Goat Paddock, Western Australia: an impact crater near the simple-complex transition

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Goat Paddock in northern Western Australia is a \sim 5 km-diameter impact crater of Eocene age excavated in gently dipping Proterozoic sandstones. Roughly radial gorges formed by post-impact erosion provide cross-sectional views of the wall and rim zone. The predominant structural theme is one of synclinal rim folding with broad zones in which bedrock strata were deformed by impact to steep, vertical and overturned attitudes. Impact breccia is found craterward of deformed bedrock, on top of it, and downdropped into fault troughs roughly concentric to the crater. The bedrock-breccia contact is sharp in some places and gradational in others. In at least one section, the entire mass of upturned bedrock and breccia was displaced radially over essentially undisturbed bedrock, as indicated by slickensides on the horizontal contact. Talus deposits are similar to breccia, but show rough size sorting and clast orientation that dips steeply craterward, indicating that the talus formed as slides down the oversteepened crater wall immediately after crater formation. Shatter cones in some clasts indicate that allogenic material is incorporated in these deposits. Suevite, characterised by ropy flow textures, and by microclasts of guartz with planar deformation features, planar fractures, and of vesiculated silica glass, was found overlying deformed bedrock at a point where the surface of the bedrock forms a nearly horizontal bench midway up the crater wall. The crater was at least partially filled by later sediments, represented by bedded conglomerate close to the crater wall grading inward to sand, silt and mudstone recovered by drillholes on the crater floor. Some of the talus and conglomerate occupy re-entrants in the crater walls, suggesting an original scalloped outline to the crater. Two drillholes, one central and one halfway to the wall, both reached brecciated sandstone after penetrating 210 m of lake sediments. Goat Paddock has a flat floor with no indication of a central uplift and a depth/diameter ratio of ~ 0.073 . This crater form, coupled with the modification of the crater walls by slumping and the scalloped outline of the crater rim suggests that Goat Paddock bridges the two traditional classes of impact crater: simple and complex.

KEY WORDS: Goat Paddock, impact craters, Kimberley Plateau, planar microstructures, shatter cones, suevite.

INTRODUCTION

Goat Paddock is a ~5 km-diameter, near-circular cratershaped valley bounded by steep cliffs—a topographic anomaly in rugged terrain at the junction of the King Leopold Range of the King Leopold Mobile Belt and the Mueller Range of the Halls Creek Mobile Belt, in the southern Kimberley Plateau of northern Western Australia (18°20'S, 126°40'E: Figure 1). Breccia was discovered in 1964 during regional mapping by the Bureau of Mineral Resources (BMR, now Geoscience Australia) and the Geological Survey of Western Australia, and an impact origin for the feature was considered at that time (Roberts et al. 1965), although no genetic interpretation was given in the formal publication (Roberts et al. 1968). An alternative possibility, that it marked the site of a large kimberlite pipe, was tested in 1972 with two mining company boreholes drilled in the crater floor. A brief reconnaissance in 1979 by the BMR, with the US Geological Survey (USGS) and Broken Hill Pty Ltd personnel, found geologic signatures of impact, although because some members of the party preferred not to commit to a genetic interpretation, the purely descriptive term 'cryptoexplosion crater' was used in the brief published report (Harms *et al.* 1980). The geology of the Goat Paddock crater was mapped the following season by J. Ferguson and A. L. Jaques (BMR) and D. J. Milton (USGS), and a gravity survey was conducted by R. Fudali (Smithsonian Institution). This report is based on this work and subsequent visits by Macdonald and Milton in 2002 and Macdonald in 2003.

GEOLOGIC SETTING

Goat Paddock has a slightly elliptical morphology. The interior plain is about 4.2 km across east-west and 4.6 km north-south. The diameter measured from the

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Figure 1 Locality map of Goat Paddock impact crater.

upper edge of the topographic rim is about 5.8 km eastwest and 6.3 km north-south (Figures 2, 3). Around most of its perimeter, Goat Paddock is bounded by steep cliffs 100-150 m high that are composed of silicified Proterozoic Pentecost Sandstone of the Kimberley Group and the overlying Hilfordy Formation of the Crowhurst Group (Tyler et al. 1998). Bedrock in the northern sector is composed of weaker units, Liga Shale of the Crowhurst Group, and sandstone, siltstone and carbonate of the Egan and Yurabi Formations of the Late Neoproterozoic Louisa Downs Group, which locally overlie the Crowhurst with an angular unconformity. Here the crater walls are more eroded, and Goat Paddock is bounded by low hills and drained by a creek to the nearby O'Donnell River. Outside of the structure, strata generally dip about 10°NNW.

Palynological study of core samples of crater fill indicate an Early Eocene age, correlated with the *Malvacipollis diversus* zone in southeast Australia (Harms *et al.* 1980).

STRUCTURE

The crater walls are dissected by roughly radial gorges (Figure 2), which allow one to effectively walk through a cross-section of the wall and rim zone of an impact crater in a way not, to our knowledge, possible elsewhere. Figure 4a is a photomosaic of the northeast side of the gorge entering the crater from the east-southeast. Post-crater conglomerate occurs at the base of the crater wall, and also at a higher level near the top of the crater wall on the southwest side of the gorge, but the bulk of exposures in this cross-section consist of steeply upturned bedrock and breccia. At lower levels of exposure, extending from immediately behind the post-crater conglomerate for several hundred metres up the

gorge, beds are near-vertical, but near the centre of the photomosaic, halfway up the wall, bedding turns from outward dips of 60° near creek level to overturned craterward dips of 40° giving the sense of a synclinal flap.

Relationships between disturbed bedrock and breccia are diverse. The contact is sometimes sharp, but often gradational with disturbance increasing through several metres, from fractured bedrock through breccia in which clasts maintain some orientation, to chaotic breccia in which orientation of clasts is undetectable. Lithologies of clasts in the impact breccia match nearby bedrock; they are unsorted by size, unoriented (except locally near the contact), and generally angular, although some appear to have been roughly rounded by milling during chaotic emplacement. The breccia typically rests on bedrock (or lies craterward in sections exposed in other gorges), but more complex juxtapositions are common. For example, in the area shown at the centre of Figure 4a, steeply dipping bedrock extending from near the creek level to the skyline is succeeded outward by breccia occupying the same vertical range.

At or close to the creek level, near-horizontal bedrock is little if at all disturbed by the impact and is seen in exposures extending as far craterward as the centre of the photomosaic. At one point, breccia immediately overlies horizontal bedrock (Figure 5a). The surface of the bedrock shows striations trending 093°, indicating the entire overlying package, upturned bedrock and breccia together, was displaced outward in a direction deviating by about 10° from a bearing directly radial to the centre of the crater. This striated surface is similar to the schliffläche beneath the schuppen at the ~ 24 km-diameter Ries Crater in Germany, but the latter are at a much shallower scaled level (Pohl et al. 1977). This mass of breccia terminates outward at an abrupt fault juxtaposing it with bedrock slightly uptilted to a 20° outward dip (Figure 4b). The fault surface strikes 020° and dips 75° craterward (Figure 5b). Slickensides pitch 75°S and apparent drag in the bedrock within 20 cm of the fault suggest the breccia moved down on the craterward side.

In the next gorge to the north (Figure 4c), exposed bedrock is all part of an overturned flap with gentle to moderate inverted craterward dips. Breccia lies above and, at the lower left of Figure 4c, craterward of this flap. The overturned flap is cut by brecciated and silicified fracture zones or breccia dykes with various dips: nearvertical, intermediate and shallow. These clearly formed after overturn of the flap, as the fault near the right-hand edge of Figure 4c displaces the overturned bedrock-breccia contact, dropping the breccia into a peripheral trough.

Putting these observations together, it appears that at an early stage in the impact event, bedrock in the rim zone outside the transient cavity was upturned outward and brecciated. What determined the boundary between coherent deformation and total disruption is unclear; differences in rock strength and pre-impact topography probably complicate any simple picture of disruption. At the same time or immediately thereafter, the disturbed mass, upturned bedrock and breccia together, were thrust outward on a surface that is nearly



Figure 2 Topographic map of Goat Paddock impact crater. Contour interval 5 m with elevations above sea-level.

horizontal where exposed, but presumably turns upward distally to the pre-impact ground surface to accommodate the expanding cavity. Outward displacement was followed by a stage of slumping inward to the transient cavity, producing peripheral troughs. On the southwest side of the gorge, opposite the face seen in Figure 4a, breccia lies distal to gently dipping bedrock, with the contact concealed by talus but apparently dipping about 45° outward, and may have been emplaced by a secondary outward displacement into such a peripheral trough.

TALUS

The structure more proximal to the crater wall is well displayed in the gorge shown in Figure 4c. Craterward of the overturned bedrock and breccia is post-crater



Figure 3 Geologic map of Goat Paddock impact crater. Note that Eocene talus was not differentiated from Eocene conglomerate, and both units were mapped together as 'Eocene conglomerate'. The unit mapped as 'breccia' includes both authigenic and allogenic breccias.







Figure 5 (a) Contact of breccia above essentially undisturbed bedrock, with striations indicating forceful radial displacement of the breccia mass (see Figure 4a for location). (b) Close-up view of the fault marked on Figure 4b, showing breccia on the craterward side (left) in contact with gently dipping bedrock (right). (c) Shatter-coned sandstone clast in post-crater talus at the base of the eastern crater wall. (d) Suevite (melt breccia), showing near-horizontal ropy flow texture.

talus. Bodies of this unit, although seen in several sections, are not large in plan view, and were not differentiated during geologic mapping. Post-crater talus is similar to breccia but distinguished by a distinct orientation, and a crude stratification and size sorting of the clasts roughly parallel to the bedrock contact, but not (except coincidentally) to bedrock stratification. Where in contact with breccia rather than bedrock, the transition is usually gradational. The talus is interpreted to be material that slid down the oversteepened crater walls immediately after their formation, incorporating rocks ejected from within the crater. Some clasts are broken fragments of welldeveloped shatter cones (Figure 5c), indicating shock pressure in the $\sim 2-10$ GPa range (French 1998). Such highly shocked material is likely derived from closer to the centre of impact. Fine-grained material seen near the base of the talus with apparent ductile flow textures and clay clasts that may be devitrified glass appears similar to the suevite described below. In plan view, the



Figure 6 (a) Photomicrograph of quartz clast in suevite showing planar microstructures. (b) Photomicrograph of silica glass clast in finer-grained matrix in suevite. The glass is highly vesiculated, with the vesicles elongated parallel to the flow banding.

larger masses of post-crater talus (and also post-crater conglomerate described below) occupy apparent reentrants in the crater wall, indicating a scalloped outline of the original crater.

SUEVITE

The only exposure of true suevite (melt breccia: Pohl *et al.* 1977; French 1998) that we identified is in a gully in the southern sector below the only permanent waterhole in the structure (Figure 3). In this gully, bedrock is again seen upturned to the vertical or beyond, but terminating upward at a surface that appears to be nearly horizontal for ~ 500 m on a transect radial to the crater, forming a bench between presumably steeper crater walls concealed beneath allogenic breccia inward and crater-fill conglomerate outward. At some small exposures on this bench, suevite lies immediately over bedrock. The suevite consists of clasts of a wide range of sizes in a partially fused matrix, forming contorted ropy masses that rest subparallel to the

underlying contact (Figure 5d). Thin-sections show that fragments have experienced a wide range of shock pressures. Some quartz grains and sandstone fragments show no obvious damage but most exhibit abundant planar fractures and planar deformation features (Figure 6a), indicating shock pressures in a $\sim 8-25$ GPa range (French 1998). More intensely shocked microclasts consist of flow-banded and vesiculated glass with feathery recrystallisation textures (Figure 6b). Although most of these clasts are angular, some wrap around other fragments and form ropy microtextures, indicating that some of the glassy fragments were still plastic at the time of emplacement. SEM analyses indicate that the fused microclasts are composed of essentially pure silica. Impact melting of quartz occurs at shock pressures of $\sim 15-20$ GPa in porous sandstones and $\sim 50-60$ GPa in crystalline rocks (French 1998); the physical characteristics of the silicified sandstones at Goat Paddock probably lie somewhere in between these values. Microclasts other than quartz and silica glass include clays, phosphate (crandallite group?) and small grains of refractory minerals (zircon, xenotime, ilmenite and ilmeniterutile aggregates).

POST-CRATER UNITS

Overlying the breccia and talus of Figure 4c, and in other sections overlying bedrock, is post-crater conglomerate. Clasts in the conglomerate closely match the bedrock and breccia in lithology, but they are distinctly rounded and size-sorted. Dips are shallower than in the talus and the contact of the two units is usually sharp and unconformable. In several areas around the crater, conglomerate is seen to rapidly grade inward and upward to grit and sand and presumably further into the mudstone of the crater floor encountered by boreholes. The fine and even bedding of the mudstone suggests that it was deposited in a crater lake. These crater fill units are thought to have been emplaced by normal sedimentary processes, probably soon after crater formation.

The subsequent geologic history of the Goat Paddock impact crater and the extent to which it may have been buried and later exhumed remain subject for future studies. Whether the ground surface at the time of impact differed significantly from the present gently northward-sloping surface outside the structure will remain uncertain until the regional geomorphologic history is better known. A flat-topped remnant of the northwest rim is heavily lateritised (Figure 3), suggesting the existence of a stable ground surface at a high level at some time between crater formation and the present.

SUBSURFACE GEOLOGY AND GEOPHYSICS

Two exploration holes were drilled by Utah Exploration Ltd in 1972, one at the centre and one midway between the centre and the wall (Figure 3). The recovered cores displayed similar sections of crater-fill sediments and **Table 1** Lithologies of two exploration holes drilled by UtahExploration Ltd. in 1972.

Depth (m)	Lithology
Centre hole	
0 - 29.9	Sand and gravel
29.9-210.	Mudstone
210 - 229	Brecciated sandstone
Off-centre hole	
0 - 29.9	Sand and gravel
29.9 - 126	Mudstone
126-138	Predominantly sand
138 - 212	Mudstone
212-216	Brecciated sandstone

Locations of the two holes are shown in Figure 3.

both encountered brecciated sandstone at essentially identical logged depths of 210 and 212 m (Table 1). The angle between bedding surfaces and the core axis in the central hole suggests the hole deviated from the vertical, so that true depth to brecciated sandstone may be $\sim 5 \text{ m}$ less than logged. Nonetheless, the two holes strongly suggest the crater had a flat floor before sedimentary filling. Neither hole encountered suevite. Aeromagnetic surveys by Amax Australia Ltd in 1979 (R. F. Fudali & S. N. Sheard unpubl. data) found three small, sharply delineated anomalies superposed on a relatively flat background. One appears to correspond to the outcropping suevite; the others may indicate local pockets of similar material beneath the crater fill. Eighty-five gravity stations along two traverses, roughly northsouth and east-west, indicate a 10 milligal negative anomaly centred on the crater that returns to regional values within less than two crater radii in all four directions (R. F. Fudali & S. N. Sheard unpubl. data). As modelled by Fudali, crater fill with a density of 1.7 g/cm^3 contrasting with undisturbed country rock with a density of 2.3 g/cm³ can only contribute ~ -4.7 milligals to the anomaly; the remainder must be due to a lowdensity breccia lens beneath the fill. A breccia lens with a –0.15 g/cm³ contrast with country rock would need to be 1250 m thick to account for the gravity anomaly. Neither the magnetic nor the gravity survey give any indication of a central uplift.

CONCLUSIONS

Impact craters are commonly categorised into one of two classes: simple and complex. Simple craters are smaller and bowl-shaped, while complex structures are larger and have central uplifts and extensive rim slumping. The critical diameter for the simple–complex transition on Earth is placed at 2–3 km for sedimentary terrain and 4–5 km for crystalline terrain (Grieve & Robertson 1979). Goat Paddock, which clearly exceeds these diameters, is neither a deep bowl nor does it show a central peak. Its depth/diameter ratio (d/D) of ~0.073, measured from the high points on the rim to the top of the brecciated sandstone in the boreholes, is much less

than Grieve and Robertson's ratios of 0.117 and 0.222 indicated for a 6 km simple crater by the extrapolated regression curves for apparent depth (top of crater rim to top of crater fill) and true depth [top of crater rim to base of crater fill (autochthonous crater floor)], respectively. However, the d/D value at Goat Paddock is more than the 0.041 apparent and 0.055 true depth/diameter (d/D) ratios indicated for a complex crater of this size. The flat-floored Goat Paddock appears to represent a transitional type between simple and complex craters that, to our knowledge, has not been explicitly described elsewhere. Its apparent uniqueness may only be due to the limited number of known terrestrial craters; analogues may be more easily found among the more abundant populations on planetary bodies less dynamic than Earth. In particular Pike (1988) described two classes on Mercury, modified-simple craters and immature-complex craters, as transitional between simple and complex. At Goat Paddock we appear to have a terrestrial example of Pike's class of modified-simple craters, which on Mercury differ from simple ones only in that they are significantly, although not much, shallower (d/D typically a little less than 1/6) and have one or more small internal features, devoid of central peaks, but including indications of incipient wall failure, slump blocks, scalloped rim crests or small flat floors' (Pike 1988 p. 197).

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