The fall and rise of metamorphic zircon

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ABSTRACT

Zircon geochronology and geochemistry are increasingly important for understanding metamorphic processes, particularly at extreme conditions, but drivers of zircon dissolution and regrowth are poorly understood. Here, we model Zr mass balance to identify \( P-T \) regions where zircon should dissolve or grow. Zirconium contents of major metamorphic minerals were assessed from published data and new measurements, and models were constructed of mineralogical development and zircon abundance for hydrous MORB and metabelites compositions along representative \( P-T \) paths. Excluding zircon, the minerals rutile, garnet, and hornblende strongly influence Zr mass balance in metabasites, accounting for as much as 40\% of the whole-rock Zr budget. Clinopyroxene and garnet contain more Zr than plagioclase, so breakdown of plagioclase at the amphibolite to eclogite facies transition, should cause zircon to dissolve slightly, rather than grow. Growth of UHP zircon is predicted over a restricted region, and most zircon grows subsequently at much lower pressure. In metapelites, zircon is predicted to undergo only minor changes to modal abundance in solid state assemblages. Partial melting, however, drives massive zircon dissolution, whereas melt crystallization regrows zircon. From a mass-balance perspective, zircon growth cannot be attributed a priori to the prograde amphibolite-eclogite transition, to UHP metamorphism, or to partial melting. Instead, zircon should grow mainly during late-stage exhumation and cooling, particularly during oxide transitions from rutile to ilmenite and melt crystallization. As predicted, most zircons from HP/UHP eclogites of the Western Gneiss Region and Papua New Guinea substantially postdate eclogite formation and maximum pressures.

Keywords: Trace elements and REE, Zr, zircon, metamorphic petrology, UHP, metabasite, geochemistry

INTRODUCTION

Zircon has long served an important chronologic role, and it is now used nearly ubiquitously to investigate metamorphic rocks that formed under extreme conditions—ultrahigh pressure (UHP), ultrahigh temperature (UHT), or both. One common assumption in UHP studies is that zircon grows at peak pressures, so metamorphic zircons directly date UHP metamorphism. While perhaps true, no rigorous theoretical justification of this assumption has been offered. An alternative implicit assumption in other studies—that zircon can grow essentially at any point along a pressure-temperature \( (P-T) \) path—appears unlikely to us for two reasons. First, zircon resists deformation, as witnessed by its retention of relict cores, so it is unlikely to accumulate defects and recrystallize. Second, minerals other than zircon have varying affinities (saturation contents) for Zr. Mass balance in reacting rocks therefore demands that as mineral assemblages and abundances change along a \( P-T \) path, this non-zircon portion of the rock will either take up or release Zr. Thus, mineral assemblage shifts may produce zircon along some portions of a \( P-T \) path but should consume zircon along others.

But, what systematics occur in such reactive systems? Is the amount of Zr taken up by non-zircon phases trivial, or can certain assemblages at specific conditions accommodate a significant portion of the total Zr? If the latter, are certain \( P-T \) trajectories or regions of \( P-T \) space, e.g., peak UHP conditions, more conducive to zircon production so are more likely to be represented by zircon ages? In the context of these questions, we first evaluated Zr saturation contents of common metamorphic minerals in equilibrium with zircon. This allowed us to evaluate what minerals other than zircon affect whole-rock Zr mass balance, for example finding that plagioclase, sheet silicates, lawsonite, and low-\( T \) amphiboles have generally low Zr contents (<1 ppm; 1 ppm = 1 \( \mu \)g/g), whereas rutile, garnet, hornblende, epidote, clinopyroxene, and titanite dominate the non-zircon mineral portion of the Zr budget (>>1 ppm; Bea et al. 2006). Second we modeled hydrous MORB and metapelites compositions and tracked changes in mineral modes and Zr contents along three hypothetical \( P-T \) paths: (1) relatively low-\( T \), UHP similar to the Alps (“Alpine-type”; e.g., Chopin et al. 1991; Scherl et al. 1991), (2) high-\( T \), high-\( P \) similar to the Western Gneiss region (“WGR-type”; e.g., Carswell et al. 2003a), and (3) moderate-\( T \), moderate-\( P \) as predicted theoretically for continental collisions (“CC-type”; e.g., England and Thompson 1984). These models allow us to generalize about what portions of a \( P-T \) path or regions of \( P-T \) space are likely to induce zircon growth, and help frame studies of metamorphic zircon chronology. We particularly emphasize implications for studies of UHP or near-UHP rocks. Our work parallels pioneering studies of zircon and monazite growth in lower \( P \) felsic compositions (Kelsey et al. 2008; Kelsey