GEOMETRY, SOURCE, TIMING, AND MECHANISMS OF MELT INTRUSIONS IN COMPLEX TERRESTRIAL CRATERS: INSIGHTS FROM THE YARRABUBA IMPACT STRUCTURE, WESTERN AUSTRALIA.

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Introduction: Impact-induced melting is an important characteristic of the cratering process that both generates and recycles the crust of planetary bodies, e.g. [1]. Intrusive melt rock bodies have been studied from relatively small terrestrial impact structures (<4 km diameter, e.g., Brent [2]) and giant impact structures Sudbury, Vredefort, and Chicxulub, e.g. [3]. Numerical simulations have advanced the understanding of the mechanisms of melt generation in impacts, e.g., [4]. Yet, many aspects of the distribution, geometry, timing, and intrusion mechanisms of impact melt rocks in mid- to large scale terrestrial impacts remain unknown.

This study combines new detailed field mapping in the central uplift of Earth's oldest preserved impact structure - Yarrabubba, Western Australia [5-6], with numerical simulations via iSALE [7].

The eroded remnants of the ~70 km diameter, ~2.229 Ga Yarrabubba impact structure currently exposes shocked Archean Yarrabubba monzogranite target rock which has been intruded by impact melt bodies (*e.g.*, Barlangi Granophyre; [5-6]). The exposed rocks occur within the central 5 km of a ~12 km wide aeromagnetic anomaly assumed to represent the central uplift [5-6]. Neither a topographic expression of the crater nor allochthonous impact breccia remains. Target granite exposed at Yarrabubba preserves shatter cones (which require at least 1-2 GPa), {112} twins in zircon are present (indicating ~20 GPa), and planar deformation features (PDFs) in quartz are prevalent (indicating at least ~12-20 GPa) [6]. However, the current erosional level at Yarrabubba is poorly constrained.

Methods and approach: Geological field mapping of outcrops containing impact melt bodies in the central uplift at Yarrabubba was performed at 1:2,000 and 1:500 scales, and utilized photomosaic imagery collected via DJI M300 drone with a Zenmuse P1 48 MP camera [8]. Automated survey flights were flown at altitudes ranging from 100 m to 120 m, resulting in photogrammetric orthomosaic and DEM data at ~5 cm/pixel. Structural data were visualized as stereographic projections, and the azimuthal traces of geological boundaries as length-weighted rose diagrams via FracPaQ [8-9].

Simulations were constructed via iSALE to produce a 70 km diameter crater in granite target rock (to 30 km depth) with a cell dimension of ~120 m x ~120 m [see 6-7]. The model was iterated at high temporal resolution (0.05 s) between saved timesteps for the first 5 seconds after impact such that the passing of the shock wave and rarefaction (shock-release) wave could captured. Following this, the model was run at a lower temporal resolution (1 s) for 300 seconds, which is sufficient time for the entire crater to develop and stabilize, and deviatoric stress states to return to approximately pre-impact conditions. Histories of stress, strain, pressure, and temperature were calculated for Lagrangian pseudocells along two vertical transects in the final crater (i.e., at 300 seconds) [10]. Given the observation that no allochthonous breccia layers of extensive coherent melt sheet is preserved at Yarrabubba, cells were chosen at depths below material shocked at 50 GPa pressure, which is considered to have resulted in complete shock melting. Radial distances were chosen to avoid the axis of radial symmetry due to simulation artefacts, yet sample within a 10 km diameter region from ground zero. The particles are at depths of 2, 3, 4, 5, 6, 7, and 8 km along transects at 2 and 5 km radial distances.

Geometry of impact melt bodies at Yarrabubba: Field mapping reveals a complex network of impact melt dykes and sheets [8]. Subvertical ~0.2 to ~6 m wide felsite dykes and granitic granophyre bodies up to ~500 m wide (map view). The dykes trend in a wide range of directions, with larger dykes radiating from the centre of the impact and in some cases forming *en echelon* arrays. Boundaries of granophyre bodies are complex and segmented, with steps and apophyses that mimic the dyke orientations. The 3D shape of the granophyre bodies is poorly constrained, but outcrops coincide with a ring-like aeromagnetic anomaly [8]. Faults with steeply dipping shatter cone surfaces and monomict breccia are spatially related to melt intrusions, extending from jogs and terminations of the dykes. Felsite dykes and granophyre bodies exploited these pre-existing damage structures which likely formed during the shock-rise phase of the impact event.

Mechanisms and sources of melting: Domains of granitoid with textures indicative of partial melting occur along some margins of granophyre bodies. These 'remelted granite' domains underwent variable degrees of static (*i.e.*, not mobilised) incipient partial melting. Similar textures are observed in 'xenoliths' within granophyre [11]. This texture is consistent with shock-release melting rather than frictional melting, indicating that the current erosional level at Yarrabubba locally achieved shock pressures >50 GPa [12]. Shock-release melting is consistent with microstructures in zircon from the Barlangi granophyre, which indicate both high shock pressures and high post-shock temperatures [6].

Petrologic and petrographic relationships among the shocked target granite, xenoliths granophyre are consistent with the Yarrabubba monzogranite being the source of the impact melt rocks [11]. Frictional melting could have had a subordinate contribution to melt in the dykes. Decompression melting is unlikely to have caused the melt bodies exposed at Yarrabubba.

Emplacement timing and mechanisms: The iSALE simulations illustrate that stress states favorable for dyke emplacement occur multiple discrete time intervals after shock release and within the first three minutes after impact, during the formation of the central uplift. During these times, at least one of the principal stresses is tensile and differential stress is small, permitting tensile failure for dyke emplacement. The timing of these episodes is consistent with field observations which suggest that dykes formed soon aftershock-release melting had occurred.

Assuming that sheet intrusions open parallel to the minimum principal stress (σ^3) direction, and the stress state conditions described above are satisfied, the trajectory of σ^3 can be used to predict the geometry of sheet intrusions at each time step for each pseudocell (Fig. 1B-F). Results show systematic changes in the orientation of σ^3 across the entire central uplift region at different times, predicting multiple overprinting dyke sets in different orientations. The first interval suitable for intrusions (at ~20 seconds after impact) predicts cylindrical vertical dykes. Subsequently, stress states for subvertical radial dykes are limited to the upper few kilometres within ~5 km radius of the preserved central uplift. Episodes of stresses required to produce inward dipping, outward dipping, and subhorizontal bodies are more spatially extensive.

These results show that stress states that would create favorable conditions for intrusion of impact melts to at least 8 km below the crater floor are possible. The presence of vertical dykes and incipient remelted granite suggests that the exposed level at Yarrabubba was originally a few km below the transient crater floor. Approximately 10 km of exhumation occurred during the impact event, followed by approximately 4-5 km of post-impact denudation.

Conclusions: Field mapping at Yarrrabubba shows felsite dykes and granophyre bodies with wide ranging orientations within the central uplift. Melt was sourced locally from target granite via shock-release melting. Frictional melting was minor and decompression melting was unlikely.

The iSALE simulations predict that episodic tensile stress states favorable for dyke emplacement occur within the first three minutes after impact during central uplift formation, after release from shock pressures and transient crater excavation. Stress analysis suggests that intrusions can form at least 8 km beneath the crater floor and follow systematic temporal evolution of predicted dyke orientations involving concentric vertical dykes, cone sheets, radial dykes at shallow depths, and deep-seated cone sheets, and finally subhorizontal to gently outward dipping sheets.

Insights from field mapping and modelling suggest that 4-5 km of erosion has occurred at Yarrabubba since the impact event.

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