2012; Mallik et al., 2015, 2016). The Al-rich phase includes garnet, spinel and plagioclase, depending on reaction pressures; it is garnet when pressure is high, and it is spinel or plagioclase under low pressure (Lambart et al., 2012; Saper and Liang, 2014). If melt is rich in K, reaction products may contain minor phlogopite (Woodland et al., 2018). High water contents in melts would form amphibole during metasomatism (Gervasoni et al., 2017; Corgne et al., 2018). The melt/rock ratio plays critical roles in crust-mantle interaction at subduction zones; on the one hand, it effectively controls the petrologic processes of metasomatic reactions, forming various types of metasomes. The fusibility of the reaction products ensures that it is easy to melt and to become the major source of subduction-related magmas. On the other hand, it significantly affects the composition of arc magmas, accelerates arc magmatic evolution and promotes continental crustal growth (Su et al., 2019; Zheng et al., 2020).

Slab-derived components may be supercritical fluids at given depth of subduction (Kessel et al., 2005; Mibe et al., 2011; Kawamoto et al., 2012). This is because with increasing pressure and temperature (above the second critical point), hydrous fluid and hydrous silicate melt become completely miscible and one single phase, which has element transport capability similar to melts (Kessel et al., 2005). Although water and silicate contents in this miscible phase mostly vary between 30 and 70 wt% (Ni et al., 2017), it can have strong element solubility only when complete misciblization of hydrous fluid and hydrous melt takes place (Zheng, 2019). It should be pointed out that supercritical fluids cannot stay long at mantle depth and during its ascent it will decompress again to form separate hydrous fluid and hydrous silicate melt (Kawamoto et al., 2012). This probably accounts for the presence of several subduction components in the mantle source of arc basalts.

In addition to hydrous fluid and hydrous melt, $CO_2$-bearing fluids or carbonatite melt can also metasomatize the mantle. It remains hotly debated as to the mechanism of decarbonization of subducting plate and its contribution to arc basalts. Studies on melt inclusions of arc basalts and volcanic gases suggest that primary arc basalts contain at least >3000 ppm $CO_2$ (Wallace, 2005; Blundy et al., 2010). Studies on sub-arc mantle xenoliths (Kamchatka arc, Kepezhinskas and Defant, 1996) show that subducted carbonates react with mantle wedge peridotites to form lherzolites or metasome veins composed of apatite, amphibole and phlogopite, suggesting obvious decarbonization during subduction (Sano and Williams, 1996). However, phase equilibria experiments and thermodynamic modeling predict that decarbonization cannot take place during subduction due to the cold subducting slab (Dasgupta et al., 2004, 2005; Thomsen and Schmidt, 2008; Tsuno and Dasgupta, 2011, 2012; Thomson et al., 2016), and consequently a large amount of carbonates can be transported to deep mantle via subduction. This is apparently at odds with high $CO_2$ contents in arc basalts and petrologic evidence for carbonatite metasomatism of the sub-arc mantle. In fact, mafic carbonatite is stable in the source of arc basaltic magma at depth of 80–160 km and it does not decarbonize significantly until in the mantle transition zone (Dasgupta, 2013; Thomson et al., 2016). To account for such discrepancy, Dasgupta (2013) put forward three mechanisms including mélange diapir, decompression/melting of $H_2O$ $+CO_2$ rich sediments and hot subduction. New experimental petrology and field observation lend supports to decompression of carbonates promoted by defluidization of hydrous sediments, which result in significant decarbonization of subducting slab at relatively shallow depths (Gorman et al., 2006; Frezzotti et al., 2011; Ague and Nicolescu, 2014; Duncan and Dasgupta, 2014). This mechanism potentially accounts for high $CO_2$ content in arc basalts.

### 5.2 Generation of arc basalts and evolution of magma reservoir

It is generally accepted that melting of the mantle wedge at subduction zones is triggered by ingression of volatile components released from subducting oceanic plate (Tatsumi et al., 1986; Tatsumi, 2005). At mid-oceanic ridges, decompression melting is induced by adiabatic upwelling of the asthenospheric mantle which allows intersection of geotherm and solidus (Klein and Langmuir, 1987). This decompression melting mechanism can also explain melting of sub-arc mantle (Tatsumi et al., 1983, Plank and Langmuir, 1988). Indeed, some arc basalts contain very low water contents, in agreement with the decompression melting model in the absence of water (Elkins-Tanton et al., 2001). However, how the relatively solid mantle wedge decompresses is an unsolved problem. Only in some sub-arc environments, asthenosphere mantle can rise to the thinned mantle wedge so that decompression takes place under anhydrous, high temperature conditions. For example, in the Japanese arc, rapid, high angle subduction of oceanic plate caused opening of back-arc basin-the Japan sea, during which the asthenosphere mantle arises and melts due to decompression (Tatsumi et al., 1983). Melting mechanisms other than decompression are needed to account for the generation of hydrous magmas, including water-induced melting and hydrous iso-thermal decompression melting (Figure 9). No matter which process is, the precise determination of solidus of wet peridotites is of critical importance in understanding formation mechanism of arc basaltic magmatism. So far, considerable difference exists between different experiments. To solve this problem, additional experiments work under different pressures and temperatures are highly desired.

The formation of peculiar arc basalts requires special mantle metasomatism or dynamic processes. For example, the arc basalts carrying OIB characteristics are likely either from a mantle wedge metasomatized by subduction-derived melts, or enriched components in the mantle wedge or upwelled mantle. Possible dynamic scenarios for generation of such magmas include ridge subduction, slab window due to slab breakoff (Mullen and Weis, 2013; Thorkelson et al., 2011) or upwelling of deep mantle such as mantle plume (Nakajima and Hasegawa, 2007), or partial melting of back-arc mantle metasomes. Those arc basalts carrying MORB signature is commonly formed in slab-window environment created by ridge subduction (Cole and Stewart, 2009).

Once generated, basaltic magmas would experience a series of evolution processes during their transport through the mantle and the crust to the surface. The arc basalt-andesite-dacite-rhyolite assemblage is traditionally considered as a result of fractional crystallization, coupled with crustal contamination (AFC) or melting-assimilation-storage-homogenization (MASH) of fluid-induced basaltic magmatism. However, recent studies show that magma reservoir in the crust is mainly present in the form of crystal mush, rather than in magma chamber full of melts as traditionally envisaged (e.g., Cooper and Kent, 2014; Cashman et al., 2017). Because of rapid heat loss of magma in cold shallow crust and the viscosity barrier caused by pressure-decrease induced crystallization (Annen et al., 2006), single vertical magma pulse does not allow the eruption. As a consequence, large-scale volcanic eruption, especially supervolcanoe's eruption requires magma storage at certain scale in the middle-upper crust (Bachmann and Bergantz, 2008). As such, as for erupted basalt at the surface, its composition evolution is not only dependent on its mantle source, but also on pre-eruption processes. Taking high-Al arc basalt as an example, the caveat is that they are formed as a result of fractional crystallization of hydrous basalt during which crystallization of plagioclase is delayed. However some experiments show that relatively high pressure (0.7–1.2 GPa) will also delay the crystallization of plagioclase in anhydrous basaltic magmas (Gust and Perfit, 1987; Draper and John-

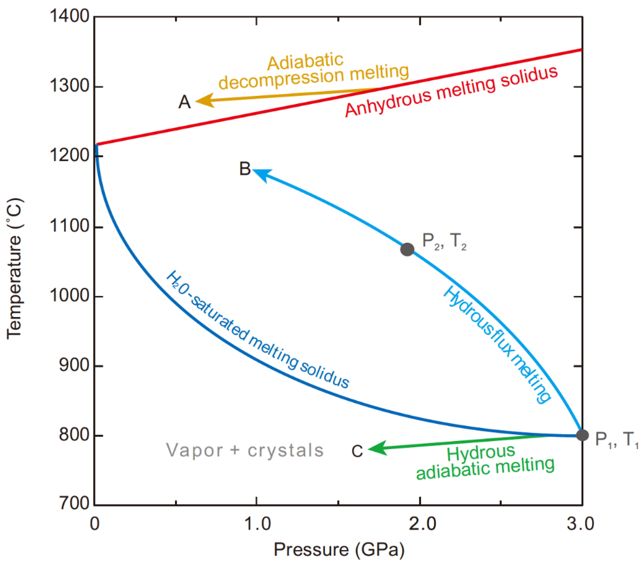


**Figure 9** Schematic diagram showing the anhydrous and $H_2O$-saturated solidii for mantle peridotite (curves) and illustrating several possible paths for melting generation in the mantle wedge (arrows) (Gaetani and Grove, 2003). A, adiabatic decompression melting; B, hydrous flux melting; C, hydrous adiabatic melting.

ston, 1992; Husen et al., 2016; Villiger et al., 2004), in other words, pyroxene crystallizes prior to plagioclase. As such differentiation of some anhydrous magmas can also lead to high-Al basalts (Gust and Perfit, 1987; Draper and Johnston, 1992; Villiger et al., 2004). Good example has been given by Eason and Sinton (2006) who discovered anhydrous tholeiitic high-Al basalt at oceanic ridges formed by high pressure fractionation of pyroxene.

### 5.3 Geochemical recycling associated with arc basaltic magmatism

Subduction zone is the principle location of geochemical recycling and is termed as subduction factory (Tatsumi, 2005). Here, sediments, oceanic crust and lithospheric mantle, together with the materials sitting above the downgoing plate, are transported to deep mantle via subduction, drag and subduction erosion. These deeply subducted materials would release fluids and/or melts to metasomatize the overlying mantle wedge, or mechanically mix with the mantle to form the source of arc basalts. Arc volcanism brings these deeply subducted materials back to the surface again (Figure10). Normal arc basalt is commonly characterized by LILE and LREE enrichment, and HFSE and HREE depletion (Figure 3), which is attributable to fluid mantle metasomatism (e.g., Tatsumi, 2005; Zheng, 2019). Tatsumi and Kogiso (2003) attributed the “arc signature” of arc basalts as a result of ingression of fluids to the mantle wedge, released by dehydration and progressive metamorphism of sediments and oceanic plate. In addition, evidence exists for the involvement of melt components in arc basalts, which are derived from sediments, basaltic oceanic crust and the materials sitting above the downgoing slab (Peacock et al., 1994; Elliott et al., 1997; Kay et al., 2005; Wang et al., 2020; Zheng et al., 2020). Even the crustal components in arc belts have been identified in many arc basalts. For instance, Nd-Hf isotopic compositions argue against trench sediments in the mantle source of arc basalts in Central Mexico but require granodiorite recycled from fore-arc through subduction erosion (Straub et al., 2015). Hence, effective identification of recycled components in the source of arc basalts, in particular, the estimation of flux of recycled materials (Figure 10), represents a thematic issue in geoscience.

### 5.4 Dynamic trigger of arc basalt formation and initiation of plate tectonics

“The present is the key to the past” is the principle of geology. Numerous studies compare Archean magmatic rocks with modern arc magmas and then argue that plate tectonics (i.e, oceanic subduction) occurred already in the Archean, and the timing of initiation is constrained at 3.0–2.5, 3.5–2.5 and >3.5 Ga (Shirey and Hanson, 1984; Smithies et al., 2003, 2004; Martin et al., 2005, 2014; Hastie et al., 2015). The core question related to the onset of plate tectonics on Earth is when the plate tectonics which are similar to modern subduction system started.

In Cenozoic subduction zones, the subduction of oceanic plate not only forms the mantle wedge structure, but also generates arc basalt from the mantle wedge (Figure 3). The interaction between slab-derived melts and the mantle wedge generates high-Nb or Nb-rich basalt, high magnesian andesite and adakites (Wang et al., 2020; and references therein). Some basalts formed at ~3.0 Ga are found enriched in LILE but depleted in HFSE. This finding led to the proposal that the plate tectonics in the sense of modern subduction mechanism was initiated as early as in 3.0 Ga (Smithies et al., 2003, 2004). Likewise, the discovery of the late Archean assemblage of boninite-high-Mg andesite-Nb-rich basalts and adakites, very similar to modern arc magmatic suites, which resulted from strong interaction between oceanic slab-derived melts and mantle wedge peridotites led to the proposal that plate tectonics was already operational at least since the late Archean (e.g., Polat and Kerrich, 2002; Smithies et al., 2004; Martin et al., 2005, 2014).

Turner et al. (2014) found that the volcano-stratographic sequence in 4.4 or 3.8 Ga green belt in Quebec, Canada are geochemically comparable to those in IBM, a type example of modern oceanic subduction zone. The basalts from this stratigraphic sequence are characterized by flat REE and HFSE, resembling fore-arc basalts which are formed as a result of decompression melting of the asthenosphere subsequent to the rupture of subducted oceanic crust. Accord-

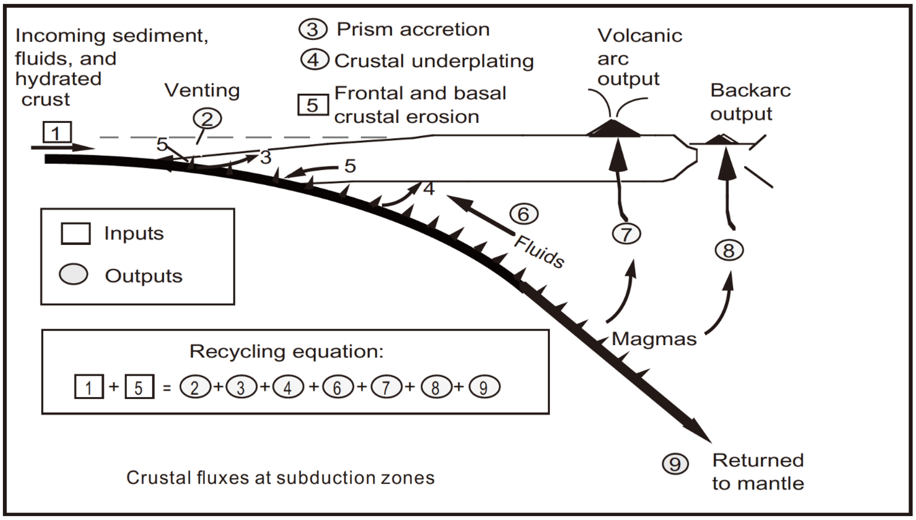


**Figure 10** The flux of crustal material and subduction components, the bulk of which is terrestrial or upper plate material, through a subduction zone (modified from Scholl et al., 1994). 1, Incoming sediment, fluids, and hydrated crust; 2, venting; 3, prism accretion; 4, crustal underplating; 5, frontal and basal crustal erosion; 6, fluids; 7, volcanic arc output; 8, backarc output; 9, returned to mantle.

ingly they suggested that plate tectonics may have been initiated as early as in 4.4 or 3.8 Ga. On the basis of the presence of negative Nb and Ta anomalies and LILE-enrichment in basalts of Archean (3.5–3.3 Ga) Onverwacht greenstone belt in South Africa, Furnes et al. (2013) speculated an origin by partial melting of a sub-arc mantle. In this sense, the early Archean already saw the operation of plate tectonics involving modern subduction system. Nevertheless, all these inferrences are geochemistry-based and require further supporting evidence from tectonics, sedimentology, and high-pressure to ultrahigh pressure metamorphism. The geodynamic mechanism by which arc basalts are generated and the initiation of plate tectonics on Earth remain one of unsolved major scientific problems in geoscience community.

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## References

Agostini S, Ryan J G, Tonarini S, Innocenti F. 2008. Drying and dying of a subducted slab: Coupled Li and B isotope variations in Western Anatolia Cenozoic volcanism. Earth Planet Sci Lett, 272: 139–147

Ague J J, Nicolescu S. 2014. Carbon dioxide released from subduction zones by fluid-mediated reactions. Nat Geosci, 7: 355–360

Aguillón-Robles A, Calmus T, Benoit M, Bellon H, Maury R C, Cotten J, Bourgois J, Michaud F. 2001. Late Miocene adakites and Nb-enriched basalts from Vizcaino Peninsula, Mexico: Indicators of East Pacific Rise subduction below Southern Baja California? Geology, 29: 531–534

Annen C, Blundy J D, Sparks R S J. 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. J Petrol, 47: 505–539

Arculus R J. 2003. Use and abuse of the terms calcalkaline and calcalkalic. J Petrol, 44: 929–935

Bachmann O, Bergantz G. 2008. The magma reservoirs that feed super-eruptions. Elements, 4: 17–21

Bacon C R, Bruggman P E, Christiansen R L, Clynne M A, Donnelly-Nolan J M, Hildreth W. 1997. Primitive magmas at five cascade volcanic fields: Melts from hot, heterogeneous sub-arc mantle. Can Mineral, 35: 397–423

Baker M B, Grove T L, Price R. 1994. Primitive basalts and andesites from the Mt. Shasta region, N. California: Products of varying melt fraction and water content. Contrib Mineral Petrol, 118: 111–129

Beard J S, Lofgren G E. 1992. An experiment-based model for the petrogenesis of high-alumina basalts. Science, 258: 112–115

Beate B, Monzier M, Spikings R, Cotten J, Silva J, Bourdon E, Eissen J P. 2001. Mio-Pliocene adakite generation related to flat subduction in southern Ecuador: The Quimsacocha volcanic center. Earth Planet Sci Lett, 192: 561–570

Beaumais A, Bertrand H, Chazot G, Dosso L, Robin C. 2016. Temporal magma source changes at gaua volcano, vanuatu island arc. J Volcanol Geotherm Res, 322: 30–47

Beccaluva L, Bianchini G, Mameli P, Natali C. 2013. Miocene shoshonite volcanism in Sardinia: Implications for magma sources and geodynamic evolution of the central-western Mediterranean. Lithos, 180-181: 128–137

Beck A R, Morgan Z T, Liang Y, Hess P C. 2006. Dunite channels as viable pathways for mare basalt transport in the deep lunar mantle. Geophys Res Lett, 33: L01202

Behn M D, Kelemen P B, Hirth G, Hacker B R, Massonne H J. 2011. Diapirs as the source of the sediment signature in arc lavas. Nat Geosci, 4: 641–646

Bénard A, Ionov D A. 2013. Melt- and fluid-rock interaction in supra-subduction lithospheric mantle: Evidence from Andesite-hosted veined peridotite xenoliths. J Petrol, 54: 2339–2378

Benton L D, Ryan J G, Savov I P. 2004. Lithium abundance and isotope systematics of forearc serpentinites, Conical Seamount, Mariana forearc: Insights into the mechanics of slab-mantle exchange during subduction. Geochem Geophys Geosyst, 5: Q08J12

Blatter D L, Sisson T W, Hankins W B. 2013. Crystallization of oxidized, moderately hydrous arc basalt at mid- to lower-crustal pressures: Implications for andesite genesis. Contrib Mineral Petrol, 166: 861–886

Bloomer S H, Stern R J, Fisk E, Geschwind C H. 1989. Shoshonitic vol-

canism in the northern Mariana arc: 1. Mineralogic and major and trace element characteristics. J Geophys Res, 94: 4469–4496
Blundy J, Cashman K V, Rust A, Witham F. 2010. A case for $CO_2$-rich arc magmas. Earth Planet Sci Lett, 290: 289–301
Blundy J, Cashman K, Humphreys M. 2006. Magma heating by decompression-driven crystallization beneath andesite volcanoes. Nature, 443: 76–80
Bourdon E, Eissen J P, Gutscher M A, Monzier M, Hall M L, Cotten J. 2003. Magmatic response to early aseismic ridge subduction: The Ecuadorian margin case (South America). Earth Planet Sci Lett, 205: 123–138
Bouvier A S, Métrich N, Deloule E. 2008. Slab-derived fluids in magma sources of St. Vincent (Lesser Antilles Arc): Volatile and light element imprints. J Petrol, 49: 1427–1448
Bouvier A S, Métrich N, Deloule E. 2010. Light elements, volatiles, and stable isotopes in basaltic melt inclusions from Grenada, Lesser Antilles: Inferences for magma genesis. Geochem Geophys Geosyst, 11: Q09004
Branney M, Acocella V. 2015. Calderas. In: Sigurdsson H, Houghton B F, Mcnutt S R, Rymer H, Stix J, Mcbirney A R, eds. The Encyclopedia of Volcanoes. London: Academic Press. 299–315
Brenan J M, Shaw H F, Ryerson F J, Phinney D L. 1995. Mineral-aqueous fluid partitioning of trace elements at 900°C and 2.0 GPa: Constraints on the trace element chemistry of mantle and deep crustal fluids. Geochim Cosmochim Acta, 59: 3331–3350
Brophy J G. 1989. Can high-alumina arc basalt be derived from low-alumina arc basalt? Evidence from Kanaga Island, Aleutian Arc, Alaska. Geology, 17: 333–336
Brophy J G, Marsh B D. 1986. On the origin of high-alumina arc basalt and the mechanics of melt extraction. J Petrol, 27: 763–789
Caricchi L, Sheldrake T E, Blundy J. 2018. Modulation of magmatic processes by $CO_2$ flushing. Earth Planet Sci Lett, 491: 160–171
Carlier G, Lorand J P, Liégeois J P, Fornari M, Soler P, Carlotto V, Cárdenas J. 2005. Potassic-ultrapotassic mafic rocks delineate two lithospheric mantle blocks beneath the southern Peruvian Altiplano. Geology, 33: 601–604
Carlson R W, Grove T L, Donnelly-Nolan J M. 2018. Origin of primitive tholeiitic and calc-alkaline basalts at Newberry Volcano, Oregon. Geochem Geophys Geosyst, 19: 1360–1377
Carroll M R, Wyllie P J. 1989. Experimental phase relations in the system tonalite-peridotite-$H_2O$ at 15 kb: Implications for assimilation and differentiation processes near the crust-mantle boundary. J Petrol, 30: 1351–1382
Cashman K V, Edmonds M. 2019. Mafic glass compositions: A record of magma storage conditions, mixing and ascent. Philos Trans R Soc A-Math Phys Eng Sci, 377: 20180004
Cashman K V, Sparks R S J, Blundy J D. 2017. Vertically extensive and unstable magmatic systems: A unified view of igneous processes. Science, 355: eaag3055
Castillo P R, Solidum R U, Punongbayan R S. 2002. Origin of high field strength element enrichment in the Sulu Arc, southern Philippines, revisited. Geology, 30: 707–710
Castillo P R, Rigby S J, Solidum R U. 2007. Origin of high field strength element enrichment in volcanic arcs: Geochemical evidence from the Sulu Arc, southern Philippines. Lithos, 97: 271–288
Castro A, Gerya T, Garcia-Casco A, Fernandez C, Diaz-Alvarado J, Moreno-Ventas I, Low I. 2010. Melting Relations of MORB-Sediment Melanges in Underplated Mantle Wedge Plumes; Implications for the Origin of Cordilleran-type Batholiths. J Petrol, 51: 1267–1295
Chadwick Jr W W, Cashman K V, Embley R W, Matsumoto H, Dziak R P, de Ronde C E J, Lau T K, Deardorff N D, Merle S G. 2008. Direct video and hydrophone observations of submarine explosive eruptions at NW Rota-1 volcano, Mariana arc. J Geophys Res, 113: B08S10
Chan L H, Leeman W P, You C F. 2002. Lithium isotopic composition of Central American Volcanic Arc lavas: Implications for modification of subarc mantle by slab-derived fluids: Correction. Chem Geol, 182: 293–300
Codillo E A, Le Roux V, Marschall H R. 2018. Arc-like magmas generated by mélange-peridotite interaction in the mantle wedge. Nat Commun, 9: 2864
Cole R B, Stewart B W. 2009. Continental margin volcanism at sites of spreading ridge subduction: Examples from southern Alaska and western California. Tectonophysics, 464: 118–136
Collins S J, Pyle D M, Maclennan J. 2009. Melt inclusions track pre-eruption storage and dehydration of magmas at Etna. Geology, 37: 571–574
Conticelli S, Marchionni S, Rosa D, Giordano G, Boari E, Avanzinelli R. 2009. Shoshonite and sub-alkaline magmas from an ultrapotassic volcano: Sr-Nd-Pb isotope data on the Roccamonfina volcanic rocks, Roman Magmatic Province, Southern Italy. Contrib Mineral Petrol, 157: 41–63
Cooper K M, Kent A J R. 2014. Rapid remobilization of magmatic crystals kept in cold storage. Nature, 506: 480–483
Corgne A, Schilling M E, Grégoire M, Langlade J. 2018. Experimental constraints on metasomatism of mantle wedge peridotites by hybridized adakitic melts. Lithos, 308-309: 213–226
Crawford A J, Falloon T J, Eggins S. 1987. The origin of island arc high-alumina basalts. Contrib Mineral Petrol, 97: 417–430
Cruz-Uribe A M, Marschall H R, Gaetani G A, Le Roux V. 2018. Generation of alkaline magmas in subduction zones by partial melting of mélange diapirs—An experimental study. Geology, 46: 343–346
Dasgupta R, Hirschmann M M, Dellas N. 2005. The effect of bulk composition on the solidus of carbonated eclogite from partial melting experiments at 3 GPa. Contrib Mineral Petrol, 149: 288–305
Dasgupta R, Hirschmann M M, Withers A C. 2004. Deep global cycling of carbon constrained by the solidus of anhydrous, carbonated eclogite under upper mantle conditions. Earth Planet Sci Lett, 227: 73–85
Dasgupta R. 2013. Ingassing, storage, and outgassing of terrestrial carbon through geologic time. Rev Mineral Geochem, 75: 183–229
De Hoog J C, Savov I P. 2017. Boron isotopes as a tracer of subduction zone processes. In: Boron Isotopes. Springer. 217–247
DeBari S M, Taylor B, Spencer K, Fujioka K. 1999. A trapped Philippine Sea plate origin for MORB from the inner slope of the Izu-Bonin trench. Earth Planet Sci Lett, 174: 183–197
Defant M J, Kepezhinskas P. 2001. Evidence suggests slab melting in arc magmas. Eos Trans AGU, 82: 65–80
Defant M J, Drummond M S. 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature, 347: 662–665
Defant M J, Jackson T E, Drummond M S, de Boer J Z, Bellon H, Feigenson M D, Maury R C, Stewart R H. 1992. The geochemistry of young volcanism throughout western Panama and southeastern Costa Rica: An overview. J Geol Soc, 149: 569–579
Defant M J, Kepezhinskas P, Defant M J, Xu J F, Kepezhinskas P, Wang Q, Zhang Q, Xiao L. 2002. Adakites: Some variations on a theme. Acta Petrol Sin, 18: 129–142
Defant M J, Richerson P M, de Boer J Z, Stewart R H, Maury R C, Bellon H, Drummond M S, Feigenson M D, Jackson T E. 1991. Dacite genesis via both slab melting and differentiation: Petrogenesis of La Yeguada Volcanic Complex, Panama. J Petrol, 32: 1101–1142
Draper D S, Johnston A D. 1992. Anhydrous pt phase relations of an aleutian high-mgo basalt: An investigation of the role of olivine-liquid reaction in the generation of arc high-alumina basalts. Contrib Mineral Petrol, 112: 501–519
Duncan M S, Dasgupta R. 2014. $CO_2$ solubility and speciation in rhyolitic sediment partial melts at 1.5–3.0 GPa—Implications for carbon flux in subduction zones. Geochim Cosmochim Acta, 124: 328–347
Eason D, Sinton J. 2006. Origin of high-Al N-MORB by fractional crystallization in the upper mantle beneath the Galápagos Spreading Center. Earth Planet Sci Lett, 252: 423–436
Elburg M, Foden J. 1999. Sources for magmatism in central sulawesi: Geochemical and Sr-Nd-Pb isotopic constraints. Chem Geol, 156: 67–93
Elkins-Tanton L T, Grove T L, Donnelly-Nolan J. 2001. Hot, shallow mantle melting under the cascades volcanic arc. Geology, 29: 631–634
Elliott T, Plank T, Zindler A, White W, Bourdon B. 1997. Element

transport from slab to volcanic front at the mariana arc. J Geophys Res, 102: 14991–15019
Ertan I E, Leeman W P. 1996. Metasomatism of Cascades subarc mantle: Evidence from a rare phlogopite orthopyroxenite xenolith. Geology, 24: 451–454
Falloon T J, Danyushevsky L V, Crawford T J, Maas R, Woodhead J D, Eggins S M, Bloomer S H, Wright D J, Zlobin S K, Stacey A R. 2007. Multiple mantle plume components involved in the petrogenesis of subduction-related lavas from the northern termination of the Tonga Arc and northern Lau Basin: Evidence from the geochemistry of arc and backarc submarine volcanics. Geochem Geophys Geosyst, 8: Q09003
Foden J, Sossi P A, Nebel O. 2018. Controls on the iron isotopic composition of global arc magmas. Earth Planet Sci Lett, 494: 190–201
Foley S F, Barth M G, Jenner G A. 2000. Rutile/melt partition coefficients for trace elements and an assessment of the influence of rutile on the trace element characteristics of subduction zone magmas. Geochim Cosmochim Acta, 64: 933–938
Freymuth H, Elliott T, van Soest M, Skora S. 2016. Tracing subducted black shales in the Lesser Antilles arc using molybdenum isotope ratios. Geology, 44: 987–990
Freymuth H, Vils F, Willbold M, Taylor R N, Elliott T. 2015. Molybdenum mobility and isotopic fractionation during subduction at the Mariana arc. Earth Planet Sci Lett, 432: 176–186
Frezzotti M L, Selverstone J, Sharp Z D, Compagnoni R. 2011. Carbonate dissolution during subduction revealed by diamond-bearing rocks from the Alps. Nat Geosci, 4: 703–706
Frisch W, Meschede M, Blakey R. 2011. Plate Tectonics: Continental Drift and Mountain Building. Berlin Heidelberg: Springer. 212
Furnes H, de Wit M, Robins B. 2013. A review of new interpretations of the tectonostratigraphy, geochemistry and evolution of the Onverwacht Suite, Barberton Greenstone Belt, South Africa. Gondwana Res, 23: 403–428
Gaetani G A, Grove T L. 1998. The influence of water on melting of mantle peridotite. Contrib Mineral Petrol, 131: 323–346
Gaetani G A, Grove T L. 2003. Experimental constraints on melt generation in the mantle wedge. Washington D C: American Geophysical Union Geophysical Monograph Series, 138: 107–134
Gaschnig R M, Reinhard C T, Planavsky N J, Wang X, Asael D, Chauvel C. 2017. The molybdenum isotope system as a tracer of slab input in subduction zones: An example from Martinique, Lesser Antilles Arc. Geochem Geophys Geosyst, 18: 4674–4689
Gervasoni F, Klemme S, Rohrbach A, Grützner T, Berndt J. 2017. Experimental constraints on mantle metasomatism caused by silicate and carbonate melts. Lithos, 282-283: 173–186
Gerya T V, Yuen D A. 2003. Rayleigh-Taylor instabilities from hydration and melting propel "cold plumes" at subduction zones. Earth Planet Sci Lett, 212: 47–62
Gill J B. 1981. Orogenic Andesites and Plate Tectonics. New York: Springer-Verlag. 390
Gorman P J, Kerrick D M, Connolly J A D. 2006. Modeling open system metamorphic decarbonation of subducting slabs. Geochem Geophys Geosyst, 7: Q04007
Gorring M, Singer B, Gowers J, Kay S M. 2003. Plio-Pleistocene basalts from the Meseta del Lago Buenos Aires, Argentina: evidence for asthenosphere-lithosphere interactions during slab window magmatism. Chem Geol, 193: 215–235
Green D H. 1973. Experimental melting studies on a model upper mantle composition at high pressure under water-saturated and water-undersaturated conditions. Earth Planet Sci Lett, 19: 37–53
Green D, Ringwood A. 1969. The origin of basalt magmas. Washington D C: American Geophysical Union Geophysical Monograph Series, 13: 489–495
Green D H, Hibberson W O, Kovács I, Rosenthal A. 2010. Water and its influence on the lithosphere-asthenosphere boundary. Nature, 467: 448–451
Green D H, Hibberson W O, Rosenthal A, Kovács I, Yaxley G M, Falloon T J, Brink F. 2014. Experimental study of the influence of water on melting and phase assemblages in the upper mantle. J Petrol, 55: 2067–2096
Green D H, Rosenthal A, Kovács I. 2012. Comment on "The beginnings of hydrous mantle wedge melting", CB Till, TL Grove, AC Withers, Contributions to Mineralogy and Petrology, DOI 10.1007/s00410-011-0692-6. Contrib Mineral Petrol, 164: 1077–1081
Grove T L, Parman S W, Bowring S A, Price R C, Baker M B. 2002. The role of an $H_2O$-rich fluid component in the generation of primitive basaltic andesites and andesites from the Mt. Shasta region, N California. Contrib Mineral Petrol, 142: 375–396
Grove T L, Till C B, Krawczynski M J. 2012. The role of $H_2O$ in subduction zone magmatism. Annu Rev Earth Planet Sci, 40: 413–439
Grove T L, Till C B, Lev E, Chatterjee N, Médard E. 2009. Kinematic variables and water transport control the formation and location of arc volcanoes. Nature, 459: 694–697
Grove T, Chatterjee N, Parman S, Médard E. 2006. The influence of $H_2O$ on mantle wedge melting. Earth Planet Sci Lett, 249: 74–89
Gust D A, Perfit M R. 1987. Phase relations of a high-mg basalt from the aleutian island arc: Implications for primary island arc basalts and high-al basalts. Contrib Mineral Petrol, 97: 7–18
Hall P S, Kincaid C. 2001. Diapiric flow at subduction zones: A recipe for rapid transport. Science, 292: 2472–2475
Hamilton W. 1964. Origin of high-alumina basalt, andesite, and dacite magmas. Science, 146: 635–637
Hanyu T, Tatsumi Y, Nakai S. 2002. A contribution of slab-melts to the formation of high-Mg andesite magmas Hf isotopic evidence from Sw Japan. Geophys Res Lett, 29: 2051
Hastie A R, Fitton J G, Mitchell S F, Neill I, Nowell G M, Millar I L. 2015. Can fractional crystallization, mixing and assimilation processes be responsible for Jamaican-type Adakites? Implications for generating Eoarchaean continental crust. J Petrol, 56: 1251–1284
Hawkesworth C J, Gallagher K, Hergt J M, McDermott F. 1993. Mantle and slab contributions in arc magmas. Annu Rev Earth Planet Sci, 21: 175–204
Hermann J, Spandler C J. 2008. Sediment melts at sub-arc depths: An experimental study. J Petrol, 49: 717–740
Hickey-Vargas R, Sun M, Holbik S. 2016. Geochemistry of basalts from small eruptive centers near Villarrica stratovolcano, Chile: Evidence for lithospheric mantle components in continental arc magmas. Geochim Cosmochim Acta, 185: 358–382
Hirschmann M M, Kogiso T, Baker M B, Stolper E M. 2003. Alkalic magmas generated by partial melting of garnet pyroxenite. Geology, 31: 481–484
Hochstaedter A G, Gill J B, Taylor B, Ishizuka O, Yuasa M, Monta S. 2000. Across-arc geochemical trends in the Izu-Bonin arc: Constraints on source composition and mantle melting. J Geophys Res, 105: 495–512
Hoernle K, Abt D L, Fischer K M, Nichols H, Hauff F, Abers G A, van den Bogaard P, Heydolph K, Alvarado G, Protti M, Strauch W. 2008. Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. Nature, 451: 1094–1097
Husen A, Almeev R R, Holtz F. 2016. The effect of $H_2O$ and pressure on multiple saturation and liquid lines of descent in basalt from the Shatsky Rise. J Petrol, 57: 309–344
Irving A J, Green D H. 2008. Phase relationships of hydrous alkalic magmas at high pressures: Production of nepheline hawaiitic to mugearitic liquids by amphibole-dominated fractional crystallization within the lithospheric mantle. J Petrol, 49: 741–756
Ishikawa T, Nakamura E. 1994. Origin of the slab component in arc lavas from across-arc variation of B and Pb isotopes. Nature, 370: 205–208
Ishizuka O, Kimura J, Li Y, Stern R, Reagan M, Taylor R, Ohara Y, Bloomer S, Ishii T, Hargroveiii U. 2006. Early stages in the evolution of Izu-Bonin arc volcanism: New age, chemical, and isotopic constraints. Earth Planet Sci Lett, 250: 385–401
Ishizuka O, Tani K, Reagan M K, Kanayama K, Umino S, Harigane Y, Sakamoto I, Miyajima Y, Yuasa M, Dunkley D J. 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island arc. Earth Planet Sci Lett, 306: 229–240
Ishizuka O, Uto K, Yuasa M, Hochstaedter A G. 2003. Volcanism in the earliest stage of back-arc rifting in the izu-bonin arc revealed by laser-

heating $^{40}Ar/^{39}Ar$ dating. J Volcanol Geotherm Res, 120: 71–85
Ishizuka O, Yuasa M, Taylor R N, Sakamoto I. 2009. Two contrasting magmatic types coexist after the cessation of back-arc spreading. Chem Geol, 266: 274–296
Johnston A D, Wyllie P J. 1989. The system tonalite-peridotite-$H_2O$ at 30 kbar, with applications to hybridization in subduction zone magmatism. Contrib Mineral Petrol, 102: 257–264
Kawamoto T, Kanzaki M, Mibe K, Matsukage K N, Ono S. 2012. Separation of supercritical slab-fluids to form aqueous fluid and melt components in subduction zone magmatism. Proc Natl Acad Sci USA, 109: 18695–18700
Kay S M, Godoy E, Kurtz A. 2005. Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central andes. Geol Soc Am Bull, 117: 67–88
Kelemen P B, Rilling J L, Parmentier E M, Mehl L, Hacker B R. 2003. Thermal structure due to solid-state flow in the mantle wedge beneath arcs. In: Eiler J, ed. Inside the Subduction Factory. Washington D C: AGU. 293–311
Kelemen P B, Hanghøj K, Greene A R. 2014. One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust. In: Turekian K K, ed. Treatise on Geochemistry (Second Edition). Oxford: Elsevier. 749–806
Kepezhinskas P, Defant M J. 1996. Contrasting styles of mantle metasomatism above subduction zones: Constraints from ultrama¢c xenoliths in Kamchatka. In: Bebout G E, Scholl D W, Kirby S H, Platt J P, eds. Subduction: Top to Bottom. Washington D C: AGU. 307–314
Kepezhinskas P K, Defant M J, Drummond M S. 1995. Na metasomatism in the island arc mantle by slab melt-peridotite interaction: Evidence from mantle xenoliths in the North Kamchatka arc. J Petrol, 36: 1505–1527
Kepezhinskas P, McDermott F, Defant M J, Hochstaedter A, Drummond M S, Hawkesworth C J, Koloskov A, Maury R C, Bellon H. 1997. Trace element and Sr-Nd-Pb isotopic constraints on a three-component model of Kamchatka Arc petrogenesis. Geochim Cosmochim Acta, 61: 577–600
Keppler H. 1996. Constraints from partitioning experiments on the composition of subduction-zone fluids. Nature, 380: 237–240
Kessel R, Schmidt M W, Ulmer P, Pettke T. 2005. Trace element signature of subduction-zone fluids, melts and supercritical liquids at 120–180 km depth. Nature, 437: 724–727
Kikuchi Y. 1888. Geological summary of the Bonin and Volcano Islands (in Japanese). Toyo Gakugei-zasshi, 5: 64–69
Kikuchi Y. 1890. On pyorxene components in certain volcanic rocks from Bonin Island. J Coll Sci Imp Univ Japan, 3: 67–89
Kimura J I, Ariskin A A. 2014. Calculation of water-bearing primary basalt and estimation of source mantle conditions beneath arcs: Primacalc2 model for windows. Geochem Geophys Geosyst, 15: 1494–1514
Kincaid C, Druken K A, Griffiths R W, Stegman D R. 2013. Bifurcation of the Yellowstone plume driven by subduction-induced mantle flow. Nat Geosci, 6: 395–399
Kincaid C, Griffiths R W. 2003. Laboratory models of the thermal evolution of the mantle during rollback subduction. Nature, 425: 58–62
Kirby S, Engdahl E, Denlinger R. 1996. Intermediate-depth intraplate earthquakes and arc volcanism as physical expressions of crustal and upper mantle meta-morphism in subducting slabs. In: Bebout G E, Scholl D W, Kirby S H, Platt J P, eds. Subduction Top to Bottom. Washington D C: AGU. 195–214
Klein E M, Langmuir C H. 1987. Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness. J Geophys Res, 92: 8089–8115
König S, Wille M, Voegelin A, Schoenberg R. 2016. Molybdenum isotope systematics in subduction zones. Earth Planet Sci Lett, 447: 95–102
Konrad-Schmolke M, Halama R, Manea V C. 2016. Slab mantle dehydrates beneath Kamchatka-yet recycles water into the deep mantle. Geochem Geophys Geosyst, 17: 2987–3007
Korenaga J, Kelemen P B. 2000. Major element heterogeneity in the mantle source of the North Atlantic igneous province. Earth Planet Sci Lett, 184: 251–268
Kuno H. 1960. High-alumina basalt. J Petrol, 1: 121–145
Kuritani T, Yokoyama T, Nakamura E. 2008. Generation of rear-arc magma induced by influx of slab-derived supercritical liquids: Implications from alkali basalt lavas from Rishiri Volcano, Kurile arc. J Petrol, 49: 1319–1342
Kushiro I. 1959. Preliminary note on alkali-dolerite of atumi district, northern Japan. Jap J Geol Geogr, 30: 259–272
Kushiro I. 1968. Compositions of magmas formed by partial zone melting of the Earth's upper mantle. J Geophys Res, 73: 619–634
Lai Y M, Song S R, Lo C H, Lin T H, Chu M F, Chung S L. 2017. Age, geochemical and isotopic variations in volcanic rocks from the Coastal Range of Taiwan: Implications for magma generation in the Northern Luzon Arc. Lithos, 272-273: 92–115
Lambart S, Laporte D, Provost A, Schiano P. 2012. Fate of pyroxenite-derived melts in the peridotitic mantle: Thermodynamic and experimental constraints. J Petrol, 53: 451–476
Lambart S, Laporte D, Schiano P. 2009. An experimental study of pyroxenite partial melts at 1 and 1.5 GPa: Implications for the major-element composition of Mid-Ocean ridge basalts. Earth Planet Sci Lett, 288: 335–347
Le Voyer M, Rose-Koga E F, Shimizu N, Grove T L, Schiano P. 2010. Two contrasting $H_2O$-rich components in primary melt inclusions from mount shasta. J Petrol, 51: 1571–1595
Leeman W P, Lewis J F, Evarts R C, Conrey R M, Streck M J. 2005. Petrologic constraints on the thermal structure of the Cascades arc. J Volcanol Geotherm Res, 140: 67–105
Leslie R A J, Danyushevsky L V, Crawford A J, Verbeeten A C. 2009. Primitive shoshonites from Fiji: Geochemistry and source components. Geochem Geophys Geosyst, 10: Q07001
Li H Y, Taylor R N, Prytulak J, Kirchenbaur M, Shervais J W, Ryan J G, Godard M, Reagan M K, Pearce J A. 2019. Radiogenic isotopes document the start of subduction in the Western Pacific. Earth Planet Sci Lett, 518: 197–210
Lin P N, Stern R J, Bloomer S H. 1989. Shoshonitic volcanism in the northern Mariana arc: 2. Large-ion lithophile and rare earth element abundances: Evidence for the source of incompatible element enrichments in intraoceanic arcs. J Geophys Res, 94: 4497–4514
Liu L, Stegman D R. 2012. Origin of Columbia River flood basalt controlled by propagating rupture of the Farallon slab. Nature, 482: 386–389
Lynn K J, Shea T, Garcia M O, Costa F, Norman M D. 2018. Lithium diffusion in olivine records magmatic priming of explosive basaltic eruptions. Earth Planet Sci Lett, 500: 127–135
Mallik A, Dasgupta R, Tsuno K, Nelson J. 2016. Effects of water, depth and temperature on partial melting of mantle-wedge fluxed by hydrous sediment-melt in subduction zones. Geochim Cosmochim Acta, 195: 226–243
Mallik A, Dasgupta R. 2012. Reaction between MORB-eclogite derived melts and fertile peridotite and generation of ocean island basalts. Earth Planet Sci Lett, 329-330: 97–108
Mallik A, Nelson J, Dasgupta R. 2015. Partial melting of fertile peridotite fluxed by hydrous rhyolitic melt at 2–3 GPa: Implications for mantle wedge hybridization by sediment melt and generation of ultrapotassic magmas in convergent margins. Contrib Mineral Petrol, 169: 48
Manning C E. 2004. The chemistry of subduction-zone fluids. Earth Planet Sci Lett, 223: 1–16
Marschall H R, Schumacher J C. 2012. Arc magmas sourced from mélange diapirs in subduction zones. Nat Geosci, 5: 862–867
Martin C, Flores K E, Harlow G E. 2016. Boron isotopic discrimination for subduction-related serpentinites. Geology, 44: 899–902
Martin H, Moyen J F, Guitreau M, Blichert-Toft J, Le Pennec J L. 2014. Why Archaean TTG cannot be generated by MORB melting in subduction zones. Lithos, 198-199: 1–13
Martin H, Smithies R H, Rapp R, Moyen J F, Champion D. 2005. An overview of adakite, tonalite-trondhjemite-granodiorite (TTG), and sanukitoid: Relationships and some implications for crustal evolution. Lithos, 79: 1–24
McGary R S, Evans R L, Wannamaker P E, Elsenbeck J, Rondenay S. 2014. Pathway from subducting slab to surface for melt and fluids

beneath Mount Rainier. Nature, 511: 338–340

McInnes B I A, Gregoire M, Binns R A, Herzig P M, Hannington M D. 2001. Hydrous metasomatism of oceanic sub-arc mantle, Lihir, Papua New Guinea: Petrology and geochemistry of fluid-metasomatised mantle wedge xenoliths. Earth Planet Sci Lett, 188: 169–183

Médard E, Schmidt M W, Schiano P, Ottolini L. 2006. Melting of amphibole-bearing wehrlites: An experimental study on the origin of ultra-calcic nepheline-normative melts. J Petrol, 47: 481–504

Meffre S, Falloon T J, Crawford T J, Hoernle K, Hauff F, Duncan R A, Bloomer S H, Wright D J. 2012. Basalts erupted along the tongan fore arc during subduction initiation: Evidence from geochronology of dredged rocks from the tonga fore arc and trench. Geochem Geophys Geosyst, 13: Q12003

Melekhova E, Blundy J, Robertson R, Humphreys M C S. 2015. Experimental evidence for polybaric differentiation of primitive arc basalt beneath St. Vincent, Lesser Antilles. J Petrol, 56: 161–192

Mibe K, Kawamoto T, Matsukage K N, Fei Y, Ono S. 2011. Slab melting versus slab dehydration in subduction-zone magmatism. Proc Natl Acad Sci USA, 108: 8177–8182

Morgan Z, Liang Y. 2003. An experimental and numerical study of the kinetics of harzburgite reactive dissolution with applications to dunite dike formation. Earth Planet Sci Lett, 214: 59–74

Moriguti T, Nakamura E. 1998. Across-arc variation of Li isotopes in lavas and implications for crust/mantle recycling at subduction zones. Earth Planet Sci Lett, 163: 167–174

Morrison G W. 1980. Characteristics and tectonic setting of the shoshonite rock association. Lithos, 13: 97–108

Mullen E K, Weis D, Marsh N B, Martindale M. 2017. Primitive arc magma diversity: New geochemical insights in the cascade arc. Chem Geol, 448: 43–70

Mullen E K, Weis D. 2013. Sr-Nd-Hf-Pb isotope and trace element evidence for the origin of alkalic basalts in the Garibaldi Belt, northern Cascade arc. Geochem Geophys Geosyst, 14: 3126–3155

Müller D, Franz L, Herzig P M, Hunt S. 2001. Potassic igneous rocks from the vicinity of epithermal gold mineralization, Lihir Island, Papua New Guinea. Lithos, 57: 163–186

Müller D, Rock N M S, Groves D I. 1992. Geochemical discrimination between shoshonitic and potassic volcanic rocks in different tectonic settings: A pilot study. Mineral Petrol, 46: 259–289

Nakajima J, Hasegawa A. 2007. Subduction of the philippine sea plate beneath southwestern japan: Slab geometry and its relationship to arc magmatism. J Geophys Res, 112: B08306

Ni H, Zhang L, Xiong X, Mao Z, Wang J. 2017. Supercritical fluids at subduction zones: Evidence, formation condition, and physicochemical properties. Earth-Sci Rev, 167: 62–71

Nicholls I A, Ringwood A E. 1973. Production of silica-saturated tholeiitic magmas in island arcs. Earth Planet Sci Lett, 17: 243–246

Nielsen S G, Marschall H R. 2017. Geochemical evidence for mélange melting in global arcs. Sci Adv, 3: e1602402

Niu Y. 2005. Generation and evolution of basaltic magmas: Some basic concepts and a new view on the origin of Mesozoic-Cenozoic basaltic volcanism in eastern China. Geol J China Univ, 11: 9–46

Pabst S, Zack T, Savov I P, Ludwig T, Rost D, Vicenzi E P. 2011. Evidence for boron incorporation into the serpentine crystal structure. Am Miner, 96: 1112–1119

Parman S W, Grove T L, Kelley K A, Plank T. 2011. Along-arc variations in the pre-eruptive $H_2O$ contents of Mariana Arc magmas inferred from fractionation paths. J Petrol, 52: 257–278

Peacock S M, Rushmer T, Thompson A B. 1994. Partial melting of subducting oceanic crust. Earth Planet Sci Lett, 121: 227–244

Peate D W, Pearce J A, Hawkesworth C J, Colley H, Edwards C M H, Hirose K. 1997. Geochemical variations in vanuatu arc lavas: The role of subducted material and a variable mantle wedge composition. J Petrol, 38: 1331–1358

Pertermann M, Hirschmann M M. 2003. Partial melting experiments on a MORB-like pyroxenite between 2 and 3 GPa: Constraints on the presence of pyroxenite in basalt source regions from solidus location and melting rate. J Geophys Res, 108: 2125

Pichavant M, MacDonald R. 2007. Crystallization of primitive basaltic magmas at crustal pressures and genesis of the calc-alkaline igneous suite: Experimental evidence from St Vincent, Lesser Antilles arc. Contrib Mineral Petrol, 154: 535–558

Pilet S, Baker M B, Stolper E M. 2008. Metasomatized lithosphere and the origin of alkaline lavas. Science, 320: 916–919

Pirard C, Hermann J. 2015. Focused fluid transfer through the mantle above subduction zones. Geology, 43: 915–918

Plank T, Kelley K A, Zimmer M M, Hauri E H, Wallace P J. 2013. Why do mafic arc magmas contain ~4 wt% water on average? Earth Planet Sci Lett, 364: 168–179

Plank T, Langmuir C H. 1988. An evaluation of the global variations in the major element chemistry of arc basalts. Earth Planet Sci Lett, 90: 349–370

Polat A, Kerrich R. 2002. Nd-isotope systematics of ~2.7 Ga adakites, magnesian andesites, and arc basalts, Superior Province: Evidence for shallow crustal recycling at Archean subduction zones. Earth Planet Sci Lett, 202: 345–360

Price A A, Jackson M G, Blichert-Toft J, Hall P S, Sinton J M, Kurz M D, Blusztajn J. 2014. Evidence for a broadly distributed Samoan-plume signature in the northern Lau and North Fiji Basins. Geochem Geophys Geosyst, 15: 986–1008

Prigent C, Guillot S, Agard P, Lemarchand D, Soret M, Ulrich M. 2018. Transfer of subduction fluids into the deforming mantle wedge during nascent subduction: Evidence from trace elements and boron isotopes (Semail ophiolite, Oman). Earth Planet Sci Lett, 484: 213–228

Rapp R P, Shimizu N, Norman M D, Applegate G S. 1999. Reaction between slab-derived melts and peridotite in the mantle wedge: Experimental constraints at 3.8 GPa. Chem Geol, 160: 335–356

Rapp R P, Watson E B. 1995. Dehydration Melting of Metabasalt at 8–32 kbar: Implications for Continental Growth and Crust-Mantle Recycling. J Petrol, 36: 891–931

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

Ringwood A E. 1990. Slab-mantle interactions. Chem Geol, 82: 187–207

Ringwood A E. 1974. The petrological evolution of island arc systems. J Geol Soc, 130: 183–204

Roeder P L, Emslie R F. 1970. Olivine-liquid equilibrium. Contrib Mineral Petrol, 29: 275–289

Rogers N. 2015. The composition and origin of magmas. In: Sigurdsson H, Houghton B F, Mcnutt S R, Rymer H, Stix J, Mcbirney A R, eds. The Encyclopedia of Volcanoes. London: Academic Press. 93–112

Ruprecht P, Plank T. 2013. Feeding andesitic eruptions with a high-speed connection from the mantle. Nature, 500: 68–72

Ruth D C S, Costa F, Bouvet de Maisonneuve C, Franco L, Cortés J A, Calder E S. 2018. Crystal and melt inclusion timescales reveal the evolution of magma migration before eruption. Nat Commun, 9: 2657

Sajona F G, Bellon H, Maury R C, Pubellier M, Cotten J, Rangin C. 1994. Magmatic response to abrupt changes in geodynamic settings: Pliocene—Quaternary calc-alkaline and Nb-enriched lavas from Mindanao (Philippines). Tectonophysics, 237: 47–72

Sajona F G, Maury R C, Bellon H, Cotten J, Defant M. 1996. High field strength element enrichment of Pliocene-Pleistocene Island arc basalts, Zamboanga Peninsula, western Mindanao (Philippines). J Petrol, 37: 693–726

Sajona F G, Maury R C, Bellon H, Cotten J, Defant M J, Pubellier M. 1993. Initiation of subduction and the generation of slab melts in Western and Eastern Mindanao, Philippines. Geology, 21: 1007–1010

Sano Y, Williams S N. 1996. Fluxes of mantle and subducted carbon along convergent plate boundaries. Geophys Res Lett, 23: 2749–2752

Saper L, Liang Y. 2014. Formation of plagioclase-bearing peridotite and plagioclase-bearing wehrlite and gabbro suite through reactive crystallization: An experimental study. Contrib Mineral Petrol, 167: 985

Savov I P, Ryan J G, D'Antonio M, Fryer P. 2007. Shallow slab fluid release across and along the Mariana arc-basin system: Insights from geochemistry of serpentinized peridotites from the Mariana fore arc. J Geophys Res, 112: B09205

Savov I P, Ryan J G, D'Antonio M, Kelley K, Mattie P. 2005. Geochemistry of serpentinized peridotites from the Mariana Forearc Conical Seamount, ODP Leg 125: Implications for the elemental recycling at subduction zones. Geochem Geophys Geosyst, 6: Q04J15

Scambelluri M, Tonarini S. 2012. Boron isotope evidence for shallow fluid transfer across subduction zones by serpentinized mantle. Geology, 40: 907–910

Scherbarth N L, Spry P G. 2006. Mineralogical, petrological, stable isotope, and fluid inclusion characteristics of the tuvatu gold-silver telluride deposit, Fiji: Comparisons with the emperor deposit. Econ Geol, 101: 135–158

Schmidt M W. 1996. Experimental constraints on recycling of potassium from subducted oceanic crust. Science, 272: 1927–1930

Schmidt M W. 2015. Melting of pelitic sediments at subarc depths: 2. Melt chemistry, viscosities and a parameterization of melt composition. Chem Geol, 404: 168–182

Schmidt M W, Jagoutz O. 2017. The global systematics of primitive arc melts. Geochem Geophys Geosyst, 18: 2817–2854

Schmidt M W, Poli S. 1998. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. Earth Planet Sci Lett, 163: 361–379

Schmidt M W, Poli S. 2014. 4.19. Devolatilization during subduction. In: Turekian K K, ed. Treatise on Geochemistry (Second Edition). Oxford: Elsevier. 669–697

Scholl D W, Plank T, Morris J, von Huene R, Mottl M J. 1994. Science opportunities in Ocean Drilling to investigate recycling processes and material fluxes at subduction zones. Avalon: Proceedings of a JOI/USSAC workshop

Schuth S, Münker C, König S, Qopoto C, Basi S, Garbe-Schönberg D, Ballhaus C. 2009. Petrogenesis of lavas along the solomon island arc, sw pacific: Coupling of compositional variations and subduction zone geometry. J Petrol, 50: 781–811

Shervais J W, Reagan M, Haugen E, Almeev R R, Pearce J A, Prytulak J, Ryan J G, Whattam S A, Godard M, Chapman T, Li H, Kurz W, Nelson W R, Heaton D, Kirchenbaur M, Shimizu K, Sakuyama T, Li Y, Vetter S K. 2019. Magmatic response to subduction initiation: Part 1. Fore-arc basalts of the Izu-Bonin Arc From IODP expedition 352. Geochem Geophys Geosyst, 20: 314–338

Shirey S B, Hanson G N. 1984. Mantle-derived Archaean monozodiorites and trachyandesites. Nature, 310: 222–224

Shuto K, Nohara-Imanaka R, Sato M, Takahashi T, Takazawa E, Kawabata H, Takanashi K, Ban M, Watanabe N, Fujibayashi N. 2015. Across-arc variations in geochemistry of oligocene to quaternary basalts from the ne japan arc: Constraints on source composition, mantle melting and slab input composition. J Petrol, 56: 2257–2297

Sisson T W, Grove T L. 1993. Experimental investigations of the role of $H_2O$ in calc-alkaline differentiation and subduction zone magmatism. Contrib Mineral Petrol, 113: 143–166

Sisson T W, Kelemen P B. 2018. Near-solidus melts of MORB + 4 wt% $H_2O$ at 0.8–2.8 GPa applied to issues of subduction magmatism and continent formation. Contrib Mineral Petrol, 173: 70

Sisson T W, Layne G D. 1993. H2O in basalt and basaltic andesite glass inclusions from four subduction-related volcanoes. Earth Planet Sci Lett, 117: 619–635

Smithies R H, Champion D C, Sun S S. 2004. Evidence for Early LREE-enriched mantle source regions: Diverse magmas from the c. 3.0 Ga Mallina Basin, Pilbara Craton, NW Australia. J Petrol, 45: 1515–1537

Smithies R H, Champion D C, Cassidy K F. 2003. Formation of Earth's early Archaean continental crust. Precambrian Res, 127: 89–101

Sorbadere F, Médard E, Laporte D, Schiano P. 2013a. Experimental melting of hydrous peridotite-pyroxenite mixed sources: Constraints on the genesis of silica-undersaturated magmas beneath volcanic arcs. Earth Planet Sci Lett, 384: 42–56

Sorbadere F, Schiano P, Métrich N, Bertagnini A. 2013b. Small-scale coexistence of island-arc- and enriched-MORB-type basalts in the central Vanuatu arc. Contrib Mineral Petrol, 166: 1305–1321

Spandler C, Pirard C. 2013. Element recycling from subducting slabs to arc crust: A review. Lithos, 170-171: 208–223

Spandler C, Yaxley G, Green D H, Scott D. 2010. Experimental phase and melting relations of metapelite in the upper mantle: Implications for the petrogenesis of intraplate magmas. Contrib Mineral Petrol, 160: 569–589

Stalder R, Foley S F, Brey G P, Horn I. 1998. Mineral-aqueous fluid partitioning of trace elements at 900–1200°C and 3.0–5.7 GPa: New experimental data for garnet, clinopyroxene, and rutile, and implications for mantle metasomatism. Geochim Cosmochim Acta, 62: 1781–1801

Stern R J. 2010. The anatomy and ontogeny of modern intra-oceanic arc systems. Geol Soc Lond Spec Publ, 338: 7–34

Straub S M, Gómez-Tuena A, Bindeman I N, Bolge L L, Brandl P A, Espinasa-Perena R, Solari L, Stuart F M, Vannucchi P, Zellmer G F. 2015. Crustal recycling by subduction erosion in the central mexican volcanic belt. Geochim Cosmochim Acta, 166: 29–52

Su B X, Zhou M F, Robinson P T. 2016. Extremely large fractionation of Li isotopes in a chromitite-bearing mantle sequence. Sci Rep, 6: 22370

Su B, Chen Y, Guo S, Chen S, Li Y. 2019. Garnetite and pyroxenite in the mantle wedge formed by slab-mantle interactions at different melt/rock ratios. J Geophys Res Solid Earth, 124: 6504–6522

Sun S, McDonough W F. 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. Geol Soc Lond Spec Publ, 42: 313–345

Syracuse E M, van Keken P E, Abers G A, Suetsugu D, Bina C, Inoue T, Wiens D, Jellinek M. 2010. The global range of subduction zone thermal models. Phys Earth Planet Inter, 183: 73–90

Tamura A, Arai S. 2006. Harzburgite-dunite-orthopyroxenite suite as a record of supra-subduction zone setting for the Oman ophiolite mantle. Lithos, 90: 43–56

Tang G J, Wang Q, Wyman D, Sun M, Li Z X, Zhao Z H, Sun W D, Jia X H, Jiang Z Q. 2010. Geochronology and geochemistry of Late Paleozoic magmatic rocks in the Lamasu-Dabate area, northwestern Tianshan (west China): Evidence for a tectonic transition from arc to post-collisional setting. Lithos, 119: 3–4

Tang M, Rudnick R L, Chauvel C. 2014. Sedimentary input to the source of Lesser Antilles lavas: A Li perspective. Geochim Cosmochim Acta, 144: 43–58

Tatsumi Y, Hamilton D L, Nesbitt R W. 1986. Chemical characteristics of fluid phase released from a subducted lithosphere and origin of arc magmas: Evidence from high-pressure experiments and natural rocks. J Volcanol Geotherm Res, 29: 293–309

Tatsumi Y, Kogiso T. 2003. The subduction factory: Its role in the evolution of the earth's crust and mantle. Geol Soc Lond Spec Publ, 219: 55–80

Tatsumi Y, Sakuyama M, Fukuyama H, Kushiro I. 1983. Generation of arc basalt magmas and thermal structure of the mantle wedge in subduction zones. J Geophys Res, 88: 5815–5825

Tatsumi Y, Takahashi T, Hirahara Y, Chang Q, Miyazaki T, Kimura J I, Ban M, Sakayori A. 2008. New insights into andesite genesis: The role of mantle-derived calc-alkalic and crust-derived tholeiitic melts in magma differentiation beneath zao volcano, NE Japan. J Petrol, 49: 1971–2008

Tatsumi Y. 1989. Migration of fluid phases and genesis of basalt magmas in subduction zones. J Geophys Res, 94: 4697–4707

Tatsumi Y. 2005. The subduction factory: How it operates in the evolving earth. GSA Today, 15: 4–10

Tatsumi Y. 2006. High-mg andesites in the setouchi volcanic belt, southwestern japan: Analogy to archean magmatism and continental crust formation? Annu Rev Earth Planet Sci, 34: 467–499

Teng F Z, Hu Y, Chauvel C. 2016. Magnesium isotope geochemistry in arc volcanism. Proc Natl Acad Sci USA, 113: 7082–7087

Tenner T J, Hirschmann M M, Humayun M. 2012. The effect of $H_2O$ on partial melting of garnet peridotite at 3.5 GPa. Geochem Geophys Geosyst, 13: Q03016

Thomsen T B, Schmidt M W. 2008. Melting of carbonated pelites at 2.5–5.0 GPa, silicate-carbonatite liquid immiscibility, and potassium-carbon

metasomatism of the mantle. Earth Planet Sci Lett, 267: 17–31
Thomson A R, Walter M J, Kohn S C, Brooker R A. 2016. Slab melting as a barrier to deep carbon subduction. Nature, 529: 76–79
Thorkelson D J, Madsen J K, Sluggett C L. 2011. Mantle flow through the Northern Cordilleran slab window revealed by volcanic geochemistry. Geology, 39: 267–270
Till C B, Grove T L, Withers A C. 2012. The beginnings of hydrous mantle wedge melting. Contrib Mineral Petrol, 163: 669–688
Tomita T. 1935. On the chemical composition of the Cenozoic alkaline suite of the circum-japan sea region. J Shanghai Sci Inst, 1: 227–306
Tonarini S, Leeman W P, Leat P T. 2011. Subduction erosion of forearc mantle wedge implicated in the genesis of the South Sandwich Island (SSI) arc: Evidence from boron isotope systematics. Earth Planet Sci Lett, 301: 275–284
Tsuno K, Dasgupta R. 2011. Melting phase relation of nominally anhydrous, carbonated pelitic-eclogite at 2.5–3.0 GPa and deep cycling of sedimentary carbon. Contrib Mineral Petrol, 161: 743–763
Tsuno K, Dasgupta R. 2012. The effect of carbonates on near-solidus melting of pelite at 3 GPa: Relative efficiency of $H_2O$ and $CO_2$ subduction. Earth Planet Sci Lett, 319-320: 185–196
Turner S, Rushmer T, Reagan M, Moyen J F. 2014. Heading down early on? Start of subduction on Earth. Geology, 42: 139–142
Turner S J, Langmuir C H, Dungan M A, Escrig S. 2017. The importance of mantle wedge heterogeneity to subduction zone magmatism and the origin of EM1. Earth Planet Sci Lett, 472: 216–228
Tursack E, Liang Y. 2012. A comparative study of melt-rock reactions in the mantle: Laboratory dissolution experiments and geological field observations. Contrib Mineral Petrol, 163: 861–876
Ulmer P, Trommsdorff V. 1995. Serpentine stability to mantle depths and subduction-related magmatism. Science, 268: 858–861
Van den Bleeken G, Muntener O, Ulmer P. 2010. Reaction processes between tholeiitic melt and residual peridotite in the uppermost mantle: An experimental study at 0.8 GPa. J Petrol, 51: 153–183
Van den Bleeken G, Müntener O, Ulmer P. 2011. Melt variability in percolated peridotite: An experimental study applied to reactive migration of tholeiitic basalt in the upper mantle. Contrib Mineral Petrol, 161: 921–945
Varfalvy V, Hébert R, Bedard J H. 1996. Interactions between melt and upper-mantle peridotites in the north arm mountain massif, Bay of islands ophiolite, Newfoundland, Canada: Implications for the genesis of boninitic and related magmas. Chem Geol, 129: 71–90
Villiger S, Ulmer P, Müntener O, Thompson A B. 2004. The liquid line of descent of anhydrous, mantle-derived, tholeiitic liquids by fractional and equilibrium crystallization—An experimental study at 1.0 GPa. J Petrol, 45: 2369–2388
Wallace P J. 2005. Volatiles in subduction zone magmas: Concentrations and fluxes based on melt inclusion and volcanic gas data. J Volcanol Geotherm Res, 140: 217–240
Wang C G, Liang Y, Dygert N, Xu W L. 2016. Formation of orthopyroxenite by reaction between peridotite and hydrous basaltic melt: An experimental study. Contrib Mineral Petrol, 171: 77
Wang C G, Liang Y, Xu W L, Dygert N. 2013. Effect of melt composition on basalt and peridotite interaction: Laboratory dissolution experiments with applications to mineral compositional variations in mantle xenoliths from the North China Craton. Contrib Mineral Petrol, 166: 1469–1488
Wang M L, Zang C J, Tang H F. 2019. The effect of *P-T* on the reaction between tonalitic melt and mantle lherzolite at 2–4 GPa and implications for evolution of North China Cratonic Lithosphere and generation of High $Mg^{\#}$ andesite. Lithos, 324-325: 626–639
Wang Q, Wyman A, Xu J F, Wan Y S, Li C F, Zi F, Jiang Z Q, Qiu H N, Chu Z Y, Zhao Z H, Dong Y H. 2008. Triassic Nb-enriched basalts, magnesian andesites, and adakites of the Qiangtang terrane (Central Tibet): Evidence for metasomatism by slab-derived melts in the mantle wedge. Contrib Mineral Petrol, 155: 473–490
Wang Q, Wyman D A, Zhao Z H, Xu J F, Bai Z H, Xiong X L, Dai T M, Li C F, Chu Z Y. 2007. Petrogenesis of Carboniferous adakites and Nb-enriched arc basalts in the Alataw area, northern Tianshan Range (western China): Implications for Phanerozoic crustal growth in the Central Asia orogenic belt. Chem Geol, 236: 42–64
Wang Q, Tang G, Hao L, Wyman D, Ma L, Dan W, Zhang X, Liu J, Huang T, Xu C. 2020. Ridge subduction, magmatism, and metallogenesis. Sci China Earth Sci, 63: 1499–1518
Whattam S A. 2018. Primitive magmas in the early Central American volcanic arc system generated by plume-induced subduction initiation. Front Earth Sci, 6: 114
Williams H M, Prytulak J, Woodhead J D, Kelley K A, Brounce M, Plank T. 2018. Interplay of crystal fractionation, sulfide saturation and oxygen fugacity on the iron isotope composition of arc lavas: An example from the Marianas. Geochim Cosmochim Acta, 226: 224–243
Wilson M. 1989. Igneous Petrogenesis. Berlin: Springer
Winter J D. 2014. Principles of Igneous and Metamorphic Petrology. Essex: Pearson Education
Wolfe R C, Cooke D R. 2011. Geology of the didipio region and genesis of the dinkidi alkalic porphyry Cu-Au deposit and related pegmatites, northern luzon, philippines. Econ Geol, 106: 1279–1315
Woodland A B, Bulatov V K, Brey G P, Girnis A V, Höfer H E, Gerdes A. 2018. Subduction factory in an ampoule: Experiments on sediment-peridotite interaction under temperature gradient conditions. Geochim Cosmochim Acta, 223: 319–349
Wu F Y, Wang J G, Liu C Z, Liu T, Zhang C, Ji W Q. 2019. Intra-oceanic arc: Its formation and evolution (in Chinese with English abstract). Acta Petrol Sin, 35: 1–15
Xia X H, Song S G, Niu Y L. 2012. Tholeiite-Boninite terrane in the North Qilian suture zone: Implications for subduction initiation and back-arc basin development. Chem Geol, 328: 259–277
Xie W, Xu Y G, Chen Y B, Luo Z Y, Hong L B, Ma L, Liu H Q. 2016. High-alumina basalts from the Bogda Mountains suggest an arc setting for Chinese Northern Tianshan during the Late Carboniferous. Lithos, 256-257: 165–181
Xu Y G. 1999. Continental basaltic magmatism related to lithospheric extension: Nature and geodynamic processes. In: Zheng Y F, ed. Progresses in Chemical Geodynamics. Beijing: Science Press. 119–167
Xu Y G, Ma J L, Huang X L, Iizuka Y, Chung S L, Wang Y B, Wu X Y. 2004. Early Cretaceous gabbroic complex from Yinan, Shandong Province: Petrogenesis and mantle domains beneath the North China Craton. Int J Earth Sci-Geol Rundsch, 93: 1025–1041
Yoder H S, Tilley C E. 1962. Origin of basalt magmas: An experimental study of natural and synthetic rock systems. J Petrol, 3: 342–532
Zhang Y Y, Yuan C, Sun M, Long X P, Wang Y P, Jiang Y D, Lin Z F. 2017. Arc magmatism associated with steep subduction: Insights from trace element and Sr-Nd-Hf-B isotope systematics. J Geophys Res Solid Earth, 122: 1816–1834
Zheng Y F. 2019. Subduction zone geochemistry: Geosci Front, 10: 1223–1254
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, 194: 104185
Zheng Y F, Chen Y X, Dai L Q, Zhao Z F. 2015. Developing plate tectonics theory from oceanic subduction zones to collisional orogens. Sci China Earth Sci, 58: 1045–1069
Zheng Y F, Chen R X, Xu Z, Zhang S B. 2016. The transport of water in subduction zones. Sci China Earth Sci, 59: 651–682
Zhu G, Gerya T V, Yuen D A, Honda S, Yoshida T, Connolly J A D. 2009. Three-dimensional dynamics of hydrous thermal-chemical plumes in oceanic subduction zones. Geochem Geophys Geosyst, 10: Q11006
Zimmer M M, Plank T, Hauri E H, Yogodzinski G M, Stelling P, Larsen J, Singer B, Jicha B, Mandeville C, Nye C J. 2010. The role of water in generating the calc-alkaline trend: New volatile data for Aleutian magmas and a new tholeiitic index. J Petrol, 51: 2411–2444

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