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Ridge subduction, magmatism, and metallogenesis

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Abstract Modern oceans contain large bathymetric highs (spreading oceanic ridges, aseismic ridges or oceanic plateaus and inactive arc ridges) that, in total, constitute more than 20–30% of the total area of the world's ocean floor. These bathymetric highs may be subducted, and such processes are commonly referred to as ridge subduction. Such ridge subduction events are not only very common and important geodynamic processes in modern oceanic plate tectonics, they also play an important role in the generation of arc magmatism, material recycling, the growth and evolution of continental crust, the deformation and modification of the overlying plates, and metallogenesis at convergent plate boundaries. Therefore, these events have attracted widespread attention. The perpendicular or high-angle subduction of mid-ocean spreading ridges is commonly characterized by the occurrence of a slab window, and the formation of a distinctive adakite–high-Mg andesite–Nb-enriched basalt-oceanic island basalt (OIB) or a mid-oceanic ridge basalt (MORB)-type rock suite, and is closely associated with Au mineralization. Aseismic ridges or oceanic plateaus are traditionally considered to be difficult to subduct, to typically collide with arcs or continents or to induce flat subduction (low angle of less than 10°) due to the thickness of their underlying normal oceanic crust (>6–7 km) and high topography. However, the subduction of aseismic ridges and oceanic plateaus occurred on both the western and eastern sides of the Pacific Ocean during the Cenozoic. On the eastern side of the Pacific Ocean, aseismic ridges or oceanic plateaus are being subducted flatly or at low angles beneath South and Central American continents, which may cause a magmatic gap. But slab melting can occur and adakites, or an adakite–high-Mg andesite–adakitic andesite–Nb-enriched basalt suite may be formed during the slab rollback or tearing. Cu-Au mineralization is commonly associated with such flat subduction events. On the western side of the Pacific Ocean, however, aseismic ridges and oceanic plateaus are subducted at relatively high angles (>30°). These subduction processes can generate large scale eruptions of basalts, basaltic andesites and andesites, which may be derived from fractional crystallization of magmas originating from the subduction zone fluid-metasomatized mantle wedge. In addition, some inactive arc ridges are subducted beneath Southwest Japan, and these subduction processes are commonly associated with the production of basalts, high-Mg andesites and adakites and Au mineralization. Besides magmatism and Cu-Au mineralization, ridge subduction may also trigger subduction erosion in subduction zones. Future frontiers of research will include characterizing the spatial and temporal patterns of ridge subduction events, clarifying the associated geodynamic mechanisms, quantifying subduction zone material recycling, establishing the associated deep crustal and mantle events that generate or influence magmatism and Cu-Au mineralization, establishing criteria to recognize pre-Cenozoic ridge subduction, the onset of modern-style plate tectonics and the growth mechanisms for Archean continental crust.

Keywords Spreading mid ocean ridge, Aseismic ridge, Oceanic plateau, Inactive arc ridge, Subduction, Magmatism, Metal minerlization, Crustal growth

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1. Introduction

Modern oceans often contain large bathymetric highs (spreading oceanic ridges, aseismic ridges or oceanic plateaus and inactive arc ridges) that, in total, constitute more than 20–30% of the total area of the world's ocean floor (Yesson et al., 2011; Harris et al., 2014). "Ridge subduction" generally involves subduction of spreading mid-ocean ridges, aseismic ridges or oceanic plateaus and inactive arc ridges (e.g., Vogt, 1973; Thorkelson, 1996; Gorring and Kay, 2001; Rosenbaum et al., 2005; Thorkelson and Breitsprecher, 2005; Madsen et al., 2006; Rosenbaum and Mo, 2011; Cao et al., 2014; Fan et al., 2016; Baillard et al., 2018). Such subduction events differ from those associated with normal oceanic plate, which generally has a crustal thickness of 6–7 km, but they are very widespread and important geological processes among the dynamic systems related to modern oceanic plates. Ridge subduction may be related to certain types of arc magmatism and distinctive recycling of mantle and crustal materials; it is likely related to episodes of continental crustal growth and evolution, unique styles of deformation in overlying plates and to the metallogenesis of some ore types. As a result, ridge subduction has become one of the hot topics in current geological research globally. However, many issues concerning ridge subductions remain controversial. In this paper, we review recent progress in the study of ridge subduction and discusses some developing research frontiers in fields related to ridge subduction.

2. Ridges in modern oceans

2.1 Spreading oceanic ridges

Mid-ocean ridges (i.e., spreading oceanic ridge (SOR)) are divergent plate boundaries associated with the most abundant volcanism in Earth's oceans (Figure 1). Modern mid ocean ridges run through the four major oceans (the Atlantic, Pacific, Indian and Arctic Oceans), and are also the longest (up to 80000 km) topographic highs in the world (Figure 2). They include the East Pacific Rise, Atlantic mid ocean ridge, Indian mid ocean ridge, and Arctic Gakkel ridge (Michael et al., 2003). In addition to the the four major oceans, mid ocean ridges also occur in some relatively small oceanic basins, including examples such as the Woodlark MOR near the Solomon archipelago in the southwestern Pacific Ocean (Yoneshima et al., 2005), the Galapagos MOR near western Central America (Abratis and Wörner, 2001), the Chile MOR in the southeastern Pacific Ocean (Bourgois et al., 2016), and the East Scotia MOR near the Scotia area (Livermore, 2003). In general, the tops of mid ocean ridges are 1–3 km higher than the oceanic basins on either side of the ridges, and are typicallhy situated at depths of 2–3 km below sea level. Some ridges, however, are exposed above sea level and form islands. For example, in Iceland and the Azores rifts or grabens are manifestations of mid ocean ridges, and in Iceland, a mid ocean ridge and mantle plume coincide. Mid ocean ridges result from the convection and upwelling of asthenosphere, and the decompression melting of upwelling asthenosphere generates basaltic magmas, which form new oceanic crust after magma ascent (Figure 1). Therefore, mid ocean ridges are not only divergent plate boundaries, but also sites for generation of oceanic crust (Figure 1), which requires that oceanic crust become older with further distance from the spreading ridge.

2.2 Aseismic reidges and oceanic plateaus

Aseismic ridges (AR) are common in oceanic basins and occur as long, linear and mountainous structures, which are produced by volcanism associated with a hot spot or mantle plume beneath the moving oceanic plate that create a series of coalescing volcanoes of various sizes (Figure 1). Once formed, they are characterized by an absence of earthquakes, which distinguishes them from MORs (Wilson, 1963; Mor-

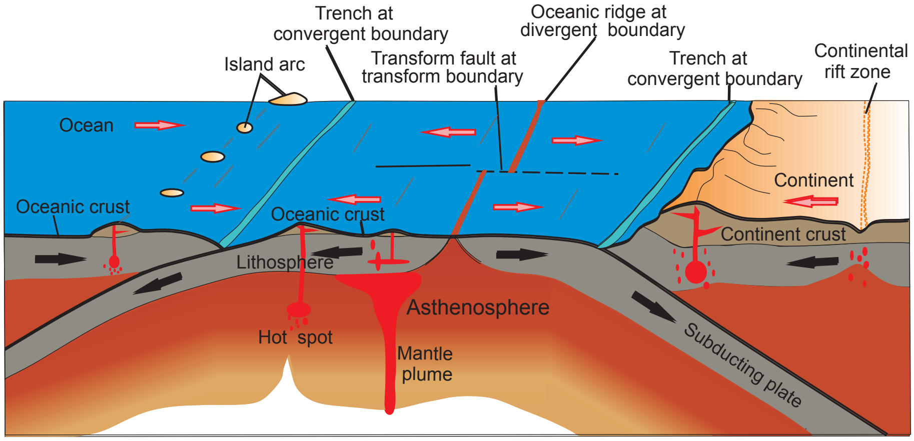

Figure 1 Ocean spreading, mantle plume or hot spot, and oceanic lithosphere subduction.

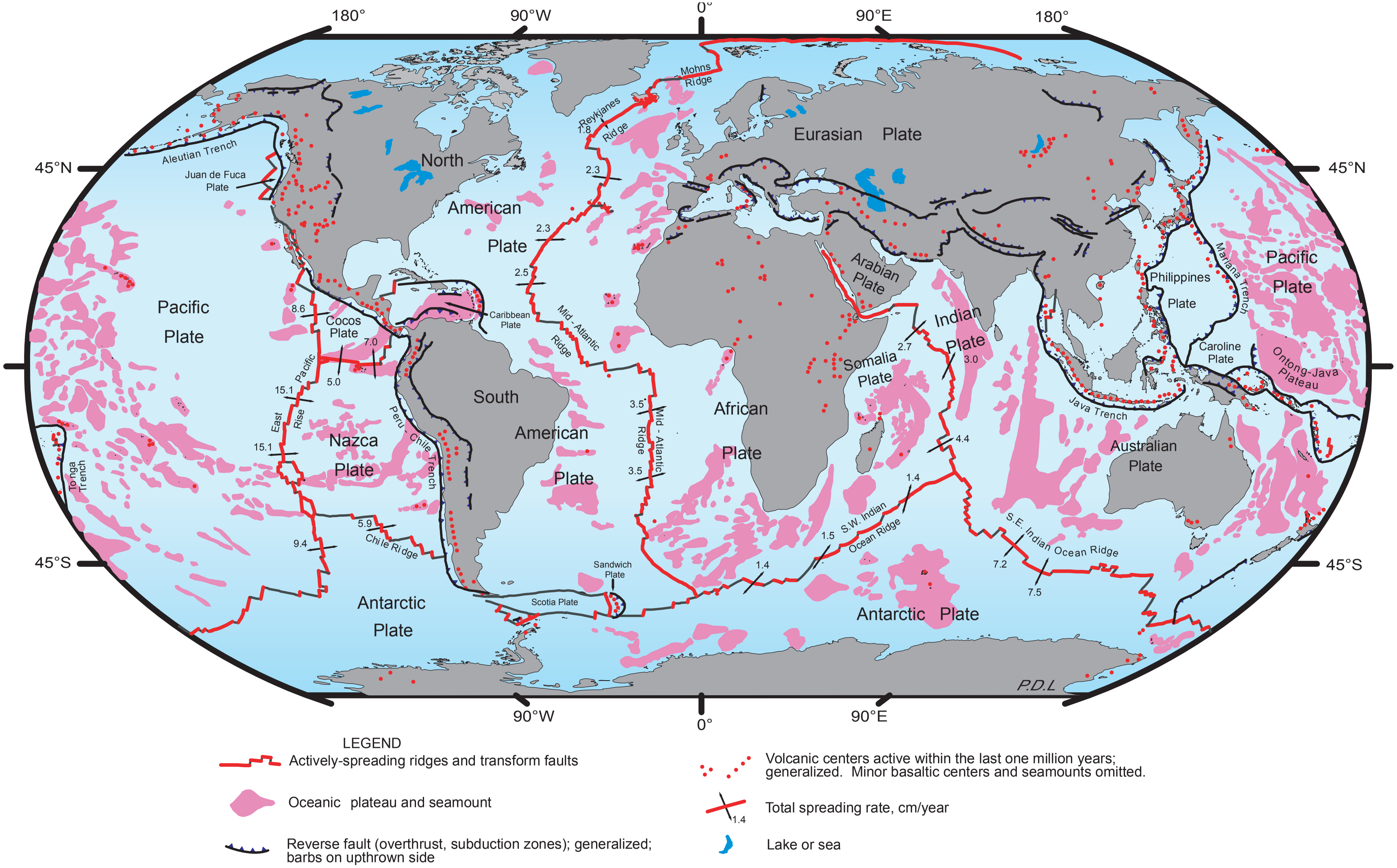

Figure 2 The distribution of spreading oceanic ridges, and oceanic plateaus or aseismic ridges in the world, modifed from NASA (https://visibleearth.nasa.gov/view.php?id=88415), Kerr (2014), and McCrory and Wilson (2009).

gan, 1971). The topography of aseimic ridges exhibits comparatively little relief but while their tops are relatively flat, the two sides are generally steep. They extend 700–5000 km with the widths and heights of 150–400 km and 2000–4000 m, respectively. Portions of some ARs rise above sea level to form oceanic islands (e.g., Hawaii). The modern oceans contain many Ars and examples include (1) Juan Fernandez, Iquique, Nazca, Carnegie, and Cocos ARs in the eastern Pacific ocean; (2) Hawaii-Emperor, Kodiak and Cobb ARs in the northern Pacific Ocean; (3) Ogasawara and Caroline ARs in the western Pacific Ocean; (4) D'Entrecasteaux, Loyalty and Louisville ARs in the southwestern Pacific Ocean; (5) Walvis or Whale, and Rio Grande ARs in the Atlantic Ocean; (6) Lomonosov AR in the Arctic Ocean and 90°E AR in the Indian Ocean.

Oceanic plateau (OP) are large and relatively flat with extensive bodies of mafic-ultramafic rocks having elevation that is higher (2–3 km) than the relief of the surrounding ocean basin and with one or more relatively steep sides. Similar to an AR, an OP is generally considered to be generated by mantle plume or hot spot activity (Mann and Taira, 2004; Zhang et al., 2014; Lu et al., 2016). There are often topographic connections between AR and OP, and they may correspond to the products of partial melting in the tail and head of a mantle plume, respectively (Sleep, 1992; Campbell, 2007; Yan and Shi, 2014). OPs occur widely in the Pacific and Indian Oceans (Figure 2). Prominent examples include Caribbean-Columbia, Ontong Java, Shatsky Rise, Hikurangi, and West Torres OPs in the Pacific Ocean and Kerguelen OP in the Indian Ocean. The Ontong Java OP and Louisville AR were considered to possibly represent the respective products of partial melting in the head and tail for the same mantle plume (Antretter et al., 2004; Kerr and Tarney, 2005; Koppers et al., 2011). It is notable that the western and southern parts of Caribbean-Columbia OP have become part of Latin American and the South American continent via accretion (Kerr and Tarney, 2005) and that, in Alaska, the Yakutat block is also recognized to be an OP that was added to the North American Continent (Eberhart-Phillips et al., 2006; Gulick et al., 2007).

2.3 Inactive arc ridges

Inactive arc ridges (IAR) are former parts of active oceanic arcs that have been isolated from active subduction due to later geological processes, such as back arc extension or subduction step back. Examples include the Kyushu-Palaue, Amami, Daito, and Oki-Daito IARs in the west Philippine Oceanic Basin (Figure 3) (Zhang et al., 2012; Nishizawa et al., 2014) and Lau IAR in the Lau Oceanic Basin (Figure 3) (Frisch et al., 2011; Yan and Shi, 2014). The IARs in the west Philippine Oceanic Basin contain Late Cretaceous-Eocene (117–37 Ma) tonalities in addition to basalts (Haraguchi et al., 2003; Hickey-Vargas, 2005; Zhang et al., 2012; Nishizawa et al., 2014), indicating that these rocks were mainly generated in an arc setting (Haraguchi et al., 2003). The west Philippine Oceanic Basin may have opened as the result of a Jurassic-Early Cenozoic arc, and the IARs in the basin retain information about the original arc (Haraguchi et al., 2003). Similarly, the Kyushu-Palau ridge was likely separated from the Izu-Ogasawara-Mariana arc by back-arc extension (Haraguchi et al., 2003; Hickey-Vargas, 2005; Ishizuka et al., 2018) and the Lau ridge was separated from the Tonga arc by the back-arc extension, and then became inactive (Frisch et al., 2011).

Compared with the oceanic crust of normal thickness (6–7 km), ARs, OPs and IARs have relatively low crustal density but greater (10–33 km) crustal thickness (Mann and Taira, 2004).

3. Spreading oceanic ridge subduction, magmatism and metallogenesis

3.1 Spreading oceanic ridge subduction

Spreading ridge subduction occurs when an active MOR intersects a subduction zone and is then subducted into the mantle along with the adjacent oceanic plates (slabs), which can potentially occur during the evolution of all subduction zones (Thorkelson, 1996). However, the differences of angles at which spreading ridges intersect subduction zones may have important effects on the subduction-related geodynamic processes. If spreading ridges subduct at low angles or parallelly with trenches, the ridges with positive reliefs collide with the continental margin, which casues the tectonic emplacement of ophiolites, and the ridges with negative reliefs may be subducted beneath continental margin (Forsythe et al., 1986; Zheng and Chen, 2016). During the perpendicular or high-angle subduction of mid-oceanic spreading ridges, due to the increase of pressure beneath the MOR as it is subducted, both the decompression melting of asthenospheric mantle beneath mid ocean ridges and the growth of oceanic crust may cease. Continuous spreading of the mid ocean ridge, however, creates a space between the two subducted oceanic slabs along the spreading axis, and beneath the overlying plate (Thorkelson, 1996; Sisson et al., 2003) (Figure 4). This space is referred to as a slab window, which is the most important feature of MOR subduction (Figure 4). In general, during the "normal" oceanic plate subduction, mantle corner flow occurs above the subducted slab. During MOR subduction, in addition to mantle corner flow, large scale upwelling of asthenospheric mantle beneath SORs can occur with the opening of the slab window. Therefore, compared to magmatism triggered by "normal" oceanic plate subduction, the magmatism triggered by the MOR subduction can produce more rock types in a greater variety of locations (Thorkelson, 1996; Sisson et al., 2003). It

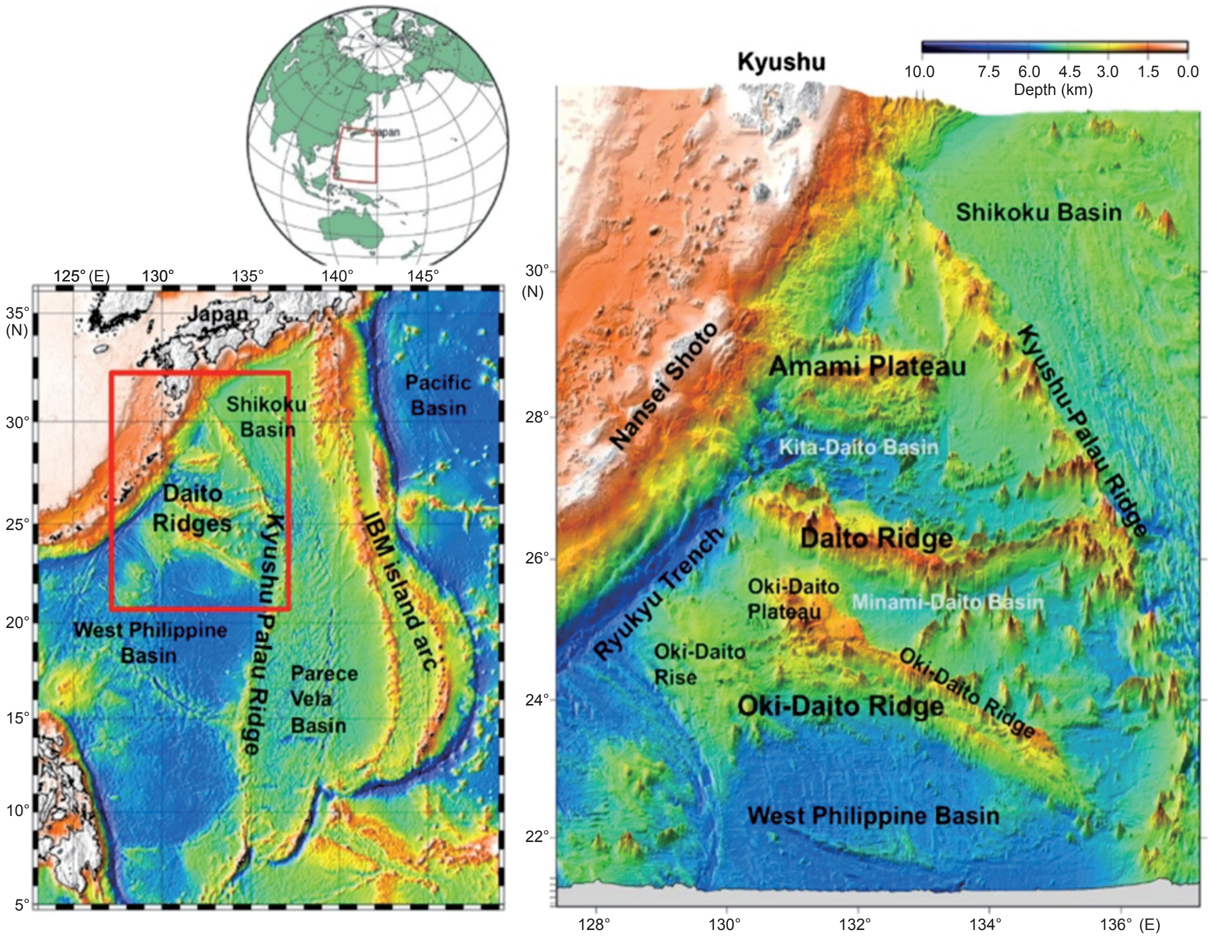

Figure 3 The distribution of inactive arc ridges in the West Philippine Basin (Nishizawa et al., 2014).

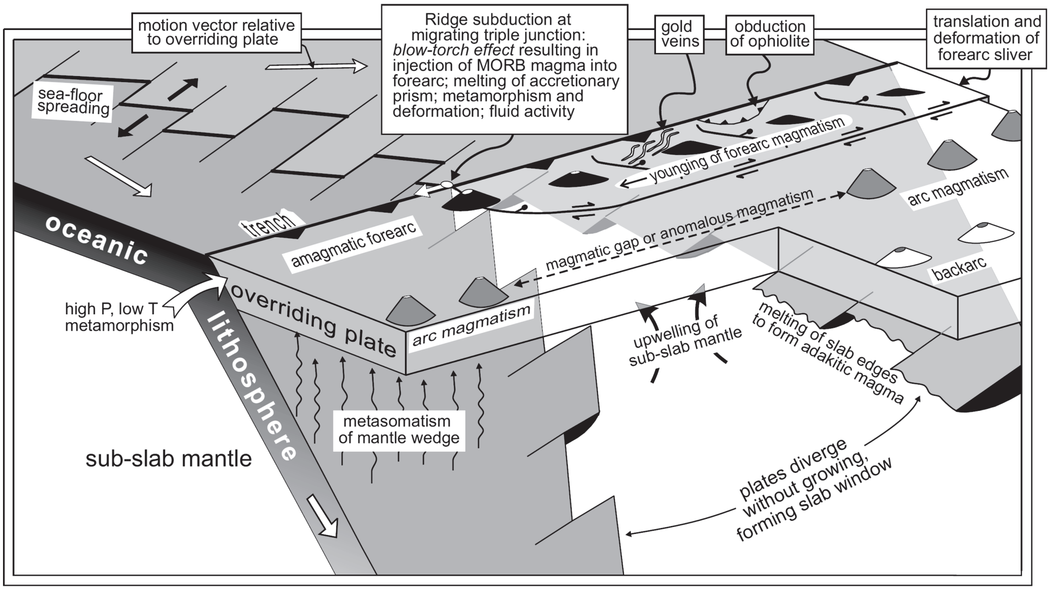

Figure 4 Spreading oceanic ridge subduction and magatism (Thorkelson, 1996; Sisson et al., 2003).

should be noted that the (perpendicular or high-angle) subduction of fossil oceanic ridges can not cause the formation of slab window.

Subduction of many spreading oceanic ridges is presently occurring in circum-Pacific subduction zones in Cenozoic. Typical cases include: (1) the Woodlark MOR in the southwestern Pacific Ocean, which is being subducted northeastward beneath the Solomon arc (Weissel et al., 1982; Yoneshima et al., 2005; König et al., 2007; Chadwick et al., 2009; Taylor et al., 2008; Schuth et al., 2011; Holm et al., 2016); (2) the Chile MOR that is being subducted southeastward beneath the South American continental arc (Lagabrielle et al., 1994, 2000; Gorring and Kay, 2001; Gorring et al., 2003; Guivel et al., 2006; Anma et al., 2009; Bourgois et al., 2016); (3) the Galapagos MOR that is being subducted eastward beneath the central American continental arc (Johnston and Thorkelson, 1997; Abratis and Wörner, 2001; Hoernle et al., 2008); (4) the Juan de Fuca SOR, which is being subducted eastward beneath the North American continental arc (Rogers et al., 1985; Cole and Basu, 1992; Madsen et al., 2006; Cole and Stewart, 2009; Thorkelson et al., 2011). In addition, studies have shown that the Kula-Farallon/Resurrection MOR was subducted beneath the Alaska Terrane during the Paleocene-Eocene (Breitsprecher et al., 2003; Haeussler et al., 2003; Benowitz et al., 2012; Scharman et al., 2012), and the Izanagi-Pacific MOR was subducted beneath the eastern Asian continent during the Early Cenozoic (60–50 Ma) (Whittaker et al., 2007; Seton et al., 2015). Other studies have suggested that the MOR between Antarctic and Phoenix plates was subducted beneath the Antarctic continent during the Miocene-Pliocene (20–3 Ma) (Eagles, 2003; Livermore et al., 2004; Breitsprecher and Thorkelson, 2009).

The most important step in establishing MOR subduction is to confirm the existence of the slab window. For example, geophysical data suggest the existence of a long-hypothesized slab window, a gap between the subducted Nazca and Antarctic lithospheres after the subduction of the Chile MOR (Russo et al., 2010a, 2010b). A gap is defined by P and S waves at a mantle depth of 100–200 km occurs where the wave velocity of mantle is clearly lower than those of the surrounding mantle, indicating that the upwelling hot asthenosphere has entered the slab window (Russo et al., 2010a, 2010b). Other types of data may provide evidence of a slab window. In one case, distinct Pb isotope compositions suggest that a slab window formed after the Woodlark MOR in the southwestern Pacific Ocean was subducted northeastward beneath the Solomon arc and the component from subducted Pacific Plate at the deep mantle depth has entered the magmatic rocks of the Solomon arc (Chadwick et al., 2009; Schuth et al., 2011).

3.2 A magmatic rock suite related to the subduction of MOR

There are similarities and differences between magmatism triggered by the subduction of normal oceanic plate and MOR. The similarities are that an “arc” magmatic rock suite (e.g., basalt-basaltic andesite-andesite-dacite-rhyolite) originates from slab fluid-metasomatized mantle due to the subduction of normal oceanic plates on two sides of the subducted oceanic ridge or slab window (Figure 4) (Benoit et al., 2002; König et al., 2007). The differences are that a “within-plate” magmatic rock suite can be generated by the associated extension and the large mount of heat provided by the upwelling asthenosphere due to the opening of the slab window during MOR subduction. Such suites can include: (1) adakites derived from subducted young oceanic crust on two sides of slab window (e.g., Kay et al., 1993; Stern and Kilian, 1996; Aguillón-Robles et al., 2001; Benoit et al., 2002; Gorring et al., 2003; Guivel et al., 2003); (2) OIB-type basaltic rocks derived from the deep upwelling asthenosphere and are similar to OIBs in trace element and Sr-Nd isotope compositions (Gorring et al., 2003; Thorkelson et al., 2011); (3) MORB-type basaltic rocks generated by decompression melting of upwelling asthenosphere at shallow depths, which are similar to MORBs in trace element and Sr-Nd isotope compositions (Cole and Basu, 1992; Lytwyn et al., 1997; Thorkelson et al., 2011); (4) Nb-enriched basalts derived from slab melt or adakitic melt-metasomatized arc mantle (Aguillón-Robles et al., 2001; Benoit et al., 2002); (5) high-Mg andesites produced by the interaction between slab melts or adakitic melts and the overlying mangtle or low-degree melting of slab or adakitic melt-metasomtized arc mantle (Rogers et al., 1985; Kay et al., 1993; Stern and Kilian, 1996; Aguillón-Robles et al., 2001; Benoit et al., 2002; Osozawa et al., 2012); (6) tholeiites generated by high-degree melting of overlying mantle due the thermal anomalies triggered by the slab window (Benoit et al., 2002); (7) rhyolites or dacites generated by partial melting of upper crustal sedimentary rocks or base metasedimentary rocks due the thermal anomalies triggered by a slab window (Cole and Basu, 1992); (8) boninites derived from melting of depleted mantle underging many time melting (Osozawa et al., 2012). Therefore, the subduction of MOR can generate both “normal” arc and “within plate” magmatic rock suites, from magma sources that contain mantle wedge peridotites, subducted oceanic crust, middle-lower crust beneath arc, and asthenosphere from the slab window. Adakites generated during the subduction of MOR exhibit trace element and Sr-Nd-Pb isotope compositions similar to altered MORBs (Aguillón-Robles et al., 2001; Benoit et al., 2002).

3.3 Metallogenesis related to the subduction of MOR

The relationship between the subduction of MOR and metallogenesis has attracted widespread attention (Haeussler et al., 1995, 2003; Ling et al., 2009; Sun et al., 2010). A typical Cenozoic case is the subduction of the Kula-Farallon/Resurrection MOR and associated Au mineralization in the Alaska area: (1) between 65–50 Ma, the Kula-Farallon/Resurrection MOR was subducted beneath the Alaska Terrane; (2) it resulted in the opening of slab windows and the upwelling of asthenosphere from the slab window heated the sediments of the forearc accretionary wedge to release fluids; (3) the fluids caused the formation of quartz vein type gold deposits (Figure 5) (Haeussler et al., 1995, 2003). Although there are many Cu and Au deposits in the Andes continental arc of South America and Papua New Guinea-Solomon island arc associated with Cenzoic subduction of oceanic plates (Solomon, 1990; Rosenbaum et al., 2005), the present subduction of Chile and Woodlark MORs are not associated with Cu-Au mineralization or quartz-vein style deposits. The latter style of deposits may exist at depth in these young settings, but the potential for the metal mineralization needs to be further studied.

4. Aseismic ridge subduction, magmatism and metallogenesis

4.1 Aseismic ridge subduction

In general, ARs or OPs have relatively low crustal density and greater crustal thickness than normal oceanic crust. Therefore, they are considered to be difficult to subduct, and mainly form collages through collisions with island or continental arc to cause the lateral growth (Niu et al., 2003, 2015; Kerr, 2014; Zhang et al., 2014; Whattam and Stern, 2015). Typical cases include: (1) the Late Mesozoic, Cretaceous Caribbean-Columbia OP (Kerr et al., 1997; Kerr, 2014) and Jurassic (Japan arc) OP (Kimura et al., 1994; Ichiyama et al., 2014) accretion along continental margins or arcs; (2) the collision between the Caroline AR and Yap arc in West Pacific Ocean (Dong et al., 2018). However, some studies have suggested that two-thirds ARs or OPs did not create collages with island or continental arcs but were subducted (e.g., McGeary et al., 1985).

Abundant geophysical data demonstrate that some ARs are being subducted now (Gutscher and Peacock, 2003; Espurt et al., 2008; Mason et al., 2010; Morell et al., 2012, 2013; Martinod et al., 2013; Baillard et al., 2018). In the East Pacific Ocean, the Juan Femandez, Iquique, Nazca, Canegie and Cocos ARs are presently associated with flat subduction (with subduction angles <30°) eastward beneath the Central and South American continents (Figure 6) (Bourdon et al., 2003; Hoernle et al., 2008; Espurt et al., 2008; Rosenbaum and Mo, 2011; Morell et al., 2012, 2013). In the North Pacific Ocean, the Kodiak and Cobb ARs are being subducted at low angle northward beneath the Alaska-Aleutian arc (Gutscher and Peacock, 2003; Eberhart-Phillips et al., 2006; Fuis et al., 2008; Worthington et al., 2012). In the West and Southwest Pacific Ocean, however, the Ogasawara, D'Entrecasteaux and Lomonosov ARs are being subducted steeply (with subduction angles >50°) (Mason et al., 2010; Martinod et al., 2013; Baillard et al., 2018).

Geodynamic reconstructions suggest that some OPs are being subducted (Fuis et al., 2008; Schuth et al., 2011; Baillard et al., 2018). In terms of characteristics and types of subduction, four types of OP subduction models may be classified as follows: (1) deep subduction: the West Torres OP in Southwest Pacific Ocean is being subducted deeply eastward beneath the Vanuatu arc (Baillard et al., 2018); (2) collision and flat subduction: the Yakutat OP collided with North American Plate, and then was subducted flatly (with subduction angle of 6°) northward beneath North American Plate and has entered for 500 km during recent 10 Ma (Eberhart-Phillips et al., 2006; Gulick et al., 2007; Fuis et al., 2008; Worthington et al., 2012); (3) collision and deep subduction: after the Ontong Java collided with the Solomon arc, the upper materials (the crustal uppermost basalts and sediments with the thickeness of 7 km) of the OP accreted along the Solomon arc, but the lower materials (80% of the crustal thickness) of the OP were subducted deeply (Petterson et al., 1997; Mann and Taira, 2004; Miura et al., 2004; Schuth et al., 2011); (4) subduction and tearing: the Meiji OP was subducted beneath the Kamchatka and Aleutian arcs, and was followed by slab tear or catastrophic slab loss (Yogodzinski et al., 2001; Levin et al., 2002, 2005).

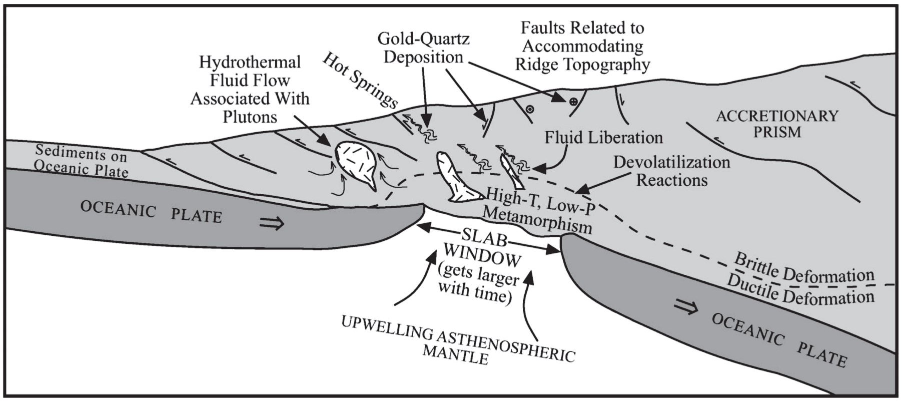

Figure 5 The spreading oceanic ridge subduction, metamorphism and Au minerlization in the Alaska area (Haeussler et al., 1995, 2003).

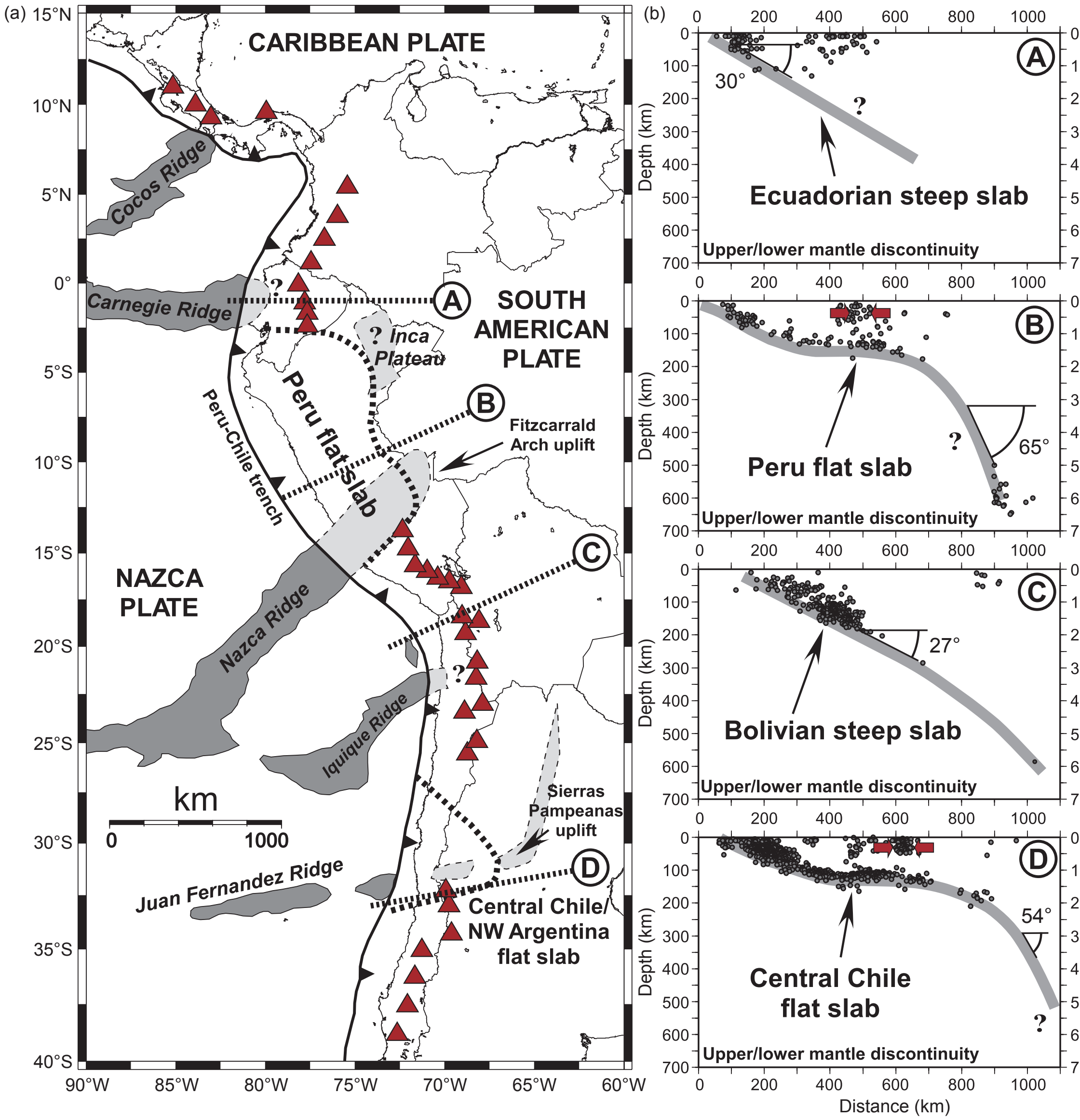

Figure 6 Geodynamic setting of the Nazca-South American convergence system (Espurt et al., 2008). (a) The Nazca plate bears many topographic anomalies (aseismic ridges or oceanic plateaus marked in gray areas) where the crust is anomalously thick and buoyant. The estimated subducted lengths of these anomalies beneath the South American plate are shown in light gray areas. Red triangles mark active andesitic volcanism. (b) Profiles of the Nazca slab beneath the South American plate from earthquake epicenters plotted.

4.2 A magmatic rock suite produced by the subduction of aseismic ridges

AR or OP subduction are commonly considered to cause the formation of volcanic gaps (McGeary et al., 1985). The most typically cited cases are the collision between the Caroline AR and Yap arc in West Pacific Ocean and the subduction of the Nazca ridge beneath South America, which did not trigger Quternary arc magmatism (McGeary et al., 1985; Dong et al., 2018; Rosenbaum and Mo, 2011). However, Cenozoic or Quaternary arc magmatism widely ocurrs in other areas where ARs or OPs are being subducted. Examples include: (1) South and Central American arcs associated with the subduction of the Iquique, Carnegie and Cocos ridges (Gutscher et al., 2000; Beate et al., 2001; Samaniego et al., 2002, 2005; Bourdon et al., 2003; Hoernle et al., 2008; Rosenbaum and Mo, 2011; Ancellin et al., 2017); (2) the Kamchatka and western Aleutian arcs associated with the subduction of the Meiji-Hawaii-Emperor AR or OP (Yogodzinski et al., 1994, 1995, 2001); (3) the Vanuatu arc associated with the subduction of the D'Entrecasteaux asiesmic ridge and the West Torres oceanic plateau (Beaumais et al., 2013, 2016; Beier et al., 2018). As the plate reconstruction of Rosenbaum et al. (2005) demonstrates, although no coeval arc magmatim may occur in the areas where the subduction of aseismic ridges is going on, arc magmatism coeval with the subduction may occur elsewhere along the arc throughout the period of AR subduction.

Magmatic rocks associated with the subduction of ARs or OPs contain: (1) The adakite–high Mg andesite–adakitic andesite–Nb-enriched basalt suite (Gutscher et al., 2000; Beate et al., 2001; Samaniego et al., 2002, 2005; Bourdon et al., 2003; Bryant et al., 2006; Yogodzinski et al., 1994, 1995, 2001; Levin et al., 2002). A typical case is the Ecuador arc associated with the subduction of the Carnegie AR (Gutscher et al., 2000; Beate et al., 2001; Samaniego et al., 2002, 2005; Bourdon et al., 2003; Bryant et al., 2006): adakites were generated by partial melting of flatly subducted AR slab, and high-Mg andesites were produced by the interaction between slab melts and mantle; some slab melts matasomatized the mantle to form pargasite, phlogopite and garnet-bearing enriched mantle. When dragged down by convection, the modified mantle undergoes a first partial melting event due to the destabilization of pargasite and produces adakitic andesites; dragged down deeper, the mantle melts a second time via the destabilization of phlogopite and produces Nb-enriched basalts. (2) The adakite-OIB-type alkaline basalt suite. A well-documented case is the Costa Rica-Panama arc associated with the subduction of the Cocos AR: adakites were generated by partial melting of subducted AR and OIB-type alkaline basalts were derived from asthenospheric mantle upwelling from the slab window (Abratis and Wörner, 2001; Hoernle et al., 2008; Gazel et al., 2015). (3) Jamaica-type adakites (high SiO_2 and Na_2O, low MgO, and high La/Yb and low Sr/Y ratios) and high-Nb basalts. The Jamaica arc is associated with the subduction of the Caribbean OP: high SiO_2 and low MgO adakites were generated by partial melting of flatly subducted OP under garnet amphibolite facies conditions, and high-Nb basalts were produced by partial melting of slab melt-metasomatized mantle wedge materials or a mantle plume-like source (Figure 7) (Hastie et al., 2010a, 2010b, 2015). (4) The basalt-basaltic andesite-andesite suite. The representative case is the Vanuatu arc associated with the subduction of the D'Entrecasteaux AR and the West Torres OP: the basalt-basaltic andesite-andesite suite was derived from fractional crystallization of magmas generated by partial melting of subduction fluid-metasomatized mantle wedge (Beaumais et al., 2013, 2016; Beier et al., 2018).

4.3 Aseismic ridge subduction and metallogenesis

In the Cenozoic, Cu-Au mineralization is associated with the subduction of some ARs. Typical cases include: (1) subduction of the Scarbprpugh AR beneath the Luzon arc (Yang et al., 1996) that formed the Baguio and Lepanto-Far South

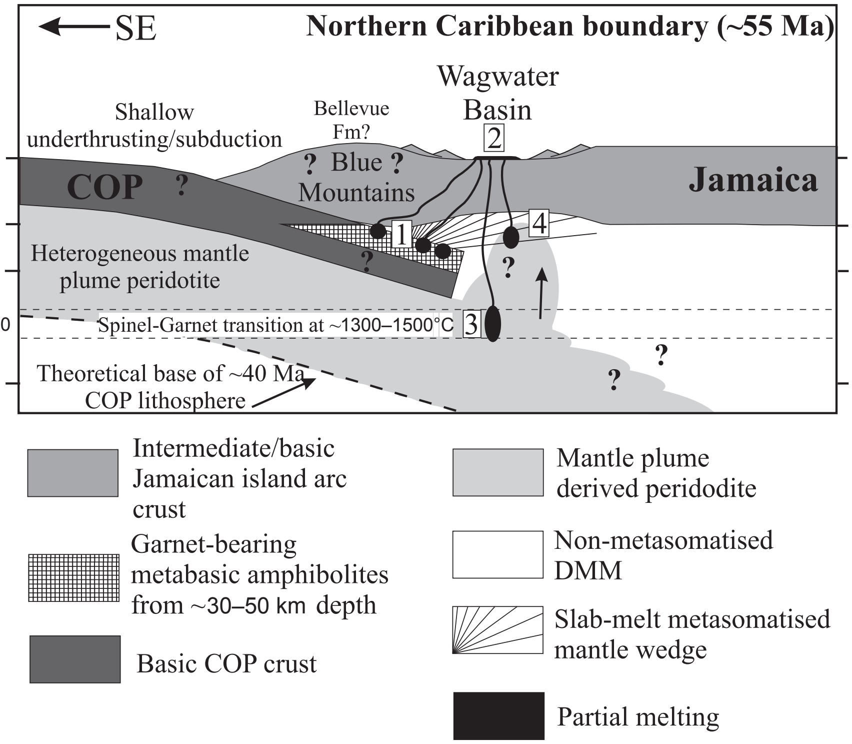

Figure 7 Tectonomagmatic model to explain the derivation of the Jamaica-type adakite–high Nb basalt suite of rocks (Hastie et al., 2015). COP: Caribbean oceanic plateau; DMM: Depleted MORB-type mantle source. The numbers on the figure refer to: (1) At 30–50 km depth, partial melting of subducted Caribbean Oceanic Plateau generated Jamaica-type adakitic magmas, which passed through the thin mantle wedge and had limited interaction with the overlying peridotite; (2) during the extension of the Wagwater basin, the decompressure melting of the upwelling mantle materials happened; (3) partial melting of mantle plume-like source generated the first type of high-Nb basalts in the deep-lying area; (4) decompressure melting of slab melt-metasomatized mantle wedge produced the second type of high-Nb basalts.

East Au deposits and the Guinaoang and Santo Tomas II Cu deposits (Cooke et al., 2005; Sun et al., 2010); (2) subduction of the Euripik Rise or OP beneath the Papua New Guinea arc (Gutscher et al., 2000), which produced the famous Grasberg, Frieda River, Ok Tedi and Porgera Cu-Au deposits (Cooke et al., 2005); (3) the subduction of the Roo Rise OP beneath the East Java Island arc (Shulgin et al., 2011) that generated the Batu Hijau Au deposits (Cooke et al., 2005); (4) the subduction of the Cocos AR beneath the Costa Rica-Panama arc in Central America (Abratis and Wörner, 2001; Hoernle et al., 2008) associated with the Cerro Colorado Cu-Au deposit (Cooke et al., 2005); (5) the subduction of the Carnegie AR beneath the Ecuador arc (Beate et al., 2001; Bourdon et al., 2003) that produced the Chaucha Cu-Mo deposit (Cooke et al., 2005); (6) the subduction of the Juan Femandez AR beneath South American continent (Rosenbaum et al., 2005) that was associated with the El Teniente, Rio Blanco and Los Pelambres super-large Cu deposits (Cooke et al., 2005; Rosenbaum et al., 2005).

Conversely, however, there is no coeval metal mineralization or deposit in the overlying plate where the Nazca AR is being subducted beneath South American continent (Cooke et al., 2005; Sun et al., 2010). In the reconstruction of Rosenbaum et al. (2005), numerous large-scale Cu deposits formed in the overlying plate when the Nazca AR was subducted beneath South American continent between 16–2 Ma.

5. Inactive arc ridge subduction, magmatism and metallogenesis

The Kyushu-Palau, Amami, Daito and Oki-Daito IAR as well as the West Philippine Oceanic Basin are being subducted beneath the Southwest Japan arc (Wallace et al., 2009; Cao et al., 2014). The subduction of the Kyushu-Palau ridge generated basalts, high-Mg andesites and adakites (Morris, 1995; Cao et al., 2014), and are linked to formation of the Hishikari and Nansatsu Au deposits (Hedenquist et al., 1994; Cooke et al., 2005).

6. Common effects of ridge subduction

The subduction of SORs, ARs or OCs and IARs is a very common and important geological process in the geodynamic system of modern oceanic plate tectonics. In addition to generating arc magmatism and metal mineralization, it can cause extension in the overlying plate or compression deformation, surface subsidence and uplift or plateau uplift, or the formation of a within-plate orogenic belt (Livaccari et al., 1981; Gutscher and Peacock, 2003; Madsen et al., 2006; Taylor et al., 2005; Espurt et al., 2008; Guillaume et al., 2009; Wallace et al., 2009; Liu et al., 2010; Rosenbaum and Mo, 2011; Benowitz et al., 2012; Martinod et al., 2013; Margirier et al., 2015; Yonkee and Weil, 2015; Salze et al., 2018) with the subduction erosion in the front part or base of the overlying plate (von Huene and Scholl, 1991; Ranero and von Huene, 2000; von Huene et al., 2004; Bourgois et al., 1996; Miura et al., 2004). Subduction erosion is a significant geological process in subduction zones, during which subducted oceanic plate removes materials from the overlying plate by tectonic activity and draws them into the deep mantle during subduction (Figure 8) (von Huene et al., 2004). The subduction of SORs, ARs or OCs and IARs readily cause or enhance subduction erosion in the overlying plate (Bourgois et al., 1996; von Huene et al., 2004; Miura et al., 2004; Bangs et al., 2006; Ramírez de Arellano et al., 2012; Vannucchi et al., 2016). Compared with accretionary plate margins formed by the subduction of the oceanic lithosphere, erosional plate margins may form because the subduction erosion process drags materials from the front part or base of the overlying plate into the deep mantle (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). In the Cenzoic Circum Pacific subduction zones, erosional plate margins occur along the western part of South and Central America, Japan-Ryukyu arc, Izu-Ogasawara-Mariana arc and the southwestern Pacific Ocean coincident with the occurrence of ridges (Figure 9). Subduction erosion is one of the mosy important mechanisms whereby subducted slab brings continental crustal materials into the deep mantle (von Huene et al., 2004; Clift and Vannucchi, 2004). The continental crustal materials that enter the deep mantle by subduction erosion can significantly change the composition of the overlying mantle wedge and sources of arc magmatism (Goss and Kay, 2006; Goss et al., 2013).

7. Scientific problems and prospects

7.1 Subduction forms and dynamic mechanisms

The oceanic plates have complex shapes and structures. Differences in the convergence angles between plates can cause a variety of geometric relationships between subducted SORs, ARs or OPs, and IARs versus the trench. These variations may result in vastly different geolgocial phenomena. Thorkelson (1996) discussed the theoretical relationships between subducted SORs convergence directions relative to subduction zones, the formation and shapes of slab windows, and the evolution of arc magmatism. However, reconstructing the detailed processes from the initial subduction of SORs to the formation of slab windows and the evolution of arc magmatism is truly challenging. Some studies suggest that if spreading ridges subduct at low angles or parallelly with trenches, the ridges with positive reliefs collide with the continental margin, and the ridges with negative reliefs may be subducted beneath continental margin (Forsythe et al.,

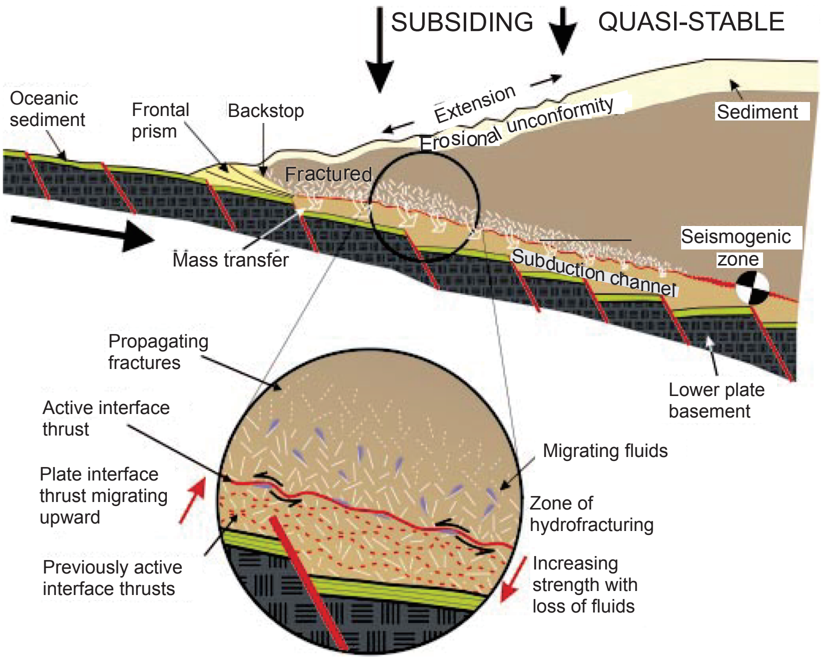

Figure 8 The subduction erosion model (von Huene et al., 2004).

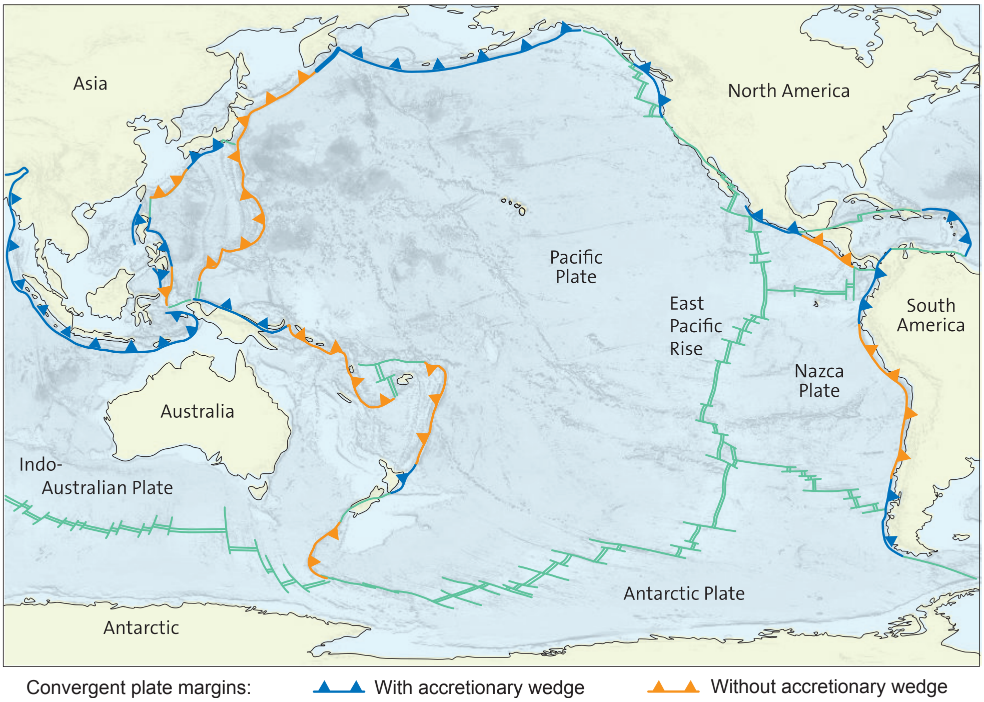

Figure 9 Accretionary (with accretionary wedge) and erosion (without accretionary wedge) pate margins in the Circum pacific subduction zone (von Huene and Scholl, 1991; Frisch et al., 2011).

1986; Zheng and Chen, 2016). In addition, numerous studies have suggested that oceanic detachment fault systems are very widespread globally and, in slow-spreading and ultraslow-spreading systems plate divergence is either not accommodated by magmatic accretion or is only accommodated episodically, and instead divergence occurs by low-angle, large offset extensional detachment faults (Cann et al., 1997; Dick et al., 2003; Smith et al., 2006; Escartín et al., 2008; Liu et al., 2014; Wu et al., 2014; Maffione et al., 2015; Gülcher et al., 2019). Therefore, oceanic crust is often missing in slow-spreading and ultraslow-spreading systems. If such systems undergo compression, there arectwo possible consequences: (1) the subduction of oceanic detachment fault systems or slow-spreading and ultraslow-spreading oceanic ridge systems happens and slab windows may be formed; (2) or, given that the oceanic detachment fault systems are weak zones of the oceanic lithosphere consisting of serpentine- and talc-bearing fault zones they may, upon compression, promote plastic strain localization adjacent to spreading ridges where lithosphere is thin and hot (Maffione et al., 2015). This may trigger initation of intra-oceanic subduction adjacent to spreading ridges (Maffione et al., 2015; Keenan et al., 2016; Gülcher et al., 2019; Zhang et al., 2019). Therefore, the results of spreading oceanic ridge subduction are very complex.

Another important issue is the contribution of various driving forces for the subduction of SORs, ARs or OPs and IARs. In general, the driving forces for the subduction of oceanic plate include ridge push, mantle convection, mantle plume, crustal thickening-triggerred gravitational potential energy (GPE), and slab pull and suction (Stern, 2007; Faccenna et al., 2013). Among them, slab pull and suction are considered as the most important, accounting for 90% of the total driving force (Stern, 2007). Similar to the subduction of the normal oceanic plate, the driving force for the subduction of SORs, ARs or OPs and IARs should be related to slab pull and suction. In addition, as mentioned above, the subduction angles for SORs, ARs or OPs and IARs in eastern and western Pacific Ocean are different: flat and deep, respectively (Rosenbaum and Mo, 2011). What are the control factors for constrainting the subduction angles? Some researches have proposed that the high seafloor topography, crustal density, slab thickness, slab age, slab suction, trench retreat, the nature and movement characteristics of overlying plate, and thermal states and rheological properties of mantle wedges may have effects on the subducion angles (Gerya et al., 2009; Martinod et al., 2013; Antonijevic et al., 2015; Zeumann and Hampel, 2016). However, the above inferences need to be tested further. Irrespective of the subduction angles, the tearing, rollback or delamination of these subducted SORs, ARs or OPs and IARs may occur (Levin et al., 2002, 2005; Guivel et al., 2006; Fuis et al., 2008; Sigloch et al., 2008; Liu and Stegman, 2012; Antonijevic et al., 2015; Portner et al., 2017; Zhao et al., 2017; Zhou et al., 2018; Zhou, 2018).

7.2 Material recycles in subduction zones

Subduction zones are an important place for the exchange of crustal and mantle materials and the transfer of energy between Earth systems (Stern, 2002; Tatsumi, 2005; Zheng et al., 2015; Zheng and Chen, 2016; Zheng and Zhao, 2017), and are referred to as the "Subduction Factory" (Tatsumi, 2005; Staudigel et al., 2010). During the classic subduction of oceanic rocks, the "Subduction Factory" processes original materials including oceanic sediments, oceanic crust, mantle lithosphere and mantle wedge, makes products including arc magmatism and continental crust. At the same time, discarded or residual materials (e.g., chemically changed slab (oceanic crust and sediments) components, and delamimated mafic lower crust) are removed and stored in the deep mantle as the source for mantle plume or hot spot magmatism (Tatsumi, 2005). However, during ridge subduction, ARs, OPs, IARs, and overlying plate materials scraped by subduction erosion are potential original materials for "Subduction Factory" (von Huene et al., 2004; Clift and Vannucchi, 2004; Goss and Kay, 2006; Goss et al., 2013; Staudigel et al., 2010), which are more enriched K, Ba, La, Ce, U, Th, Pb, Rb and Cs contents than normal oceanic crust and can play an important role in the chemical heterogeneity of the global mantle (Staudigel et al., 2010). Recent studies suggest that the components from some subducting ARs (e.g., Cocos and Louisville) have entered into mantle flow regimes in subduction zones and are recycled by arc magmatism (Turner and Hawkesworth, 1997, 1998; Hoernle et al., 2008; Timm et al., 2013; Gazel et al., 2015). The essential question is: how to discriminate exactly the contribution components from ARs, OPs, IARs (Beate et al., 2001; Samaniego et al., 2002, 2005; Bourdon et al., 2003; Bryant et al., 2006; Hoernle et al., 2008; Gazel et al., 2015) and those materials scraped off the overlying plate by subduction erosion (Goss and Kay, 2006; Goss et al., 2013).

7.3 Deep geodynamic mechanisms for the generation of magmatism

As mentioned above, the perpendicular or high-angle subduction of mid-oceanic spreading ridges generally forms slab windows that allow for large scale asthenosphere upwelling. The upwelling asthenosphere introduces abundant heat and materials that promote the generation of abundant and diverse magmatism (Thorkelson, 1996; Thorkelson and Breitsprecher, 2005). However, if spreading ridges subduct at low angles or parallelly with trenches, the ridges with positive reliefs collide with the continental margin, which does not form slab windows. In addition, the perpendicular or high-angle subduction of fossil oceanic ridge does also not cause the formation of slab windows. In these two cases, there is no large mount of heats without slab windows, which impedes the generation of magmatism. Although subduction of ARs or OPs was considered to have caused volcanic gaps (e.g., McGeary et al., 1985), the subduction of some Cenozoic AR or OP and IARs have triggered magmatism is many cases (Gutscher et al., 2000; Beate et al., 2001; Bourdon et al., 2003; Beaumais et al., 2013, 2016). Which geodynamic mechanisms cause the generation of magmatism beneath island or continental arcs? In general, in addition to the subduction fluid addition into mantle wedge, the heat provided by asthenospheric mantle wedges above a subducted slab (McGeary et al., 1985; Gutscher et al., 2000; Gerya et al., 2009; Frisch et al., 2011), the asthenospheric mantle flowing laterally into the space between the mantle wedge and the descending slab due to slab rollback (Zheng et al., 2016; Zheng and Chen, 2016; Zheng, 2019; Zheng et al., 2020) or the upwelling asthenosphere beneath the tearing subducted slab (Yogodzinski et al., 2001; Rosenbaum et al., 2008) play crucial roles in the generation of arc magmas. e. g., during the slab rollback, the asthenospheric mantle heats the surface of the rollbacking slab, and casues partial melting of slab materials and the generation of felsic (including adakitic) melts, which interact with or metasomatize mantle to form adakite, high andesites, Nb-enriched basaltic rocks or OIB-type basalts (e.g., Bourdon et al., 2003; Tang et al., 2010; Zheng et al., 2015, 2016, 2020; Zheng and Chen, 2016; Zheng, 2019; Hao et al., 2019). Nevertheless, some adakites may be derived from partial melting of the ancient oceanic crust at fossil subduction zones due to continental rifting (Zheng and Zhao, 2017).

However, recent geophysical prospecting and numerical simulation indicate that the subduction of SORs can cause the formation of slab windows, which trigger asthenospheric material upwelling above the subducted slab (Russo et al., 2010a, 2010b). The subduction of ARs or OPs and IARs can cause the tearing or delamination (Levin et al., 2002, 2005; Liu et al., 2010; Liu and Stegman, 2012; Cao et al., 2014; Antonijevic et al., 2015; Portner et al., 2017; Zhao et al., 2017) of the subducted slab. Therefore, hot asthenospheric materials from beneath the slab may upwell above the slab (Portner et al., 2017; Zhao et al., 2017), which provides important materials and heat for the generation of arc magmatism (Figure 10) (Yogodzinski et al., 2001; Rosenbaum et al., 2008; Manea et al., 2013).

7.4 The deep control mechanisms and contributing factors for metallogenesis

The subduction of SORs, ARs or OPs and IARs can cause the formation of metal deposits (e.g., Haeussler et al., 1995, 2003; Ling et al., 2009; Cooke et al., 2005; Rosenbaum et al., 2005; Sun et al., 2010, 2015; Tang et al., 2010; Cao et al., 2011; Zhan et al., 2015). Although some studies have suggested that subducted oceanic crust-derived melts and their interaction with mantle can transport metallogenetic materials that form or enhance metal mineralization (Mungall, 2002; Ling et al., 2009; Sun et al., 2010), the metallogenetic systems are very complex (e.g., Rosenbaum et al., 2005) because they are influenced by many factors (e.g., Rosenbaum et al., 2005). Taking Cenozoic AR subduction in South America as an example, some metallic mineral deposits are associated with contemporary subduction of ARs (e.g., Juan Fernandez, Nazca, Carnegie and Cocos), and mainly occur in the volcanic gap or the late epoch of magmatic activities (Cooke et al., 2005; Rosenbaum et al., 2005), but some other metallic mineral deposits are not associated with coeval subduction of aseismic ridges (e.g., Iquique) (Rosenbaum et al., 2005). Some studies suggested that surface compressure deformation, crustal thickening, subduction angle change, magmatic evolution, fluid activity, occurrence types (volcanic eruption or magmatic intrusion) or slab melting may have important effects on the metallogenesis (Kay and Mpodozis, 2001; Rosenbaum et al., 2005).

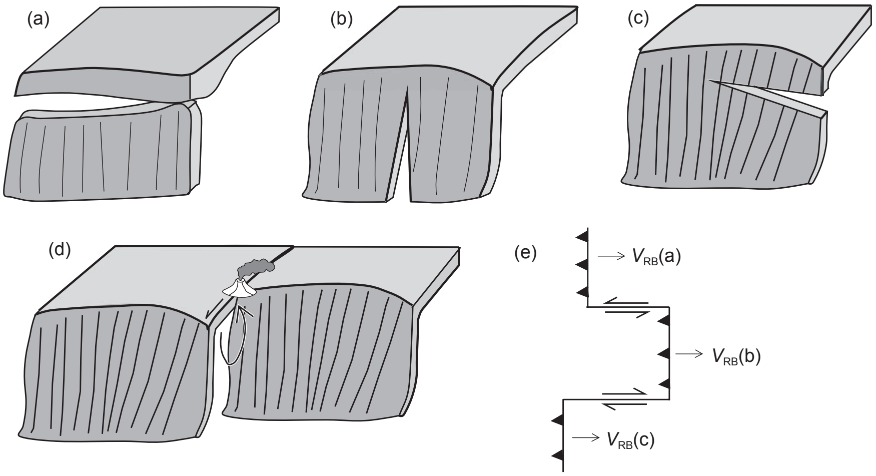

Figure 10 Schematic illustrations of processes involving tearing and/or breakoff of subducting slabs (Rosenbaum et al., 2008). (a) Slab breakoff associated with the final detachment of a lithospheric slab. Slab breakoff commonly follows collisional processes and is sometime referred as collisional delamination. (b) A vertical propagating tear. (c) A horizontal propagating tear. (d) Three-dimensional structure of a lithospheric tear fault that separates two subducting segments. The curved arrow indicates upwelling of hot asthenospheric material, which can trigger tear-related magmatism during fault propagation. (e) Two tear faults (indicated by double arrows) that connect three segments of a subduction system characterized by differential rollback velocities (V_{RB}(b)>V_{RB}(a) >V_{RB}(c)). Triangles indicate the direction of subduction and single arrows indicate the direction of subduction rollback.

Therefore, while ridge subduction is not a necessary factor for the formation of large subduction-related ore deposits, it may trigger geodynamic conditions that favour giant magmatic-hydrothermal ore deposits (e.g., Rosenbaum et al., 2005). In addition, in the above-mentioned subduction processes, magma source, oxygen fugacity, and volatile content have important effects on the formation of large ore deposits (e.g., Ling et al., 2009; Sun et al., 2010; Sun et al., 2013, 2015; Zhang et al., 2013; Zhan et al., 2015).

7.5 Identification of pre-Cenozoic ridge subduction

Cenozoic or ongoing subduction of MORs, ARs or OPs and IARs may be identified by geophysical methods (e.g., Yogodzinski et al., 2001; Levin et al., 2002, 2005; Fuis et al., 2008; Wallace et al., 2009; Russo et al., 2010a, 2010b; Gutscher et al., 1999; Gutscher and Peacock, 2003; Schuth et al., 2011; Cao et al., 2014; Baillard et al., 2018). However, it is very difficult to identify ancient or fossil subduction of MORs, ARs or OPs and IARs by such methods. Therefore, the question of how to trace pre-Cenozoic ridge subduction is an important scientific challenge at the forefront of geodynamic and ore deposit studies that should be resolved as quickly as possible. In recent years, some researchers have tried to identify pre-Cenozoic MOR subduction in terms of rock suites (Geng et al., 2009; Sun et al., 2007, 2009, 2013; Ling et al., 2009, 2011, 2013; Cai et al., 2010; Zhang et al., 2010; Osozawa et al., 2012; Tang et al., 2010, 2012a, 2012b; Zhu et al., 2013; Meneghini et al., 2014; Schoonmaker et al., 2014; Kuiper, 2016; Li et al., 2014, 2016; Windley and Xiao, 2018). For example, recognition of diverse magmatic suites including Late Carboniferous MORB-type, OIB-type basalts, basalt-A-type charnockite, high-Mg granite, diorite dike-adakite suite with MORB-like Sr-Nd-Pb isotope compositions in the Jungar area of West China suggested a geodynamic setting featuring MOR subduction with a slab window (Tang et al., 2010, 2012a, 2012b). Similarly, the occurrence of late Early Cretaceous MORB-type basalts, Nb-enriched basalts, andesites, dacites and “Jamaica-type” adakites as well as fossil OP blocks consisting of abundant OIB-type basalts in the Bangonghu-Nujiang ophiolite zone indicate that Early Cretaceous subduction of an OP played an important role in the subduction zone evolution in this area (Hao et al., 2019). It should be noted that although rock assemblages and their spatio-temporal distribution were widely used to trace pre-Cenozic subduction processes of SORs, ARs or OPs and IARs (e.g., Morris, 1995; Gorring et al., 2003; Thorkelson et al., 2011; Cao et al., 2014), the petrogenesis of some rocks may be controversial. e.g., some OIB-type basalts were considered as symbolic rocks for affirming that the formation of slab windows and the upwelling of asthenospheric mantle after the subduction of the spreading oceanic ridge (e.g., Gorring et al., 2003; Thorkelson et al., 2011). However, some recent studies suggested that these OIB-tpye basalts were possibly derived by partial melting of mantle wedge source metasomatized by subducted oceanic crust-derived melts, which were enriched Nb and Ta due to the rutile breakdown (e.g., Zheng et al., 2015, 2016, 2020; Zheng and Chen, 2016; Zheng, 2019). Therefore, identifying diagnostic rock assemblages for tracing pre-Cenozic subduction processes of SORs, ARs or OPs and IARs needs to further be explored in depth. In addition, as noted above, oceanic plates have complex shapes and structures, and their subductions may result in correspondingly complex subduction forms and highly variable geolgocial phenomena. Therefore, identifying pre-Cenzoic subduction of SORs, ARs or OPs and IARs remains a challenging issue.

7.6 The initiation of plate tectonics and continental crust growth mechanisms

The initial time of plate tectonics is one of the hottest geological issures in the world. Although some researchers believe that modern-style plate tectonics has occurred since Archean and that growth of Archean continental crust was related to the subduction of oceanic crust, timing of the initial occurrence of plate tectonics (i.e., oceanic crustal subduction) (3.0–2.5, 3.5–2.5 or >3.5 Ga) remains highly controversial (Shirey and Hanson, 1984; Kerrich et al., 1998; Smithies, 2000; Polat et al., 2002; Polat and Kerrich, 2002; Smithies et al., 2003, 2004; Martin et al., 2005, 2014; Hastie

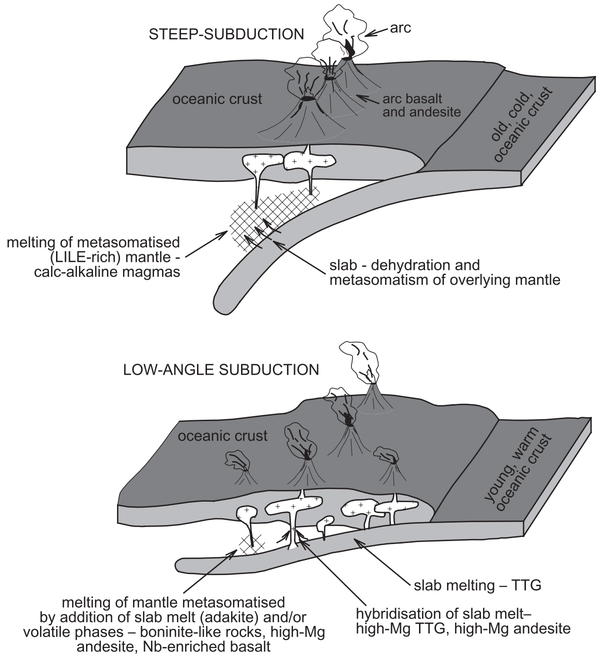

Figure 11 Modern-style steep- and low-angle subduction (Smithies et al., 2003), showing contrasting magma sources. Note that a mantle wedge still occurs during flat- and low-angle subduction and slab-derived melts typically interact significantly with that wedge.

et al., 2010a, 2010b, 2015). In terms of the combined occurrence of Late Archean (3.0–2.5 Ga) rock suites similar to the boninites, high-Mg andesites (sanukitoids), Nb-enriched basalts and adakites of modern arcs, studies show that geological processes similar to modern plate tectonics (oceanic crustal subduction) (Figure 11) start in the Late Archean at the latest, and partial melting of subducted oceanic plate and the interaction between the resulted melts and mantle wedges generated above rock suites (Kerrich et al., 1998; Polat et al., 2002; Polat and Kerrich, 2002; Smithies et al., 2004; Martin et al., 2005, 2014). However, some other researchers suggested that the plate tectonic processes were active since the Early Archean (e.g., Hastie et al., 2010a, 2010b, 2015; Martin et al., 2014), possibly through a distinct type of "Archean flat-subduction" without a mantle wedge (Figure 12), which would have been distinct from Cenozoic flat subduction of either oceanic lithosphere or ARs with a mantle wedge (Smithies et al., 2003). Many studies have suggested that partial melting of subducted OP may result in the formation of Archean tonalities, trondhjemites and granodiorites (TTG) and may be an important mechanism for crustal growth (Hastie et al., 2010a, 2010b, 2015; Martin et al., 2014; Gazel et al., 2015). For example, Early Archean (>3.5 Ga) TTG are similar to the "Jamaica-type"adakites, which were generated by partial melting of Late Cretaceous OP at the garnet amphibolite facies conditions during Early Cenzoic flat subduction without mantle wedge or with very thin mantle wedge in the Caribbean area (Figure 7) (Hastie et al., 2010a, 2010b, 2015). This indicates that the shallow flat subduction of oceanic plates mainly consisting of OPs (i.e.,"Archean flat-subduction") has occurred since the Early Archean (Hastie et al., 2010a, 2010b, 2015) and was possibly related to abundant mantle plumes and the widespread occurrence of OPs due to a relatively high geothermal gradient in Early Archean (e.g., Martin et al., 2014). Conversely, numerical simulation shows that, with a high geothermal gradient in Archean, the strength of subducted slab is too weak to support continuously flat subduction and promotes frequent slab breakoff and episodic or intermittent subduction (van Hunen and Moyen, 2012). van Hunen and Moyen (2012) suggested that the model for Early Archean shallow flat subdudction should be abandoned. Therefore, the geodynamic mechanism of plate tectonics remains unclear in the early Archean, and the genesis of Archean TTG and growth mechanisms of the early continental crust require further study. Zheng and Zhao (2020) suggest that Archean and Proterozoic are characterized by ancient plate tectonics, in which there was not only the overarching warm subduction of ductile plate margins but also asthenospheric upwelling for active rifting along thinned convergent plate boundaries.

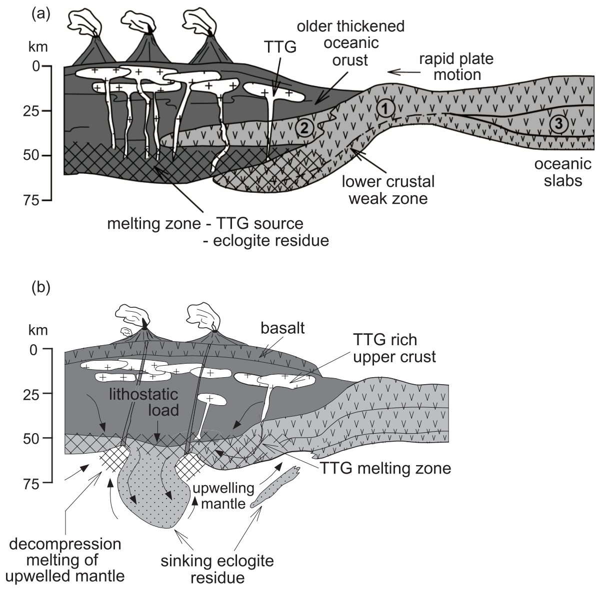

Figure 12 Cartoon showing possible mode of early Archaean crustal evolution by Archaean flat-subduction (Smithies et al., 2003). TTG crust is produced as the lower part of thickened mafic crust melts and is converted to eclogite. (a) Oceanic crust (slab ①) subducted beneath slightly older thickened mafic (oceanic) crust. It also shows Archaean flat-subduction initiated at lower-crustal weak zones (slabs ② and ③) speculated to develop in thick and warm crust. (b) Eclogite is delaminated and replaced by "TTG-fertile" oceanic crust from the sides and from above (lithostatic loading).

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