The Foelsche structure, Northern Territory, Australia: An impact crater of probable Neoproterozoic age

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Abstract—The Foelsche structure is situated in the McArthur Basin of northern Australia (16°40'S, 136°47'E). It comprises a roughly circular outcrop of flat-lying Neoproterozoic Bukalara Sandstone, overlying and partly rimmed by tangentially striking, discontinuous outcrops of dipping, fractured and brecciated Mesoproterozoic Limmen Sandstone. The outcrop expression coincides with a prominent circular aeromagnetic anomaly, which can be explained in terms of the local disruption and removal or displacement of a regional mafic igneous layer within a circular area at depth. Samples of red, lithic, pebbly sandstone from the stratigraphically lowest exposed levels of the Bukalara Sandstone within the Foelsche structure contain detrital quartz grains displaying mosaicism, planar fracturing (PFs) and planar deformation features (PDFs). PFs and PDFs occur in multiple intersecting sets with orientations consistent with a shock metamorphic origin. The abundance and angular nature of the shocked grains indicates a nearby provenance. Surface expression and geophysical data are consistent with a partly buried complex impact crater of ~6 km in diameter with an obscured central uplift ~2 km in diameter. The deformed outcrops of Limmen Sandstone are interpreted as relics of the original crater rim, but the central region of the crater, from which the shocked grains were likely derived, remains buried. From the best available age constraints the Foelsche structure is most likely of Neoproterozoic age.

INTRODUCTION

Because of crustal recycling, the Earth's impact record is strongly biased towards young or large continental impact events (e.g., Grieve et al., 1995). Relatively few impact structures of Proterozoic age are known, and most of these are deeply eroded. Australia has the best Proterozoic impact record (Shoemaker and Shoemaker, 1996), and the number of known sites is continually growing. There are several reasons for this. Firstly, Australia contains large areas of exposed Proterozoic rocks, including extensive Proterozoic basins that are only weakly to moderately deformed. Many of these areas have undergone very slow erosion, or have been covered and then exhumed during the later Phanerozoic. While Australia is potentially the key to constraining the cratering rate during the Proterozoic (Shoemaker and Shoemaker, 1996), it is also clear that the record is still far from complete. Here we provide details of the discovery of a new probable impact structure of Neoproterozoic age from northern Australia.

REGIONAL GEOLOGICAL SETTING

The Foelsche structure is situated near the Gulf of Carpentaria in northern Australia (16°40'S, 136°47'E; Fig. 1). Geologically, it is sited within the McArthur Basin, a thick succession of unmetamorphosed, and for the most part only weakly deformed Palaeo- to Mesoproterozoic sedimentary rocks and volcanics exposed over ~200 000 km². The basin is essentially contiguous with the partially contemporaneous South Nicholson Basin, Lawn Hill Platform and Mt. Isa Basin to the southeast. This region is proving a fruitful hunting ground for impact structures, and also contains several circular surface and geophysical structures of uncertain origin yet to be investigated (Fig. 1; Table 1).

Stratigraphy

The southern McArthur Basin succession is subdivided into four main unconformity-bound groups; the Tawallah, McArthur, Nathan and Roper groups in ascending order (Rawlings, 1999).
Locally, the McArthur Basin rocks are unconformably overlain by relatively thin sequences of Neoproterozoic, Cambrian and Cretaceous age. The succession in the Foelsche area is significantly attenuated compared to that further west in the central part of the exposed basin. In particular the McArthur group is absent, and most of the Roper group has been removed by erosion, apparently prior to the formation of the Foelsche structure. The oldest stratigraphy exposed in the Foelsche area consists of the Tawallah group. Although probably several thousand metres in thickness, as it is elsewhere (Rawlings, 1999), only the upper part is exposed locally. Because of the low topography and flat-lying nature of the strata, no good stratigraphic sections are present in the immediate region. For this reason we have used information from a nearby mineral
Table 1. Summary data for impact structures and circular structures in Fig. 1.

<table>
<thead>
<tr>
<th>Impact structures</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Diameter (km)</th>
<th>Age</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goyder</td>
<td>13°29' S</td>
<td>135°02' E</td>
<td>3*</td>
<td>Pre-Cretaceous-Mesoproterozoic</td>
<td>Haines (1996)</td>
</tr>
<tr>
<td>Strangways</td>
<td>15°12' S</td>
<td>133°35' E</td>
<td>25</td>
<td>Neoproterozoic (646 ± 42 Ma)</td>
<td>Spray et al. (1999)</td>
</tr>
<tr>
<td>Foelsche</td>
<td>16°40' S</td>
<td>136°47' E</td>
<td>6</td>
<td>Neoproterozoic</td>
<td>This paper</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circular structures</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Diameter (km)</th>
<th>Age</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barranundi</td>
<td>16°49' S</td>
<td>136°40' E</td>
<td>4</td>
<td>Palaeoproterozoic</td>
<td>This paper</td>
</tr>
<tr>
<td>Gupuliyul</td>
<td>13°19' S</td>
<td>134°06' E</td>
<td>10</td>
<td>Mesoproterozoic</td>
<td>Sweet et al. (1999)</td>
</tr>
<tr>
<td>Spear Creek</td>
<td>17°16' S</td>
<td>135°50' E</td>
<td>1.2</td>
<td>?Post Cambrian</td>
<td>Colliver (1984); this paper</td>
</tr>
</tbody>
</table>

*Diameter of Goyder refers to exposed central uplift only.

exploration diamond drill hole (DDH HO1; McMahon, 1970), in order to determine the likely upper Tawallah group stratigraphy and formation thicknesses at the Foelsche structure itself. This drill hole is sited ~3 km southwest (16°43.1' S, 136°47.9' E) of the southern edge of the aeromagnetically defined margin of the Foelsche structure. In descending order the upper Tawallah group stratigraphy at Foelsche probably comprises dolomitic mudstones and fine-grained sandstones of the Wollongorong and Aquarium Formations and the Wununmanta Sandstone. A mafic igneous unit, the Settlement Creek Volcanics, typically occurs between the Aquarium and Wollongorong Formations or lies within the latter. Once assumed to represent surface lava flows, the typically doleritic Settlement Creek Volcanics is now believed to be mainly of shallow intrusive origin (Jackson et al., 2000). In HO1 it comprises two discrete sills, 25 and 35 m thick and separated by 25 m of mudstone. The upper has intruded into the lower Wollongorong Formation, while the lower intrudes the contact between the Aquarium and Wollongorong Formations. It is the presence of this mafic material that we consider is responsible for the distinctive aeromagnetic signature of the Foelsche structure, but it has not been possible to determine with certainty how many sills are present at the Foelsche structure itself. Only a few metres of Wollongorong Formation is present above the Settlement Creek Volcanics in HO1, and in nearby outcrops it has been entirely removed by post-Tawallah group erosion. Whether any Wollongorong Formation survives at the Foelsche structure is uncertain. The Tawallah group is unconformably overlain by the early Mesoproterozoic Nathan group, represented here only by the thin Karns Dolomite. Due to pre-Roper group erosion only ~30 m or less of this formation is likely to be present locally. The Karns Dolomite is overlain unconformably by the Mesoproterozoic Roper group represented locally only by the Limmen Sandstone. In flat-lying outcrops northeast of the Foelsche structure only ~20 m of this unit are exposed. Younger formations of the Roper group were probably deposited in the area, but were removed by erosion before deposition of the Bukalarra Sandstone. The Bukalarra Sandstone is a post-McArthur Basin formation that crops out as local relics of a once more extensive shallow marine cover sequence. We consider it to be of Neoproterozoic age (see discussion below). Apart from Quaternary cover, the Bukalarra Sandstone represents the youngest strata in the immediate vicinity of the Foelsche structure. Table 2 summarises the stratigraphy in the Foelsche area and provides estimates of unit thicknesses.

THE FOELSCHE STRUCTURE

The Foelsche structure is a roughly circular feature that can be discerned on aerial photographs (Fig. 2) as well as geological (Yates, 1963) and topographic maps. The name is derived from the Foelsche River, which flows past the northern edge of the structure at a locality known as Kelly Gap. The surrounding region is characterised by essentially flat-lying Palaeo- to Mesoproterozoic McArthur Basin and younger strata. Outside of the Foelsche structure, structural disturbance is generally restricted to northwest trending faults that display relatively little displacement. The topographic feature is accompanied by a prominent circular aeromagnetic anomaly (Fig. 3). It is this feature in particular that attracted our attention to the site. The only gravity data is on a regional scale, which has been of no use in this study.

The topographic expression of the Foelsche structure is dominated by a semi-circular range of low hills ~5 km in diameter. The higher eastern side rises to a flat surface about 70–80 m above the immediately surrounding terrain, while the western side is lower and more strongly dissected by drainage.
**TABLE 2. Stratigraphy of the Foelsche area down to Wunnumntyala Sandstone inclusive.**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Age</th>
<th>Description</th>
<th>Regional thickness*</th>
<th>Thickness in Foelsche area†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bukalara sandstone</td>
<td>Neoproterozoic</td>
<td>Grey medium- to coarse-grained lithic sandstone with distinctive water escape features</td>
<td>200 m</td>
<td>&lt;100 m</td>
</tr>
<tr>
<td>Bukalara sandstone, lower unnamed member</td>
<td>Neoproterozoic</td>
<td>Red pebbly lithic sandstone and conglomerate</td>
<td>Absent</td>
<td>~25 m+</td>
</tr>
<tr>
<td>Limmen sandstone (Roper group)</td>
<td>Mesoproterozoic (~1500 Ma)</td>
<td>White fine-grained silicified quartzose sandstone with cross-beds</td>
<td>250 m</td>
<td>&lt;20 m due to pre-Bukalara erosion</td>
</tr>
<tr>
<td>Karns dolomite (Nathan group equivalent)</td>
<td>Mesoproterozoic (~1590 Ma)</td>
<td>Stromatolitic and evaporitic dolostone</td>
<td>800 m</td>
<td>&lt;30 m due to pre-Limmen erosion</td>
</tr>
<tr>
<td>Wollongorang Formation (Tawallah group)</td>
<td>Palaeoproterozoic (~1730 Ma)</td>
<td>Evaporitic dolostone, mudstone, shale and sandstone</td>
<td>200 m</td>
<td>Thin or absent due to pre-Karns erosion</td>
</tr>
<tr>
<td>Settlement Creek Volcanics (Tawallah group)</td>
<td>Palaeoproterozoic (~1725 Ma)</td>
<td>Dolerite sills; minor hornfelsed mudstone enclaves</td>
<td>100–200 m</td>
<td>85 m (total of two sills and hornfels)</td>
</tr>
<tr>
<td>Aquarium Formation (Tawallah group)</td>
<td>Palaeoproterozoic (~1735 Ma)</td>
<td>Evaporitic mudstone and fine-grained glauconitic sandstone</td>
<td>100–200 m</td>
<td>&gt;200 m</td>
</tr>
<tr>
<td>Wunnumntyala sandstone (Tawallah group)</td>
<td>Palaeoproterozoic (~1740 Ma)</td>
<td>Pink fine- to medium-grained quartzose sandstone with ripples and cross-beds</td>
<td>250 m</td>
<td>Unknown, but probably &gt;200 m</td>
</tr>
<tr>
<td>Lower Tawallah group</td>
<td>Palaeoproterozoic (~1740–1800 Ma)</td>
<td>Sandstone, volcanics, mudstone, dolostone</td>
<td>1000's m</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

* A summary of regional stratigraphy and thicknesses is provided by Rawlings (1999).
† Thickness of units in the Foelsche area is based on diamond drill hole data (McMahon, 1970) and on unpublished mapping by D. J. Rawlings.

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**FIG. 2.** (a) Vertical aerial photograph of the Foelsche structure. (b) Annotated version distinguishing outcrops of deformed rim sandstone (Limmen Sandstone) and infilling Bukalara Sandstone. Scattered low outcrops of Karns Dolomite are common outside of the circular feature. The dark patch in the southeast corner is a fire scar. **Indicates approximate locality of samples analysed for shocked quartz and field photographs.**
fractured Limmen Sandstone (Fig. 4a) gives way inward into a zone of mega-brecia comprising angular blocks of sandstone up to house size (Fig. 4b,c). All of the clasts appear to be derived from the Limmen Sandstone. Further inward the mega-brecia is onlapped by gently dipping red conglomeratic sandstone comprising the lower member of the Bukalara Sandstone (Fig. 4c,d). Although discontinuous, the outcrops of deformed Limmen Sandstone can be inferred to be relics of a ring about 5–6 km in outer diameter. Outward of the outcrops of Limmen Sandstone are scattered exposures of flat-lying and largely undisturbed Karns Dolomite. Very minor poor exposures of dolerite of the Settlement Creek Volcanics were located on the southwest side of the structure (Fig. 2), but the relationships to other units is not clear at this locality.

**Aeromagnetic Signature**

The Foelsche structure has a distinctive aeromagnetic signature, which stands out prominently on a recently acquired regional data set sponsored by the Northern Territory Geological Survey (Fig. 3). The surrounding region is characterised by irregular medium frequency anomalies, probably related to variations in thickness and depth of mafic sills (the Settlement Creek Volcanics) and northwest-trending linear anomalies that represent faults offsetting these magnetic sources, some of which may themselves be intruded by mafic dykes. With the exception of what is referred to here as the Barramundi structure (see below), the Foelsche structure comprises the only distinctly circular aeromagnetic anomaly in the area.

The Foelsche aeromagnetic anomaly has a sharp outer edge ~5.5 km in diameter, inboard of which lies a distinct annular magnetic trough 4 km in diameter. Closer to the centre there is a somewhat discontinuous annular magnetic ridge ~2.5 km in diameter surrounding a central magnetic low. The southwestern margin of the structure is somewhat disrupted by a northwest-trending linear magnetic anomaly, which coincides with a lineament also seen on aerial photographs (Fig. 2). This feature is interpreted as a fault.

The Barramundi structure (after nearby Barramundi stockyard) is a sharp-edged circular aeromagnetic low centred ~19 km southwest of the Foelsche structure (16°49'S; 136°40'E; Figs. 1 and 3). The anomaly is smaller (~4 km in diameter) and less visually prominent than that at Foelsche, but is otherwise similar. The Barramundi structure was only noticed during regional aeromagnetic interpretation after fieldwork was completed, and thus the site has not been examined on the ground. However, from aerial photography it appears that the region is covered by undisturbed Karns Dolomite, apparently obscuring the cause of the anomaly.

**Shocked Mineral Grains**

Hypervelocity impacts involve shock pressures far in excess of those associated with other natural crustal phenomena. Such
Fig. 4. Field photographs from the northeastern margin of the Foelsche structure. (a) Dipping ridge of fractured Limmen Sandstone marking the inferred crater rim; the view is towards the crater centre, which is covered by the low plateau of Bukalara Sandstone visible on the skyline. (b) Mega-breccia of Limmen Sandstone situated inboard of the ridge shown in (a); note hammer at bottom right for foreground scale. (c) View from mega-breccia shown in (b) towards the flat-lying crater fill sediments of the Bukalara Sandstone; the low cliff ~200 m distant is comprised of the lower conglomeratic member. (d) Close-up of lower conglomeratic sandstone member of the Bukalara Sandstone exposed in cliffs in (c). Thin sections from this site reveal common clasts of shocked quartz and possible impact melt.

Shock pressures induce a variety of irreversible changes in minerals that can be used as indicators of impact processes. Because of its near ubiquity in crustal rocks and its simple crystal structure, quartz has become the best-studied and most useful mineral of identifying shock metamorphism. Shocked quartz displays two distinct forms of planar microstructures: planar fractures (PFs) and planar deformation features (PDFs) (Stöffler and Langenhorst, 1994; Langenhorst and Deutsch, 1998; French, 1998). PFs are sharp, straight fractures, typically occurring in parallel sets with >15 μm spacing. PDFs are sharp, straight, planar, optical discontinuities, which occur in sets with typically 2–10 μm spacings. They are not fractures, but rather thin planes of amorphous silica, which in some cases can become thermally annealed after formation leaving discontinuous planes of Inclusions (so-called decorated PDFs). Both PFs and PDFs commonly occur as multiple intersecting sets with different orientations. A characteristic, which is used to distinguish shock-induced planar microstructures from superficially similar features with other origins, is that both types form parallel to rational crystallographic planes, most commonly planes with low Miller indices. PFs and PDFs form at shock pressures ranging between 8 and 35 GPa (Langenhorst and Deutsch, 1998). Another common shock effect is grain mosaicism, a highly irregular mottled extinction distinct from undulose extinction of tectonic origin. Mosaicism in quartz forms at similar shock pressures to PFs and PDFs (Langenhorst and Deutsch, 1998).

The red pebbly sandstone comprising the lowest part of the Bukalara Sandstone on the northeastern side of the Foelsche structure (Figs. 2 and 4c,d) was examined in thin section for evidence of shock metamorphism. If the Foelsche structure were of impact origin, we reasoned that this stratigraphic unit was a good candidate for containing reworked material from within the crater, particularly from the central uplift where shocked lithologies should occur. Isolated sand-sized quartz clasts displaying PFs, PDFs and grain mosaicism were found
to be present in all thin sections examined (Fig. 5). Typically around 2–10% of quartz grains show some features consistent with shock damage. Most PDFs are sharp and continuous, rather than being decorated, and up to five distinct sets of PDFs were found in a single grain. In the best examples the sets cover most or all of an individual grain. The orientations of planar microstructures and the quartz c-axis was measured using a universal stage attached to a petrological microscope following techniques described in Engelhardt and Bertsch (1969) and Stöffler and Langenhorst (1994). A stereo plot of the measured orientations and a template of rational crystallographic planes were used to index the measured sets. To allow unique indexing, only grains displaying multiple sets of planar microstructures were used. In total 83 planar microstructures were measured in 27 selected multi-set grains in four thin sections (Table 3). Each thin section was from a separate sample collected over a narrow stratigraphic interval. The full data set is plotted as a frequency histogram of the polar angle (the angle between the pole to the set and the quartz c-axis) in Fig. 6a. In most cases the microstructures could be confidently identified as either PDFs or PFs, although in some cases PDF and PF sets, of different orientation, have been measured in the same grain. In total 86% of measured PDFs and 70% of measured PFs could be indexed to rational crystallographic planes using a standard template that allows for 5° error in measurements (Fig. 6b,c). The lower percentage of indexed PFs is probably due to the fact that grains containing abundant PFs often display strong undulose extinction and a degree of mosaicism making accurate

Fig. 5. Photomicrographs (crossed polars) of shock features in quartz. (a) Two prominent intersecting sets of fresh PDFs. Note the sharp angular margin to the original grain and the unshocked quartz overgrowths at top. (b) Single set of PDFs parallel to \( \omega (10\overline{1}3) \). This grain displays other sets when rotated on the universal stage. (c) Three distinct sets of planar fractures. (d) Planar fractures and incipient PDF development.
TABLE 3. Orientation of indexed PDF and PF sets in 27 quartz grains.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Miller–Bravais index</th>
<th>Polar angle with c-axis</th>
<th>Number of PDFs</th>
<th>Frequency of PDFs (%)</th>
<th>Number of PFs</th>
<th>Frequency of PFs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c)</td>
<td>(0001)</td>
<td>0.00(^\circ)</td>
<td>5(^*)</td>
<td>10.0</td>
<td>5</td>
<td>15.2</td>
</tr>
<tr>
<td>(\omega)</td>
<td>{10(\overline{1})3}</td>
<td>23.95(^\circ)</td>
<td>16</td>
<td>32.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\pi)</td>
<td>{10(\overline{1})2}</td>
<td>32.42(^\circ)</td>
<td>4</td>
<td>8.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\zeta)</td>
<td>{1(\overline{1})2}</td>
<td>47.73(^\circ)</td>
<td>5</td>
<td>10.0</td>
<td>1</td>
<td>3.0</td>
</tr>
<tr>
<td>(rz)</td>
<td>{10(\overline{1})1}, {01(\overline{1})1}</td>
<td>51.79(^\circ)</td>
<td>8</td>
<td>16.0</td>
<td>11</td>
<td>33.3</td>
</tr>
<tr>
<td>(\rho)</td>
<td>{21(\overline{3})1}</td>
<td>73.71(^\circ)</td>
<td>1</td>
<td>2.0</td>
<td>2</td>
<td>6.1</td>
</tr>
<tr>
<td>(z)</td>
<td>{51(\overline{6})1}</td>
<td>82.07(^\circ)</td>
<td>4</td>
<td>8.0</td>
<td>1</td>
<td>3.0</td>
</tr>
<tr>
<td>(a)</td>
<td>{1(\overline{1})20}</td>
<td>90.00(^\circ)</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>9.1</td>
</tr>
<tr>
<td>Unindexed</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>14.0</td>
<td>10</td>
<td>30.3</td>
</tr>
<tr>
<td>Total</td>
<td>–</td>
<td>–</td>
<td>50</td>
<td>100.0</td>
<td>33</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Indexing was carried out using stereonet plots and a template following methods detailed in Engelhardt and Bertsch (1969) and Stöffler and Langenhorst (1994).

*Note that (0001) “PDFs” are likely to represent mechanical Brazil twins rather than true PDFs (Stöffler and Langenhorst, 1994).

c-axis measurements difficult. The PDFs show a strong peak in abundance parallel to \{10\(\overline{1}\)3\} (\(\omega\)), while PFs are dominated by sets parallel to \{10\(\overline{1}\)1\}, \{01\(\overline{1}\)1\} (\(rz\)). From comparisons with numerous studies at well-established impact structures (see summaries in Stöffler and Langenhorst, 1994; Langenhorst and Deutsch, 1998; French, 1998), the orientation data reported here is fully consistent with the presence of shock metamorphism in the measured grains. Subsequent to obtaining orientation data, further thin sections were cut from samples of the conglomeratic unit collected at scattered localities around the northern part of Foelsche (we have examined ~15 thin sections in total). Preliminary observations confirm that grains with shocked appearance are widespread at this stratigraphic interval within the Foelsche structure. Further studies are required to determine the stratigraphic range of shocked clasts and changing abundance with location and stratigraphic level.

The dominance of unshocked quartz grains and unshocked quartz overgrowths around all grains clearly demonstrates that it is specific individual quartz grains, not the rocks themselves that are shocked. Although the sediments contain grains ranging from well-rounded to angular, the shocked grains are almost exclusively highly angular suggesting very limited transport from a local source. Because the shocked grains may come from different locations, which were exposed to different shock pressures, the combined orientation patterns cannot be meaningfully analysed in terms of any particular shock pressures. Individual grains appear to range from very weakly shocked to moderately shocked, and rarely strongly shocked, under the common scheme reviewed in Stöffler and Langenhorst (1994) (their Table 5), suggesting that shock pressures of up to at least 20 GPa may be represented by some grains. However, this scheme is based mainly on studies of shock in crystalline rocks and Grieve et al. (1996) have suggested that porous sedimentary targets produce different characteristic orientation patterns.

The thin sections also contain common clasts of igneous material up to small pebble size. While some of these clasts appear to be altered dolerite and thus may be derived from the Settlement Creek Volcanics, the majority comprises altered very fine-grained (originally glassy?) material, often with tiny phenocrysts (Fig. 7), which cannot be easily matched to any known volcanic units in the region. We tentatively consider that this material may represent clasts of impact melt. Other lithic clasts include common chert, most likely derived from the Karns Dolomite, which is often silicified, and mudstone, which could be sourced from several local formations.

DISCUSSION

Interpretation of Field Data

The Foelsche structure is interpreted as a partly buried complex impact crater. The arcuate outcrops of deformed Limmen Sandstone are considered to represent relics of the rim of the final collapse crater. The fact that flat-lying and undisturbed Karns Dolomite crops out beyond the rim, but at the same structural level, implies that the Limmen Sandstone has collapsed inward from a slightly higher level. This original level is indicated by outcrops of flat-lying Limmen Sandstone overlying Karns Dolomite ~2 km northwest of the crater rim. The central uplift, which can be inferred from the geophysical data (see below), appears to be completely buried by the Bukalara Sandstone. The burial of the crater, probably soon after formation, has led to the preservation of part of the rim, a feature not normally associated with craters of this age. The abundance of shocked grains and possible impact melt in the crater fill material supports infilling and burial of the crater...
prior to significant erosional degradation. Figure 8 schematically summarises the interpreted subsurface structure based on both surface geology and geophysical interpretation, as well as the post-impact history of the Foelsche impact structure.

Interpretation of Aeromagnetic Data

Impact structures, particularly large ones, may create their own magnetic anomalies by differentially altering the magnetic properties of the target rocks and by the crystallisation of new magnetic phases in impact melt rocks (Pilkington and Grieve, 1992). In this particular case the magnetic anomaly can be largely explained in terms of the local removal and displacement of a preexisting magnetic layer within the near-surface target rocks. Although the anomaly has not been modelled in detail, we contend that the following explanation is consistent with the inferred stratigraphy and the expected structure of a small complex impact crater. The outer margin of the anomaly is interpreted as an edge effect created by the removal or disruption
of much or all of the Settlement Creek Volcanics from the outer region of the excavation zone of the transient cavity. The inner magnetic ridge may indicate the presence of an annulus of deformed dolerite that has survived within the displaced zone, inboard of the deepest part of the excavated zone, or may reflect the presence of preserved magnetic impact melt. The sharp inner edge of this ridge can be explained as another edge effect created by the local upturning and removal of the dolerite and/or melt during the formation of a ~2 km diameter central peak. However, without drilling the subsurface structure of the central region remains speculative. From the magnetic interpretation it can be inferred that the original outer rim of the final collapse crater was ~6 km in diameter, a figure entirely consistent with the exposed remnants of the rim.

The Barramundi structure appears similar to the Foelsche structure in that it is also manifest mainly as an edge effect apparently related to the local absence of a regional magnetic horizon, presumably the Settlement Creek Volcanics, within a circular area. However, the presence of undisturbed Karns Dolomite at the surface implies that it must be older than the Foelsche structure. Although it could represent a buried structure of similar origin, other explanations are possible, and it is unlikely that the cause can be elucidated without drilling.

![Fig. 7. Photomicrograph (crossed polars) showing sand-sized clasts of fine-grained igneous material (IG) which may represent impact melt derived from the central portions of the crater. These clasts contain minute phenocrysts of probable feldspars in an aphanitic groundmass. The other clasts are quartz (Q), one of which (SQ) shows evidence of shock metamorphism.](image)

Fig. 8. Series of schematic cross sections through the Foelsche structure to illustrate the inferred internal structure, stratigraphy and post-impact history. The subsurface structure is speculative as no drilling or detailed geophysical modelling has yet been undertaken. The cross sections are vertically exaggerated, but no specific scale is implied. (a) Flat-lying target stratigraphy just prior to impact in the Neoproterozoic. At the time of impact the land surface probably comprised eroded Limmen Sandstone. A small thickness of Wollogorang Formation may lie between the Settlement Creek Volcanics and the Karns Dolomite. The Settlement Creek Volcanics are shown as a single unit for simplicity, but may comprise multiple mafic igneous layers. (b) Freshly formed complex impact crater. (c) Shortly after impact the crater was buried beneath the Bukalara Sandstone and younger formations. A unique lower conglomeratic unit was apparently confined to the inside of the crater and is believed to contain a significant proportion of material eroded from the crater walls and central uplift. (d) Erosion to the present day has exposed relics of the collapsed rim, preserving deformed Limmen Sandstone at a lower structural level than its occurrence in surrounding areas. The inner parts of the crater remain buried beneath a plateau of Bukalara Sandstone. The preservation of this topographic feature is probably a consequence of a significantly greater thickness of erosion resistant Bukalara Sandstone being present within the crater in comparison with surrounding areas. The shocked clasts within the lower conglomeratic unit are inferred to lie at a level below shocked basement at the peak of the buried central uplift.
Age

The Foelsche impact event occurred during the time interval bracketed by the deposition of the Limmen Sandstone and the Bukalara Sandstone. The Limmen Sandstone is early Mesoproterozoic in age, as indicated by a U-Pb zircon date of $1492 \pm 4$ Ma for a tuffaceous horizon in the conformably overlying Mainoru Formation (Abbott and Sweet, 2000). The Bukalara Sandstone is unfossiliferous and we consider it to be of Neoproterozoic age. This age assessment is based on the presence of probable Neoproterozoic fossils found in rocks overlying an assumed laterally equivalent unit elsewhere (Haines, 1998). Previous interpretations of an Early Cambrian age (e.g., Muir, 1980) were based on the putative presence of trace fossils, but we reinterpret these features as inorganic dewatering structures. In any case the Bukalara Sandstone can be no younger than Middle Cambrian, which is the biostratigraphic age of unconformably overlying fossiliferous limestones in areas west of the Foelsche structure. As indicated earlier, the Limmen Sandstone is situated stratigraphically near the bottom of the Roper group, suggesting local removal of the rest of the Roper group by erosion. In the region surrounding the Foelsche structure, the Bukalara Sandstone lies unconformably on the Limmen Sandstone or over older units, suggesting that the erosion occurred prior to deposition of this younger formation. We see no evidence that the impact event involved any post-Limmen formations of the Roper group and thus suggest that the target surface consisted of flat-lying eroded Limmen Sandstone. Evidence for good preservation of part of the rim suggests that the crater was buried shortly after impact. Thus, the impact event most likely occurred during the Neoproterozoic, probably close to the time of deposition of the infilling Bukalara Sandstone.

Addition to the McArthur Basin Neoproterozoic Cratering Record

If we include the probable Foelsche structure, the McArthur Basin and contiguous Lawn Hill Platform now contain five established impact structures: Liverpool (1.6 km), Goyder (3 km wide central uplift), Strangways (25 km), Foelsche (6 km) and Lawn Hill (18 km) (Table 1). Of these Strangways (646 ± 42 Ma: Spray et al., 1999), Lawn Hill (Shoemaker and Shoemaker, 1996) and Foelsche are most likely of Neoproterozoic age. Liverpool may also be of Neoproterozoic age (Shoemaker and Shoemaker, 1997), while the age of Goyder remains poorly constrained in the interval between the Mesoproterozoic and the Cretaceous (Haines, 1996).

The McArthur Basin and similar geological terrains in northern Australia are already important for constraining the long-term cratering rate, in particular the Neoproterozoic cratering rate on Earth (Shoemaker and Shoemaker, 1996). These regions are generally little deformed, have simple "layer cake" stratigraphy, and have undergone very slow erosion rates, making them ideal for the long-term preservation and recognition of impact structures. However, despite the abundance of known impact structures, the area as a whole has not been searched exhaustively for more subtle features and it is likely that others remain to be discovered. The continuing search will be important in further refining the Proterozoic impact rate. In addition to the Barramundi structure, which we noted near Foelsche, several anomalous circular features that could be of impact origin are known from the McArthur–Lawn Hill region, but studies aimed at establishing their origin have yet to be carried out. These include the Camooweal structure (a 30 km diameter buried structure marked by a prominent circular aeromagnetic anomaly; Glikson, 1996) and the Gupuliyl structure (a 10 km diameter circular deformed zone; Sweet et al., 1999) (Table 1). During this study we also examined a small (~1.2 km diameter) prominent circular structure located in Cambrian rocks overlying the McArthur Basin near Spear Creek, ~121 km west-southwest of Foelsche (17°16.5' S, 135°50' E; Fig. 1). The feature has attracted the attention of several exploration companies looking for Kimberlites or metalliferous diatremes (Dampier Mining, 1981; Collier, 1984), and the site has been penetrated by several shallow percussion drill holes and one diamond drill hole, which failed to find any evidence of a central igneous pipe. We examined the structure in the field and in drill core because available exploration maps showed features suggestive of it being the central part of an eroded impact structure. However, no evidence of impact processes were found in the field or from petrographic examination of core in thin section, and the origin of the circular feature remains indeterminate at the present time. It could be related to dissolution and collapse of carbonate rocks at depth. We feel it is important to document failures as well as successes in the search for new impact structures.

CONCLUSION

The Foelsche structure is interpreted as a partly exhumed ~6 km diameter complex impact crater which was buried close to the time of impact during the Neoproterozoic. Evidence for impact comes from the geological and geophysical structure of the feature, which can be interpreted in terms of a down faulted (collapsed) rim and a buried central uplift, both contrasting markedly with the flat-lying nature of the surrounding strata. The presence of angular shock-metamorphosed quartz grains within immature sediments infilling the crater confirms a close association with impact processes. However, only drilling of the site can fully elucidate the subsurface structure and confirm the inferred source of the shocked clasts. The recognition of the Foelsche structure as a probable impact crater adds to the Australian and McArthur Basin Proterozoic impact record, which is important for constraining global cratering rates during this part of Earth history.
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