Tsunamis and super-hurricanes after the Acraman asteroid impact

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Introduction

Little is known about the long-term environmental consequences of a large asteroid impact. Specific consequences, such as those reviewed by Toon et al. (1997), were based on modelling of global nuclear warfare, numerical simulations of atmospheric and climate models, and inferences from the geological record for the Cretaceous–Tertiary (K–T) impact. The Chicxulub impact off the Yucatan Peninsula in central America, thought to have been responsible for extinction of the dinosaurs (Alvarez et al., 1980), now appears to have predated the 65 Ma K–T boundary by ~300 000 years. It coincided with intense volcanism that resulted in high biotic stress and greenhouse warming, but no major extinctions. Furthermore, it was suggested that impacts with craters up to 170 km diameter did not cause mass extinctions or long-term environmental changes (Keller, 2005). However, Williams and Gostin (2005) suggested the low palaeolatitude of the Acraman asteroid impact in South Australia, though defined by a final crater rim 90 km in diameter, might have magnified the effects on the Ediacaran environment. The Ediacara biota, first identified in the northern Flinders Ranges and now recognised in many places around the world, is a collection of marine fossils comprising the first soft-bodied animals that included interpreted cnidarians (jellyfishes and sea-pens), flat segmented worms, primitive arthropods and possible echinoderm ancestors.

Recent fieldwork in the northern Flinders Ranges has identified a layer of boulder-sized debris within the Bunyeroo Formation that is uniquely related to the Acraman impact structure (Fig. 1). The debris layer is thought to have been deposited as the Beltana Diapir was unroofed by the seismic shock of the impact. An interpreted sequence of events resulting from the Acraman impact is reported here, based on outcrop relationships near the diapir (Fig. 2). It points to a sustained period of climatic upheaval during sedimentation of the Bunyeroo Formation, where the environment was affected by super-hurricanes as a result of the increase in greenhouse caused by the impact of an asteroid that may have been 5 km in diameter. Acraman is among the largest 5% of known terrestrial impact structures (Williams and Gostin, 2005).

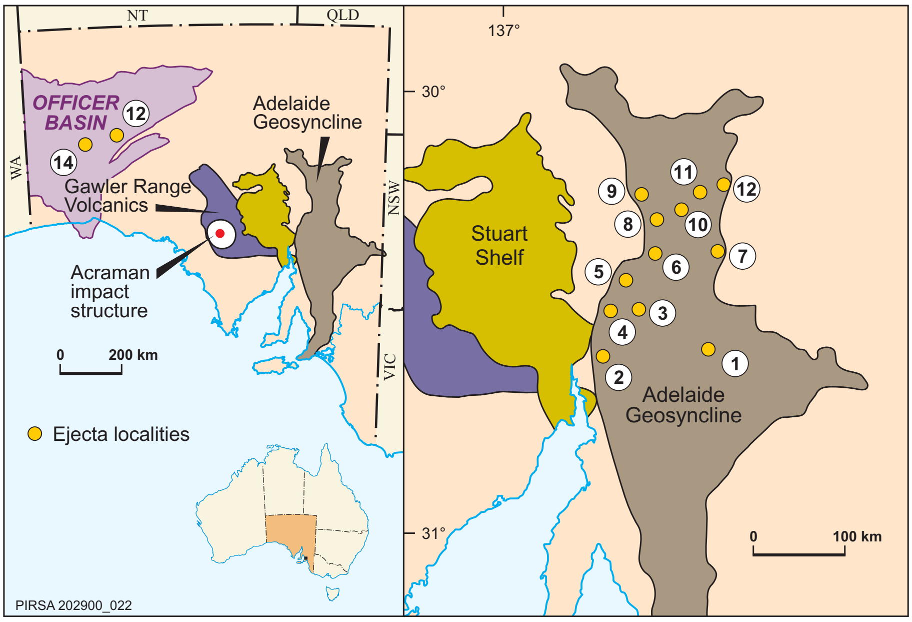


Fig. 1 *Location of the Acraman impact site and ejecta localities (after Wallace et al., 1996). 1, Bagalowie; 2, Pichi Richi Pass; 3, Yappala; 4, Warrakimbo; 5, Merna Mora; 6, Bunyeroo Gorge – Brachina Gorge; 7, Reaphook Hill; 8, Parachilna Gorge; 9, Trebilcock Gap; 10, Donkey Valley; 11, Jubilee Mines; 12, Wearing Hills; 13, DDH Observatory Hill No.1; 14, DDH Lake Maurice West.*

Nature of the Acraman impact

The Acraman impact structure, Australia's largest impact feature, is centred within a 30 km-diameter depression now occupied by Lake Acraman in the Gawler Ranges on central Eyre Peninsula, ~100 km north of Minnipa (Williams, 1986; Fig. 1). It is uniquely related to an ejecta horizon containing shattered fragments of Gawler Range Volcanics (GRV) within the Neoproterozoic Bunyeroo Formation of the Flinders Ranges, and its lateral equivalents that covered a large part of South Australia (Fig. 1; Gostin et al., 1986, 1989; Gostin and Williams, 1986). This work formed the basis for a major research effort on the Acraman asteroid impact that has spanned the last 25 years (Williams and Gostin, 2005). Since its discovery, there has been speculation on the environmental effects of this event at ~580 Ma. It was considered that after the short-term impact effects generated from seismic shock and tsunamis had subsided, the environment returned to its pre-impact state with quiet deposition of red mud of the Bunyeroo Formation (Wallace et al., 1996).

The Acraman impact-ejecta horizon occurs 40–80 m above the base of the Bunyeroo Formation and represents an important chronostratigraphic marker (Wallace et al., 1990). It is represented by a thin (<0.4 m) sandstone and breccia layer consisting mostly of angular sand to cobble-sized fragments derived from the Mesoproterozoic GRV (Gostin et al., 1986). Wallace et al. (1996) identified two sequence types. Type 1 ejecta sequence is characterised by a basal lonestone-breccia passing up to sandy mudstone and overlying graded sandstone where the clasts are extremely well sorted and normally graded. It resulted from suspension settling of impact ejecta and disturbed host sediments. Type 2 ejecta sequence comprises basal breccia grading up to a fine sand, but differs from the Type 1 sequence by containing abundant rounded

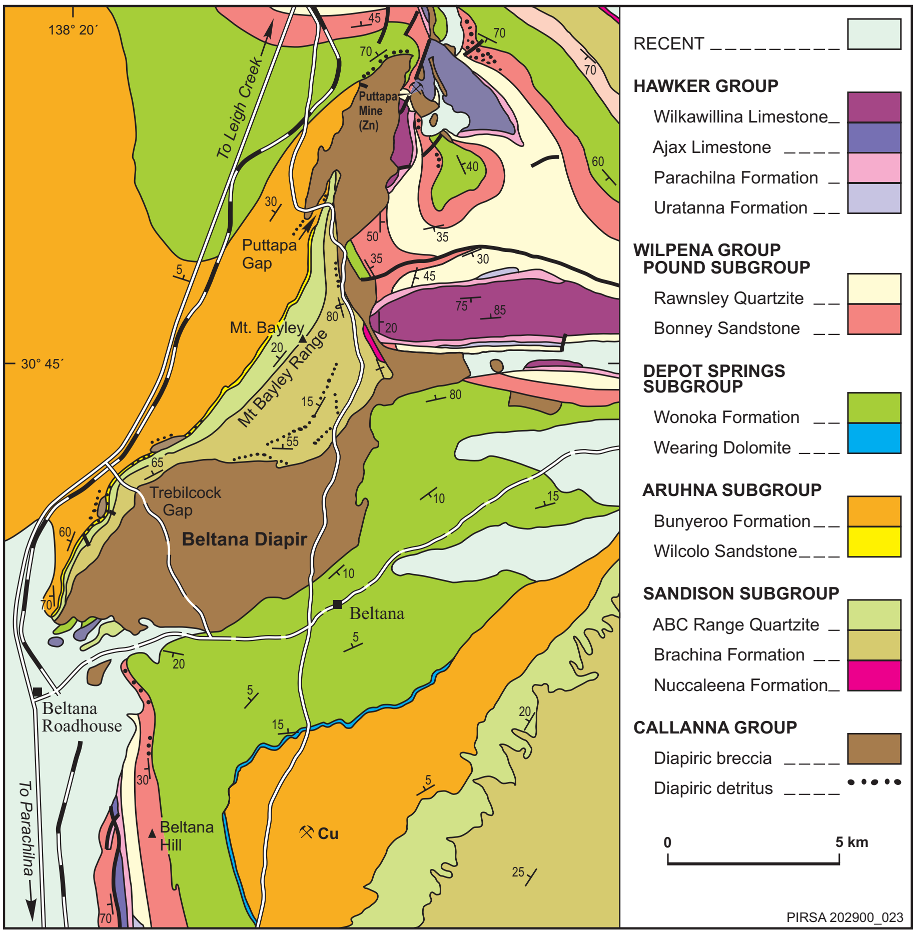


Fig. 2 Geology of the Beltana Diapir showing the flanking sediments of the salt withdrawal mini-basin (after Dyson, 1999).

quartz with no sandy mudstone unit, is moderately to poorly sorted and weakly graded, and commonly displays cross-lamination. Type 2 sequences resulted from impact-generated tsunamis, with deposition of gravity flows characterised by variable reworking of Type 1 ejecta.

Impact-ejecta layer at Beltana Diapir

An impact-ejecta layer resembling the Type 1 sequence as described above has been found adjacent to the Beltana Diapir where the Bunyeroo Formation flanks the Mount Bayley Range in the northern Flinders Ranges (Fig. 2). The Mount Bayley Range represents, for the most part, outcrop of the ABC Range Quartzite and upper Brachina Formation that were deposited in a salt withdrawal mini-basin during evolution of the Beltana Diapir (Dyson, 1999). Here, a several-centimetre-thick impact ejecta horizon is recognised with difficulty due to the poor outcrop. It appears locally conformable with the underlying Bunyeroo Formation shale except that the latter is disrupted. North and south of Trebilcock Gap, the impact ejecta horizon passes laterally into a metre-thick bed of breccia comprising a variety of clast types, including:

- angular, reddish brown clasts of GRV
- fragments of reddish orange, cross-bedded sandstone
- clasts and blocks of brecciated ABC Range Quartzite
- disrupted mudstone (now shale) of the Bunyeroo Formation
- disrupted blocks of flaggy Wilcolo Sandstone
- rounded cobbles of ABC Range Quartzite from the Wilcolo Sandstone
- clasts and brecciated blocks of red jasper from the Callanna Group as part of the source rock stratigraphy for the diapir.

The angular clasts of GRV are typically rhomboidal in shape and may reflect the naturally occurring fracture pattern of the volcanics that was exploited by the asteroid impact (V.A. Gostin, University of Adelaide, pers. comm., 2005). The breccia bed is interpreted as a debris flow deposited almost immediately after the Acraman impact due to unroofing of the diapir as a result of seismic shock. Differences in induration between the ABC Range Quartzite and the fluvial-shoreface facies of the Wilcolo Sandstone suggest a major time break between the two units. The first two categories of clast types entrained within the debris flow may have been derived by reworking of Type 1 and 2 sequences, respectively. In keeping with the terminology of Wallace et al. (1996), it is referred to as a Type 3 sequence that may have been deposited by a later tsunami after the diapir had breached.

The base of the debris flow marks an angular unconformity that overlies disrupted and overturned shale beds of the Bunyeroo Formation. North and south of Trebilcock Gap (Fig. 2), the debris flow is traced into a several-metre-thick disrupted bed of dolostone that is separated from a large body of diapiric breccia by ~50 m of overturned shale. The diapiric breccia was previously interpreted as a slump mass that resulted from extrusion of an allochthonous salt tongue (Dyson, 1999). South of Trebilcock Gap, the diapiric breccia is bounded on its northern side by an S-shaped fold (Fig. 2) that is compatible with unlithified sediment of the Wilcolo Sandstone and basal Bunyeroo Formation being overridden by extrusive salt (M.P.A. Jackson, University of Texas at Austin, pers. comm., 2005). The present outcrop of the diapiric breccia may represent emplacement just prior to extrusion, and the several-metre-thick disrupted bed of dolostone would have been deposited as a debris flow off the exposed mass of diapiric breccia.

Post-Acraman lower Bunyeroo Formation

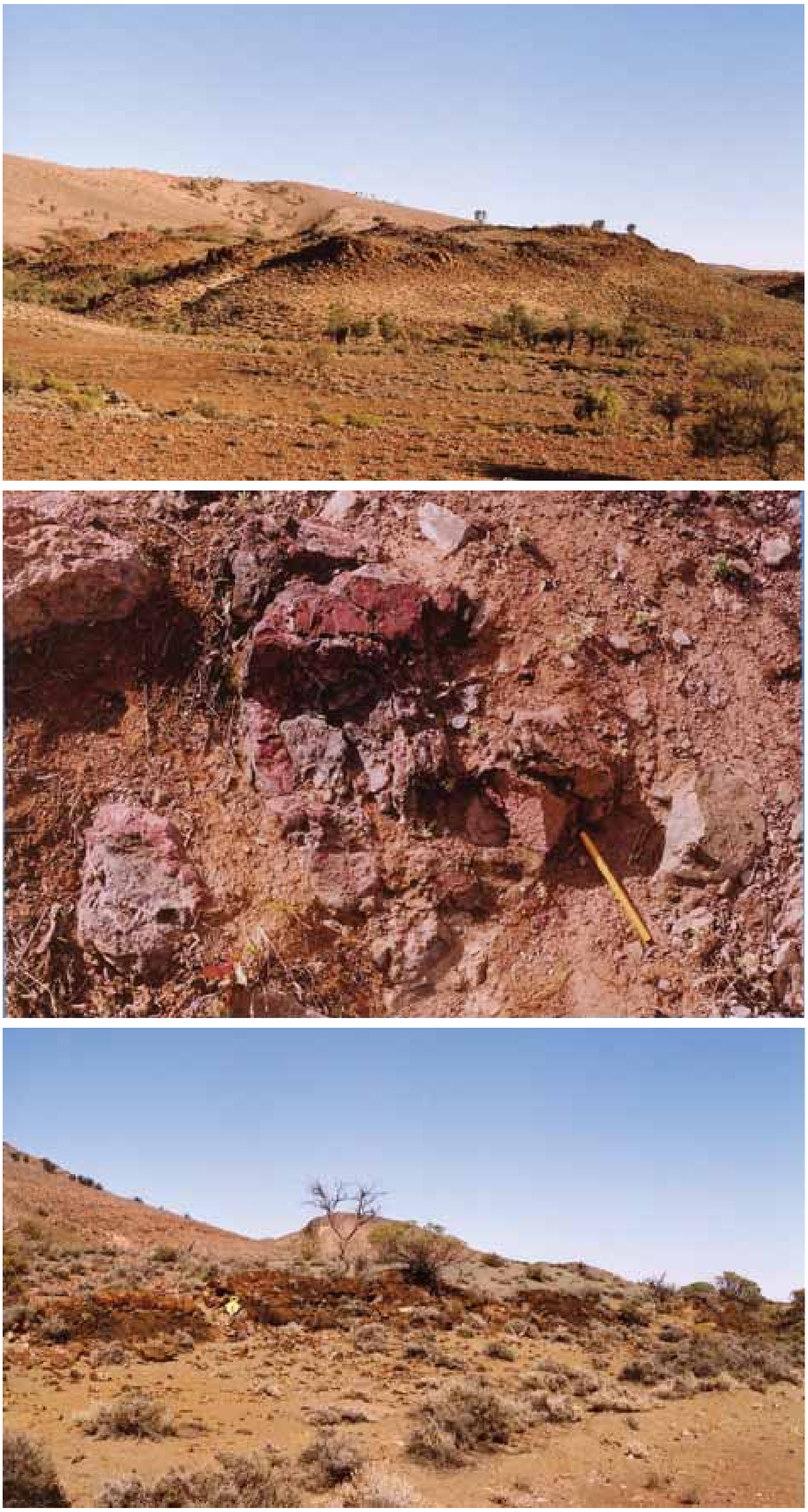
The Bunyeroo Formation along the Mount Bayley Range comprises a thick succession of massive to weakly laminated shale, minor thin-bedded, fine-grained sandstone, and occasional interlaminated gravel and breccia. However, north and south of Trebilcock Gap in the immediate vicinity of the two diapiric breccia bodies (Fig. 2), the debris flow of the Type 3 sequence is overlain by a thick (~100 m) succession of shale punctuated by several lenticular, metre-thick beds of dolostone. The dolostones contain occasional angular clasts of ABC Range Quartzite and red jasper, and are massively bedded or display horizontal lamination and hummocky cross-stratification (HCS). The sharp base of the dolostone beds is commonly planar.

These thick beds of dolostone are interpreted as debris flows deposited off a steep submarine escarpment adjacent to the diapir during giant storms. There are no debris flows of this nature below the Acraman impact-ejecta horizon at Beltana Diapir. Storm surge against the escarpment resulted in diapiric detritus being entrained in seaward-flowing density currents off the diapir. Almost immediately, if not simultaneously, the debris flows were reworked by storm-generated oscillatory currents. This resulted in the series of lenticular dolostone beds containing HCS that are considered to represent giant wave ripples. These starved ripples display a wavelength ranging from 3 m just above the Acraman horizon to 5 m at the top of this succession. These dimensions are correlated with maximum unbreaking wave heights of ~90 m and 150 m, respectively, based on the approach outlined in Dyson (1995).

Environmental effects of the Acraman impact

Seismic shock from the impact may have destabilised methane hydrates trapped in deep-water dolomite of the lower Bunyeroo Formation that was deposited after the glacio-eustatic lowstand associated with the underlying Wilcolo Sandstone. Methanogenesis within these sediments was possibly related to bacterial processes adjacent to seafloor mound springs over a buried diapir (von der Borch, 1999). Methane is thought to have an effect four times greater than carbon dioxide on greenhouse, and thus the generation of super-hurricanes might have deposited the storm beds seen above the Acraman horizon at Beltana Diapir. It is suggested that the negative shift in $\delta^{13}C$ at the Acraman horizon (Walter et al., 2000) may have resulted from the release of methane following the asteroid impact.

The increase in scale of the mega-ripples that cap the debris flows suggests an increase in storm intensity over a possible time scale of ~300 000 years (based on a sedimentation rate of 1 m/3000 years). It may reflect a change in climate, from an initial impact winter to one exhibiting extreme greenhouse conditions that was accompanied by the further release of methane hydrates from deep-water dolomite during the ensuing transgression. Such a change is observed above other deep-water dolomites within the Adelaidean succession, interpreted to have been deposited under the influence of cold (-5° to +5°C), anoxic pore waters (Dyson, 1992, 1996) that were most likely associated with methanogenesis. Each dolomite is overlain by storm-influenced or storm-dominated



Top: *Large mass of diapiric breccia south of Trebilcock Gap thought to have been emplaced as a result of seismic shock from the Acraman asteroid impact.* (Photo 401970)
Centre: *Brecciated red jasper and quartz in debris flow with pen pointing to a lone clast of GRV, north of Trebilcock Gap.* (Photo 401971)
Bottom: *Series of 5 m-wavelength dolostone lenses in lower Bunyeroo Formation north of Trebilcock Gap, where the upper surface is interpreted as a train of mega-ripples formed by storm reworking of a thick-bedded debris flow.* (Photo 401972)

shelf facies. This shift in facies is also seen in the Bunyeroo Formation at Beltana Diapir. The interpreted Ediacaran acritarch diversification, thought to be a recovery event following the asteroid impact (Grey et al., 2005), may have evolved under increasing greenhouse conditions.

Sequence of post-Acraman events at Beltana Diapir

A sequence of post-Acraman events is suggested based on observation at Beltana Diapir:

- disruption of host sediments by impact-induced seismic shock
- diapir reactivation and steepening of the submarine escarpment
- deposition of fall-out debris as Type 1 sequence
- impact-induced tsunami resulted in deposition of Type 2 sequence that partially reworked the fall-out debris layer
- piercement of sediment canopy and extrusion of diapiric breccia with deposition of debris flow off the submarine escarpment that reworked Type 1 and 2 beds
- deposition of thick-bedded debris flows off the submarine escarpment during giant storms for a considerable time.

Implications

The impact-induced seismic shock was thought to be ~10 on the Richter scale (Williams and Gostin, 2005) and possibly of a magnitude not previously recorded. It resulted in sudden reactivation of the Beltana Diapir and hastened development of the mini-basin salt canopy. The seismic shock possibly affected other diapirs (e.g. Mucatoona, Patawarta, Pinda) but did not coincide with local volcanism. However, the identification of an extremely thin ejecta layer away from the Adelaide Geosyncline would be a difficult task. The Acraman event might be recognised in other Neoproterozoic basins by the presence of Type 3 and storm-generated debris flows, or flood basalts and/or volcaniclastics that were deposited as a result of the seismic shock. There is potential for discovery of such layers on other parts of the former Rodinian Supercontinent.

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PIRSA assists with tsunami rebuilding in Sri Lanka

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In late August 2005, PIRSA received a request from the International Committee of the Red Cross (ICRC) in Colombo, Sri Lanka, for geological maps to assist in water resource management activities following the Boxing Day tsunami. They were particularly in need of coverage for the northern and eastern provinces of the country. According to their information, the then South Australian Department of Mines and Energy's Drafting Branch in the 1980s provided cartographic information to the Sri Lanka Geological Survey to compile geological maps of portions of the country. Unfortunately, the current Geological Survey and Mines Bureau of Sri Lanka could not locate copies of these maps so the ICRC appealed to PIRSA for assistance.

John Ragless of PIRSA Spatial Information Services (formerly Drafting Branch) discovered that only one copy each of the requested maps had been retained: a multi-coloured geological map and black-and-white mineral resources, metamorphic and structural maps at a scale of 1 inch to 8 miles (1:506 880). These were printed by D.J. Woolman, Government Printer, South Australia in 1982. Wayne Cowley of the Geological Survey Branch also uncovered a small number of later 1:100 000 and 1:250 000 geological maps in the branch collection; these were prepared with assistance from the British Geological Survey and AusAid (including John Parker of Geosurveys Australia). These maps covered central and southwestern Sri Lanka, including the city of Galle, severely affected by the tsunami.

Following further discussions with the ICRC staff, it was decided to scan all of the maps and provide them in JPEG, PDF and georeferenced TIFF format suitable for ArcView, free of charge. The CD was received in Sri Lanka on 10 October. The ICRC indicated that they might also request hardcopy plots of the maps in the future. The materials used for printing the maps were also offered to the ICRC and the Sri Lanka Geological Survey and Mines Bureau so that further print runs could be made in Sri Lanka.