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The Mesoproterozoic thermal evolution of the Musgrave Province in central Australia — Plume vs. the geological record

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A B S T R A C T

The >1090 to <1040 Ma Giles Event added extraordinary volumes of mantle derived magma to the crust of the Musgrave region of central Australia. This included one of Earth's largest mafic intrusions – the Mantamaru intrusion – and the c. 1075 Ma formation of the Warakurna large igneous province, which spread dolerite intrusions across ~1.5 million km^2 of western and central Australia. It also included one of the most voluminous additions of juvenile felsic material to Earth's crust, with the development of one of the world's longest-lived rhyolitic centres, including the Talbot supervolcano. Previous suggestions that the event was the result of a deep mantle plume cannot adequately account for the >50 m.y. duration of mantle derived magmatism or the fact that isolated localities such as the Talbot Sub-basin preserve the entire magmatic record, with no discernible regional age progressive spatial trend. For at least 100 m.y. before the Giles Event, the Musgrave region experienced high- to ultra-high crustal temperatures — possibly as an ultra-hot orogen born from a c. 1300 Ma back-arc. Granitic magmatism prior to the Giles Event also involved a significant mantle-derived component and was accompanied by mid-crustal ultra-high temperature (>1000 °C) metamorphism reflecting a thin and weak lithosphere. This magmatism also resulted in a mid-crustal (~25 km deep) layer greatly enriched in radiogenic heat producing elements that strongly augmented the already extreme crustal geotherms over a prolonged period. The Giles Event may have been triggered when this regional Musgrave thermal anomaly was displaced, and again significantly destabilised, along the Mundrabilla Shear Zone — a continent-scale structure that juxtaposed the Musgrave Province against the easterly extension of the Capricorn Orogen where pre-existing orogen-scale structures were in extension. These orogen-scale structures funnelled the magmas that produced the Warakurna large igneous province and the intersection of the Musgrave thermal anomaly and the Mundrabilla Shear Zone was the site of the Talbot supervolcano. Although previously thought to be a result of a deep mantle plume, the Giles Event was more likely the product of intra-plate tectonic processes involving an anomalous and prolonged thermal pre-history, a magma-focussing lithospheric architecture and large-scale tectonic movements.

1. Introduction

The plume hypothesis predicts a thermally buoyant mass ascending from at or near the core–mantle boundary and impinging on the lithosphere, where the head spreads laterally and transfers the results of large degree decompression melting to the surface as a short lived (e.g. <5 m.y.) mafic large igneous province (LIP), flood basalt or 'trap' (e.g. Wilson, 1963; Morgan, 1971). Trailing the head, the plume stem continues to provide a mantle melt anomaly and as the lithospheric plate migrates, this interaction between plume and plate tectonics produces characteristic hotspot tracks of unidirectional age progressive mantle magmatism — of which the Hawaiian–Emperor chain is the best known example. It has since been suggested that unlike short-lived magmatism related to initial impingement of a plume head, plume stems may remain active for up to 130 m.y. (e.g. Courtillot et al., 2003). This early view of mantle plumes provided an eloquent explanation for some large and linear and often intra-plate thermal anomalies that found no obvious or easy explanation within the plate tectonic paradigm we widely accept. It has itself gained widespread acceptance backed by strong theoretical and experimental support (e.g. Griffiths and Campbell, 1990; van Keken, 1997: Campbell and Davies, 2006) and by seismic tomography data that have been interpreted to image discrete crust to core low-velocity columns beneath these near surface thermal anomalies (e.g. Nolet et al., 2006; Zhao, 2009).

However, when the large and increasing number of plumes or hotspots that are proposed to be currently active or to have been active

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within the last 100 m.y. (at least 60 according to Zhao, 2007) are viewed in this context, the number for which firm support for a deep mantle origin can be given is actually quite small (7–12; e.g. Courtillot et al., 2003; Zhao, 2007). It has been suggested that the remaining thermally anomalous zones of mantle melting are better attributed to mantle upwellings rooted at shallower mantle levels (e.g. Courtillot et al., 2003; DePaolo and Manga, 2003; Zhao, 2007). Some of these might be secondary results of deep mantle plumes ('secondary', 'baby' or 'edge' plumes; King and Ritsema, 2000; Courtillot et al., 2003; Wilson and Downes, 2006). However, others likely relate in some more direct way to plate tectonics. For example, c. 20 m.y. of intraplate magmatism in the Jemez Mountains of New Mexico (USA) is thought to reflect a thermal anomaly resulting from a combination of thermal erosion of the lithosphere and rifting associated with development of the Rio Grande Rift (e.g. Wolff et al., 2005; Byerly and Lassiter, 2012). Similarly, mantle flow around a rapidly retreating and fragmenting subducting slab can produce various focussed mantle upwellings that could lead to both flood basalts and hotspot-track volcanism. This has recently been proposed to explain the Snake River–Yellowstone volcanic province (e.g. Faccenna et al., 2010; James et al., 2011) — widely considered a classic result of a deep mantle plume (e.g. Shervais and Hanan, 2008). Faccenna et al. (2010) suggest that in other zones of complex subduction trajectories such as the central Mediterranean and the North Fiji, Lau and west Philippine Basins, subduction-induced upper-mantle upwelling could explain plume-like features such as ocean island basalt-like geochemistry, positive non-isostatic topography and low seismic velocity zones in areas not directly associated with mantle wedge melting. An interesting corollary of this is that identifying any potential interaction between plumes (deep-mantle or secondary) and plate tectonic processes becomes a difficult exercise.

A trend in geological literature is that the older the terrain being examined, the more likely any thermal or melting anomaly will be attributed to a deep mantle plume. One reason for this is that the largely secular decrease in mantle temperatures through time (e.g. Herzberg et al., 2010) means that deep mantle plumes may have been more common in the past than they are today (e.g. Groves et al., 2005). However, the same argument applies to shallow-mantle upwellings whether related to real plumes or a result of plate tectonic processes. Distinguishing between these two potential origins of shallow upwelling is clearly important in establishing the geological history of a region, but may not be easy for ancient or poly-deformed and metamorphosed terranes. Nevertheless, controversies around examples such as the Snake River–Yellowstone volcanic province show that the plume hypothesis should not be regarded as a 'default model' in explaining melting anomalies. A rigorous appraisal of the tectonic setting and regional geological history of ancient and complicated rock records might find reasonable plate tectonic solutions replacing more convenient plume-related solutions.

Here, we examine the Mesoproterozoic evolution of the Musgrave Province of central Australia. The geological history of this province included the >1090 to <1040 Ma Giles Event. Within the duration of this event, but more laterally spread over approximately 1.5 million km^2 of central and Western Australia, dolerite dykes and sills were intruded from 1078 to 1073 Ma, forming the Warakurna large igneous province (LIP) (Wingate et al., 2004). This magmatism has been attributed to a deep mantle plume (Zhao and McCulloch, 1993; Wingate et al., 2004; Pirajno, 2007; Godel et al., 2011; Pirajno and Hoatson, 2012) centred on the Musgrave Province itself, where one of the worlds largest layered mafic–ultramafic intrusions was emplaced at the same time. However, the Musgrave Province lies within the zone where the three main cratonic masses of Proterozoic Australia amalgamated along fundamental sutures that remained active throughout the remaining Proterozoic. The region has a protracted history of high to ultra-high crustal temperatures, thin lithosphere and mantle-derived magmatism that spans from the c.1220 Ma beginning of the Musgrave Orogeny to the <1040 Ma end of the Giles Event. Using new and published geochronological and geochemical data, we show that the Giles Event and the Warakurna LIP were more likely a consequence of the unusual tectonic evolution of the region than to any deep mantle plume.

2. Geological context

The east-trending Musgrave Province (Fig. 1) has been locked at the convergence point of the three main Precambrian cratonic elements of Australia since at least the Mesoproterozoic. Outcrop is dominated by granite formed during several Mesoproterozoic events, but the earliest crustal record is revealed primarily in the Nd- and Hf-isotopic systematics of these rocks and has been interpreted in terms of a range of basement components including Archaean and a c. 1950 Ma juvenile mafic to intermediate component (Kirkland et al., 2013), modified by further juvenile additions at a 1650–1550 Ma convergent margin (Wade et al., 2008; Kirkland et al., 2013). Granites intruded during a c. 1410 Ma event are isolated and very poorly preserved, however, the 1345–1293 Ma Mount West Orogeny (Howard et al., 2011) produced the widely preserved granites of the Wankanki Supersuite (Fig. 1). These are metaluminous, calcic to calc-alkaline granodiorites and monzogranites compositionally similar to those in modern continental arcs (Smithies et al., 2011), and were emplaced predominantly within the southwestern part of the Musgrave Province, and mainly between c. 1326 and 1312 Ma (Gray, 1971; Sun et al., 1996; White et al., 1999; Howard et al., 2011 and references within). It has been suggested that this event marks the final subduction and accretion event in the amalgamation of the North, West and South Australian Cratons (Giles et al., 2004; Betts and Giles, 2006; Smithies et al., 2011; Kirkland et al., 2013). If this is true then the accretionary (orogenic) component of this process likely continued beyond the age of the youngest calc-alkaline Wankanki granite and is constrained only by the c. 1220 Ma maximum age for the Musgrave Orogeny.

The 1220–1150 Ma Musgrave Orogeny involved mylonitic deformation and widespread, high-temperature, basement reworking in what is suggested to be an intraplate setting (Wade et al., 2008; Smithies et al., 2011). The dominant east-southeast structural trend of the west Musgrave Province likely reflects a crustal architecture established during or before the Musgrave Orogeny and was modified and reactivated during later events. Relict northeast-trending folds and geophysical traces preserve perhaps the earliest structural regime that may relate to northwest–southeast compression (e.g. Aitken et al., 2012). Locally rapakivi-textured granites with an orthopyroxene-bearing anhydrous primary mineralogy intruded the mid-crust, forming the Pitjantjatjara Supersuite of ferroan, alkali-calcic granites (Fig. 1). The granites were emplaced at temperatures up to 1000 °C (Smithies et al., 2011) and intrusion coincided with a newly recognised 100 m.y. period (c. 1220–1120 Ma) of province-scaled ultrahigh-temperature (UHT) metamorphism (e.g. King, 2008; Kelsey et al., 2009, 2010; Smithies et al., 2011).

3. The Giles Event

During the Mesoproterozoic Giles Event, mafic to felsic magmas were emplaced into and erupted on to the Musgrave Province over a period that probably began before c. 1090 Ma and ended after c. 1040 Ma (e.g. Edgoose et al., 2004) but possibly extended to ages as young as 1010 Ma. These magmas are all grouped into the Warakurna Supersuite. The Ngaanyatjarra Rift (Evins et al., 2010) is the structural expression of the Giles Event. Bimodal volcanic rocks of the Warakurna Supersuite also form the main component of the Bentley Supergroup (Fig. 1) and the outcrop range of these rocks defines the preserved extent of the Bentley Basin, the main depositional basin related to the Ngaanyatjarra Rift (Evins et al., 2010). Evins et al. (2010) recognised at least 8 phases to this magmatism related to the Ngaanyatjarra Rift, although these can effectively been rationalized into 4 major stages. Three of these are restricted to the Ngaanyatjarra Rift itself. The fourth is the formation of the Warakurna LIP.

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