Western Australia's own super volcano: part of the torturous thermal history of the west Musgrave Province

by

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Super volcanoes are the elite of the volcanic fraternity boasting an eruptive history that includes at least one single eruptive volume of ≥450 km^3 (e.g. Sparks et al., 2005). Such events are of considerable geological interest not only because of their great 'wow value' and their potentially devastating impact on life and climate, but also because the high rates of felsic magma production, migration and accumulation required imply some quite specific geological conditions. These in turn tell us about the prevailing thermal structure, thermal evolution and architecture of the crust, revealing fundamentally significant processes that go beyond the crustal scale and that must have a major bearing on regional tectonic evolution.

Volcanic systems like the Snake River Plains – Yellowstone system of North America provide recent examples of super-volcanic eruptions, but evidence in the geological record for ancient examples is rare. However, our work in the west Musgrave region of far eastern Western Australia (Fig. 1) has recently shown that the Mesoproterozoic rhyolitic stratigraphy of the Talbot Sub-basin records one of the world's longest-lived and most voluminous known felsic volcanic systems. It includes several super-eruption units and rates as one of geological history's largest contributions of juvenile felsic material to the continental crust outside of a subduction environment.

The Talbot Sub-basin is a component of the Bentley Basin and the Ngaanyatjarra Rift (Evins et al., 2010), and is filled by rocks of the Bentley Supergroup which include the bimodal volcanic expression of the Mesoproterozoic Giles Event. This event included emplacement of the regional Alcurra Dolerite dyke swarm during the short evolution of the early (c. 1075 Ma) Warakurna Large Igneous Province (LIP) (Wingate et al., 2004). However, mantle-derived mafic volcanism and comagmatic and isotopically equivalent (i.e. juvenile) rhyolitic volcanism preceded and post-dated this LIP, lasting for >30 Ma and potentially for 100 Ma, between at least c.1077 and c.1047 Ma. This volcanism included the formation of a second LIP — in this case a silicic LIP — as a series of voluminous rhyolite deposits interleaved with regional tholeiitic basalt flows (Fig. 2). At least 20 separate rhyolite units (and many more individual eruptive units) form layers of very-high temperature (some >900ºC) ignimbrites, rheomorphic ignimbrites, flows, and sub-volcanic intrusions, with many individual eruptive volumes reflecting super eruptions (e.g. Medlin et al., 2011).

The preserved (i.e. minimum) volume of rhyolite is ~21 840 km^3. Because the isotopic and geochemical evidence indicates that the rhyolites evolved directly from the same parental magmas as the interlayered basalts, we can combine the preserved volume of extruded basalt with the volume of parental basalt required to produce the rhyolite to give a minimum of 227 760 km^3 of mantle-derived magma required to produce the total preserved volcanic pile of the Talbot Sub-basin. Notably, of the total required mantle-derived magma, <5% erupted as basalt. The Talbot Sub-basin is only one of several sub-basins of the Bentley Basin or the Ngaanyatjarra Rift. At least five additional felsic volcanic units are recognized within the other, less well studied, sub-basins. Extrapolating magma volume calculations for the Talbot Sub-basin across the other sub-basins permits speculative estimates of initial mantle-derived magma input volumes of approximately 2.19 x 106 km^3. These calculations ignore the giant layered Giles (G1) intrusions, and associated massive gabbros (G2) of the Warakurna Supersuite, as well as the basalts of the lower Kunmarnara Group into which those intrusions were emplaced, and the rocks of the Warakurna LIP.

Although the Bentley Supergroup is dominated by felsic rocks, its origin is fundamentally basaltic in composition. The abundance of rhyolitic compositions relates directly to high and sustained lower- to mid-crustal temperatures, which permitted extensive compositional evolution of magmas. Likewise, the volume of eruptive rhyolite, and in particular the occurrence of super-eruptive volumes, requires unusual circumstances which also relate directly to the sustained thermal structure of the crust. The thermal state of the lower crust has to allow the 'processing' of enormous volumes of mafic magma and rock to form felsic magmas. Complex zircon age data and zircon age/growth-structure relationships (e.g. rocks intruding or overlying rocks with 'younger' zircon ages; complex zircon growth and dissolution textures) indicate

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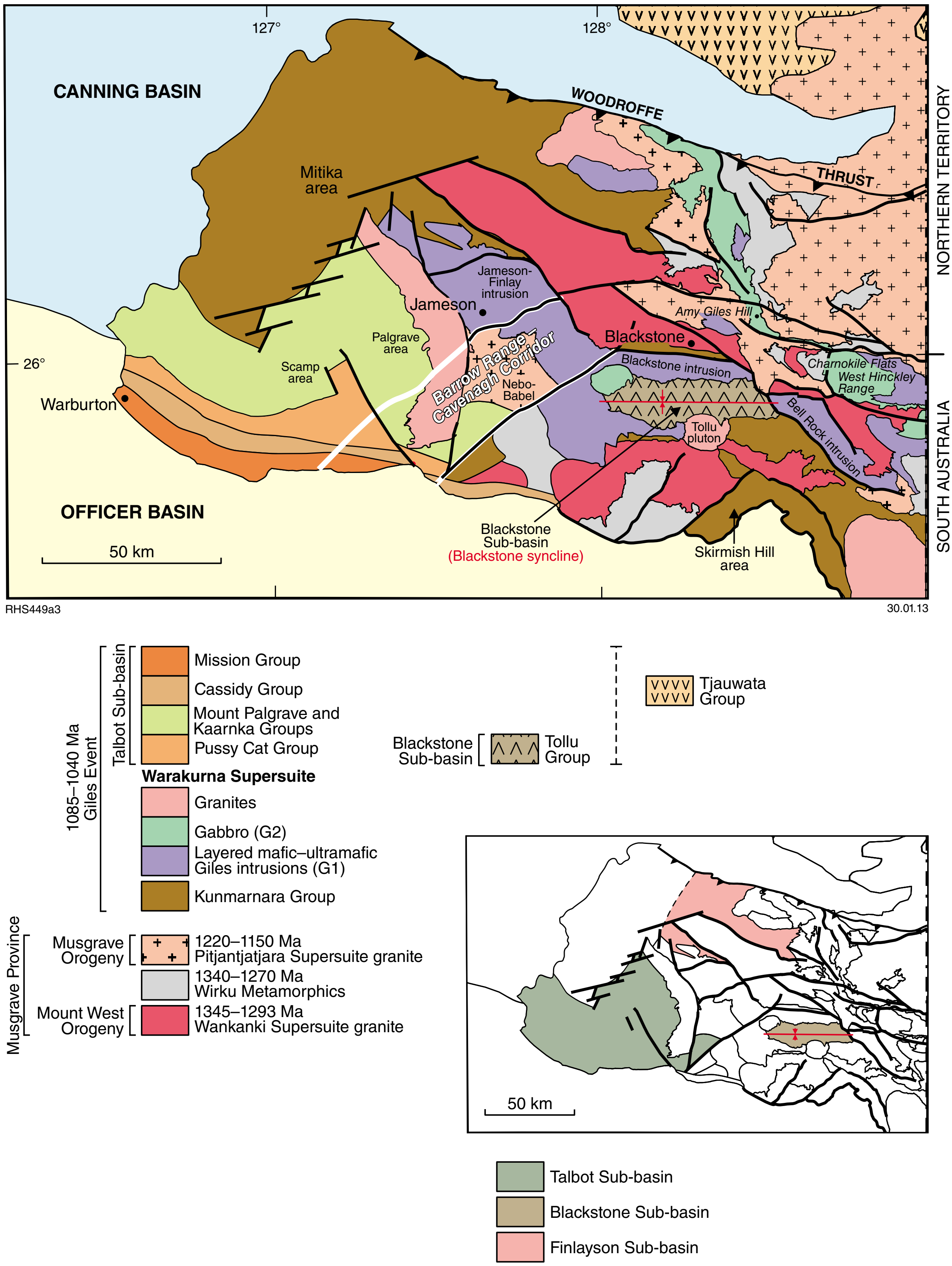

Figure 1. **Simplified interpreted bedrock geology of the west Musgrave Province, showing the preserved extents of the various sub-basins of the Bentley Basin**

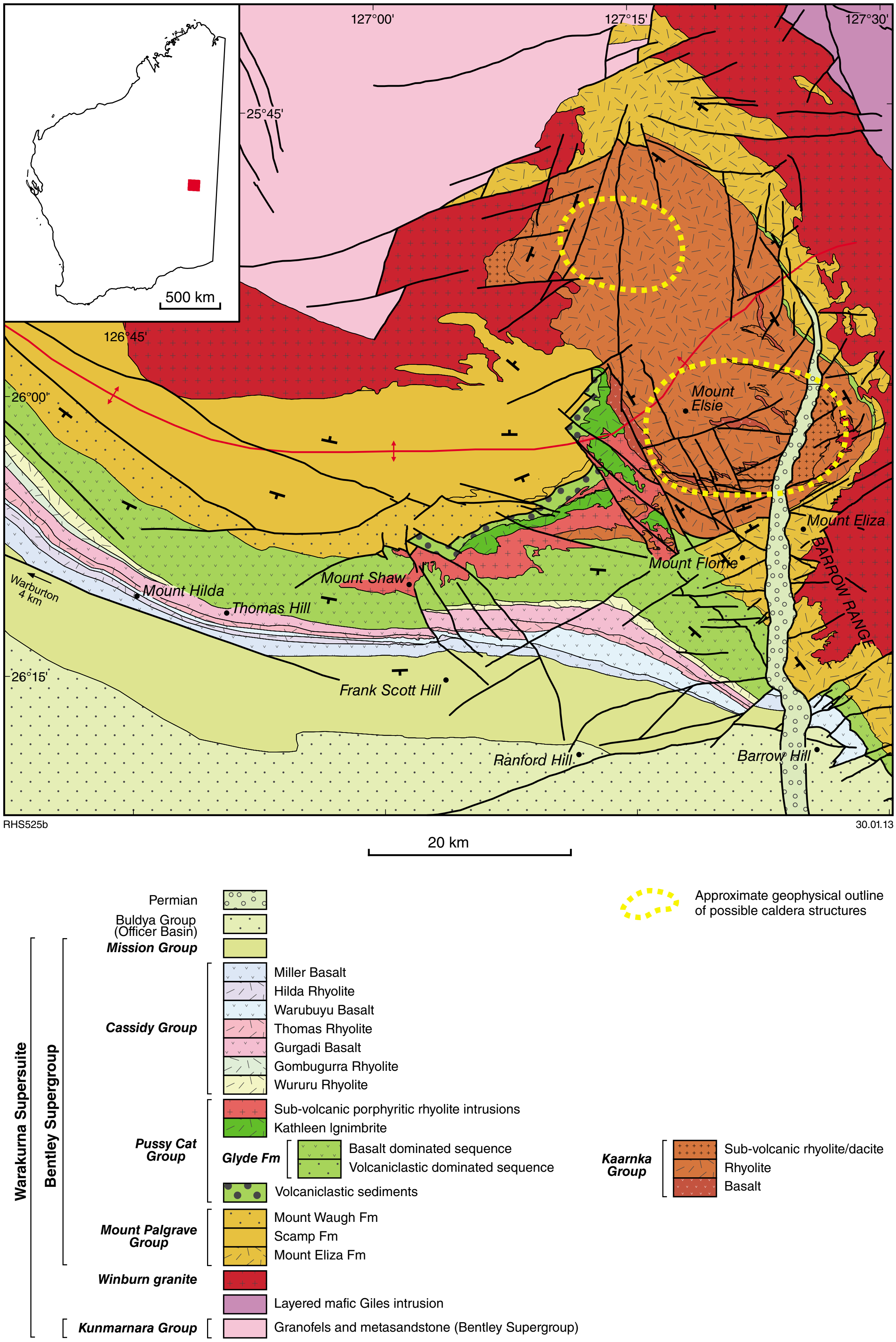

Figure 2. Detailed interpreted bedrock geology of the Talbot Sub-basin

that a significant process in rhyolite eruption involved remobilization of mid- to upper-crustal crystal-mush chambers. Hence, felsic melts generated in the lower crust must have been efficiently transported to higher crustal levels. There, the mid- to upper-crustal chamber level itself must have been unusually hot to maintain the thermal state of accumulating magmas, to reduce the thermal energy required to remobilize crystal mushes and to maximize the melt accumulation efficiency needed to form super-eruptive magma volumes.

The Bentley Supergroup, the Warakurna LIP, the giant layered Giles (G1) intrusions, and the associated massive gabbros (G2) of the Warakurna Supersuite, reflect a huge transfer of mantle material into the crust throughout the Giles Event. This has previously been linked to a mantle plume (e.g. Wingate et al., 2004). In the case of the Talbot Sub-basin, however, the >30 Ma duration of mantle-derived magmatism at a single isolated region is difficult to relate to a mantle plume. Even a conservative drift rate of 2 cm per year removes the crustal plate by >600 km from an initial stationary asthenospheric plume source.

The key to the evolution of the Giles Event is in the thermal structure established during the preceding Musgrave Orogeny. A uniquely defining theme in the geological evolution of the Musgrave Province is sustained and highly anomalous heat flow. The evolution of the Musgrave Orogeny, between c. 1220 and 1150–1120 Ma, was strongly controlled by the crustal architecture established during the earlier amalgamation of Proterozoic Australia. The anomalously thin crust developed in the Musgrave region during the Musgrave Orogeny coincided with one of the world's largest and longest-lived (c. 70–100 Ma) belts of mid-crustal ultra-high temperature (UHT) (i.e. > 900ºC) conditions. Evidence for UHT conditions stops at ~1120 Ma. However, even if the decline of mid-crustal temperatures below UHT conditions at c.1120 Ma indicates that the thermal driver of the Musgrave Orogeny had waned, rates of thermal diffusion are such that the geothermal gradient throughout the Giles Event would have been significantly higher than normal (e.g. Currie and Hyndman, 2006) simply as a result of the Musgrave Orogeny. Nevertheless, the geochronological record shows that zircon-forming events did continue between c. 1120 and c. 1090 Ma and the further, virtually continuous and voluminous, flux of basalt and isotopically juvenile rhyolite throughout the Giles Event shows that the Musgrave region continued to focus mantle heat and magma until at least 1047 Ma.

The simplest suggestion is that the torturous thermal evolution of this region has a common long-lived cause. The evolution of the Giles Event is likely linked to the earlier thermal structure established during the Musgrave Orogeny and perpetuated through regular continued mantle inputs throughout the Giles Event. The underlying cause is tectonics — the crustal architecture established as cratonic elements of Proterozoic Australia amalgamated, as well as the ongoing far-field effects of tectonic processes operating along the margins of the combined craton.

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