Editorial

The Subduction Factory: Geochemical perspectives

Formation of new ocean crust at spreading ridges and consumption of old ocean crust back into the mantle through subduction zones are the two key elements of plate tectonics. Plate subduction is of critical importance for the transport of materials, e.g., carbon, water and silicates, from the surface of the Earth into the mantle. It fractionates elements, forms arc magmas, and is a significant contributor to the formation and evolution of the continental crust and a variety of ore deposits. Subducted slabs, processed through subduction zones, may also be recycled into mantle plumes, i.e., the source regions of large igneous provinces and ocean island basalts. Overall, knowledge on processes associated with plate subduction is essential for understanding Earth's evolution, origin and operation of plate tectonics.

The Subduction Factory describes the chemical and physical processes during plate subduction, with interconnected processes of spreading, subduction, and recycling (Fig. 1). This special issue on the Subduction Factory includes 16 papers on topics ranging from dehydration metamorphism (Gao et al., 2014; Tao et al., 2014), convergent margin magmatism (Kimura and Nakajima, 2014; Liu et al., 2014), and oxygen fugacity (Lee et al., 2014) to isotopes (Feng et al., 2014; Shen et al., 2014; Wang et al., 2014), recycling of subducted materials (Frezzotti et al., 2014; Xu, 2014; Yang et al., 2014; Xu et al., 2014b), growth of the continental crust (Zhang et al., 2014), and the formations of mantle plumes (Hanyu et al., 2014; Tatsumi et al., 2014) and carbonatite (Xu et al., 2014a).

Dehydration metamorphism is a key process during plate subduction. Niobium and Ta are traditionally taken as the most immobile elements during subduction as shown by studies of arc rocks (Pearce and Peate, 1995; Pearce et al., 2005). Recent studies, however, suggest that they can be mobile and fractionated during dehydration in ultra-high pressure terranes (Xiao et al., 2006). The detailed mechanism that controls Nb/Ta fractionation remains debated (Ding et al., 2009, 2013; Xiong et al., 2011; Niu, 2012; Marschall et al., 2013). Gao et al. (2014) in this volume demonstrates Nb/Ta fractionation during the growth of metamorphic rutile from aqueous solutions during exhumation of deeply subducted continental crust. The suprachondritic Nb/Ta ratios in rutile are attributed to the breakdown of high Nb/Ta hydrous minerals such as phengite and biotite during the exhumation of the ultra-high metamorphic terrane, based on field observations and ages of the rutile (Gao et al., 2014).

Carbon cycling is another hot topic related to the Subduction Factory (Mikhail et al., 2013; Morrill et al., 2013; Duncan and Dasgupta, 2014). The stability of carbonates during subduction is essential for understanding the detailed recycling processes. Tao et al. (2014) identified a subsolidus reaction of "dolomite (ankerite) = magnesite (siderite) + aragonite" in two carbonated eclogites from western Tianshan (also called Chinese Tianshan). They then carried out experiments to study the effect of Fe on the stability of dolomite at high pressures (up to 8 GPa) and temperatures (600–1200 °C). Both petrological observations and experimental studies indicate that the stability of dolomite decreases with increasing Fe content in the solid solution of dolomite and ankerite at high pressure (Tao et al., 2014). These results have major implications on the recycling of subducted carbonates.

Arc magmatism also plays an important role in the cycling of subducted carbon. Studies on carbonate-bearing K-rich igneous rocks from western Tianshan suggest that decarbonation of the subducted slab is the primary agent to carbonize the mantle wedge. The K-rich alkaline magma, which formed from partial melting of metasomatised (i.e., phlogopite bearing) mantle wedge in the sub-arc region, is a

favorable agent to transport subducted carbon back to the Earth's surface during carbon recycling in subduction zones, because of the high CO_2 solubility in alkaline mafic magma (Yang et al., 2014).

Subducted carbon may also be transformed into diamond (Frezzotti et al., 2014) depending on the oxygen fugacity. Microdiamonds in garnet of graphite-free ultrahigh pressure metamorphic (UHPM) rocks from Lago di Cignana (western Alps, Italy) represent the first occurrence of diamond in a low-temperature subduction complex of oceanic origin ($T = \sim600\,°C$; $P = \sim3.2$ GPa), in an H_2O-rich C–O–H crustal fluid. Diamond formation started when the H_2O-rich fluid reached the excess concentration of C required for the spontaneous nucleation of diamond. These observations and thermodynamic modeling suggest that the interplay of rock-buffered fO_2 and the prograde $P–T$ path at high pressures may actually control carbon saturation and the precipitation of diamond (Frezzotti et al., 2014).

Carbonatite is generally taken as mantle-derived magmatic rocks in different tectonic settings (Andersson et al., 2013; Dasgupta et al., 2013; de Moor et al., 2013; Kaminsky et al., 2013; Martin et al., 2013; Tappe et al., 2013; Comin-Chiaramonti et al., 2014; Woodard and Hetherington, 2014). It is often associated with ore deposits (Bhushan and Kumar, 2013; Foley et al., 2013; Nikiforov et al., 2014), which may be formed directly from subducted carbonates or reactivated by subduction processes (Yang et al., 2009; Ling et al., 2013b). In this volume, carbonatite in South Qinling orogenic belt was attributed to the Early-Middle Triassic recycled Mianlue oceanic crust. The rocks contain a slight depletion in radiogenic Sr and minor variation in ε_{Nd} values close to the CHUR, but a wide range of initial Pb isotopic compositions that suggest mixing of EM1 and HIMU mantle end-members, together with enrichments of heavy carbon. This further supports an incorporation of recycled inorganic carbon into the carbonatite magmas (Xu et al., 2014a).

Convergent margin magmatism is essential for the evolution of the continental crust (Rudnick et al., 2000; Foley et al., 2003; Rapp et al., 2003; Xiao et al., 2006; Niu et al., 2013) and the formation of certain types of ore deposits (Sun et al., 2013; Zajacz et al., 2013). Subduction released-fluids are generally taken as a critical factor that triggers convergent margin magmas. The behavior of water in the mantle wedge and its role in magma genesis have been studied by combining geochemical and geophysical methods (Kimura and Nakajima, 2014). The results show that while water released from the subducting slab is essential for arc magmas genesis, considerable amount of water can be carried deeper into the mantle by the subducting slab and in nominally anhydrous minerals in the wedge mantle. This study thus provides strong constraints on the behavior of water
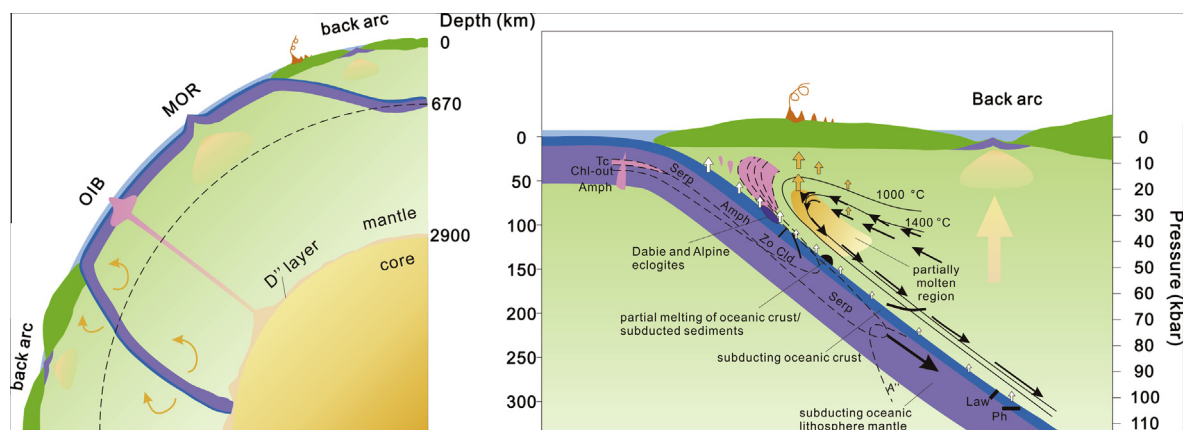

Fig. 1. Illustration of the Subduction Factory (Hacker et al., 2003; Sun, 2003), modified after Sun (2003). There are two types of subducting oceanic slabs (left), "flat" subduction stagnant at the bottom of the upper mantle, and "steep" subduction penetrate into the lower mantle and stored there for billions of years, part of which are recycled back as plumes. The dehydration processes during plate subduction is controlled mainly by minerals, e.g., chlorite (Chl), amphibole (Amph), chloritoid (Cld), zoisite (Zo), allanite, lawsonite (Law), serpentine (Serp), phengite (Ph), talc (Tc), etc. The decomposition of amphibole is taken as the trigger of arc magmatism (Tatsumi and Kogiso, 1997), whereas the decomposition of phengite is responsible to high fluorine magmas away from the subduction zone (Li et al., 2012), although subduction-zone dehydration metamorphism may be more complex in explaining the magmatism (Xiao et al., 2012). Both oceanic crust and lithospheric mantle lose considerable amount of materials on the way down to the lower mantle, e.g., dehydration, melting (Schmidt and Poli, 1998) and floating of serpentinite (Lee and Chen, 2007). In addition to arc volcanic rocks and BABB, both MORB and OIB contain recycled components derived from subduction zones (Sun et al., 2008). During plate subduction (right), the subducting slab undergoes dehydration, metamorphism, partial melting of sediments (Schmidt and Poli, 1998) and even slab melting (Defant and Drummond, 1990), forming arc magmas (Arculus, 1994), adakites (Defant and Drummond, 1990) and related ore deposits (Iizasa et al., 1999; McInnes et al., 1999; Lee et al., 2012; Li et al., 2013b). It also triggers backarc extensions and hydrothermal mineralization (Yang and Scott, 1996; Sun et al., 2004).

and elements during plate subduction (Kimura and Nakajima, 2014).

Post-collisional magmatism may also contribute significantly to the growth and evolution of the continental crust (Whalen et al., 2006; Niu et al., 2013; Song et al., 2014). The Tibetan Plateau provides a good opportunity to study the relationship between postcollisional magmatism and crustal evolution (Chung et al., 1998; Chung et al., 2003). In this volume, Liu et al. (2014) report a study on the post-collisional, potassium-rich magmatism from Xungba basin in southern Tibet, China. They recognized two types of rocks, ultrapotassic (Group 1) and potassic (Group 2) volcanism of the same age of ∼23 Ma. The authors conclude that the magmas were generated from the upper mantle (Group 1) and thickened lower crust (Group 2), respectively, which represent responses to the intra-continental subduction between India and Asia, the crustal thickening and uplift of the Tibetan Plateau, in the very early Miocene (Liu et al., 2014).

Arc magmas have systematically higher oxygen fugacities compared to MORBs (Ballhaus, 1993; Brandon and Draper, 1996; Parkinson and Arculus, 1999; Sun et al., 2012). This has been attributed to either addition of subduction released fluids (Brandon and Draper, 1996; Sun et al., 2007b; Kelley and Cottrell, 2009), slab melts (Mungall, 2002), or effects of magmatic evolution (Lee et al., 2010). In this Special Issue, the potential importance of magma recharge in generating primitive basalts enriched in water, ferric iron, and other incompatible components is discussed (Lee et al., 2014). Recharging of magma chambers, in particular, could lead to correlated increases in water and oxygen fugacity. Lee et al. (2014) also speculate that recharge effects may be most pronounced in deep-seated magma chambers found in mature island arcs or continental arcs.

The North China Craton was destroyed in the Cretaceous (Xu, 2007; Zhu et al., 2012b), possibly by thermal erosion (Xu et al., 2004; Menzies et al., 2007) or delamination (Gao et al., 2004). Other studies suggest that dehydration fluids from the subducted/subducting Pacific plate (Niu, 2005), changes in subduction regime (Sun et al., 2007a), ridge subductions (Ling et al., 2013a), or subduction in general (Zhu et al., 2012a) caused the decratonization. Xu (2014) in this volume provides evidence for the involvement of recycled oceanic crust components in the source of intraplate basalts that were emplaced during 90–40 Ma in the north and northeast China. He argues that components derived from recycled oceanic crust may have been derived from stagnant Pacific slab within the mantle transition zone, which has been seismically detected (Kárason and van der Hilst, 2000; Wang and Chen, 2009; Li et al., 2013a; Li and Yuen, 2014). The results imply that the influence of Pacific plate subduction on the eastern Asian continent can be traced back at least to the Late Cretaceous. This supports that the Pacific subduction is a potential trigger of the destruction of the North China Craton (Niu, 2005; Sun et al., 2007a; Ling et al., 2013a; Xu, 2014).

The sublithospheric mantle of north China is consistently hydrous (Xu et al., 2014b). The concentrations of structural hydroxyl, total water and hydrogen isotopes in phenocryst minerals from continental basalts in the North China Craton indicate the presence of molecular water in nano fluid inclusions, which were possibly formed from structural hydroxyl to molecular water during melt ascent. The mantle source of these continental basalts is estimated to have similar water contents to that of oceanic island basalts, providing a possible genetic link to slab-mantle interactions (Xu et al., 2014b).

It is widely believed that mantle plumes contain recycled components derived from materials subducted to the lower mantle (Hofmann and White, 1982), although the detailed process and mechanism is still in debate (Niu and O'Hara, 2003; Sun et al., 2011; Niu et al., 2012). In this volume, the formation of plumes has been discussed in two perspectives (Hanyu et al., 2014; Tatsumi et al., 2014). Precise Pb–Sr–Nd–Hf–He isotopic data together with $^{40}Ar/^{39}Ar$ and K/Ar ages of HIMU lavas from St. Helena in the Atlantic indicate that the HIMU components for St. Helena and Austral Islands have Th/U values (κ) between 3.3 and 3.7, which suggests that either the HIMU precursor was an unaltered ancient oceanic crust, or perhaps more likely, altered oceanic crust with minimal enrichment of U by hydrothermal fluids in the less oxic marine environment of the late Archaean or early Proterozoic. The unradiogenic $^{87}Sr/^{86}Sr$ of the HIMU components also suggests the removal of Rb during subduction dehydration (Hanyu et al., 2014).

It is also proposed that refractory melting residue complementary to the formation of the continental crust, i.e., the 'anti-continent', is likely to detach from arc crust as a result of a density inversion, descend into the lower mantle and accumulate at the base of the mantle. Geochemical modeling suggests that this accumulating anti-continent contributes to a deep-seated mantle plumes, providing an alternative mechanism for recycling into the deep mantle (Tatsumi et al., 2014).

Metagabbros in Late Cretaceous Lilong batholith in the eastern Gangdese arc, Tibet, display geochemical features of juvenile crust in continental magmatic arcs, and an original magmatic differentiation trend,

with gabbros formed as the cumulates, whereas diorites as the crystalline products of evolved magmas. The Lilong batholith forms an arc crustal section with a possible thickness of 20–30 km, and may have an overall andesitic composition, which supports for the "andesite model" of continental crust growth (Zhang et al., 2014).

Isotopes are useful to understand the Subduction Factory. Both conventional isotope systems, e.g., Pb, and non-conventional systems, e.g., Mg and Ca, are discussed in this volume. Shen et al. (2014) reported 57 feldspar Pb isotopes of orthogneisses from three exhumed UHPM slices in the Dabie orogen, and found that the Pb isotope compositions of subducted lower continental crust have less radiogenic Pb than the subducted upper crust, but they are distinct from the orogenic evolution curve in the Pb isotope plumbotectonic model. The Pb isotope compositions of these orthogneisses, therefore, might be dominated by the compositions of their protoliths. Retrograde metasomatism in the exhumed ultra-high pressure metamorphic rocks may also influence their isotope compositions (Shen et al., 2014).

The nature and extent of Mg isotope fractionation during subduction-driven prograde metamorphic dehydration is not well understood. Direct comparison of Mg isotopic ratios among genetically related meta-mafic rocks including greenschist, amphibolite and eclogite exposed in the Subduction Factory show no systemic Mg isotopic changes with increasing metamorphic grade, indicating that Mg isotope fractionation by high-grade metamorphic dehydration is limited. This has implications in applying Mg isotopes for understanding both crustal accretion and recycling (Wang et al., 2014), because the continental crust has Mg isotopes distinctively different from that of the mantle (Li et al., 2010; Teng et al., 2010; 2013).

Large Ca isotopic variations have recently been observed in terrestrial igneous rocks, suggesting that Ca isotopes can be used to study some important processes including planet formation, mantle evolution, and sediment recycling by subduction. It is thus important to understand Ca isotope fractionation factors between two most important Ca-bearing minerals in the upper mantle, clinopyroxene and orthopyroxene ($\Delta^{44}Ca_{clinopyroxene-orthopyroxene}$). Feng et al. (2014) used first-principles calculations to obtain $\Delta^{44}Ca_{clinopyroxene-orthopyroxene}$. Their results show that orthopyroxene has much higher $^{44}Ca/^{40}Ca$ than its co-existing clinopyroxene at high temperatures. They also reveal that the $\Delta^{44}Ca_{clinopyroxene-orthopyroxene}$ strongly depends on Ca content in orthopyroxene. Such compositional effect on $\Delta^{44}Ca_{clinopyroxene-orthopyroxene}$ provides a convincing interpretation to the different isotopic fractionations between coexisting

orthopyroxene and clinopyroxene observed in natural peridotite xenoliths (Feng et al., 2014).

As illustrated by papers in this volume, the field of geochemical studies on the Subduction Factory is evolving rapidly. Yet, many fundamental questions on the chemical processes during plate subduction remain obscure. More studies are needed for detailed dehydration processes and the pathways of subduction-released fluids, the controlling factors responsible to the high oxygen fugacity at convergent margins, serpentinization and deep recycling of water, effects of subducted slabs on arc, intra-plate and plume magmatisms, recycling of C, F, Cl and S through plate subduction.

Acknowledgments

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