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Decoupling of U–Pb dates from chemical and crystallographic domains in granulite facies zircon

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ABSTRACT

High spatial resolution (12 µm spot size) and high density (up to 22 spots per crystal) U–Pb ion probe data were acquired for zircon crystals from a mafic granulite in the Canadian shield. The zircon grains are metamorphic in origin and were subjected to a subsequent high-pressure granulite facies event. $^{207}Pb/^{206}Pb$ dates span ≥650 Ma, and can be used to define discrete intracrystalline domains of dates by contouring the age results. The boundaries of these domains cut at high angles across compositional zonation revealed by cathodoluminescence, backscatter, Hf and U chemical mapping, and electron backscatter diffraction misorientation data. The results indicate decoupling of radiogenic Pb behavior from other trace elements in the zircon crystals. Previously published U–Pb ID-TIMS data define a highly linear discordia array with an upper intercept at 2554.5±4.3 Ma associated with initial zircon growth during granulite facies metamorphism, and a lower intercept at 1896.0±18.0 Ma associated with a second granulite facies metamorphic event that caused U–Pb discordance. The intracrystalline patterns of ion probe dates are incompatible with multiple zircon growth events, and are inconsistent with reported examples of zircon recrystallization in which resetting of the U–Pb systematics was accompanied by modification of zircon chemistry and CL patterns. Grains lack discernible core–rim variations expected for diffusion profiles, and diagnostic indicators of low temperature radiation damage-enhanced Pb loss are absent. Rather, the data appear to require heterogeneous Pb loss from non-metamict metamorphic zircon during high-temperature metamorphism, implying that under certain circumstances other intracrystalline fast pathways facilitate Pb loss in metamorphic zircon crystals. This result is incompatible with conventional thinking regarding Pb mobility in zircon, and indicates that important aspects of Pb behavior in zircon are not yet fully understood.

1. Introduction

Zircon is widely used to decipher the history and origin of magmatic, metamorphic and sedimentary rocks. A solid understanding of the conditions under which zircon is a closed or open system is crucial for accurately interpreting its chronological and geochemical record, and extensive study has been devoted to this problem. The refractory character of zircon allows it to retain chronological and geochemical information through most pressure–temperature conditions encountered in the crust. The low mobility of U, Th, Pb, and other trace elements by thermally controlled volume diffusion in zircon is supported both by experimental studies (Cherniak et al., 1997; Cherniak and Watson, 2000), and by the preservation of primary zoning and original crystallization ages despite younger high-temperature metamorphic events (Hanchar and Miller, 1993; Möller et al., 2002). Long considered an ideal U–Pb geochronometer, the record contained within zircon crystals is increasingly exploited by isotopic studies of Hf (e.g., Kinny and Maas, 2003) and oxygen (e.g., Valley, 2003), as well as trace element studies (e.g., Rubatto, 2002; Harley and Kelly, 2007), including Ti-in-zircon thermometry (e.g., Watson and Harrison, 2005; Fu et al., 2008).

Despite the durability of zircon, it has long been known that it is not immune to isotopic and chemical disturbance. At low temperatures, Pb loss can occur in severely radiation damaged crystals (e.g., Silver and Deutsch, 1963; Cherniak et al., 1991). At high-grade conditions, solid-state recrystallization and fluid-alteration can reset U–Pb systematics (e.g., Pidgeon et al., 1998; Schaltegger et al., 1999; Hoskin and Black, 2000; Carson et al., 2002). Recent study demonstrated that plastic deformation of zircon under crustal conditions can enhance the mobility of REEs, U, Th, and Pb in zircon domains characterized by high dislocation densities (Timms et al., 2006; Reddy et al., 2007; Moser et al., 2009).

Imaging and interpreting the internal structure of zircon crystals is indispensable for deciphering U–Pb geochronological data and zircon evolution (e.g., Corfu et al., 2003). The imaged zircon features typically reflect significant phases of metamorphic and magmatic crystallization,

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metamictization, alteration, recrystallization, and strain. Zircon cathodoluminescence (CL) is primarily controlled by REE and U concentrations, and innumerable studies indicate that CL variability can help identify zircon domains of discrete age. Zircon backscatter (BSE) reveals contrasts in the average atomic number within the crystal, and is primarily influenced by Hf and U variability (Hanchar and Miller, 1993). The low diffusivity of Pb documented in zircon would imply that it may, to first order, behave similarly to elements such as U, Hf, and REEs of equivalent or even lower mobility within the zircon structure (see Fig. 7 of Cherniak and Watson, 2000). An example of the coupled response of Pb and other elements in the zircon crystal is the resetting of U–Pb systematics through recrystallization, typically accompanied by a change in trace element patterns and an associated modification of CL zonation (e.g., Pidgeon, 1992; Pidgeon et al., 1998; Schaltegger et al., 1999; Hoskin and Black, 2000). Pb is unique, however, in that it is not structurally bound like U, Hf, and REEs that substitute for other elements in the crystal structure. Radiation damage-enhanced Pb loss is an example in which the behavior of Pb is not in sync with other elements in the zircon crystal.

Here we report an unusual example of metamorphic zircon in which the Pb and trace element behavior were decoupled during high-pressure granulite facies metamorphism. The distributions of dates within individual zircon crystals do not correlate with CL, BSE, chemical zonation, or misorientation patterns. We evaluate the mechanisms that may be responsible for the U–Pb systematics, and consider the implications for the interpretation of U–Pb zircon data.

2. Geological context

The analyzed zircon crystals were extracted from a sample of mafic granulite gneiss (02M133A) collected in the Chipman domain of the East Lake Athabasca region, along the Snowbird tectonic zone in the western Canadian shield (Fig. 1A). The East Lake Athabasca region contains an extensive tract of granulite facies rocks with peak metamorphic pressures from 1.0 to > 1.5 GPa and temperatures > 750 ºC. Petrological and thermobarometric analysis of sample 02M133A revealed that the gneiss preserves (1) an early $Grt_1 + Cpx_1 \pm Pl_1 + Qtz$ assemblage that yielded conditions of ~1.3 GPa, 850 °C, (2) a $Hbl_2 + Pl_2$ matrix assemblage formed during rehydration, and (3) a second granulite facies assemblage characterized by early Grt_3 and later $Opx_3 + Cpx_3 + Pl_3$ that yielded conditions of ~1.0 GPa, 800–850 °C (Mahan et al., 2008). The interpretation that this rock underwent two phases of high-pressure granulite

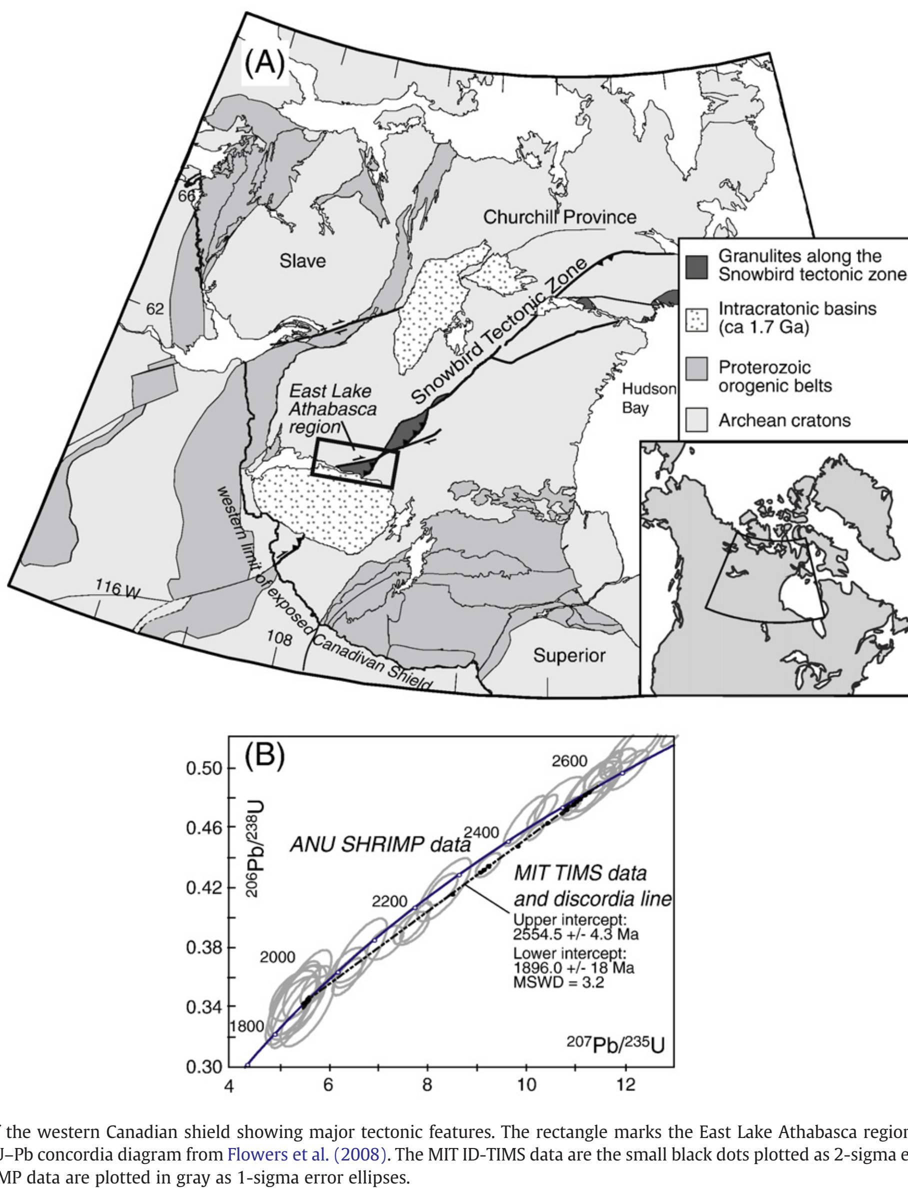

Fig. 1. (A) Geological map of the western Canadian shield showing major tectonic features. The rectangle marks the East Lake Athabasca region where mafic granulite sample 02M133A was collected. (B) U–Pb concordia diagram from Flowers et al. (2008). The MIT ID-TIMS data are the small black dots plotted as 2-sigma error ellipses with the associated discordia line. The ANU SHRIMP data are plotted in gray as 1-sigma error ellipses.