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Adakitic rocks at convergent plate boundaries: Compositions and petrogenesis

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Abstract Adakitic rocks are intermediate-acid magmatic rocks characterized by enrichment in light rare-earth elements, depletion in heavy rare-earth elements, positive to negligible Eu and Sr anomalies, and high La/Yb and Sr/Y ratios. Cenozoic adakitic rocks generated by partial melting of subducted oceanic crust (slab) under eclogite-facies conditions (i.e., the original definition of "adakite") occur mainly in Pacific Rim volcanic arcs (intra-oceanic, continental, and continental-margin island arcs), whereas those generated by partial melting of thickened lower crust occur mainly in Tethyan Tibetan collisional orogens. In volcanic arcs, adakitic melts derived from the melting of subducted oceanic crust metasomatize the mantle wedge to form a unique rock suite comprising adakite–adakite-type high-Mg andesite–Piip-type high-Mg andesite–Nb-rich basalt–boninite. This suite differs from the basalt-andesite-dacite-rhyolite suite formed from mantle wedge metasomatized by fluids derived from subducted oceanic crust. Previously published data indicate that partial melting of mafic rocks can generate adakitic magmas under pressure, temperature, and hydrous conditions of 1.2–3.0 GPa, 800–1000°C, and 1.5–6.0 wt.% H_2O, respectively, leaving residual minerals of garnet and rutile with little or no plagioclase. Cenozoic Au and Cu deposits occur proximally to adakitic rocks, with host rocks of some deposits actually being adakitic rocks. Adakitic rocks thus have important implications for both deep-Earth dynamics and Cu-Au mineralization/exploration. Although studies of Cenozoic adakitic rocks have made many important advances, there remain weaknesses in some important areas such as their tectonic settings, petrogenesis, magma sources, melt-mantle interactions of pre-Cenozoic adakitic rocks, and their relationship with the onset of plate tectonics and crustal growth. Future research directions are likely to involve (1) the generation of adakitic magmas by experimental simulations of partial melting of different types of rock (including intermediate-acid rocks) and magma fractional crystallization at different temperatures and pressures, (2) the relationship between magma reservoir evolution and the formation of adakitic rocks, (3) the tectonic setting and petrogenesis of pre-Cenozoic adakitic rocks and related geodynamic processes, (4) interactions between slab melts and the mantle wedge, (5) the formation of Archean adakitic tonalite-trondhjemite-granodiorite and its link to the onset of plate tectonics and crustal growth, and (6) the relationship between the formation of adakitic rocks and metal mineralization in different tectonic settings.

Keywords Adakite, Subduction zone, Collisional zone, Petrogenesis, Metallogenesis, Dynamic process

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1. Introduction

The theory of plate tectonics was developed in the late 1960s, and the petrogenesis of arc magmatic rocks has attracted considerable attention since then (Frisch et al., 2011). The origin of basalt-andesite-dacite-rhyolite rock assemblages has become an important petrological topic related to arc-system evolution (Ringwood, 1974). There is consensus that arc basalts are derived from partial melting of mantle wedges, but the petrogenesis of intermediate-acid rocks such as andesite, dacite, and rhyolite remains controversial. Adakites are typical arc magmatic rocks and were named by Defant and Drummond (1990). They include intermediate-acid (SiO_2≥56.0 wt.%) calc-alkaline volcanic rocks (andesite, dacite, and rhyolite) and corresponding intrusive rocks (tonalite and trondhjemite) derived by partial melting of subducted young (≤25 Ma) basaltic oceanic crust under eclogite-facies conditions, characterized by strong depletion in heavy rare-earth elements (HREEs; Yb≤1.90 ppm; Y≤18 ppm; 1 ppm=1 $\mu g\ g^{-1}$) and high Sr contents (≥400 ppm) and La/Yb (≥20) and Sr/Y (≥40) ratios. The term "adakite" stems from the discovery of Cenozoic arc magmatic rocks on Adak Island of the Aleutian Islands, Alaska (Kay, 1978). Adakites have attracted wide attention and become a focus of research in the solid-Earth-science field owing to their important implications for geodynamics and metal mineralization. Adakites occur mainly in Cenozoic volcanic arcs (e.g., the Pacific Rim), but felsic rocks with similar geochemical characteristics also occur in Cenozoic collisional zones (e.g., Tethy and Tibet; Chung et al., 2003; Hou et al., 2004) and intra-plateau locations (e.g., Hoh Xil and Qiangtang, China; Wang et al., 2005, 2008b). Some pre-Cenozoic (i.e., Mesozoic, Paleozoic, Proterozoic, and Archean) igneous rocks are geochemically similar to adakites (e.g., Martin, 1999; Zhang et al., 2001; Xu et al., 2002; Gao et al., 2004; Martin et al., 2005; Wang et al., 2006a, 2006b). In addition to the partial melting of subducted oceanic crust, the formation of these rocks, sometimes accompanied by Cu-Au mineralization, is closely related to deep geodynamic processes such as continental subduction and collision, crustal thickening and delamination, magma underplating or mixing, and melt–mantle interaction (e.g., Zhang et al., 2001; Defant et al., 2002; Wang et al., 2001a, 2001b, 2003, 2007a, 2007b, 2007c, 2008a, 2008b).

The naming of these rocks is open to question (e.g., Tarney and Jones, 1994; Harris et al., 1996; Yumul et al., 2000; Conrey et al., 2001; Sheppard et al., 2001; Zhang et al., 2001; Ge et al., 2002; Zeng et al., 2011), with some having geochemical characteristics similar to those of adakites but not occurring in volcanic arcs or being generated by partial melting of subducted oceanic crust; their petrogenesis is therefore different. To avoid confusion in the naming of felsic rocks with adakitic characteristics, we earlier proposed a rule for the naming of igneous rocks: naming should not depend on the rock's petrogenesis or tectonic setting but rather should reflect its most fundamental characteristic, regardless of its hypothesized petrogenesis or tectonic setting (Wang et al., 2007a, 2008a). Although adakitic rocks may be of different petrogenesis and tectonic setting, with slightly different elemental and isotopic compositions, they have some characteristics in common in that they (1) contain feldspar, amphibole, and biotite; (2) comprise andesitic, dacitic, or rhyolitic rocks and corresponding intrusive rocks; (3) have intermediate-acid compositions (SiO_2≥56.0 wt.%), with enrichment in light rare-earth elements (LREEs), strong depletion in HREEs with Yb≤1.9 ppm and Y≤18 ppm, high Sr contents (≥400 ppm) and La/Yb (≥20) and Sr/Y (≥40) ratios, and negligible to positive Sr-Eu anomalies (e.g., Le Maitre, 2002; Castillo, 2006, 2012; Wang et al., 2008a). Magmatic rocks with these characteristics are therefore termed "adakitic rocks" here (Wang et al., 2007a, 2008b), with this type including the adakites previously named by Defant and Drummond (1990) and generated by partial melting of subducted oceanic crust in arc settings.

A fundamental principle of geology is that the present is the key to the past. The study of young (i.e., Cenozoic) adakitic rocks and related metal mineralization formed under clearly defined tectonic settings may therefore provide insights into the petrogenesis and geodynamics of pre-Cenozoic adakitic rocks and related metallogenesis. Cenozoic adakitic rocks occur mainly at convergent plate boundaries, and the present study, based on a review of studies of slab melting and adakitic rocks, aimed to describe advances in research on Cenozoic adakitic rocks and associated rock assemblages, summarizing the generation conditions and metallogenetic implications of adakitic magmas, and discussing existing problems and future directions for the study of adakitic rocks.

2. Partial melting of subducted oceanic crust and the "adakite" concept

The theory of plate tectonics was developed in the late 1960s, and there has since been debate as to whether arc magmatic rocks could have been generated by partial melting of subducted oceanic crust under eclogite-facies conditions. It has been suggested that such partial melting played an important role in the formation of intermediate-acid magmatic rocks. On the basis of experimental melting studies, Green and Ringwood (1968) suggested that calc-alkaline intermediate-acid magmatic rocks could be generated by the partial melting of eclogites, the protolith of which is mid-ocean-ridge basalt (MORB), at mantle depths of 100–150 km, leaving a residue of pyroxene+plagioclase+minor garnet. Arth and Hanson (1972, 1975) suggested that late Archean

(2.7 Ga) tonalite-trondhjemite-granodiorite (TTG) series rocks with strong depletion in HREEs (e.g., Yb=0.02–1.20 ppm) may have been generated by partial melting of basaltic rocks during subduction or at the crustal base of a thick crustal pile, leaving a residue of garnet and pyroxene. Nicholls (1974) and Ringwood (1974) proposed a three-stage model for the evolution of arc calc-alkaline intermediate-acid magmatic rocks involving: (1) partial melting of quartz eclogites (subducted slab), generating rhyolitic-dacitic magmas; (2) interaction between felsic magmas and overlying mantle peridotites to form pyroxenites; and (3) ascension of diapirs of pyroxenite, and its partial melting to form magmas that further fractionated to produce calc-alkaline magmatic rocks. Some studies applied this model in accounting for the formation of intermediate-acid magmatic rocks in Cenozoic volcanic arcs of the Pacific Rim. For example, Thorpe et al. (1976) and López-Escobar et al. (1977, 1979) suggested that Cenozoic intermediate-acid volcanic rocks and granitoids with intensive REE fractionation (La/Yb≥15) and strong depletion in HREEs (Yb=0.70–1.9 ppm) may have been generated as described by this model. Kay (1978) found that Cenozoic high-Mg andesites (HMAs) on Adak Island, containing augite phenocrysts, plagioclase, and augite microcrystals, exhibit strong depletion in HREEs (Yb<1.00 ppm; La/Yb≥40) and have high MgO contents (≥4.50 wt.%), suggesting that they were generated by interaction between melts derived from partial melting of subducted basaltic oceanic crust and mantle-wedge peridotites under eclogite-facies conditions.

During the 1980s, a model involving partial melting of subducted oceanic crust in the formation of Archean TTGs (strongly depleted in HREEs) was widely supported (Condie, 1981; Nisbet, 1984; Martin, 1986). However, there was debate as to whether partial melting of subducted oceanic crust could form intermediate-acid arc magmatic rocks, and the partial melting of mantle wedge metasomatized by fluids released from subducted oceanic crust to produce basaltic arc magmas was suggested as an alternative, with further evolution forming andesites, dacites, and rhyolites (e.g., Gill, 1981; Tatsumi et al., 1986). This latter suggestion accounted for the genesis of most calc-alkaline igneous rocks in volcanic arcs and became the mainstream theory of formation of continental-arc andesites. On the basis of studies of Cenozoic volcanic rocks in Baja California, Mexico, Rogers et al. (1985) named a new type of volcanic rock-bajaite-closely associated with subduction of hot spreading ridges and characterized by strong depletion in HREEs and Y, high Sr and MgO contents, and relatively low SiO_2 contents (<56.3 wt.%). The source of bajaites was considered to be similar to the mantle source of most arc magmatic rocks, except for the occurrence of garnet in the former. Gromet and Silver (1987) suggested that Cretaceous intermediate-acid intrusive rocks with strong HREE depletion (Yb=0.22–1.44 ppm) in the Peninsular Ranges of North America were generated by partial melting of underplated and thickened (>45 km) basaltic lower crust, leaving an eclogitic residue that entered the mantle during delamination.

Through a study of Cenozoic arc magmatic rocks in the Pacific Rim, Defant and Drummond (1990) suggested that partial melting of subducted oceanic crust under eclogite-facies conditions could produce intermediate-acid magmatic rocks with unique geochemical characteristics, naming them “adakites”. Defant and Drummond (1990) compared adakites with Archean TTGs, and suggested that the former are present analogs of the latter, with the onset of plate tectonics occurring during the Archean, and Archean crustal growth being related to partial melting of subducted oceanic crust under eclogite-facies conditions. Subsequent studies have considered how partial melting of subducted oceanic crust forms adakites, the interactions between adakitic magmas and mantle, and the metallogenetic implications of adakites. In 2002, the term “adakites” was included in a classification and glossary of igneous rocks (Le Maitre, 2002). In 2005, Martin et al. (2005) proposed separate sub-types of high- and low-silica adakites, with the former being generated by interaction between slab melts and mantle wedge, and the latter by partial melting of mantle wedge metasomatized by slab melts (with SiO_2 contents as low as 50.0–56.0 wt.%). Adakites of Adak Island and bajaites of Baja California can thus be classified as low-silica adakites. Those of Adak Island contain no olivine and their magmas were not equilibrated with mantle peridotites, indicating that they were not directly derived from partial melting of mantle peridotites but rather represent products of interactions between slab melts and mantle peridotites (Kay, 1978). Bajaites are a type of olivine-bearing HMA generated directly by partial mantle melting (Rogers et al., 1985). Therefore, we do not support adakitic rocks being low-silica (<56.0 wt.% SiO_2) mantle melts (Martin et al., 2005) but favor the original definition of intermediate-acid (SiO_2≥56.0 wt.%) rocks not directly derived from partial melting of ultramafic mantle rocks (Defant and Drummond, 1990).

Intermediate-acid magmatic rocks with petrological and geochemical characteristics similar to those of adakites generated by partial melting of subducted oceanic crust, but not being generated by partial melting of subducted oceanic crust, have attracted attention owing to the important implications of their petrogenesis for metal mineralization (e.g., Atherton and Petford, 1993; Petford and Atherton, 1996; Zhang et al., 2001; Xu et al., 2002; Chung et al., 2003; Gao et al., 2004; Hou et al., 2004; Wang et al., 2005, 2006a, 2006b, 2007a, 2007b, 2007c, 2008a, 2008b; Castillo, 2006). These rocks have also been termed high-Ba-Sr granitoids (Tarney and Jones, 1994), adakitic or adakite-like rocks (Yumul et al., 2000; Harris et al., 1996), C-type adakites (Zhang et al., 2001), crustally derived adakites (Sheppard et al., 2001), Sr-rich andesites (Conrey et al., 2001), and high-Sr/low-Y intermediate-acid magmatic rocks (Ge et al., 2002; Zeng et al., 2011). Here, we apply the term "adakitic rocks" to those intermediate-acid magmatic rocks that have petrological and geochemical characteristics similar to adakites generated by partial melting of subducted oceanic crust.

3. Compositions and magma sources of Cenozoic adakitic rocks at convergent plate boundaries

Previous studies have shown that Cenozoic adakitic rocks occur primarily at convergent plate boundaries (Figure 1a) including, for example, intra-oceanic arcs, continental arcs, continental-margin island arcs (Defant and Drummond, 1990; Gutscher et al., 2000), and continental collision zones (Chung et al., 2003; Hou et al., 2004). Cenozoic adakitic rocks have only minor occurrences in intra-continental environments, as in the Qiangtang and Hohxil blocks of the northern Tibetan Plateau (Wang et al., 2005, 2008), most of which are closely associated with Cu, Au, or Mo mineralization (Figure 1a, 1b).

3.1 Cenozoic adakitic rocks in intra-oceanic arcs

Intra-oceanic arcs occur where one oceanic lithosphere is subducted beneath another. Cenozoic intra-oceanic arc adakites occur mainly in the Aleutian, Izu-Bonin-Mariana, Malaysia-Indonesia, and Solomon-Fiji-Tonga arcs (e.g., Kay, 1978; Yogodzinski et al., 1995; Yogodzinski and Kelemen, 1998; König et al., 2007; Danyushevsky et al., 2008; Falloon et al., 2008; Schuth et al., 2009; Coldwell et al., 2011; Li et al., 2013) (Figure 1). These adakites include andesites, dacites, and granite porphyries with ages of 43.1–2.5 Ma. They have variable SiO_2 contents (55–74 wt.%) and relatively low total-alkali (2.0–7.0 wt.%) and K_2O (<3.0 wt.%) contents, thus being low-K tholeiite and calc-alkaline series rocks, as indicated by (Na_2O+K_2O)-SiO_2 and K_2O-SiO_2 plots (Figure 2). They are characterized by significant fractionation of REE with enrichment in LREEs and depletion in HREEs, positive Sr anomalies, negligible Eu anomalies, depletion in Nb and Ta (Figure 3a, 3b), low K_2O/Na_2O ratios and Th contents (Figure 4a), and clearly depleted Sr-Nd isotopic compositions (ε_{Nd}=+5 to +12; $^{87}Sr/^{86}Sr$=0.7028–0.7042; Figure 4b). Miocene adakitic rocks in the Solomon arc exhibit MORB-like Hf isotopic compositions (ε_{Hf}=+12 to +14; Schuth et al., 2009). Collectively, Cenozoic intra-oceanic arc adakitic rocks generally exhibit Sr-Nd-Hf isotopic compositions similar to those of subducted oceanic crust, indicating the major contribution of the latter to their generation. However, melts derived from subducted slab would inevitably be contaminated by the mantle wedge, which would elevate their MgO contents and $Mg^\#$ ($100\times Mg^{2+}/(Mg^{2+}+Fe^{total})$) values (Figure 5a) (e.g., Stern and Kilian, 1996; Rapp et al., 1999).

Cenozoic adakitic rocks in intra-oceanic arcs are commonly considered to be generated by partial melting of subducted oceanic crust with a garnet-bearing residue, which would produce melts with high Sr and low Y and HREE contents. Melts derived from subducted oceanic crust would interact with the overlying mantle wedge during their ascent, increasing their Mg, Cr, and Ni contents and eventually erupting at the surface or intruding intra-oceanic arc crust to form adakitic rocks (e.g., Kay, 1978; Yogodzinski et al., 1995; Yogodzinski and Kelemen, 1998; König et al., 2007). However, subducted oceanic crust would partially melt only under certain conditions, as follows. Defant and Drummond (1990) suggested that adakitic rocks may be derived from young (≤25 Ma) and thus hot slab. Modeling by Peacock et al. (1994) indicates that only slab of age ≤5 Ma could be melted to form adakitic rocks. Gutscher et al. (2000) suggested that subducted oceanic slab may reside in the upper mantle for sufficiently long periods during flat subduction for even moderately old (up to 50 Ma) oceanic crust to be heated to temperatures sufficient for partial melting. Yogodzinski et al. (2001) proposed that partial melting of subducted oceanic slab is determined not only by slab age but also by slab geometry. For example, the occurrence of adakitic rocks on Kamchatka Peninsula (Russian Far East) and the Aleutian Islands could be ascribed to partial melting of the edge of a torn slab. Based on differences in slab age and subduction rate between eastern and western segments of the Aleutian Islands, modeling by Lee and King (2010) indicates that slab melting in the western islands is associated with a younger slab age and lower subduction rate. Factors controlling slab melting may thus involve slab age, geometry, and subduction rate.

3.2 Cenozoic adakitic rocks in continental arcs

Continental arcs are volcanic arcs at continental margins, unseparated from continents during subduction of oceanic lithosphere, and are the main locations of Cenozoic adakitic rocks in, for example, Chile, Peru, Ecuador, Colombia, Costa Rica, Panama, Mexico, and Canada on the eastern Pacific arc system (Figure 1) (e.g., Gutscher et al., 2000; Beate et al., 2001; Oyarzun et al., 2001; Samaniego et al., 2002; Bourdon et al., 2003; Kay et al., 1993; Reich et al., 2003; Rodríguez et al., 2007; Goss and Kay, 2006; Coldwell et al., 2011; Chiaradia, 2009; Gazel et al., 2015). These adakitic rocks are mainly andesite-dacite-rhyolite-granodiorite porphyries with ages of 50–0.1 Ma. They are very similar to continental-margin island-arc adakitic rocks in composition, with variable and high SiO_2 (54.0–74.0 wt.%), total-alkali (3.0–10.0 wt.%), and K_2O (0.1–4.5 wt.%) contents (Figure 2). Most are calc-alkaline and high-K calc-alkaline series rocks char-

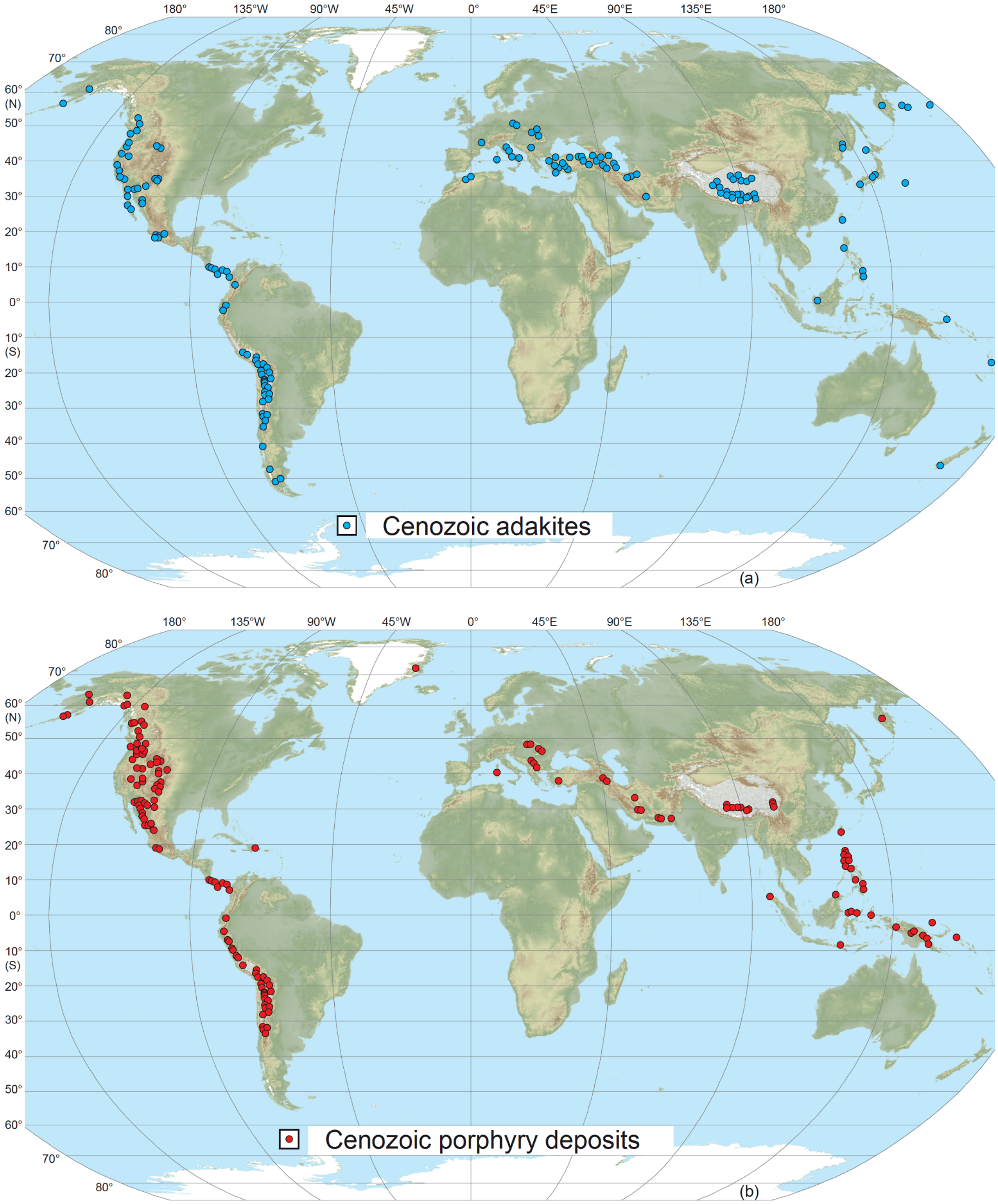

Figure 1 The worldwide occurrence of (a) Cenozoic adakitic rocks and (b) porphyry copper deposits. Data for adakitic rocks are from Defant and Drummond (1990), Stern and Kilian (1996), Castillo et al. (1999), Gutscher et al. (2000), Yogodzinski et al. (2001), Chung et al. (2003), Hou et al. (2004), Wang et al. (2005, 2008b), Macpherson et al. (2006), Richards and Kerrich (2007), Falloon et al. (2008), Chiaradia (2009), Goss et al. (2013), Gazel et al. (2015), Pang et al. (2016), Ou et al. (2017), and references therein. Data for porphyry copper deposits are from Hou and Cook (2009), Lee and Tang (2020), and references therein.

acterized by strong REE fractionation with LREE enrichment and HREE depletion, negligible Eu anomalies, slight negative to positive Sr anomalies (Figure 3e, 3f), and high K_2O/Na_2O ratios and Th contents (Figure 4a). They have variable enriched to depleted Sr-Nd isotopic compositions (ε_{Nd}=−4 to +8.5; $^{87}Sr/^{86}Sr$=0.7030–0.7064; Figure 4), indicating multiple source components. Pliocene adakitic rocks in the Costa Rica and Panama arcs of Central America exhibit MORB-like Li, Fe, and Zn isotopic compositions (δ^7Li=1.4‰–4.2‰; $\delta^{56}Fe$=0.063‰–0.133‰; $\delta^{66}Zn$=0.23‰–0.33‰; Tomascak et al., 2000; He et al., 2017; Huang et al., 2018), indicating contributions of subducted basaltic crust. Melt inclusions with adakitic affinities in Mt. Shasta (USA) arc-volcanic rocks (<0.1 Ma) have low and

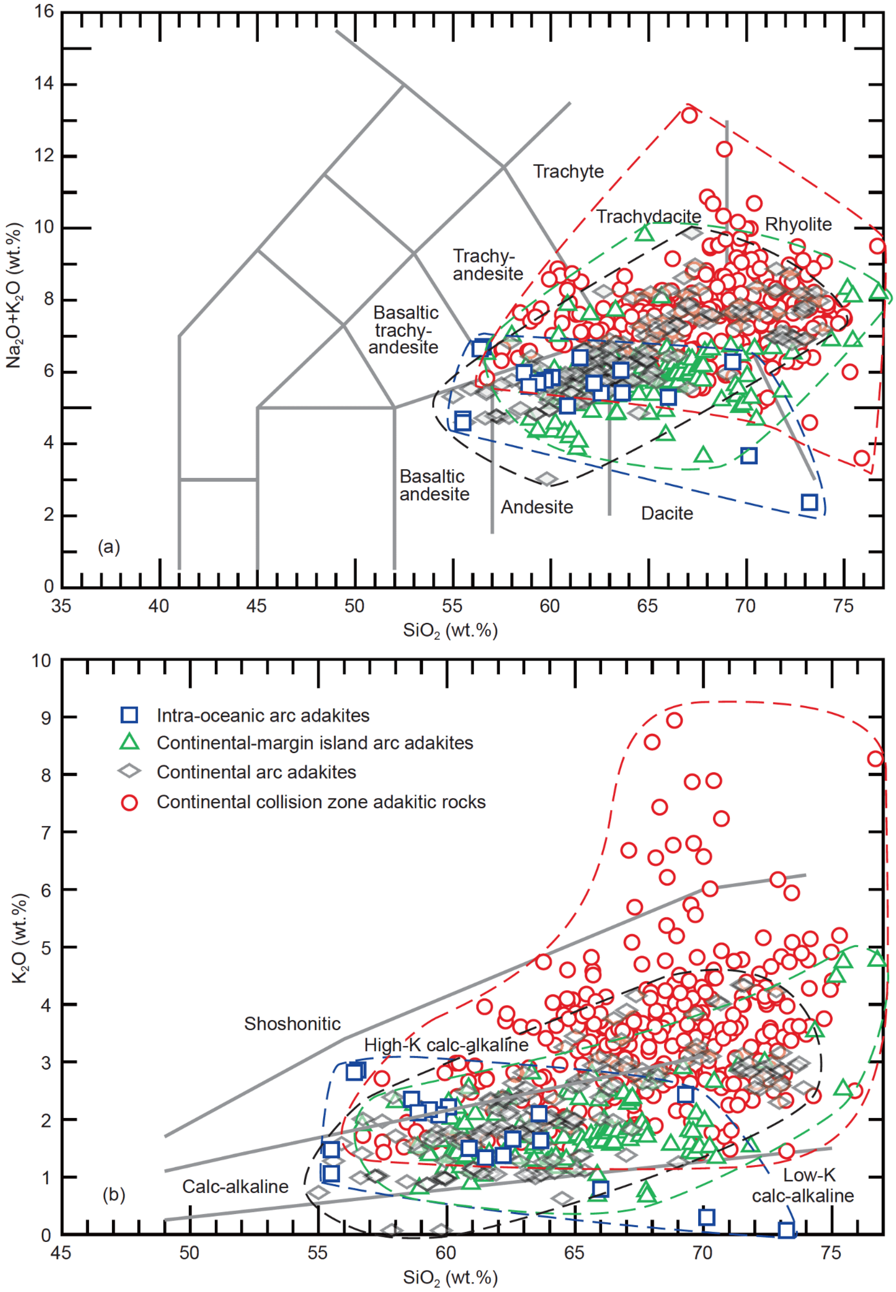

Figure 2 Major-element compositions of Cenozoic adakitic rocks at convergent plate boundaries (intra-oceanic arcs, continental arcs, continental-margin island arcs, and continental collisional zones). (a) SiO$_2$-(K$_2$O+Na$_2$O); (b) SiO$_2$-K$_2$O. Data sources are as follows: Intra-oceanic arcs—Kay (1978), Yogodzinski et al. (1995), Yogodzinski and Kelemen (1998), Falloon et al. (2008), Danyushevsky et al. (2008), Schuth et al. (2009), Li et al. (2013); continental-margin island arcs—Sajona et al. (1993, 1994, 1996), Castillo et al. (1999, 2007), Macpherson et al. (2006), Coldwell et al. (2011), Breitfeld et al. (2019), Pineda-Velasco et al. (2018), Hu et al. (2019), Payot et al. (2007); continental arcs—Reich et al. (2003), Bourdon et al. (2002, 2003), Petrone and Ferrari (2008), Castillo (2008), Ickert et al. (2009), Rooney et al. (2011), Chiaradia (2009), Oyarzun et al. (2001), Rodríguez et al. (2007), Rabbia et al. (2017), Beate et al. (2001), Martínez-Serrano et al. (2004); continental collisional zones—Chung et al. (2003), Hou et al. (2004), Wang et al. (2005), Gao et al. (2007), Guo et al. (2007), Jahangiri (2007), Zeng et al. (2011), Zheng et al. (2012), Jiang et al. (2014), Ma et al. (2014), Zhang et al. (2014), Long et al. (2015), Yang et al. (2015), Moghadam et al. (2016), Pang et al. (2016), Wang et al. (2016), Liu et al. (2017), Nia et al. (2017), Ou et al. (2017).

MORB-like B contents (0.7–1.6 ppm) and variable and low δ^{11}B values (−21.3‰ to −0.9‰), suggesting generation by partial melting of residual slab after progressive dehydration (Rose et al., 2001).

The formation of continental arcs may be related to or influenced by subduction of normal oceanic crust and aseismic ridges or oceanic plateaus, spreading oceanic ridges, subduction erosion, crustal thickening, or delamination. The petrogenesis of continental-margin arc adakitic rocks is thus complex, with their sources likely including subducted slabs, aseismic ridges/oceanic plateaus and overlying sediments, spreading ridges, and edges of torn slabs (e.g., Stern

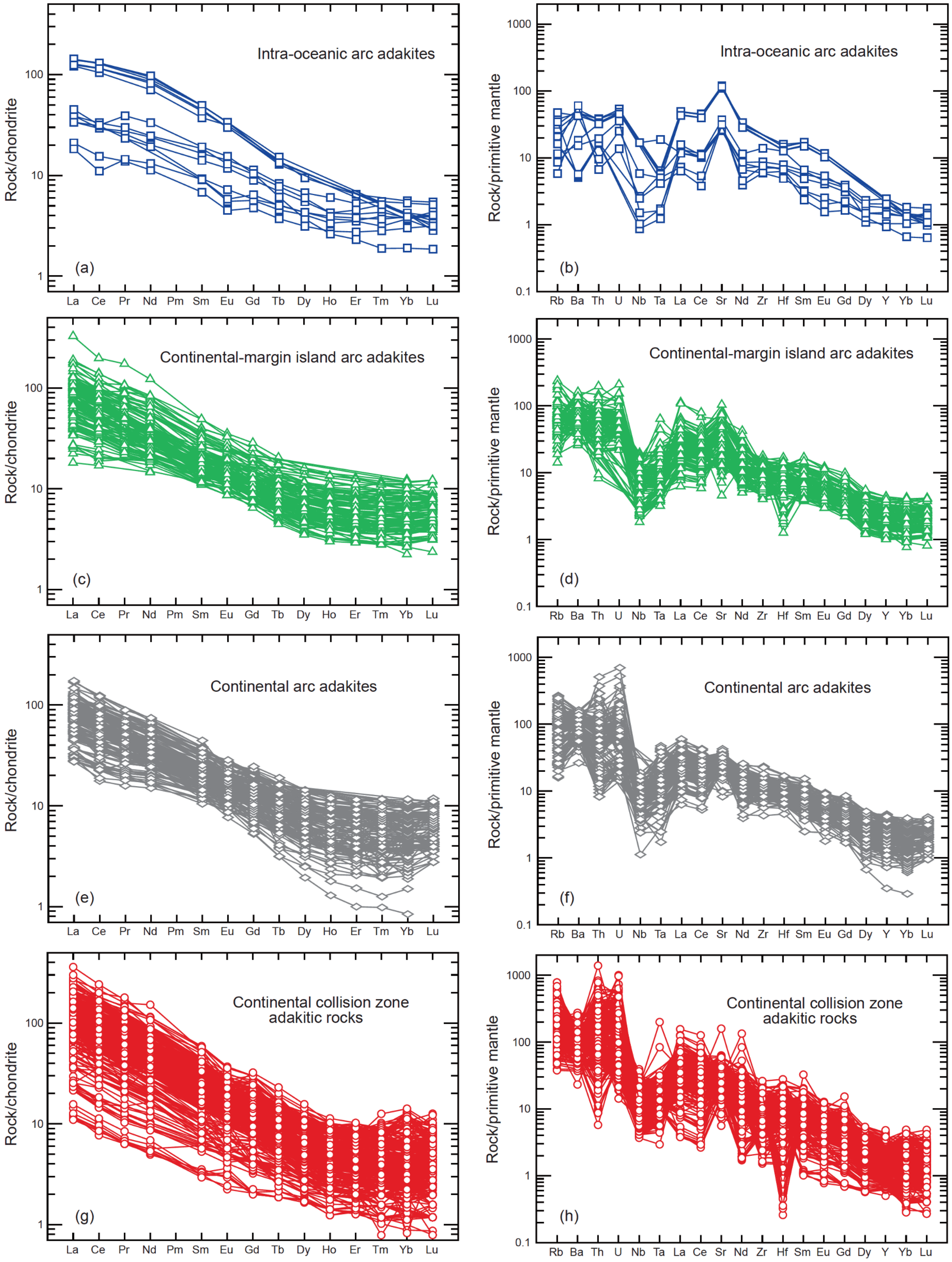

Figure 3 Trace-element compositions of Cenozoic adakitic rocks at convergent plate boundaries: ((a), (b)) intra-oceanic arcs; ((c), (d)) continental-margin island arcs; ((e), (f)) continental arcs; ((g), (h)) continental collisional zones. Data sources are as for Figure 2. Chondrite and primitive-mantle values are from Sun and McDonough (1989).

and Kilian, 1996; Gutscher et al., 2000; Abratis and Wörner, 2001; Beate et al., 2001; Samaniego et al., 2002; Bourdon et al., 2003; Martínez-Serrano et al., 2004; Breitsprecher and Thorkelson, 2009; Gazel et al., 2015; Bourgois et al., 2016; Wang et al., 2020), fore-arc crustal material derived from subduction erosion (Goss and Kay, 2006), and thickened or delaminated lower crust (Kay and Mahlburg, 1991, 1993; Kay et al., 1993; Kay and Mpodozis, 2001; Atherton and

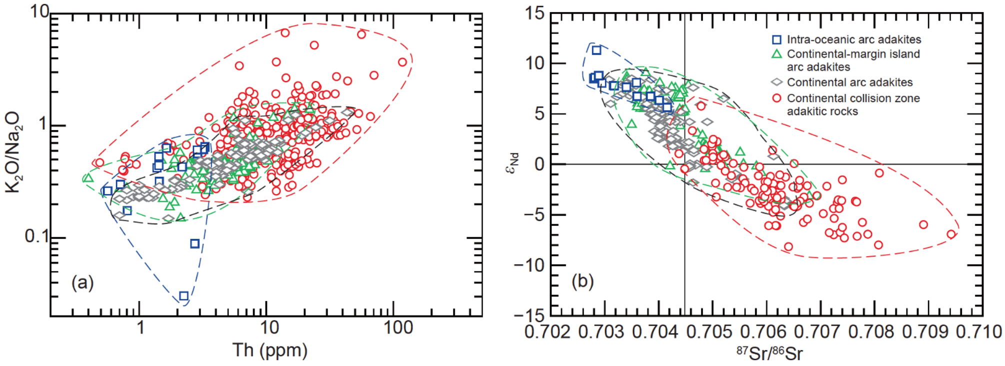

Figure 4 Compositions of Cenozoic adakitic rocks at convergent plate boundaries (intra-oceanic arcs, continental-margin island arcs, continental arcs, and continental collisional zones). (a) (K_2O/Na_2O)-Th; (b) ε_{Nd}-($^{87}Sr/^{86}Sr$). Data sources are as for Figure 2.

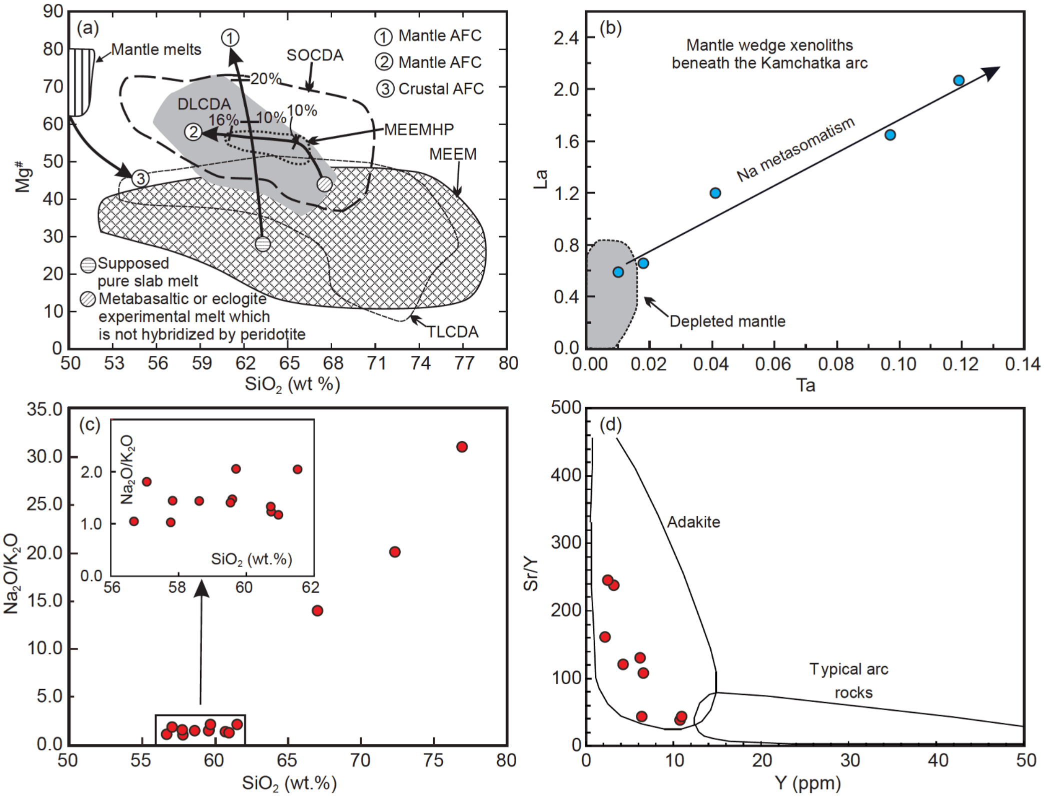

Figure 5 Interaction between slab-derived melts and the mantle wedge. (a) Mg#-SiO_2 plot for adakites and experimental melts (Wang et al., 2006a, 2006b). The slab melts could be contaminated by the mantle during ascent, resulting in an increase in Mg#. Experimental melts and natural adakites are abbreviated as follows: MEEM=metabasaltic and eclogite experimental melts (1–4 GPa); MEEMHP=metabasaltic and eclogite experimental melts hybridized by peridotite; TLCDA=thick-lower-crust-derived adakitic rocks; DLCDA=delaminated-lower-crust-derived adakitic rocks; SOCDA=subducted-oceanic-crust-derived adakites. (b) La-Ta plot for sub-arc mantle peridotite xenoliths from the Kamchatka arc (Defant and Kepezhinskas, 2001; Defant et al., 2002). La is mobile in aqueous fluids, but Ta is immobile, so the positive correlation between La and Ta implies that metasomatism by Na-rich slab melts is a common occurrence in the sub-arc mantle, in addition to fluid-related metasomatism. ((c), (d)) (Na_2O/K_2O)-SiO_2 and (Sr/Y)-Y plots for melt inclusions hosted in olivine from the Philippine sub-arc mantle peridotite xenoliths. Data are from Schiano et al. (1995).

Petford, 1993; Petford and Atherton, 1996; Castillo, 2008; Ickert et al., 2009; Coldwell et al., 2011).

3.3 Cenozoic adakitic rocks in continental-margin island arcs

Cenozoic continental-margin island-arc adakitic rocks occur mainly in the Kuril, Japanese, Ryukyu, Luzon-Philippines, and Malaysia-Indonesia islands (e.g., Sajona et al., 1993, 1994, 1996; Castillo et al., 1999, 2007; Macpherson et al., 2006; Payot et al., 2007; Coldwell et al., 2011; Pineda-Velasco et al., 2018; Breitfeld et al., 2019; Kamei et al., 2009; Hu et al., 2019) (Figure 1). These rocks are mainly andesite-dacite-rhyolite-granodiorites with ages of 17–0.3 Ma and

SiO_2 contents (57–77 wt.%) similar to those of intra-oceanic arc adakitic rocks, but with slightly higher total-alkali (3.5–10.0 wt.%) and K_2O (0.5–5.0 wt.%) contents (Figure 2). Most are calc-alkaline and high-K calc-alkaline series rocks characterized by strong REE fractionation, LREE enrichment, HREE depletion, negligible Eu anomalies, slight negative to positive Sr anomalies (Figure 3c, 3d), and relatively high K_2O/Na_2O ratios and Th contents (Figure 4a). They have variable Sr-Nd isotopic compositions (ε_{Nd}=−3 to +9; $^{87}Sr/^{86}Sr$=0.7034–0.7068) partly overlapping those of adakitic rocks in intra-oceanic arcs (Figure 4b). Basaltic oceanic crust, subducted sediment, continental-arc crust, and subsequent crustal fractional crystallization and assimilation could thus all play key roles in generating Cenozoic adakitic rocks in continental-margin island arcs. For example, parental magmas of late Cenozoic (2 Ma) adakitic rocks (high-Sr andesites and dacites) from the southwest Japan arc are best explained by the mixing of partial melts from oceanic crust (F=5–15%) and sediment (F=30%) at ratios of 80:20–55:45 (Pineda-Velasco et al., 2018), with parental magmas undergoing FC (fractional crystallization) processes in the crustal chamber before erupting to form adakitic rocks. Partial melting of subducted crust in this area may be ascribed to either subduction of the young Philippine Sea Plate (Morris, 1995; Peacock and Wang, 1999) or slab tear caused by subduction of ridges on the Shikoku Basin Plate (Pineda-Velasco et al., 2018). Considering these examples, it appears that continental-margin island arcs are generated in either of two ways: horizontal accretion of previous island arcs to continental margins due to continuous subduction of oceanic lithosphere, or separation of continental arcs from continental margins due to back-arc spreading during subduction of oceanic lithosphere beneath continental lithosphere (Xu et al., 2020).

3.4 Cenozoic adakitic rocks in continental collision zones

Cenozoic continental-collision-zone adakitic rocks occur mainly in the Tethyan tectonic domain across Eurasia in, for example, the Carpathian-Pannonian (e.g., Seghedi et al., 2004), Greece (e.g., Marchev et al., 2013), Turkey-Iran (e.g., Dokuz et al., 2013; Jahangiri, 2007; Moghadam et al., 2016; Nia et al., 2017; Omrani et al., 2008; Pang et al., 2016; Topuz et al., 2011), and Himalaya-Tibet (e.g., Chung et al., 2003, 2005, 2009; Hou et al., 2004, 2012; Wang et al., 2005, 2008b; Gao et al., 2007; Guo et al., 2007; Zeng et al., 2011; Zheng et al., 2012; Jiang et al., 2014; Ma et al., 2014; Zhang et al., 2014; Long et al., 2015; Liu et al., 2017; Ou et al., 2017) regions. They comprise mainly granites-(granodiorite porphyries)-dacites-rhyolites with ages of 56–2.5 Ma and SiO_2 contents (57.0–77.0 wt.%) similar to those of Cenozoic arc adakitic rocks, but with higher total-alkali (3.5–13.0 wt.%), K_2O (0.1–4.5 wt.%; Figure 2), and Th (Figure 4a) contents and K_2O/Na_2O ratios. They are calc-alkaline, high-K calc-alkaline, and shoshonite series rocks characterized by strong LREE/HREE fractionation, negligible Eu anomalies, and slight negative to positive Sr anomalies (Figure 3g, 3h). They have the most enriched Sr-Nd isotopic compositions of Cenozoic adakitic rocks (ε_{Nd}=−8 to +6; $^{87}Sr/^{86}Sr$=0.7044–0.7094; Figure 4b), consistent with multiple crustal components in their sources, such as thickened ancient lower crust and subducted continental crust. Juvenile continental crust and remnant oceanic crust may also have contributed to their generation. The formation of these adakitic rocks can thus be linked to continental subduction, slab break-off, and lithospheric delamination. Cenozoic adakitic rocks in Tethy-Tibetan collisional orogens were considered to have mainly been generated by partial melting of thickened lower crust occur mainly in Tethy-Tibetan collisional orogens.

4. Adakites and coexisting rock suites in Cenozoic arcs, and slab-melt metasomatism

The basalt-andesite-dacite-rhyolite association represents the most widely distributed arc magmatic rocks, which are generally considered to be associated with basaltic parental magmas produced by melting of fluid-metasomatized peridotite in the mantle wedge, and their subsequent intra-crustal differentiation processes such as crustal contamination and fractional crystallization (e.g., Gill, 1981; Tatsumi et al., 1986). Adakites rarely coexist with basalts or basaltic andesites, but some trachybasalts and shoshonites occur together with adakites in continental arcs of Latin America and North America (Defant and Drummond, 1990). These mafic rocks are characterized by high Nb contents (or insignificant depletion in Nb) and are thus termed “High-Nb basalts” (Defant et al., 1991, 1992). Some studies have also reported “Nb-rich basalts” (Nb=7–16 ppm; Na/La>0.5) in arcs of the Philippines, Kamchatka, California, and Ecuador (Sajona et al., 1993, 1996; Kepezhinskas et al., 1997; Defant and Kepezhinskas, 2001; Defant et al., 2002; Bourdon et al., 2003). In these arcs, Nb-rich basalts are generally considered to be produced by the melting of mantle metasomatized by slab-derived melts (Sajona et al., 1993, 1996; Kepezhinskas et al., 1997; Defant and Kepezhinskas, 2001; Defant et al., 2002). Adakites may also coexist with ocean-island basalt (OIB)- and MORB-like basaltic rocks in extensional settings related to ridge subduction (Cole and Stewart, 2009; Thorkelson et al., 2011; Tang et al., 2012), with the OIB-type being derived from melting of deep mantle and the latter from decompression melting of upwelling asthenosphere or interaction between depleted oceanic lithosphere and upwelling asthenosphere (Thorkelson et al., 2011; Tang et al., 2012).

In Cenozoic arcs, adakites usually coexist with high-Mg or magnesian andesites, in addition to the above basaltic rocks. HMAs can be categorized into four sub-types: adakitic, bajaitic, sanukitic, and boninitic HMAs (Tang and Wang, 2010). Cenozoic Adak-type HMAs occur mainly in the Aleutian arc and contain augite phenocrysts, and plagioclase and augite microlites, but lack olivine. They were formed through the interaction of slab-derived melts with mantle peridotite (Kay, 1978; Yogodzinski et al., 1995). Cenozoic Piip-type HMAs and sanukitoids occur respectively on Piip Island of the western Aleutian arc and in the Sanuki region of the Miocene Setouchi volcanic belt in southwestern Japan. Their major mineral constituents are olivine, clinopyroxene, and orthopyroxene (Tatsumi and Ishizaka, 1981, 1982a, 1982b; Yogodzinski et al., 1994; Tatsumi, 2006); they have similar MgO contents and REE patterns, and were produced by partial melting of mantle peridotite metasomatized by subducted sediments or fluids (Tang and Wang, 2010). The bajaites were named in Baja California, Mexico (Rogers et al., 1985; Saunders et al., 1987). Cenozoic bajaites comprise mainly olivine, clinopyroxene, orthopyroxene, plagioclase, and amphibole and were formed through partial melting of amphibole-bearing mantle peridotites produced by slab-melt-related metasomatism (Benoit et al., 2002; Castillo, 2008; Pallares et al., 2007; Maury et al., 2009). Boninite is a type of high-Mg volcanic rock rich in bronzite phenocrysts, glass matrix, and augite microlites, but lacking plagioclase crystals (Kikuchi, 1890; Cameron et al., 1979). They are characterized by SiO_2, MgO, and TiO_2 contents of >52 wt.%, >8 wt.%, and <0.5 wt.%, respectively (Le bas, 2000), U-shaped REE patterns, and significant depletion in high-field-strength elements (HFSEs) (Tang and Wang, 2010). Boninites are generally considered to be formed through the melting of depleted mantle peridotites metasomatized by fluids derived from subducted sediments (Ishizuka et al., 2006, 2011; Tang and Wang, 2010).

Representative examples of adakites and coexisting rock suites in Cenozoic arcs include (1) Adak- and Piip-type HMAs in the western Aleutian arc (Yogodzinski et al., 1994, 1995, 2001; Yogodzinski and Kelemen, 1998); (2) adakite-HMA-boninite associations in the Solomon, Tonga, and Mariana arcs, Southwest Pacific (Schuth et al., 2009; Falloon et al., 2008; Li et al., 2013); (3) adakite-HMA-Nb-rich basalt associations in the Philippines, Kamchatka, and Ecuador regions (Sajona et al., 1993, 1996; Kepezhinskas et al., 1997; Beate et al., 2001; Bourdon et al., 2003); and (4) adakite-bajaite-Nb-rich basalt-MORB-type tholeiitic basalt associations in Baja California (Benoit et al., 2002). It has been suggested that metasomatism related to slab- or sediment-derived melts may produce a unique rock suite comprising adakite-Adak-type HMA-Piip-type HMA-Nb-rich basalt-boninite (Defant and Kepezhinskas, 2001; Defant et al., 2002), distinguished from the (calc-alkaline basalt)-andesite-dacite-rhyolite association formed by melting of mantle wedge metasomatized by fluids derived from subducted oceanic crust.

Previous studies have provided experimental and petrological evidence of interactions between slab-derived melts and peridotite in the mantle wedge, as follows. (1) Experimental studies have indicated that melts have low $Mg^{\#}$ values (<47) at pressures of 1–4 GPa (Figure 5a), increasing significantly after reaction with peridotite (Rapp et al., 1999; Wang et al., 2006a, 2006b). (2) Mantle peridotite xenoliths in Cenozoic volcanic rocks from the Kamchatka arc contain Nb-rich basaltic and adakitic veins and pyroxene grains with high Na and Sr contents and La/Yb ratios. LREE contents of peridotite xenoliths are positively correlated with HFSE contents (Figure 5b), indicating that the sub-arc mantle had been metasomatized by Na-rich melts (Kepezhinskas et al., 1995, 1996; Defant and Kepezhinskas, 2001; Defant et al., 2002). (3) Melt inclusions hosted in olivine from the Philippine sub-arc mantle peridotite xenoliths in Cenozoic volcanic rocks exhibit Na-rich (Na_2O/K_2O=1.0–31.0) adakitic characteristics (Figure 5c, 5d), also suggesting that the sub-arc mantle had been metasomatized by Na-rich melts (Schiano et al., 1995; Defant and Kepezhinskas, 2001). (4) Cenozoic arc adakites have lower Na_2O contents (typically <5 wt.%) than melts of basalts produced experimentally at high pressures owing to the assimilation of low-Na mantle minerals and crystallization of Na-rich amphibole by slab melts (Xiong et al., 2006).

5. Petrological and metamorphic phase-equilibrium modeling and high-*P*-*T* melting constraints on adakitic magma generation

5.1 Adakitic melts associated with rocks of eclogite–high-pressure-granulite facies

Occurrences of adakitic rocks genetically associated with rocks of eclogite-high-pressure-granulite facies are considered evidence that adakitic rocks are likely derived from partial melting of deeply subducted oceanic/continental crust. Recent studies have provided typical examples such as the following. (1) Adakitic veinlets and intrusions coexisting with retrograde ultra-high-pressure metamorphic (UHPM) eclogites (or high-pressure granulites) in the North Qaidam UHPM belt, NW China, where adakitic melts were generated by partial melting of eclogites at 446–420 Ma, partially postdating peak eclogite-facies metamorphism at 440–430 Ma. Petrological and geochronological data suggest that the adakitic magmas were produced through decompression melting of UHP eclogites at *P*-*T* conditions of 1.5–2.0 GPa and 800–950°C during exhumation (Chen et al., 2012; Yu S Y et al., 2015, 2019; Song et al., 2014; Zhang G B et al., 2015; Zhang L et al., 2015). (2) Zoisite-bearing adakitic pegmatites coexisting with retrograde eclogites in the Münchberg Massif, Germany, with eclogites of MORB composition recording minimum peak-metamorphic *P-T* conditions of 2.0–2.5 GPa and 600–700°C and eclogite-facies metamorphic ages of 395–380 Ma. These pegmatites were derived from partial melting of the associated eclogites under peak *P-T* conditions of >2.3–3.1 GPa and 680–750°C during subduction of oceanic crust, finally crystallizing at 0.9 GPa and 620–650°C during the uplift stage (Franz and Smelik, 1995; Liebscher et al., 2007). (3) Multiphase solid inclusions in HP-UHP rocks, including (i) diamond-bearing polyphase inclusions containing phlogopite, quartz, paragonite, phengite, and rutile within garnet in UHP metamorphic gneiss from Erzgebirge, Germany, thought to represent hydrous melts formed under UHP metamorphic conditions (*P*>4.5 GPa; *T*, 1000°C) and which crystallized at low pressures during exhumation (Stöckhert et al., 2001); (ii) multiphase solid inclusions with high Sr/Y ratios typical of adakitic rocks in garnet from UHP eclogites in the Dabie orogen, China, which crystallized from hydrous melts as a result of dehydration melting of phengite in the eclogites during exhumation (Gao et al., 2012, 2013; Hermann et al., 2013; Zheng and Hermann, 2014); (iii) "nanogranite" melt inclusions in garnet of HP granulite in the Bohemian Massif of the central European Variscan orogen, formed through partial melting of subducted crust under peak-metamorphic *P-T* conditions of 2.3–3.0 GPa and 850–950°C (Ferrero et al., 2015). These microscopic-scale examples provide further support for the likely generation of adakitic melts through partial melting of rocks of eclogite-high-pressure-granulite facies.

5.2 Genetic connection between eclogitic xenoliths and generation of adakitic TTG melts

Some eclogite xenoliths hosted in magmatic rocks are considered to have a close genetic link with adakitic and TTG magmas, including the following examples. (1) Eclogite and garnet clinopyroxenite xenoliths in Early Cretaceous (132–130 Ma) high-Mg adakitic intrusions of the Xuzhou-Huaibei region on the southeastern margin of the North China Craton. The xenoliths define peak-metamorphic *P-T* conditions of >1.5 GPa and 800–1060°C. Eclogite zircon and rutile yield ages of 209–132 Ma, similar to those of their host rocks and providing a genetic link with adakitic intrusions (e.g., Xu et al., 2006, 2009; Xiong et al., 2015). (2) Eclogite xenoliths hosted in kimberlites of the Siberian and South African Archean (3.5–2.5 Ga) cratons (e.g., MacGregor and Manton,1986; Ireland et al., 1994; Jacob et al., 1995; Beard et al., 1996; Rollinson, 1997; Snyder et al., 1997; Rudnick et al., 2000). Geochemical data indicate that the low-MgO eclogite xenoliths represent residues of subducted oceanic crust after extraction of TTG melts, whereas high-MgO xenoliths represent residues of cumulates from thickened arc root after extraction of TTG melts (e.g., Horodyskyj et al., 2007).

5.3 Phase-equilibrium modeling adakitic and TTG melts under eclogite to HP granulite-facies conditions

Recent studies have applied phase-equilibrium modeling to constrain the generation of adakitic or TTG melts (e.g., Wang et al., 2015, 2017: Palin et al., 2016; Johnson et al., 2017; Wei et al., 2017; Ge et al., 2018; Hernández-Uribe et al., 2020). Melts generated by partial melting of Archean tholeiites at 1.0–1.8 GPa and 800–950°C are most consistent with natural Archean TTG in terms of their major- and trace-element compositions (Palin et al., 2016). At low pressures, melts enriched in Sr and depleted in HREEs and HFSEs cannot be produced because of the presence of plagioclase and absence of garnet and rutile in metabasite. At high pressures, melts are enriched in K as Na becomes compatible in clinopyroxene (Schmidt and Poli, 2014), which is inconsistent with the enrichment of Na in adakite and TTG. Furthermore, the amount of melt generated at high pressures is limited, as metabasite is almost completely dehydrated at depth. Using MORB as the source rock, phase-equilibrium modeling indicates that optimal *P-T* conditions for the generation of TTG are 1.0–2.5 GPa and 800–1000°C (Wei et al., 2017). Phase-equilibrium modeling (Hernández-Uribe et al., 2020) further indicates that partial melting of MORB and altered MORB at >2.7 GPa and 820–840°C can generate high-silica adakitic melts. Furthermore, thermodynamic modeling indicates that Eoarchean TTGs (Sr/Y≥100) were generated at >1.6 GPa and 800–830°C with 2–3 wt.% H_2O (Ge et al., 2018). In summary, phase-equilibrium modeling indicates that adakites are generated under *P-T* conditions of 1.0–1.6 GPa and 800–1000°C.

5.4 Experimental petrological constraints on the generation of adakitic melts

High-temperature/high-pressure melting experiments have been undertaken to elucidate conditions for the generation of adakitic magmas, with results indicating that mafic source and residual minerals (garnet, rutile, and plagioclase) determine the compositions of adakitic rocks (e.g., Rapp et al., 1991, 1999, 2003; Sen and Dunn, 1994; Rapp, 1995; Rapp and Watson, 1995; Prouteau et al., 2001; Skjerlie and Patiño Douce, 2002; Xiong et al., 2005; Xiong, 2006; Nair and Chacko, 2008; Qian and Hermann, 2013; Sisson and Kelemen, 2018). Adakites are generally depleted in HREEs and Y, indicating the presence of residual garnet in source magmas (as HREEs and Y are compatible in garnet; Defant and Drummond, 1990). Experimental studies indicate that garnets enriched in Fe and Ca (almandite (Alm)>40 mol.%) form only during partial melting of mafic or eclogitic sources at pressures above 1.0 GPa (Rapp, 1995; Rapp and Watson, 1995; Sisson and Kelemen, 2018), although the melts would not be equilibrated with residual garnet unless the pressure was above 1.2 GPa (Rapp, 1995). Furthermore, the proportion of residual garnet in the source may increase with increasing pressure (Figure 6; Nair and Chacko, 2008), resulting in strong depletion of HREEs and Y in melts (Sen and Dunn, 1994; Rapp and Watson, 1995; Rapp et al., 1999). HFSEs such as Nb, Ta, and Ti are generally depleted in adakitic rocks (Xiong et al., 2005; Xiong, 2006) and, considering that these elements are compatible in rutile, residual rutile in the source must be required for the formation of adakitic rocks (Xiong et al., 2005). A melting experiment involving hydrous basalt (2 or 5 wt.% H_2O) at 1.0–2.5 GPa and 900–1100°C has indicated that rutile is a necessary residual phase during the generation of adakitic rocks, and occurs at pressures above 1.5 GPa (Xiong et al., 2005). Based on this minimum pressure (1.5 GPa) for rutile appearance, the depth for TTG production via melting of subducted oceanic crust must exceed 50 km (Xiong et al., 2005; Xiong, 2006). Sisson and Kelemen (2018) found that melts generated by partial melting of mafic oceanic crust at 1.4–2.8 GPa are depleted in Nb and Ti, with residual garnet and rutile.

Another definitive characteristic of adakites is their positive to negligible Eu and Sr anomalies in REE and trace-element spider diagrams (Figure 3). Eu and Sr are compatible in plagioclase, so a source with little or no plagioclase is required for the generation of adakitic magmas. Melting experiments with basites indicate that plagioclase generally disappears at a pressure of 1.3 GPa (Sisson and Kelemen, 2018; Qian and Hermann, 2013) or >2.2 GPa (Rapp and Watson, 1995) during dehydration (H_2O=1.5–2.0 wt.%) or water-rich melting (H_2O=4.0–6.0 wt.%), respectively.

The Na- and K-rich characteristics of adakitic melts have also attracted attention. Experimental data indicate that the high alkalinity of such melts is controlled by source lithology, H_2O content, and melting pressure (Prouteau et al., 2001; Skjerlie and Patiño Douce, 2002; Wang et al., 2003a; Wang et al., 2007a; Xiao and Clemens, 2007). Melts derived from K-rich sources are more enriched in K. For the same source material, melts generated by anhydrous melting are enriched in K, whereas melts generated by hydrous melting are enriched in Na. Furthermore, the K content of melts increases with increasing melting pressure. Prouteau et al. (2001) demonstrated that melts generated by partial melting of MORB at 1.0–3.0 GPa, 800–1000°C, and 2.0–10.0 wt.% H_2O have major-oxide (K_2O and Na_2O) compositions similar to those of natural adakites.

In summary, metamorphism and melting studies of adakitic granitoids, adakitic “nanogranite” melt inclusions associated with eclogites or high-pressure granulites, eclogite or garnet pyroxenite xenoliths in adakites, and phase-equilibrium modeling have provided constraints on the generation of adakitic magmas. The unique features of adakitic rocks, including depletion in HREEs and Nb-Ta-Ti, positive to negligible Eu anomalies, positive Sr anomalies, and their K_2O and Na_2O contents, can be explained by basic-rock melting conditions of 1.2–3.0 GPa, 800–1000°C (Figure 6), and 1.5–6.0 wt.% H_2O, leaving residues of garnet and rutile and little or no plagioclase.

6. Relationship between adakitic rocks and metal mineralization

Porphyry deposits provide about 75% of the global produc-

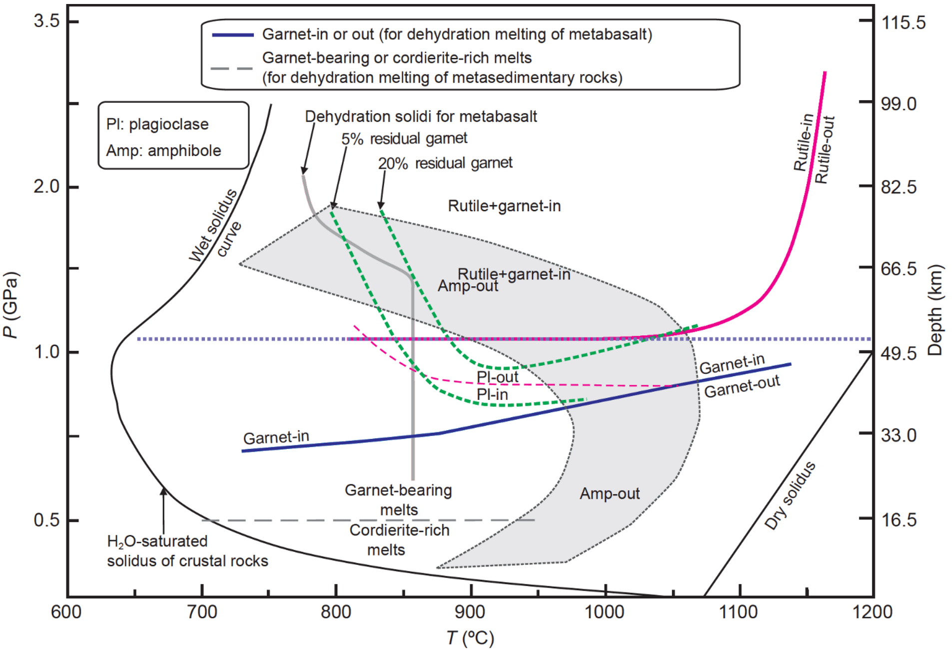

Figure 6 Pressure-temperature conditions for the generation of adakitic melts (after Wang et al., 2016)

tion of Cu, 50% of Mo, 20% of Au, and large amounts of other metals (Sillitoe, 2010), so studies of their formation are of both scientific and economic significance. Subduction zones are the most productive porphyry deposit areas, and most Cenozoic porphyry deposits occur on circum-Pacific magmatic arcs and in the Tethyan orogen (Figure 1b), overlapping the distribution of Cenozoic adakitic rocks (Figure 1a), and most ore-forming intrusions are adakitic (e.g., Thiéblemont et al., 1997; Sajona and Maury, 1998; Oyarzun et al., 2001; Defant and Kepezhinskas, 2001; Defant et al., 2002; Wang et al., 2003a, 2003b; Hou, 2010; Loucks, 2014). There is consensus that porphyry deposits are products of fluid exsolution from shallow magma bodies (Hedenquist and Lowenstern, 1994; Richards, 2003; Sillitoe, 2010; Audétat and Simon, 2012). Although not all adakitic rocks have the potential to form ore deposits, adakitic geochemical characteristics are widely regarded as being an indicator of fertile intrusions and hydrous, oxidized, and S-rich magmatic properties (Defant and Kepezhinskas, 2001; Defant et al., 2002; Wang et al., 2003a, 2003b; Loucks, 2014; Sillitoe, 2018).

The genetic relationship between adakitic rocks and porphyry deposits has been widely studied, with reasons suggested for adakitic rocks being favorable for metal mineralization including the following.

(1) Efficient extraction of chalcophile elements from the mantle wedge induced by injection of slab-derived oxidized melts. An important factor that increases the ore-forming potential of adakitic rocks is the contribution of oxidized slab-derived melts, with the solubility of Fe_2O_3 in slab-derived melts being 10^4 times that in fluids. The injection of large amounts of Fe_2O_3 would increase the oxidation state of the mantle wedge, promoting the extraction of chalcophile elements by suppressing saturation with sulfides during partial melting, and resulting in the generation of Cu- and Au-rich magmas and ore deposits (Mungall, 2002). Tectonic settings favorable for the genesis of porphyry deposits include the subduction of young lithosphere, slow or oblique convergence, cessation of slab subduction, very deep subduction (~300 km), and flat subduction (Mungall, 2002).

(2) Chalcophile element-rich magma sources (or oceanic crust). Cu and Au are moderately incompatible elements with contents in oceanic crust of 60–125 ppm (average 74 ppm), higher than those in the mantle (30 ppm) and continental crust (27 ppm). Partial melting of oceanic crust is therefore more conducive to the generation of Cu-rich magmas and ore deposits (Ling et al., 2009; Sun et al., 2010, 2013, 2015; Zhan et al., 2015).

(3) Very high water contents in adakitic magmas. Adakitic magmas can be formed from H_2O-rich primitive basaltic melts by the fractionation of amphibole (without plagioclase) because high magmatic water contents facilitate amphibole fractionation while suppressing plagioclase saturation, leading to depletion in Y and enrichment in Sr in derivative magmas. This may explain the genetic link between adakitic rocks and porphyry deposits (e.g., Richards and Kerrich, 2007; Richards, 2011; Loucks, 2014; Williamson et al., 2016; Sillitoe, 2018), with high magmatic water contents being essential for generating porphyry deposits (Sillitoe, 2010).

(4) Crystal fractionation at high pressures, with the production of adakitic magmas being controlled by deep magma chambers because of the removal of garnet and amphibole at high pressures (Chiaradia, 2009; Chiaradia and Caricchi, 2017; Lee and Tang, 2020). This is consistent with porphyry deposits being more common in very thick magmatic arcs. Garnet fractionation can also increase the oxidation state of magmas (Tang et al., 2019), making them favorable for the genesis of porphyry deposits (Lee and Tang, 2020).

(5) Partial melting of amphibole-rich rocks in thickened lower continental crust. In subduction, collision, and intraplate environments, hornblende breakdown in thickened lower continental crust can produce large amounts of aqueous fluids (Kay and Mpodozis, 2001; Wang et al., 2003a, 2003b; Hou, 2010), leading to partial melting of the lower crust and an increase in magmatic H_2O content and oxygen fugacity (Hou, 2010), enhancing ore-forming potential.

(6) Interaction between mantle and melt. Partial melting of subducted oceanic crust (e.g., Defant and Drummond, 1990), delaminated lower crust (e.g., Xu et al., 2002, 2006, 2008; Gao et al., 2004; Wang et al., 2006a, 2006b, 2007a, 2007b), and subducted continental crust (Wang et al., 2008b; Jiang et al., 2014) can generate adakitic magmas, all of which are associated with ore-deposit formation (Wang et al., 2006a, 2006b, 2007b; Wang et al., 2008a). Favorable settings for ore-deposit genesis therefore include subduction zones, collisional zones, and intraplate extensional environments (Wang et al., 2008a).

7. Scientific problems and frontiers of future research

7.1 Tectonic setting and genesis of adakitic rocks

7.1.1 Diversity of tectonic setting of pre-Cenozoic adakitic rocks

Determining the tectonic setting of adakitic rocks is key to unveiling their petrogenesis. The tectonic setting of Cenozoic adakitic rocks is very clear: they occur mainly in subduction and collisional zones and to a lesser degree in intra-continental settings (Figure 1). Some Pre-Cenozoic adakitic rocks are associated with Cu-Au deposits in, for example, eastern China, the Qinling, Songpan-Ganzi, Qiangtang, and Gangdese regions, and central Asia. However, the tectonic setting of adakitic rocks in most areas is not well constrained, except for some in areas with clear tectonic settings, such as Jurassic-Cretaceous adakitic rocks in the Gangdese region that were generated in an arc setting related to subduction of the Neo-Tethys oceanic lithosphere. There are many areas containing Jurassic-Cretaceous adakitic rocks in eastern China (Zhang et al., 2001; Xu et al., 2002, 2006, 2009; Wang et al., 2003, 2004a, 2004b, 2006a, 2006b, 2007; Gao et al., 2004; Ling et al., 2009; Liu et al., 2010; He et al., 2011; Ma et al., 2012, 2015, 2016; Sun et al., 2010, 2013, 2015; Li et al., 2009, 2013; Xu et al., 2014; Yang et al., 2014a, 2014b; Dai et al., 2017), but whether these rocks were generated in an intra-continental extensional, continental-margin arc, or back-arc extensional setting remains controversial, with inconsistent viewpoints arising concerning their genesis. Furthermore, some adakitic magmatic rocks occur in convergent plate boundaries within continental areas but were formed after paleo-plate subduction, possibly in association with thinning of thickened lithosphere caused by accretion/collisional orogenic processes (Wang et al., 2017; Zhao et al., 2017). For example, the formation of Early Cretaceous adakitic rocks in the Dabie orogen was related to reworking of Triassic collisional orogenic belts (Wang et al., 2001b; Wang et al., 2017; Zhao et al., 2017). Therefore, to decipher the petrogenesis of pre-Cenozoic adakitic rocks generally, there needs to be a focus on better constraining their tectonic settings.

7.1.2 *Diversity of magma and heat sources, and mechanisms of magma generation*

Magma sources for subduction-zone adakites may include subducted basaltic oceanic crust, subducted continental crust, subducted slab sediment, mélange, and crustal materials eroded from the subduction-zone upper plate. The subducted slab may comprise young or old oceanic crust, oceanic plateau, aseismic ridge, residual arc ridge, or spreading mid-ocean ridge (Wang et al., 2020). Subduction styles may include steep subduction, flat subduction, subduction roll-back, subducted slab tear, subduction underplating, and subduction erosion (Wang et al., 2020). In addition to fluid effects, the thermal state also plays a key role in slab melting and arc magma production (Zheng, 2019, Xu et al., 2020), whether the heat source is the asthenospheric mantle wedge, asthenospheric flow between subducted slab and mantle wedge during slab roll-back (Zheng et al., 2016; Zheng and Chen, 2016; Zheng and Zhao, 2017; Zheng, 2019; Zheng et al., 2020), or asthenospheric upwelling through a slab tear (Yogodzinski et al., 2001; Rosenbaum et al., 2008; Wang et al., 2020). For example, when a subducted slab rolls back, the asthenospheric mantle heats and melts the slab surface, producing adakites, HMAs, Nb-rich basalts, or OIB-type basalts (Bourdon et al., 2003; Tang et al., 2010; Zheng et al., 2015, 2016, 2020; Zheng and Chen, 2016; Zheng and Zhao, 2017; Zheng, 2019; Hao et al., 2019; Xu et al., 2020; Wang et al., 2020). Magmas, heat sources, and magma generation mechanisms are thus diverse, making it difficult to elucidate the petrogenesis of subduction-zone adakites.

7.1.3 *Generation of adakitic magmas*

The initial materials in earlier melting experiments were generally MORB-like rocks, and further work is needed to constrain the formation of adakitic magmas by the melting of mafic rocks depleted in Nb and Ta. Furthermore, some adakitic rocks in the North China Craton (Ma et al., 2012, 2015, 2016) and Japan arc (Kamei et al., 2009) are suggested to have been formed by melting of the lower crust at low pressures (1.0–1.2 GPa), corresponding to depths of 30–40 km, with likely source rocks being granulites (Jiang et al., 2007) or intermediate–felsic rocks (Kamei et al., 2009). Experimental petrological data alternatively indicate that adakitic rocks in the North China Craton originated mainly from medium- and high-K metabasites (Xiong et al., 2011). Phase-equilibrium modeling of metabasites, the solubility of TiO_2 in felsic liquids, and the correlation between Nb/La and La/Yb ratios of adakitic rocks confirm that many adakitic rocks in the Dabie, Jiaodong, and North China cratons were formed by partial melting with a rutile residue (Xiong et al., 2011). These adakitic magmas would be expected to originate from a source at >50 km depth (Xiong et al., 2011). It is therefore necessary to further constrain the formation conditions of adakitic magmas with melting experiments based on initial materials of intermediate–felsic rocks at high temperatures and pressures.

The definition of adakites has been extended by some authors to include rocks with SiO_2 contents of <56 wt.% and mantle-derived bajaite (the "low-silica" adakites) with a suggested formation mechanism involving the direct melting of mantle peridotites (e.g., Martin et al., 2005). However, available experimental data suggest that melting products of peridotites are dominated by basaltic and rare high-Mg andesitic melts (SiO_2<57 wt.%; MgO>6.0 wt.%) under hydrous conditions (Figure 7). Cenozoic volcanic and adakitic rocks in collisional belts have high SiO_2 (>55 wt.%) and low MgO (<6.0 wt.%) contents (Figures 2 and 7), indicating that these rocks could not be directly derived from partial melting of the mantle. It is also unclear whether adakitic magmas can be formed by partial melting of other rocks (e.g., pyroxenite), and this needs to be further constrained through high-temperature/pressure experiments.

7.1.4 *Evolution of adakitic magma*

Many previous studies have shown that adakitic rocks can be produced by partial melting of mafic rocks at high pressure (>1.2 GPa; depth equivalent 40 km) (Figure 6), but igneous processes such as fractional crystallization, magma mixing, assimilation–fractional crystallization, and MASH (melting, assimilation, storage and homogenization) that deep-crustal magma may undergo during migration from magma source

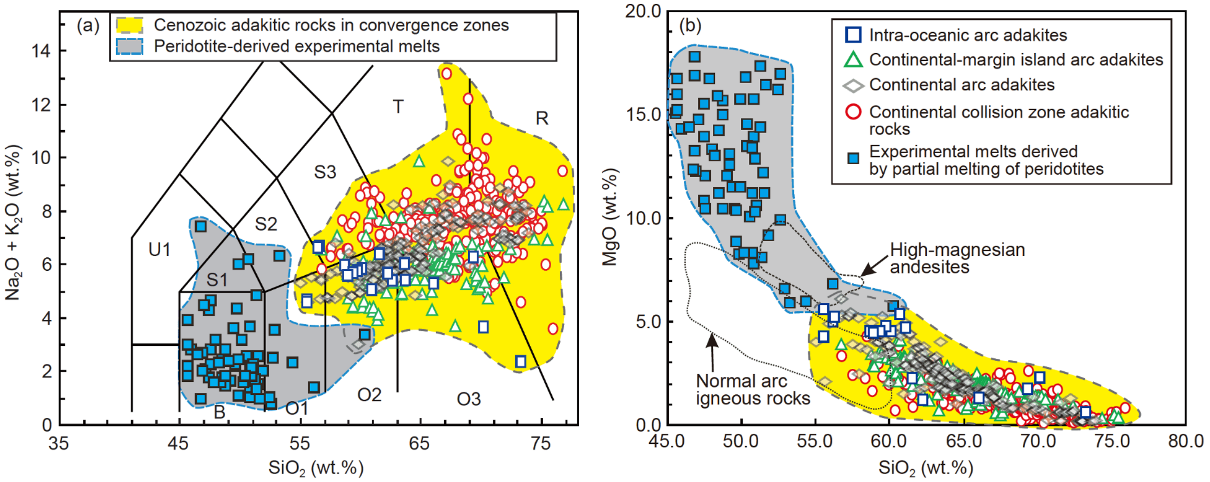

Figure 7 Comparison between experimental melts of peridotites and Cenozoic adakitic rocks. (a) SiO_2-(Na_2O+K_2O); (b) SiO_2-MgO. U1, tephrite; B, basalt; O1, basaltic andesite; O2, andesite; O3, dacite; S1, trachybasalt; S2, basaltic trachyandesite; S3, trachyandesite; T, trachyte/trachydacite; R, rhyolite. Experimental melt peridotite compositions are from Hirose and Kushiro (1993), Baker and Stolper (1994), Baker et al. (1995), Hirose and Kawamoto (1995), Kushiro (1996), Hirose (1997), and Hirose and Kushiro (1998). Fields of normal arc-volcanic rocks and HMAs are from McCarron and Smellie (1998).

to final eruption or emplacement are also critical to the formation of adakitic rocks. Some studies have suggested that adakitic rocks can be formed by fractional crystallization and assimilation of crustal materials, high-pressure fractional crystallization, and magma mixing (e.g., Castillo et al., 1999; Müntener and Ulmer, 2006; Macpherson et al., 2006; Guo et al., 2007; Streck et al., 2007; Li et al., 2009, 2013; Dai et al., 2017). Recent studies have also suggested that the storage and evolution of magmas in the crust involves a "crystalline mush" being kept in "cold storage" rather than in a high-temperature magma chamber. This crystalline mush effectively extends the thermal lifetime of magma in the cooler upper and middle crust, crucial for the growth and evolution of magma reservoirs (Cashman and Giordano, 2014; Bachmann and Huber, 2016; Edmonds et al., 2019; Sparks et al., 2019). As an example of this, a recent study has shown that melts in equilibrium with early crystallized amphibole are of adakitic compositions, whereas melts in equilibrium with late-crystallized amphibole do not have such characteristics (Tang et al., 2017). The processes of long-distance magma migration and evolution after the generation of adakitic magmas thus remain poorly constrained.

7.2 Genetic link between adakitic melts and eclogite–granulite-facies metamorphism

Typical examples of adakitic melts associated with rocks of eclogite–high-pressure-granulite facies from the North Qaidam, Münchberg Massif, and Dabie orogens have been listed above. Zoisite-bearing pegmatites in the Münchberg Massif are considered to have been produced through partial melting under peak eclogite-facies conditions, and adakitic rocks in the North Qaidam orogen and high-Sr/Y "nanogranites" in the Dabie orogen through decompression melting of UHP eclogite during exhumation (e.g., Chen et al., 2012; Song et al., 2014; Zheng and Hermann, 2014; Zhang et al., 2015a, 2015b; Gao et al., 2012, 2013). Previous studies have reported a close association between Archean eclogites and adakitic TTGs in Belomorian Province, Russia (Mints et al., 2010, 2014). However, the Belomorian eclogites have recently been shown to be of Paleoproterozoic age (*ca.* 1.90 Ga), with no likely genetic link to TTG gneiss of protolith age 3.5–2.6 Ga (Yu H L et al., 2019). Partial melting of General's Hill eclogite of the Sulu orogen, China, has been documented at microscopic to field scales, but felsic veins associated with these eclogites do not have an adakitic signature (Wang et al., 2014). It can therefore be concluded that most reported granitic rocks coexisting with eclogites were formed after peak eclogite-facies metamorphism and not all have adakitic geochemical characteristics. Granitic rocks associated with granulite (*P*, 1.0–1.4 GPa; *T*, 750–850°C or >900°C), garnet amphibolite, and garnet pyroxenite, characterized by adakite- or TTG-like signatures with high Sr/Y ratios and Sr contents, low Y and Yb contents, and positive Eu and Sr anomalies, have also been reported in some areas, including New Zealand, Pakistan, and Scotland (Stevenson et al., 2005; Garrido et al., 2006; Stowell et al., 2010; Johnson et al., 2012). It follows that fundamental questions remain concerning (1) how mineral solubility and elemental partitioning vary along subduction and exhumation pathways at mantle depths of >80 km (Zheng and Hermann, 2014); (2) availability of further field or petrological evidence that adakitic melts can be produced under peak eclogite-facies conditions; (3) the *P*-*T* conditions, fluid contents, and geochemical compositions of melts generated during partial melting of HP-UHP metamorphosed rock (eclogite and its associated intermediate-acid metamorphic rocks) during exhumation; and (4) whether adakitic melt can be generated during HP granulite-facies metamorphism and, if so, what differences there are in composition, *P-T* conditions, and residual minerals between these melts and those produced under eclogite-facies conditions.

7.3 Mechanism of interaction between slab melts and mantle in subduction zones

In addition to slab-derived fluids, the interaction between slab-derived melts and mantle-wedge peridotite plays an important role in determining the nature of sources of arc magmatism. In subduction zones, basaltic oceanic crust, continental crust, sediments, mélange, and overlying plate materials (produced by subduction erosion processes) can be transported to sub-arc depths, with all being potential sources of adakite. When adakitic melts are produced at sub-arc depths, they may infiltrate and react with the mantle wedge, with products ranging from a high-$Mg^{\#}$ melt to metasomatized mantle, depending on melt/rock ratios (Xu et al., 2020). At low melt/rock ratios, adakitic melts would be completely consumed in metasomatic reactions with the mantle wedge, whereas at high melt/rock ratios, they would become Mg-rich melts (Rapp et al., 1999; Xu et al., 2020). Furthermore, Mg-rich melts could become HMAs at relatively low melt/rock ratios (<1), or Mg-rich, high-silica adakitic melts at higher melt/rock ratios (>1) (Su et al., 2019), with metasomatic mantle thus being the source of high-Nb basalts and HMAs (Sajona et al., 1993, 1996; Kepezhinskas et al., 1997; Defant and Kepezhinskas, 2001; Defant et al., 2002; Bourdon et al., 2003). Supercritical fluids also exist at sub-arc depths (Kessel et al., 2005; Kawamoto et al., 2012; Mibe et al., 2011; Zheng et al., 2011; Ni et al., 2017) and separate into aqueous fluids and melts during ascent (Kawamoto et al., 2012). Materials carried into the deep mantle are therefore diverse, mechanically mixing with mantle-wedge peridotite and releasing fluids, melts, and even supercritical fluids that in turn react with surrounding mantle. These processes have significant impacts on the formation of sources of arc magmatic rocks and the global material cycle (Zheng, 2019). Further research questions concern (a) whether metasomes of different compositions can be formed by reactions between mantle-wedge peridotite and aqueous solutions, hydrous melts, and supercritical fluids; and (b) relationships between such metasomes and compositional variations in arc magmatic rocks (Zheng and Hermann, 2014).

7.4 Archean adakitic TTG formation and its relationship to continental crust growth and the onset of plate tectonics

TTG is the primary rock type in Archean continental crust, and whether there are relationships between its formation and plate tectonics, oxygen generation, and evolution of Earth habitability is a “hot issue” in the field of Earth sciences. Defant and Drummond (1990) realized that Cenozoic adakites have compositions similar to those of Archean TTG, with TTG formation being related to subduction and melting of oceanic slabs. Subsequent studies compared the two species to elucidate the mechanism of Archean continental crustal growth and the onset of plate tectonics (Martin, 1999; Martin et al., 2005; Smithies, 2000; Condie, 2005; Rapp et al., 2010; Hastie et al., 2010, 2015). Although Archean TTG and adakitic compositions may be similar, that of TTGs is not stable but varies with time. For example, >3.5 Ga TTG has low Mg, Cr, Ni, and Sr contents, whereas <3.0 Ga TTG has high Mg, Cr, Ni, and Sr contents (Smithies et al., 2003; Martin et al., 2005). This effect is considered to be related to oceanic lithosphere subduction, with no mantle-wedge compositional contribution in the former and with a contribution in the latter. This would mean plate tectonics began before 3.5 Ga (Martin, 1999; Martin et al., 2005; Hastie et al., 2010, 2015). However, some authors consider that modern arc-setting rock assemblages of boninite, HMA (sanukite), Nb-rich basalt, and adakite formed during the late Archean (3.0–2.5 Ga), with modern plate tectonics (oceanic subduction) beginning at that time (Kerrich et al., 1998; Smithies, 2000; Polat et al., 2002; Polat and Kerrich, 2002; Smithies et al., 2004). Although comparative studies of Cenozoic adakites and Archean TTG enable progress in constraining Archean continental crustal growth and the onset of plate tectonics, core divergences thus remain. In particular, results of magmatic petrological studies are not consistent with those of structural geology, sedimentation, HP-UHP metamorphism, or numerical modeling, so further work is needed. The formation of Archean adakitic TTGs and their relationship to crustal growth and the onset of plate tectonic thus remain unresolved issues.

7.5 Genetic link between adakitic rocks and ore deposits

The ore-forming potential of adakites may be enhanced by high oxygen fugacities of slab-derived melts, chalcophile-element-rich magma sources (or oceanic crust), high magmatic water contents in adakitic magmas, crystal fractionation at high pressures, hornblende breakdown in thickened continental lower crust, and interactions between mantle and melt, but which factor plays the predominant role remains controversial. Some studies have suggested that the genetic link between adakitic rocks and ore deposits can be ascribed mainly to magmatic water contents (e.g., Richards and Kerrich, 2007; Richards, 2011; Loucks, 2014; Williamson et al., 2016; Sillitoe, 2018), but this is inconsistent with the observation in volcanic systems in southwest Japan of a negative correlation between magmatic water contents and Sr/Y ratios, that is, adakitic melts are formed preferentially from H_2O-poor magmas at high pressures (Zellmer et al., 2012). A recent study has also indicated that low-Sr, H_2O-rich, ore-forming magmas were derived from high-Sr, H_2O-poor parent melts (Zhou et al., 2020a). Other studies have suggested that garnet fractionation at high pressures produces oxidized magmas favorable for generating porphyry deposits (e.g., Lee and Tang, 2020), whereas others have proposed that the formation of calc-alkalic, Cu-mineralizing magmas is controlled by magnetite fractionation, with sulfide-rich cumulate precipitation from water-rich magmas being triggered by magnetite crystallization in thick crust and with these cumulates being recycled in subsequent magmatic activity (e.g., Chiaradia, 2014). As indicated by Zheng Y F et al. (2019), there are three steps of metal enrichment during ore-deposit formation in oceanic subduction zones: (1) preliminary enrichment of metals in the mantle wedge through metasomatism by subducting slab-derived fluids; (2) secondary enrichment of metals in mafic magmas during partial melting of metasomatic mantle domains and magma differentiation; and (3) enrichment through partial melting of mafic igneous rocks in the lower crust to produce felsic magmas, whose fractional crystallization gives rise to magmatic–hydrothermal fluids for final mineralization. Compressional collisional zones are generally regarded as being unfavorable environments for generating ore deposits, but numerous magmatic-hydrothermal deposits have been found in typical collisional zones such as the Tibetan Plateau and Qinling-Dabie orogen (e.g., Hou et al., 2009; Hou, 2010; Zheng Y F et al., 2019). Deep processes associated with ore-deposit formation in continental collisional zones are therefore another important topic in current research. Some authors have suggested that ore-forming magmas in continental collisional zones were derived from partial melting of metal-rich cumulates in the lower crust, formed in a previous subduction stage (Hou et al., 2015; Zheng Y C et al., 2019). Alternatively, ore-forming magmas may be products of partial melting of lithospheric mantle (Lu et al., 2015; Holwell et al., 2019) fertilized by slab-derived fluids (Zheng Y F et al., 2019). Both of these hypotheses emphasize the contribution of early subduction processes to ore-deposit formation in continental collisional zones (Hou et al., 2015; Zheng Y F et al., 2019). Outstanding questions relate to magma properties of adakitic melts (melt/fluid compositions, temperature, pressure, water content, and oxygen fugacity), the genetic relationship between adakitic magmas, and ore-deposit genesis in different tectonic settings, with differences between the genesis of fertile and barren adakitic rocks yet to be explained.

In summary, future research should focus on the clarification of relationships between partial melting of different types of rock (including intermediate-acid rocks); fractional crystallization of melts at different temperatures and pressures; the generation of adakitic magmas; magma reservoir evolution and the formation of adakitic rocks; tectonic setting and the petrogenesis of pre-Cenozoic adakitic rocks and related geodynamic processes; slab-melt–mantle interactions and metasomatism; the formation of Archean adakitic TTG and the onset of plate tectonics and crustal growth; and relationships between the formation of adakitic rocks and associated metal mineralization in different tectonic settings.

8. Conclusions

Adakitic rocks are intermediate-acid magmatic rocks with unique geochemical characteristics and important geodynamic and metallogenetic implications. Cenozoic adakites generated by partial melting of subducted oceanic crust (slab) occur mainly in Pacific Rim volcanic arcs (intra-oceanic arcs, continental arcs, and continental-margin island arcs). Cenozoic adakitic rocks generated by partial melting of thickened lower crust mainly occur at the Tethys-Tibetan Collisional Orogenic Belt. In volcanic arc areas, interactions between slab-derived adakitic magmas and the mantle wedge can form a unique rock suite comprising adakite-Adak-type HMA-Piip-type HMA-Nb-rich basalt-boninite. Partial melting of basic rocks can generate adakitic magmas under *P-T* conditions of 1.2–3.0 GPa and 800–1000°C with H_2O contents of 1.5–6.0 wt.%, leaving residual mineral assemblages of garnet and rutile, with little or no plagioclase. Host rocks of some Cenozoic Cu-Au deposits are adakitic rocks, with significant implications for Cu-Au mineralization and exploration. Although studies of Cenozoic adakitic rocks have made many important advances, gaps remain in some important areas, with petrogenesis and related metal mineralization being important future research directions.

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