From subduction magmatism to cratonization: an isotopic perspective from the Capricorn Orogen

by

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The differentiation of continental crust is a fundamental process in the evolution of our planet. Partial melting of the deep crust and transport of those melts to shallower levels results in a chemically stratified crust, with a refractory, dehydrated lower portion overlain by a complementary enriched upper portion (e.g. Rudnick, 1995). This chemical differentiation process also fractionates the heat-producing elements (HPE; U–Th–K), which are generally enriched in crustal melts, preferentially moving them to shallower depths. The progressive chemical stratification of the crust greatly alters its thermal structure and rheology through time, ultimately promoting the long-term stability of the continents (McKenzie and Priestley, 2008; Afonso and Ranalli, 2004; Sandiford and McLaren, 2002).

Long-lived orogenic systems that preserve evidence for multiple tectono-magmatic episodes can provide a window into crustal differentiation and stabilization. However, since the deep crust is not accessible, these processes have to be investigated through indirect methods. Various isotopic systems, such as the Sm–Nd and Lu–Hf isotopic composition of whole rocks and zircons, respectively, can provide critical information on the timing of melt generation and melt sources in the deep crust as well as processes that might modify the melt during transportation and emplacement.

The Capricorn Orogen

The Proterozoic Capricorn Orogen of Western Australia is ideally suited for an isotopic study of crustal differentiation and stabilization processes because it has a long-lived tectonic history. The orogen exposes four cycles of magmatism that record a progressive evolution from subduction and continental convergence to intracontinental reworking and eventual cratonization (Johnson et al., 2016; Korhonen and Johnson, 2015; Sheppard et al., 2010a). The oldest component of the orogen is the Glenburgh Terrane, which is interpreted to be an exotic microcontinent within the Capricorn Orogen (Johnson et al., 2011a; Occhipinti et al., 2004). Neoarchean to Paleoproterozoic gneisses that make up this terrane represent the Cycle 1 magmatic rocks (Fig. 1).

The Glenburgh Terrane is interpreted to have collided with the Pilbara Craton during the 2215–2145 Ma Ophthalmia Orogeny (Johnson et al., 2011b; Occhipinti et al., 2004), although an associated magmatic arc on either the Pilbara Craton or Glenburgh Terrane margin has yet to be identified. Collision of the Pilbara Craton – Glenburgh Terrane with the Yilgarn Craton to form the West Australian Craton, took place during the latter part (1965–1950 Ma) of the Glenburgh Orogeny (Johnson et al., 2011b; Occhipinti et al., 2004) producing Cycle 2 rocks in a magmatic arc (Fig. 1). Following the final assembly of the West Australian Craton, the orogen was structurally and thermally reworked during at least five punctuated, intraplate orogenic events (Fig. 1). Many of the events, particularly the older ones, were accompanied by the intrusion of voluminous syntectonic felsic magmatic rocks, including Cycle 3 and 4 rocks (Fig. 1). These magmatic rocks all show similar ‘calk-alkaline’ major, trace and rare earth element whole-rock chemistries indicating that they were generated and emplaced entirely within an intraplate tectonic setting (Sheppard et al., 2010b). Following Cycle 4 magmatism, the orogenic crust displays a broad secular change to more rigid behaviour akin to that of the bounding Archean Yilgarn and Pilbara Cratons (Fig. 1), allowing the emplacement of abundant mafic dykes and sills into the shallow crust (Morris and Pirajno, 2005; Wingate, 2003), and the formation of thick intracontinental sedimentary basins (Cutten et al., 2016).

Isotopic data

Samarium–neodymium whole-rock data, and Lu–Hf and $\delta^{18}O$ isotopic data from previously well-dated magmatic and inherited zircon from the four main felsic magmatic cycles are used here to highlight the differentiation and thermal history of this tract of orogenic crust.

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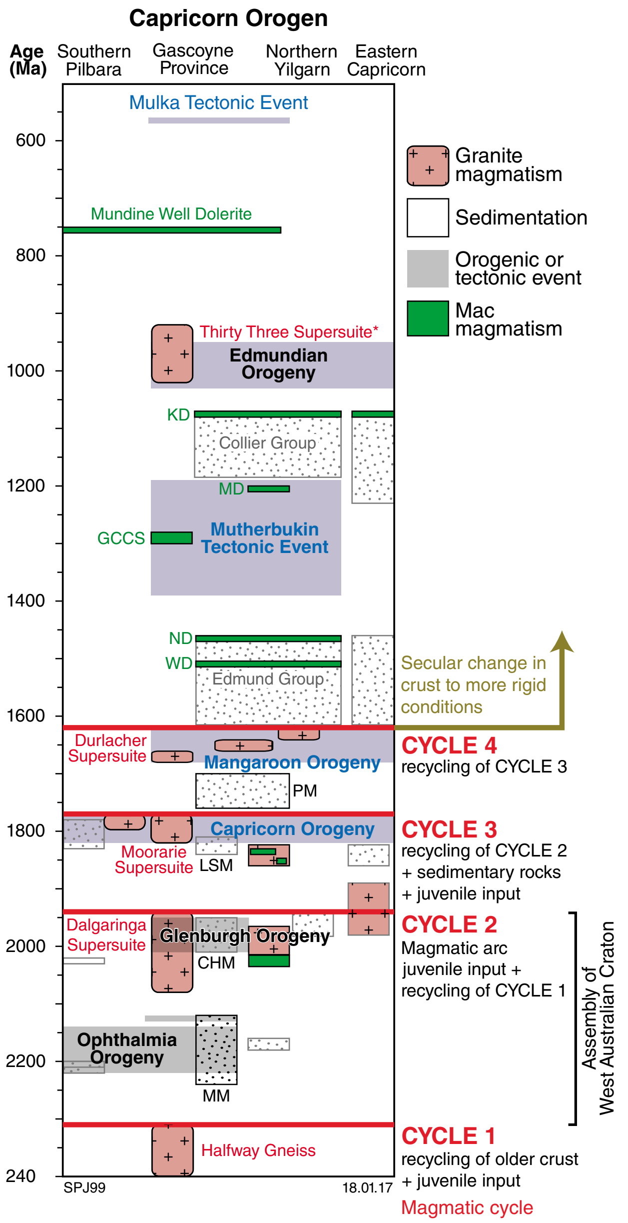

Figure 1. Time–space event summary of the Capricorn Orogen (after Korhonen and Johnson, 2015). Magmatic cycles shown in red; * denotes minor, localized intrusions. Magmatic evolution models from Johnson et al. (2011a,b, 2016). Orogenic events associated with the assembly of the West Australian Craton are shown in grey; reworking events are shown in blue. Abbreviations: CHM, Camel Hills Metamorphics; GCCS, Gifford Creek Carbonatite Suite; KD, Kulkatharra Dolerite; LSM, Leake Spring Metamorphics; MD, Muggamurra Dolerite; MM, Moogie Metamorphics; ND, Narimbunna Dolerite; PM, Pooranoo Metamorphics; WD, Waldburg Dolerite

Granitic and mafic rocks from each of the four magmatic cycles have a wide range of initial whole-rock Nd and zircon Hf isotopic compositions, forming vertical arrays that are generally more evolved than the Chondritic Uniform Reservoir (CHUR; Fig. 2). These arrays are commonly interpreted to indicate a simple two-component mixing between radiogenic (juvenile) crust and highly evolved crust, either in a deep crustal setting during magma generation, or by assimilation of evolved shallow crustal material during magma emplacement, or both. However, complimentary $\delta^{18}O$ isotopic data from the same zircon (Fig. 3) provide more detail on the source and transport history of the melt (Johnson et al., 2016).

Cycle 3 rocks were generated in a complex tectono-magmatic setting, from three main source components including minor amounts of mantle-derived material, shallow crustal rocks and a significant contribution from a previously unknown 2280–2115 Ma-aged deep- to mid-crustal component (D–MC, Fig. 3). Cycle 4 granitic rocks show no isotopic evidence for the involvement of mantle-derived source components, and appear to have been generated by the direct melting and recycling of rocks similar in isotopic composition to Cycle 3 rocks as well as interaction with the D–MC (Fig. 3).

Crustal differentiation and cratonization

The progression, from an active magmatic arc (Cycle 2) to reworking with minor amounts of new crustal growth (Cycle 3) to exclusive reworking (Cycle 4), was accompanied by a progressive decrease in the contribution from mantle-derived sources (Fig. 3), and a complimentary increase in radiogenic heat production (Fig. 4; Johnson et al., 2016; Korhonen and Johnson, 2015). This progression is also reflected by an increase in the Th/U content of magmatic zircon with time (Fig. 4; Korhonen and Johnson, 2015). The greatest step in heat production and zircon Th/U contents is recorded by Cycle 4 rocks (Fig. 4), following which the orogen did not experience any additional major felsic magmatic events (Fig. 1). In the Capricorn Orogen, the principal driver of differentiation of the crust was a decreasing accessibility to fertile mantle sources following collision. The generation of voluminous felsic magmatic rocks during Cycles 3 and 4 would have led to a complementary and rapid depletion in the lower crust, eventually leading to completely refractory lower crust during the generation of Cycle 4 rocks.

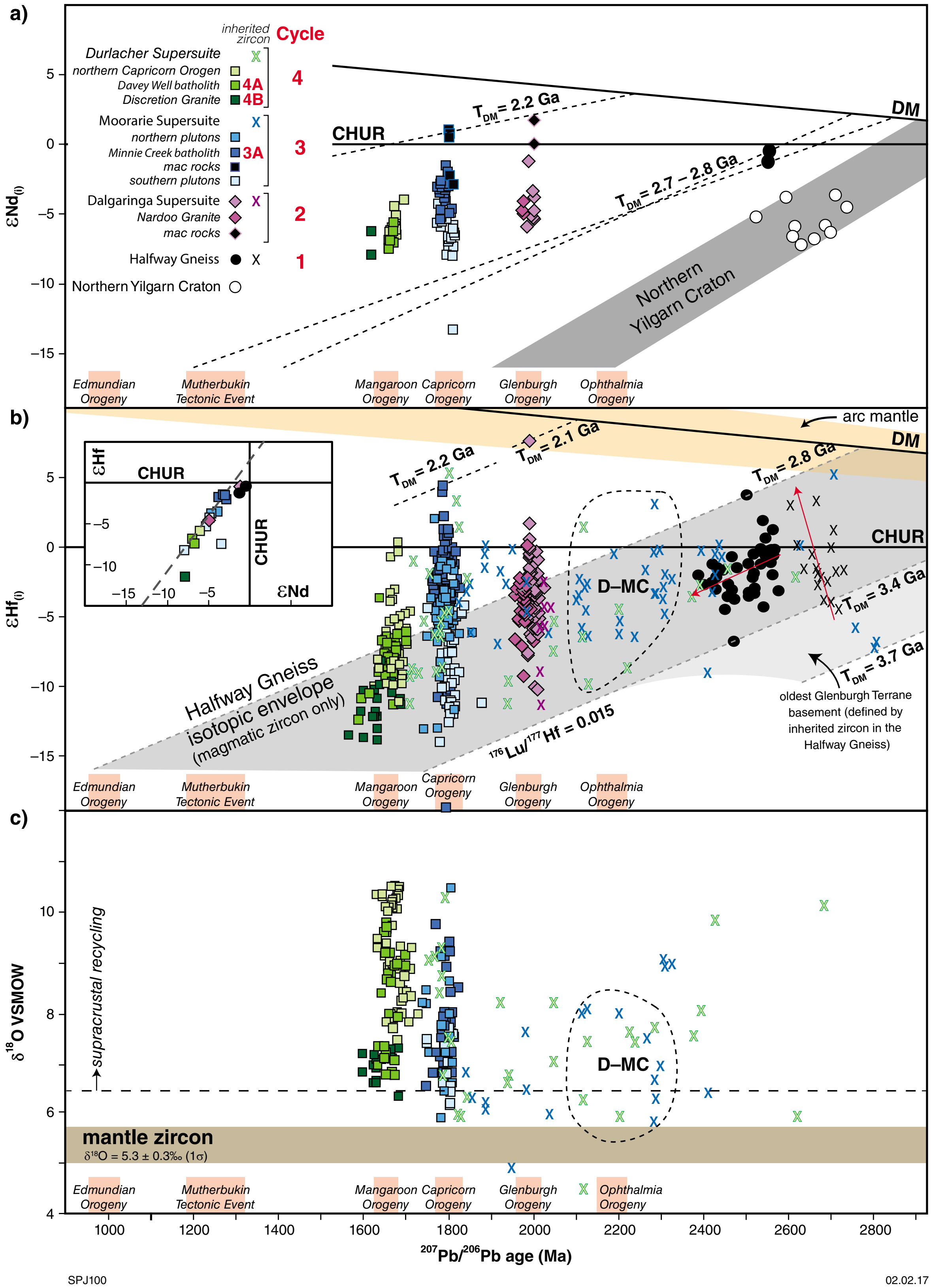

Figure 2. a) Whole-rock $\varepsilon Nd_{(i)}$ evolution diagram for both felsic and mafic magmatic rocks of the Capricorn Orogen and the northern Yilgarn Craton; b) $\varepsilon Hf_{(i)}$ evolution diagram for magmatic and inherited zircons from felsic magmatic rocks comprising the four main magmatic cycles. The field for arc mantle is based on the data of Dhumie et al. (2012); c) $\delta^{18}O$ VSMOW evolution diagram for magmatic and inherited zircons from Cycle 2 and Cycle 3 magmatic rocks. The compositional field for zircon in equilibrium with mantle-derived melts has a $\delta^{18}O$ VSMOW value of 5.3 ± 0.3‰ (1σ; Valley, 2003). The area labelled 'D–MC' (deep- to mid-crust) in b) and c), represents a previously unknown crustal source component that has contributed significantly to the isotopic composition of Cycle 3 and 4 magmatic rocks.

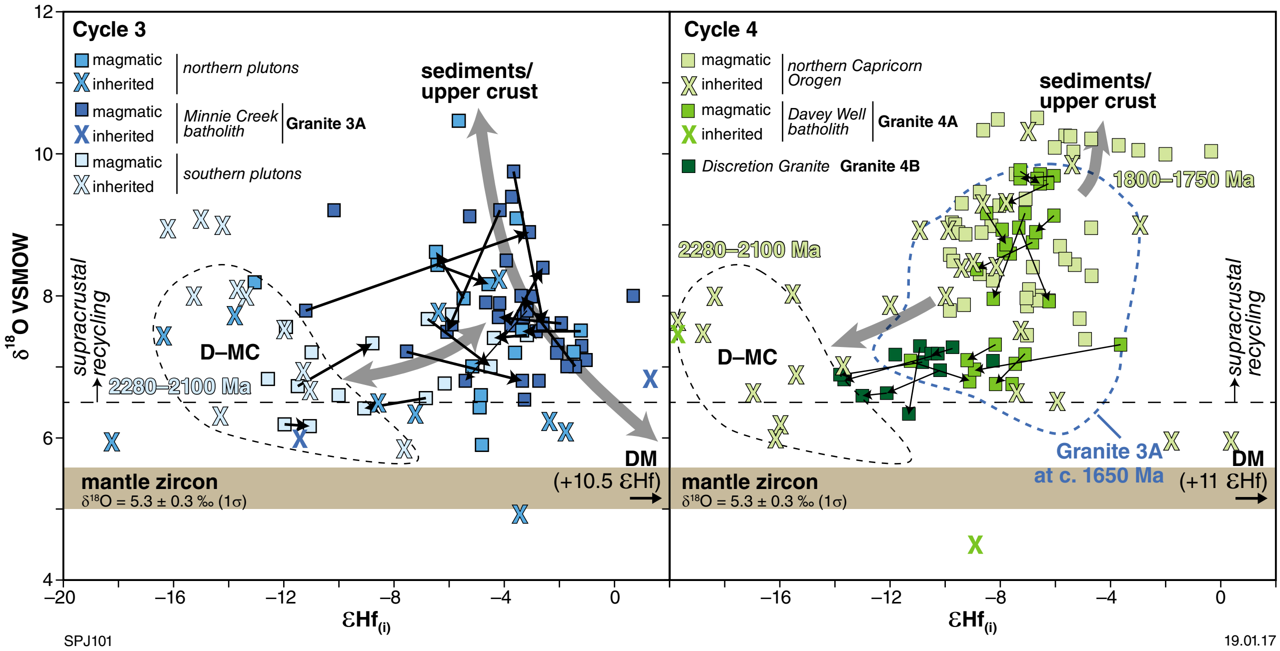

Figure 3. δ^{18}O vs $\varepsilon Hf_{(i)}$ plot for magmatic zircons in: a) Cycle 3 and; b) Cycle 4 granitic rocks formed during intracontinental reworking. Analyses were made in central and edge regions of magmatic grains where possible to track the isotopic evolution of individual magma pulses and batches — arrows show centre–edge pairs. The compositional field for zircon in equilibrium with mantle-derived melts has a δ^{18}O VSMOW value of 5.3 ± 0.3‰ (1σ; Valley, 2003). Abbreviations: D–MC — deep- to mid-crustal component

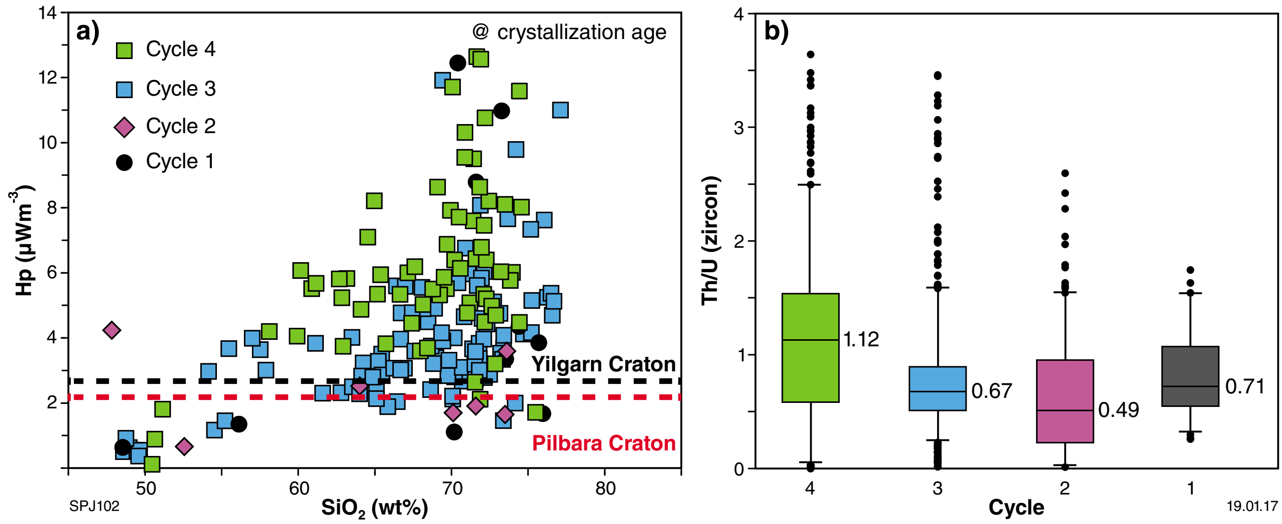

Figure 4. a) Calculated present-day heat production (Hp in μWm^{-3}) vs whole-rock SiO_2 content for the four main magmatic cycles. Dashed lines show average granite heat production for the Yilgarn and Pilbara Cratons; b) box-and-whisker plots (after Korhonen and Johnson, 2015) showing the median Th/U ratio of magmatic zircon from the four main magmatic cycles. Whiskers extend to 95th and 5th percentiles; outliers shown as closed dots

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