Use and abuse of zircon-based thermometers: A critical review and a recommended approach to identify antecrystic zircons

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ABSTRACT

Zircon- and bulk-rock Zr-based thermometric parameters have become fundamental to petrogenetic models of magmatism, from which broader geochronological and tectonic implications are being made. In particular, petrogenetic models have become increasingly reliant on Ti concentration in zircon geothermometry (TZircTi) and zircon saturation temperature (TZircsat). A feature of many of these studies is an implicit assumption that all zircons present in the host igneous rock are autocrystic, that is, crystallised from the surrounding melt. However, it has long been recognised that zircons present in an igneous rock can be inherited either from the surrounding country rock or source region (xenocrysts), or from earlier phases of magmatism or the magmatic plumbing system (antecrysts). Distinguishing these different origins for zircon crystals or domains within crystals is not straightforward.

Here, we first review the utility and reliability of zircon-based thermometers for petrogenetic studies and show that TZircsat is a theoretical temperature and cannot be used to constrain magmatic or partial melting temperatures. It is a dynamic variable that changes during magma crystallisation, and essentially increases as fractional crystallisation proceeds, whereas true magmatic temperatures (TMagma) decrease. Generally, in Temperature-SiO2 space, the cross-over point of these two temperatures is magmatic system dependent, and also affected by the type of calibration used for the TZircsat calculations. Consequently, each magmatic system needs to be evaluated independently to assess the validity and usefulness of TZircsat. A fundamental conclusion of TZircsat and TMagma relationships assessed here is that new zircon generally only crystallises in silicic (granitic/rhyolitic) melt compositions, and thus autocrystic zircons should not be assumed to be present in igneous rocks with bulk compositions < 64 wt% SiO2, although inherited and minor zircons crystallising from late-stage differentiated melt pockets can be present. This highlights the importance of discriminating autocrystic from inherited zircons in igneous rocks.

We then review techniques available to discriminate autocrystic from inherited zircons, and propose a new methodology to assist in the identification of autocrystic zircons for emplacement age determination and separate evaluation of inherited zircon components. The approach uses two strands of data: 1) zircon data such as zircon morphologies, textures, compositions and U-Pb ages, and 2) whole-rock data, in particular SiO2 and coupled geothermometry (TZircsat and TMagma) to estimate whether the magma was zircon-saturated or undersaturated. To test this new protocol, we use as examples, several Phanerozoic granitic rocks intersected by drilling in Queensland where contextual information is limited, and show how antecrystic and xenocrystic zircons and monazites can be distinguished. In contrast, where zircons are metamict (for example, high U and Th-rich zircons), much of the ability to discriminate is impacted because such zircons have suffered Pb loss and have modified compositions (e.g., higher TZircTi). We recommend an integrated approach incorporating whole-rock chemistry, independent geothermometric constraints, zircon composition, textures and ages obtained by routine cathodoluminescence and LA-ICP-MS or ion microprobe analysis to provide increased confidence for the discrimination of inherited zircons from autocrystic zircons and determination of the emplacement age.

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1. Introduction

Zircon is a key mineral for geological studies due to its occurrence in a wide range of rock types, its geochemical resilience in a range of geologic environments and conditions, and lack of incorporation of common Pb during crystal growth facilitating radiometric dating. Zircon is commonly used to: 1) determine the replacement ages of igneous rocks thereby providing chronostratigraphic constraints with application to the definition of geologic time boundaries, terrane histories and correlations, regional tectonics, plate reconstructions and supercontinent cycles (Li et al., 2002; Kamo et al., 2003; Ramezani et al., 2007; Hawkesworth et al., 2010; Cramer et al., 2015; Faleiros et al., 2016; Sheppard et al., 2016), 2) define timescales of magma generation and eruption, with implications for the understanding of volcanic hazards (e.g., Reid et al., 1997; Brown and Fletcher, 1999; Charlier et al., 2005; Turner and Costa, 2007), 3) constrain sediment provenance (e.g., Thomas, 2011; Gehrels, 2014), 4) evaluate the conditions of granite petrogenesis (e.g., Hogan and Sinha, 1991; Chappell et al., 1998; Miller et al., 2003; Kemp et al., 2005; Bea et al., 2007; Collins et al., 2016), including Hadean conditions of silicic magma generation (e.g., Peck et al., 2001; Harrison et al., 2008), and 5) unravel the nature and evolution of crustal sources (Hawkesworth and Kemp, 2006; Kemp et al., 2006). Despite the use of zircon geochemistry and geochronology to constrain many problems in Earth Sciences, much debate exists over the use and interpretation of zircon-based information. Such debates include whether for igneous rocks the spread of ages along concordia represents magma residency, Pb loss, inheritance or destruction. This paper first reviews the utility and reliability of commonly used zircon-based information for petrogenetic studies. We then review existing approaches to identify inherited zircon (antecrysts/xenocrysts) following which, a new methodology is described for identifying the presence of inherited zircon, and tested with granitic rock examples.

2. Zircon- and bulk-rock Zr-based thermometric parameters used in igneous petrogenetic and tectonic studies

Temperature is a fundamental parameter that affects the rheological behaviour and crystallisation history of magmas as well as the partial melting conditions of source rocks. A variety of mineral-based geothermometers (e.g., Fe-Ti oxides, Ti-in-quartz, plagioclase-hornblende, pyroxene-hornblende or two-pyroxene) have traditionally been used to estimate magmatic temperatures (see Anderson et al., 2008 for a review). However, such thermometers have limitations in their applicability due to mineral susceptibility to subsolidus re-equilibration, mineral pairs not being in equilibrium (Bacon and Hirschmann, 1988), hydrothermal alteration, metamorphism and weathering that can affect the primary compositions of igneous minerals, or the lack of co-existing mineral pairs. As a result of the low diffusivity of Ti in zircons, zircon resistance to weathering, alteration and metamorphism, and the great ease in analysing Ti-in-zircon, particularly by LA-ICP-MS, many studies are increasingly reliant on the Ti-in-zircon thermometer (Watson and Harrison, 2005; Moecher et al., 2014; Collins et al., 2016) for temperature constraints in igneous rocks. Similarly, the routine acquisition of bulk-rock composition in petrogenetic studies promotes the application of zircon saturation thermometry based on Zr concentration and major element composition (Watson and Harrison, 1983) to understanding igneous petrogenesis. Reinforcing this point is in a survey of articles published since 2013, only 14 results were obtained for a search of “Fe-Ti oxide thermometer” versus 262 results for “Ti-in-zircon thermometer”, and 282 for “zircon saturation temperature” (retrieved 24th July 2017 using Google Scholar). The following sections review these two geothermometric approaches and highlights several issues in their applicability to igneous petrogenetic studies.

2.1. Ti-in-zircon geothermometry

Due to the isovariant substitution of Si by tetravalent Ti, and the relatively well-constrained chemical potential of Ti in crustal rocks, Ti content of zircon is attributed to changes in intensive variables (Watson et al., 2006). Specifically, Ti content in the zircon structure is dependent on temperature, independent of pressure, and assuming Ti activity is known, Ti in zircon can be used to estimate the magma temperature at the time of zircon crystallisation (Watson et al., 2006; Ferry and Watson, 2007). Consequently, the application of the Ti-in-zircon thermometer (Equ. (1); Watson et al., 2006) to petrogenetic studies has steadily increased over the last 10 years, and has become central to debates on the thermal state and dynamics of the early crust, as based on Ti-in-zircon thermometry on Archean and Hadean zircons (Coogan et al., 2016).