



Metamorphic zirconology of continental subduction zones



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ABSTRACT

Zircon is widely used to date geological events and trace geochemical sources in high-pressure (HP) to ultrahigh-pressure (UHP) metamorphic rocks of continental subduction zones. However, protolith zircons may be modified by three different types of metamorphic recrystallization via mechanisms of solid-state transformation, metasomatic alteration and dissolution reprecipitation; new zircon growth may be induced by dehydration reactions below the wet solidus of crustal rocks (metamorphic zircon) or peritectic reactions above the wet solidus (peritectic zircon). As a consequence, there are different origins of zircon domains in high-grade metamorphic rocks from collisional orogens. Thus, determining the nature of individual zircon domains is substantial to correct interpretation of their origin in studies of isotopic geochronology and geochemical tracing. We advocate an integrated study of zircon mineragraphy (internal structure and external morphology), U-Pb ages, mineral inclusions, trace elements, and Lu-Hf and O isotope compositions. Only in this way we are in a position to advance the simple zircon applications to metamorphic zirconology, enabling discrimination between the different origins of zircon and providing constraints on the property of fluid activity at subduction-zone conditions.

The metamorphic recrystallization of protolith zircons and the new growth of metamorphic and peritectic zircons are prominent in HP to UHP metamorphic rocks of collisional orogens. These different types of recrystallized and grown zircons can be distinguished by their differences in element and isotope compositions. While the protolith nature of metamorphosed rocks dictates water availability, the P-T conditions of subduction zones dictate the property of subduction-zone fluids. The fluids of different properties may be produced at different positions of subducting and exhuming crustal slices, and they may physically and chemically mix with each other in continental subduction channels. Such fluids can act as an important agent not only for the physical transport of protolith zircons but also for the chemical transport of element Zr and other fluid-mobile incompatible trace elements from the subducted crust to the mantle wedge. Therefore, the discrimination between the different types of zircons provides a powerful means to decipher the role of fluids in subduction zone processes.

1. Introduction

Zircon is a common accessory mineral in crustal rocks. Because of its high physiochemical stability and refractory nature, zircon is widely used to date geological events and trace geochemical sources (e.g., Hermann et al., 2001, 2013; Valley, 2003; Zheng et al., 2004, 2006a; Watson and Harrison, 2005; Kemp et al., 2006; Harley and Kelly, 2007a; McClelland and Lapen, 2013; Kohn et al., 2015; Taylor et al., 2016). This is because zircon is rich in U and Th but poor in Pb and has the high closure temperature of Pb diffusion (Zheng and Fu, 1998; Cherniak and Watson, 2003). Thus, zircon U-Pb dating has been one of the most commonly used and effective methods in geochronological studies (e.g., Wu and Zheng, 2004; Harley et al., 2007; Rubatto and

Hermann, 2007a). As a phase enriched in Hf relative to radioactive Lu, zircon retains a strong fingerprint of the isotopic feature of crustal sources from which it crystallized. This provides robust evidence for growth and reworking of crustal rocks in the Earth's history (e.g., Kemp et al., 2006; Zheng et al., 2006a, 2007a; Scherer et al., 2007). Zircon may contain significant amounts of temperature- or process-sensitive trace elements such as rare earth elements (REE) and Y as well as high field strength elements (HFSE), which can provide compelling evidence for conditions of zircon growth. This is important to reconstruction of magmatic and metamorphic processes and to tracing the origin of host rocks (e.g., Harley et al., 2007; Rubatto and Hermann, 2007a). Although mineral O isotopes have a high sensitivity to low-temperature surface processes, zircon has the high stability in preserving its O

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isotope composition. Thus, zircon O isotope studies have been an effective means to discriminate the role of low-temperature versus high-temperature processes in its host rocks (e.g., Valley, 2003; Chen et al., 2011). Because of these unique properties, zircon is widely used in geological dating and geochemical tracing in various processes such as magma crystallization, partial melting, metamorphism, fluid action and hydrothermal mineralization, leading to the emergence of a new research branch named as zirconology.

Zircon can grow or recrystallize under various conditions during hydrothermal, metamorphic, anatectic to magmatic processes (e.g., Rubatto, 2002; Wu and Zheng, 2004; Hoskin, 2005; Harley and Kelly, 2007b; Schaltegger, 2007). Geochemical information recorded in zircon can be correctly interpreted only when zircon growth conditions can be clearly linked to the evolutionary history of host rocks in subduction zones. High-pressure (HP) to ultrahigh-pressure (UHP) metamorphic rocks in collisional orogens generally experience multistages of evolution (Rumble et al., 2003; Zheng et al., 2003a), and metamorphic dehydration and partial melting of crustal rocks at subduction-zone conditions may produce different types of fluids such as aqueous solutions, hydrous melts and supercritical fluids (Zheng et al., 2011a; Zheng and Hermann, 2014). For these reasons, there are different origins of zircon in HP to UHP metamorphic rocks. Relict zircons (protolith zircons of either magmatic or detrital origins) may suffer variable extents of metamorphic recrystallization through structural modification and chemical alteration in response to changes in P-T conditions and fluid accessibility; new zircon may grow during metamorphic dehydration and partial melting at subduction-zone conditions. As a consequence, the orogenic metamorphic rocks may contain not only recrystallized zircons of different types but also newly grown zircons of different types. The recrystallization of protolith zircons and the growth of new zircons in crustal rocks may take place under a broad range of P-T conditions during prograde, peak or post-peak greenschist-, amphibolite-, eclogite- and granulite-facies conditions (e.g., Fraser et al., 1997; Wu et al., 2006; Baldwin and Brown, 2008; Liu and Liou, 2011).

With the advanced application of zircon studies to dating of geological events and tracing of geochemical sources and processes, the term zirconology has been used increasingly in the literature (e.g., Zheng, 2009; Xia et al., 2009, 2010; Chen et al., 2010, 2011; Nemchin et al., 2012; Tichomirowa et al., 2012; Li et al., 2013). This involves an integrated study of zircon mineragraphy (internal structure and external morphology), U-Pb ages, mineral inclusions, trace elements, and Lu-Hf and O isotopes. Such a zirconological study is necessary in order to correctly interpret observations from zircons in crustal and mantle rocks. This is a big step in applying a single mineral to studies of metamorphic geology and geochemistry. For this reason, this paper provides a review on the studies of metamorphic zirconology in UHP metamorphic rocks from continental subduction zones. Although many of examples are taken from the Dabie-Sulu orogenic belt in China, available data from the other typical UHP terranes on Earth are also taken into account. The results indicate that different types of zircons can be discriminated by studying their properties during recrystallization and growth in continental subduction zones. This also provides constraints on the fluid action during subduction-zone processes.

2. Fundamentals for metamorphic zirconology

In the present review of metamorphic zirconology, magmatic zircon is referred to as that crystallized from magmatic melts, and relict zircon is referred to as those inherited from crustal protoliths (some are of magmatic origin whereas the other is of detrital origin). On the other hand, metamorphic zircon is referred to as that formed through dehydration reactions below the wet solidus of crustal rocks, and peritectic zircon is referred to as those crystallized through peritectic reactions above the wet solidus of crustal rocks. While magmatic melts have separated from their parental rocks and transported upwards with

large extent of evolution by fractional crystallization, anatectic melts are not separated from their parental rocks and thus only experienced the smallest extent of fractional crystallization. Nevertheless, anatectic zircon may grow from anatectic melts in which the local oversaturation of Zr is achieved by fractional crystallization of Zr-poor minerals. Therefore, the physical and chemical properties of subduction-zone fluids are a key to mineralogical processes that form or rework zircon at continental subduction-zone conditions. Understanding these properties and processes is substantial not only to petrogenetic interpretation of zircons from high-grade metamorphic rocks in collisional orogens but also to tectonic interpretation of their U-Pb ages and geochemical signatures (e.g., Wu and Zheng, 2004; Harley and Kelly, 2007a, 2007b; Rubatto and Hermann, 2007a, 2007b; Zheng, 2009, 2012; Hermann et al., 2013).

As defined in petrology of magmatic rocks, a magma is a mixture of crystal and melt, whereas the melt is short of crystalline minerals. Thus, a melt is part of a magma rather than whole magma. The difference between melt and magma is the occurrence and amount of crystalline minerals in the melt. A melt becomes a magma as soon as rock-forming minerals have significantly crystallized from the melt. A felsic melt is produced by partial melting of crustal rocks. Anatexis is referred to as partial melting of lower degrees to result in migmatization, generating anatectic melts that have not left their parental rocks. The anatectic melts were produced through peritectic reactions at temperatures above the wet solidus of crustal rocks. Typically, the anatectic melt is produced by migmatization, and its crystallized product is veinlets in metamorphic rocks, leucosomes in migmatites (metatexite and diatexite) and pegmatite veins in felsic gneisses. Geochemically, the anatectic melt has achieved thermodynamic equilibrium with the peritectic mineral in partitioning of water and incompatible trace elements, but it is not with the relict mineral. On the other hand, magmatism requires partial melting of higher degrees with significant transport and accumulation of anatectic melts. Thus, magmatic melts have escaped from their parental rocks (migmatites) with significant evolution in petrology. The anatectic melt becomes the magmatic melt after its significant evolution with fractional crystallization of rock-forming minerals. Therefore, the magmatic melt has achieved thermodynamic equilibrium with the crystallized minerals in partitioning of water and incompatible trace elements.

Zircon grown under different environments can entrap the concurrently grown minerals, fluids and melts as its inclusions, which provide important records of its formation conditions and mechanism (e.g., Hermann et al., 2001; Liu and Liou, 2011; Li et al., 2013). The occurrence of inclusions (mineral, fluid or melt) in zircon provides an opportunity to correlate the growth zones of zircon with metamorphic/anatectic conditions. This is usually realized by identifying the distribution of mineral inclusion assemblage, CL images and trace element composition of zircon or mineral inclusions (e.g., Hermann et al., 2001; Liu and Liou, 2011). However, the relationship between inclusion species and host zircon domains is commonly complicated, limiting its application to zircon genesis. Three mechanisms have been proposed to account for the occurrence of inclusions in zircon (e.g., Gebauer et al., 1997; Liu et al., 2001; Zheng et al., 2011b): (1) entrapping of concurrently grown minerals, fluids or melts during zircon growth; (2) squeezing/crystallizing of inclusions along fractures into the pre-existing zircon; (3) transforming of precursor mineral inclusions into new mineral inclusions during metamorphism.

Once inclusions were entrapped into zircon, their composition can hardly change because of the refractoriness of zircon. Elastic models suggest that transformation of a precursor quartz to coesite appears unlikely to happen (e.g., Gillet et al., 1984; Van Dermolen and Van Roermund, 1986). In this regard, the third mechanism seems unlikely. Healed structures of earlier deformed minerals and disturbed structures such as patch zoning and resorption can be found around secondary inclusions by detailed microstructure imaging (e.g., Gebauer et al., 1997; Dubińska et al., 2004). In contrast, cracks or healing traces

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