New records of Ediacaran Acraman ejecta in drillholes from the Stuart Shelf and Officer Basin, South Australia

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Abstract—New occurrences of the Acraman impact ejecta layer were recently discovered in two South Australian drillholes, SCYW-79 1a (Stuart Shelf) and Munta 1 (Officer Basin) using lithostratigraphy, acritarch biostratigraphy, carbon isotope stratigraphy, and biomarker anomalies to predict the stratigraphic position. The ejecta layer is conspicuous because it consists of pink, sand-sized, angular fragments of volcanic rock distributed along the bedding plane surface of green marine siltstone. In SCYW-79 1a it forms a layer 5 mm thick; in Munta 1 the ejecta layer is thin and discontinuous because of its distance (~550 km) from the impact structure. Palynological, biomarker, and carbon isotope anomalies can now be shown to coincide with the ejecta layer in SCYW-79 1a and Munta 1 suggesting the Acraman impact event may have had far reaching influences on the rapidly evolving Ediacaran biological and geochemical cycles.

INTRODUCTION

The Acraman impact structure (Williams 1986; Williams and Gostin 2005) lies within the early Mesoproterozoic Gawler Range Volcanics of the Gawler Craton in central South Australia (Fig. 1). The structure is deeply eroded such that the original crater diameter must be inferred and is controversial (ranging from ~30 to >90 km). A detailed discussion of crater size estimate using new data from ejecta thickness and distribution gives a diameter of 85–90 km (Williams and Wallace 2003), which agrees with the original estimate based on relict morphology (Williams 1986) and gravity and magnetic anomalies (Williams 1994a, 1994b; Williams et al. 1996). This makes Acraman one of the largest impact events recognized in Australia. Ejecta comprising sand to boulder-sized clasts of fractured and shocked felsic volcanic rock and rare impact spherules are preserved in relatively deep marine sediments of the Bunyerroo Formation (Adelaide Rift Complex) and Dey Dey Mudstone (Officer Basin) (Fig. 2) over an ~550 km radius from the crater center (Fig. 1) (Gostin et al. 1986; Wallace et al. 1989; Hill et al. 2004; Williams and Gostin 2005).

The age of the Acraman impact event is uncertain and there are few geochronological constraints on the stratigraphic section that contains it. The underlying boundary for the Ediacaran Period GSSP has been defined in

Enorama Creek, Flinders Ranges, South Australia (Fig. 1) at the contact between glacial diamictite of the Elatina Formation and the base of the Nuccaleena Formation, the overlying “cap” carbonate (Fig. 2) (Knoll et al. 2004). This contact is present in SCYW-79 1a at 1010.7 m, more than 600 m below the ejecta layer. However there is no direct geochronological constraint (U-Pb zircon date) for the Ediacaran global stratotype section and point (GSSP). Age estimates depend on correlation with other sections that probably correlate with the Elatina and Nuccaleena Formations and that have direct geochronological constraints. These include the boundary between diamictite and cap carbonate in sections in Namibia and China, which are both dated at ~635 Ma (Hoffmann et al. 2004; Condon et al. 2005). Alternatively, the Elatina and Nuccaleena Formations could correlate with diamictite and a cap carbonate on King Island intruded by a sill dated at 575 ± 4 Ma and diamictite in Tasmania, which postdates a rhyodacite with a SHRIMP U-Pb age of 582 ± 4 Ma, suggesting that the glaciation could be ~580 Ma (Calver et al. 2004). A single detrital zircon grain from the Bonney Sandstone, hundreds of metres above the Acraman ejecta layer and below the first Ediacara-type bilaterians, and which could record penecontemporaneous volcanism, was dated at 556 ± 24 Ma (Ireland et al. 1998). The Acraman impact is therefore no older

Fig. 1. Acraman impact structure and impact ejecta localities in outcrop (Adelaide Rift Complex) and drillholes (Officer Basin, Stuart Shelf and Torrens Hinge Zone) (after Wallace et al. 1996). X marks the location of the Ediacaran global stratotype section and point (GSSP). G: Giles 1; L: Lake Maurice West 1; M: Munta 1; Mu: Murnaroo 1; OH: Observatory Hill 1; S: SCYW-79 1a; W: WWD 1.

than ~635 Ma and no younger than ~556 Ma. Based on the chemostratigraphic time scale of Walter et al. (2000), and by intercalation of the impact event about halfway between the glaciation and the first appearance of the bilaterians, the estimated age of the Acraman impact event is either ~625 Ma (if the Elatina Formation correlates with the Ghaub Formation of Namibia and the Nantuo Formation of China) or ~570 Ma (if the Elatina Formation is a correlative of the Croles Hill Diamictite of Tasmania), or between these ages.

Acraman was large enough to cause a global catastrophe (Toon et al. 1997; Williams and Wallace 2003), but the extent to which such bolide impacts can affect the biosphere and biogeochemical cycles on a regional or global scale is hard to ascertain. This is because a plethora of potentially concurrent processes (e.g., glaciation, sea level change, ocean stagnation, volcanism) make it difficult to untangle cause and effect (Twitchett 2006). In Australia, deposition appears to have taken place at a steady rate throughout the interval in question and no other major environmental perturbations are evident at the time of the Acraman impact that could account for some of the responses recorded. No mass extinction has been linked to the Acraman impact event, but this probably reflects the

impoverished state of the biota immediately following glaciation. In Australia, there is an evolutionary diversification of large complex acritarchs (acanthomorphs, probable phytoplanktonic green algae [Marshall et al. 2005]) just above the ejecta layer (Grey et al. 2003; Grey 2005; Willman et al. 2006). Several of the taxa recorded in Australia are also known from Siberia (Moczyłowska et al. 1993), China (Zhang et al. 1998; Yuan and Hofmann 1998), and the East European Platform (Veis et al. 2006) at about the same stratigraphic level. In Australia, only a few taxa of simple, smooth-walled leiospheres (Figs. 3A and 3B) have been recorded after the glaciation. No evidence of species diversification has been observed, although numbers of specimens show a marked increase up to the time of the impact. Thereafter, the number of smooth-walled acritarchs and other biota, such as filaments and mat fragments, show a marked decline in numbers. By contrast, complex acritarchs (Fig. 3C–F), which may have been present in small numbers before the impact, and which show an ability to encyst and lie dormant until light, temperature, and nutrient conditions improve, probably survived the impact and subsequently diversified both in the number of species and number of

Fig. 2. Stratigraphy and correlation of drillholes containing the Acraman impact ejecta layer (shown as a continuous horizontal line through all the drillholes and including the depths where it is intercepted) and a generalized stratigraphic column for the Ediacaran Period in the Adelaide Rift Complex (ARC). On the ARC column are shown a 635–580 Ma age for the base of the Ediacaran Period, a less than ~556 Ma age for the Bonney Sandstone (Ireland et al. 1998), an estimated age range of 625–570 Ma for the Acraman impact event (see explanation in text) and an ~542 Ma age for the Ediacaran–Cambrian boundary (Gradstein et al. 2004). LMW 1: Lake Maurice West 1; OH 1: Observatory Hill 1; M: Murnaroo Formation; DD: Dey Dey Mudstone; K: Karlaya Limestone; WDM: Wilari Dolomite Member; Ta: Tanana Formation; Ca: Cambrian; Cz: Cenozoic; El: Elatina Formation; N: Nuccaleena Formation; Br: Brachina Formation; A: ABC Range Quartzite; Bu: Bunyerroo Formation; Wo: Wonoka Formation; Bo: Bonney Sandstone; Ra: Rawnsley Quartzite.

specimens (Grey 2005). Nearly fifty new taxa appeared within 5 or so million years (Grey 2005) exhibiting an evolutionary pattern reminiscent of recovery from mass extinction events (Twitchett 2006). The association between acritarch diversification and the position of the ejecta layer has now been recorded in SCYW-79 1a, a composite section based on WWD 1 and Mount James 1, Observatory Hill 1, Lake Maurice West 1, Munta 1, Murnaroo 1 and Giles 1 (Grey et al. 2003; Hill et al. 2004; Grey 2005; Willman et al. 2006 and unpublished data).

There are also carbon isotope anomalies in SCYW-79 1a, Observatory Hill 1 and Munta 1 (Calver and Lindsay 1998; Calver 2000; Grey et al. 2003; Hill et al. 2006) and biomarker anomalies (McKirdy et al. 2006; Webster et al. 2006) that coincide with the ejecta layer as confirmed by the new data presented in this paper. The carbon isotope changes are similar to those across the Permian–Triassic mass extinction–radiation event (Holser 1997) suggesting the Acraman impact event affected the long-term carbon cycle. There are two biomarker anomalies temporally linked to the Acraman

impact event. The first is a eukaryotic signature shown by a marked increase in ethylcholestane abundance in many sediment samples that begins slightly below the body fossil appearance of acanthomorphs and persists for about 20 million years (McKirdy et al. 2006). The second is a bacterial signature expressed in the relative abundance of highly branched alkanes, which virtually disappear over ~20 m of relatively deep-water mudstone in drillhole Munta 1 at the ejecta layer, reappearing 5 m below the onset of the eukaryotic anomaly (Webster et al. 2006). The latter anomaly probably reflects the initial collapse of the biosphere in response to the impact event and hence the food supply for bacterial heterotrophs, and the former marks the appearance and diversification of encysting chlorophyte algae

CHARACTERISTICS OF THE ACRAMAN EJECTA LAYER

The ejecta layer was first identified from a number of field locations in the Adelaide Rift Complex (Gostin et al. 1986) and

Fig. 3. Photomicrographs of acritarch species before (A, B) and after (C–F) the Acraman impact ejecta layer (Grey 2005). A: *Leiosphaeridia crassa* (Naumova 1949) Jankauskas in Jankauskas et al. 1989, and B: *Leiosphaeridia tenuissima* Eisenack 1958, are typical species of the Ediacaran Leiosphere Palynoflora (ELP). C–F are typical species from each of the four zones of the Ediacaran Complex Acanthomorph Palynoflora (ECAP). C: *Appendisphaera barbata* (Grey 2005), broken specimen but with well preserved ornament; D: *Tanarium conoideum* (Kolossova 1991 emend. Moczyłowska et al. 1993); E, *Tanarium pycnacanthum* (Grey 2005); F, *Ceratosphaeridium mirabile* (Grey 2005).

subsequently recognized in drill core in WWD 1 from the Adelaide Rift Complex and in drillholes Lake Maurice West 1 and Observatory Hill 1 from the Officer Basin (Wallace et al. 1989, 1990). Evidence for the presence of the layer consisted of: (1) the abundance of red, angular acid volcanic clasts; (2) the similarity of clast lithologies with those at the Acraman impact site and field localities in the Adelaide Rift Complex; (3) the presence of planar deformation features (PDFs) in quartz together with other shocked minerals; and (4) the presence of an Ir anomaly similar to those found in the Adelaide Rift Complex (Gostin et al. 1989). In both outcrop and drillholes there is commonly a lower, primary ejecta layer and one or two thinner ejecta layers above this that have been interpreted as reworked, possibly by associated tsunami effects (Wallace et al. 1996).

ACRAMAN EJECTA IN DRILLHOLE SCYW-79 1a

SCYW-79 1a, situated on the Stuart Shelf of the Adelaide Rift Complex (Fig. 1) (30°07'30"S, 137°09'24"E),

penetrated the Bunyeroo Formation between 301.0 and 385.0 m (Fig. 2). The depth of the ejecta layer was predicted from lithostratigraphy, acritarch biostratigraphy, and the change from fractured to non-fractured zircon crystals in palynological residues (Hill et al. 2004). The core is fragmented, so the ejecta is not seen in vertical section in the core tray, but can be observed on broken core surfaces as scattered grains. What is interpreted as the primary ejecta layer was discovered at 374.90 m where it consists of pink sand-sized clasts in a band of green dolomitic siltstone about 5 mm thick (Fig. 4). A similar layer of clasts also in a green dolomitic band is present 20 cm above at 374.70 m. The surrounding lithology is massive red-brown siltstone.

In thin section the lower and presumed primary ejecta horizon contains sand-sized angular clasts concentrated in three closely spaced millimeter-thick lamina with similar clasts scattered in the enclosing green dolomitic siltstone (Fig. 5). The clasts comprise hematitically altered plagioclase, K-feldspar and felsic volcanic rock fragments. Quartz, mafic grains altered to bright green chlorite, chert and

Fig. 4. a) Side-on photograph and b) plan view photograph (courtesy of S. George) of ejecta layer at a depth of 374.9 m in drillhole SCYW-79 1a (PIRSA Repository #1107114). Pink grains are acid volcanic rock fragments.

Fig. 5. Photomicrograph of ejecta layer at a depth of 374.9 m in drillhole SCYW-79 1a (PIRSA Repository #1107114). The field of view shows two of the three lamina that make up the layer. Clasts are predominantly hematitically altered feldspar and felsic volcanic rock fragments (dark) partially cemented by diagenetic dolomite (pale). Plane polarized light.

opaque minerals form minor components. The average clast size is about 0.4 mm with a maximum of 0.8 mm. Grains are angular to crudely rounded and typically equant. All clasts are consistent with derivation from the Gawler Range Volcanics and the assemblage is similar to that described from the Acraman ejecta layer elsewhere (Gostin and Zbik 1999; Wallace et al. 1996; Hill et al. 2004). Diagenetic dolomite is present in the interstices between volcanic clasts and in places may be replacing earlier mineral phases. The thin,

presumably reworked, layer of grains at 374.70 m contains an identical assemblage of clasts and alteration products with similar size ranges (Fig. 6).

No shocked minerals were found in SCYW-79 1a but in thin sections from the Acraman layer in the Adelaide Rift Complex sand-sized quartz grains rarely show PDFs. The best shock evidence comes from large clasts of volcanics. There was also not enough material available for the possible detection of an Ir anomaly. Therefore, the evidence that this is

Fig. 6. Photomicrograph of reworked ejecta layer at a depth of 374.7 m in drillhole SCYW-79 1a (PIRSA Repository #1107113). Hematitically altered feldspar and felsic volcanic rock fragments (dark) are locally surrounded by diagenetic dolomite (pale). Plane polarized light.

a record of the primary ejecta layer is equivocal. However, the presence of a second layer of ejecta at 374.70 m is consistent with occurrences in the Adelaide Rift Complex where there is a lower, primary ballistic ejecta layer often with larger rock fragments and a second, sand-sized ejecta layer separated from the primary layer by up to 15 cm of green siltstone. In SCYW-79 1a the angular nature of the labile feldspar and acid volcanic rock fragments and poor sorting all argue for minimal reworking in the upper layer. The small size of the angular fragments in the lower layer in SCYW-79 1a and the thinness of both the layers can be explained by evidence that shows the ejecta layer thins considerably to the north within the Adelaide Rift Complex and that the grain size of the primary ejecta layer varies dramatically along strike, from boulder-sized to sand-sized within only a few centimeters. For these reasons we suggest that the ejecta layer at 374.90 m is most likely to be primary.

ACRAMAN EJECTA IN DRILLHOLE MUNTA 1

Munta 1, situated in the eastern Officer Basin (Fig. 1) ($28^{\circ}21'22''\text{S}$, $131^{\circ}53'57''\text{E}$), penetrated the Dey Dey Mudstone between 1675.0 and 1973.0 m (Fig. 2). The approximate stratigraphic position of the Acraman ejecta layer was predicted using three independent lines of evidence: acritarch biostratigraphy, carbon isotope stratigraphy, and biomarker anomalies. At 1884.36 m (Fig. 7) a trail of pink, angular, sand-sized clasts are present on a bedding plane

Fig. 7. Photograph of pink, acid volcanic rock fragments on green siltstone bedding plane at a depth of 1884.36 m in drillhole Munta 1 (PIRSA Repository #1107115).

surface within a thin green band surrounded by otherwise red siltstone. In hand specimen the ejecta layer is similar to that in Giles 1 (Hill et al. 2004). In thin section (Fig. 8), the clasts are between 0.1 and 0.4 mm in diameter and form a discontinuous layer with grains spaced up to several millimeters apart. The grains comprise hematitically altered plagioclase, K-feldspar and felsic volcanic rock fragments typical of other

Fig. 8. Photomicrograph (crossed polars) of ejecta layer at a depth of 1884.36 in Munta 1 (PIRSA Repository #1107115). The isolated clasts (inside white circles) comprise hematitically altered felsic volcanic rock fragments.

occurrences of Acraman ejecta. No definitive shock effects were observed but this is not surprising considering the small amount of material in thin section and that shock effects in quartz, such as PDFs, are rare in sand-sized debris in outcrop in the Adelaide Rift Complex. Any shock effects in feldspars have likely been destroyed by the intense diagenetic alteration. As for SCYW-79 1a there was too little material available for Ir analysis. Although the ejecta layer is thin and discontinuous, because of the distance from the crater, we suggest that this is the primary ejecta layer. It coincides with carbon isotope (Calver and Lindsay 1998; Hill et al. 2006) and biomarker anomalies (McKirdy et al. 2006; Webster et al. 2006), which strengthens this argument.

CONCLUSIONS

This report of Acraman impact ejecta, probably as the primary layer, in drillholes SCYW-79 1a from the Stuart Shelf and Munta 1 from the Officer Basin brings to seven the number of drillholes in which the ejecta layer has been identified. The relative position of the ejecta layer in other drillholes, acritarch biostratigraphy, carbon isotope stratigraphy, and biomarker anomalies narrowed down the interval in which it might be present and allowed for the discovery of its position in SCYW-79 1a and Munta 1. Its presence confirms correlations previously suggested by Wallace et al. (1989) to the Ediacaran section above the GSSP in the Adelaide Rift Complex and also confirms observations

by Grey (2005) about the position of the ejecta layer relative to the first appearance of acanthomorph acritarchs. Since the ejecta layer was discovered in Murnaroo 1 (Hill et al. 2004), additional palynological studies have shown that the same biostratigraphic succession is present above the ejecta layer in that drillhole and that the first appearance of acanthomorph acritarchs has now been narrowed down to about 50 m above the Acraman ejecta layer (Willman et al. 2006). Ongoing acritarch biostratigraphy (Willman), carbon isotope stratigraphy (Hill), and biomarker research (L. J. Webster, University of Adelaide) in additional drillholes from the Officer Basin and Stuart Shelf aims to better determine what role the Acraman event played in Australian Ediacaran biotic and geochemical evolution. Once this is determined global correlations will be attempted to determine how far reaching the effects of the Acraman impact were.

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