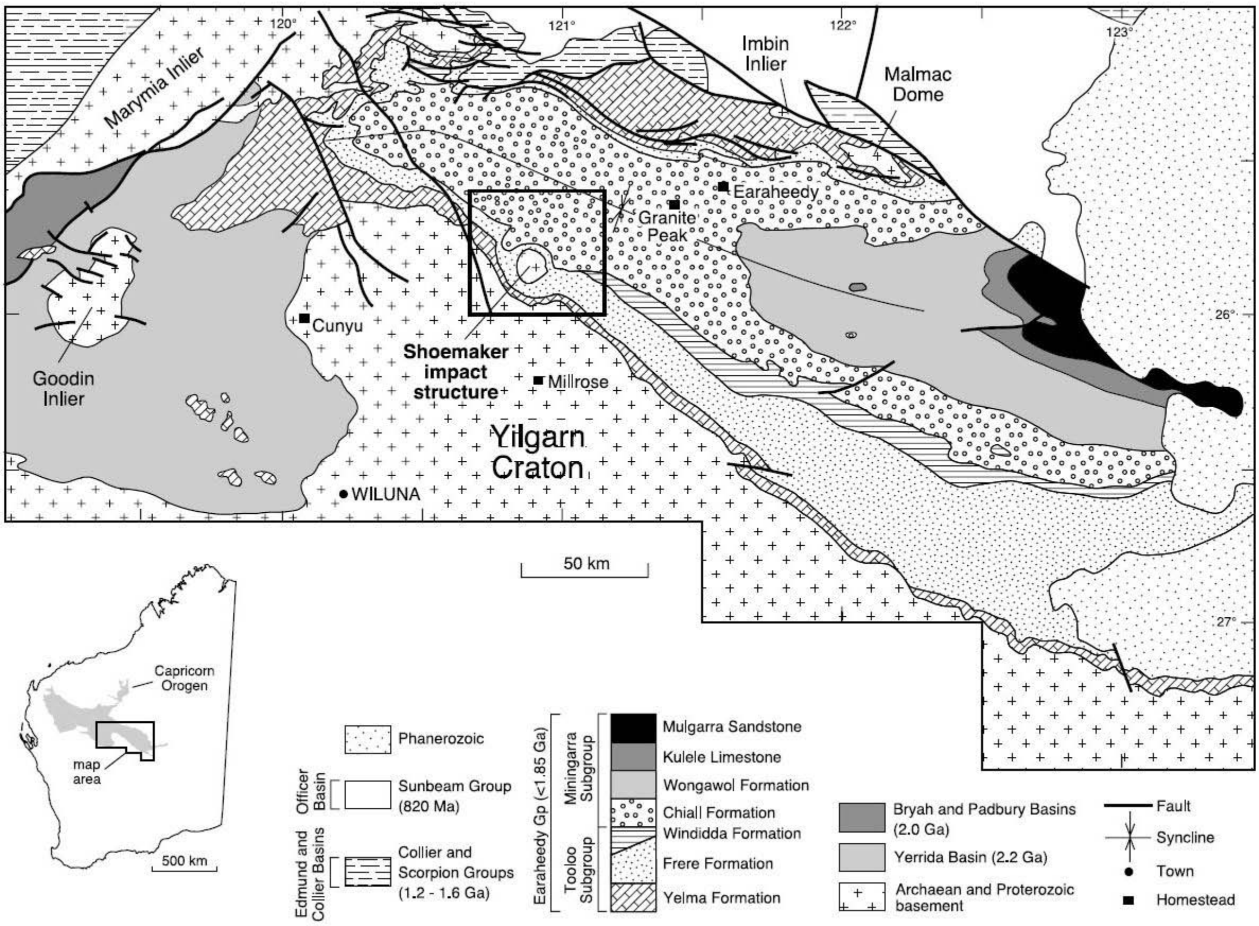

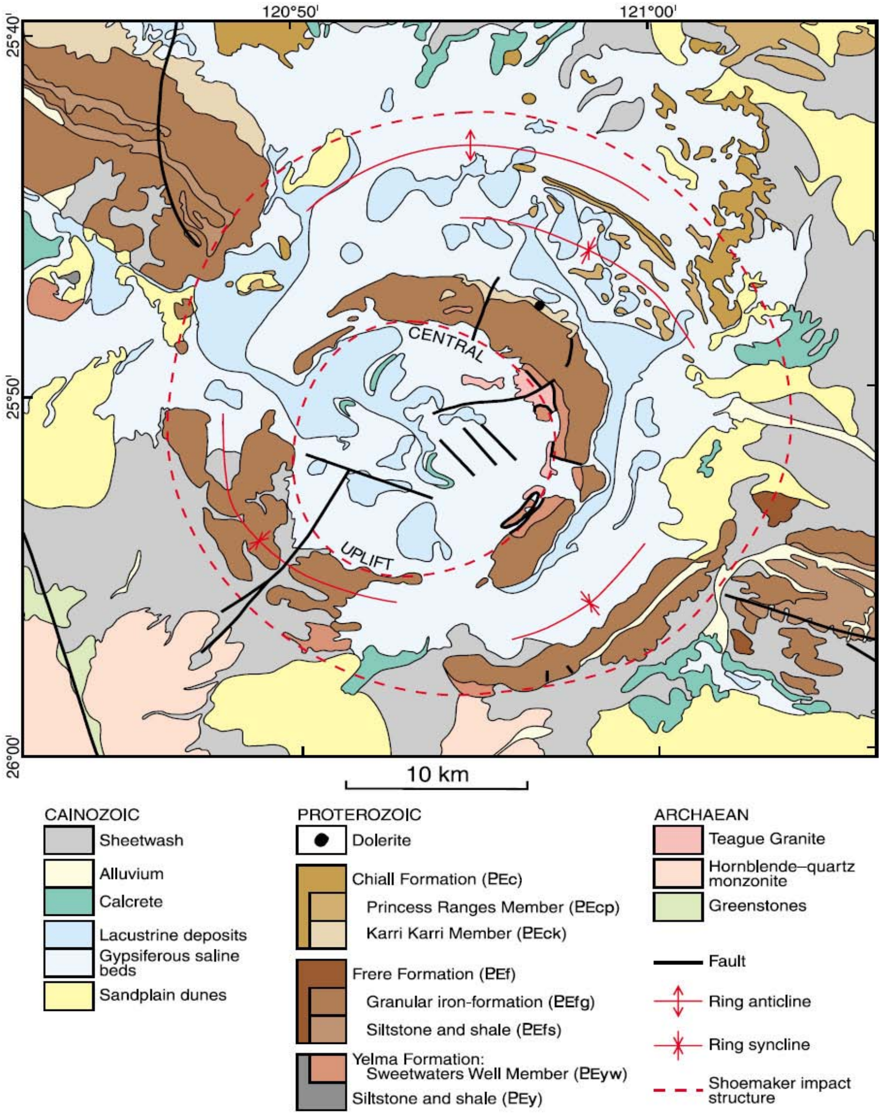

Figure 1a (above): Simplified geological map of the Earaheedy Basin on the northern margin of the Yilgarn Craton. Square shows location of Figure 2.

Figure 1b (left): Simplified geological map of the Shoemaker Impact Structure.

Both figures are from Pirajno et al. (2003).

Shoemaker Impact Structure John Bunting and Mike Freeman

The Geological Survey of Western Australia has supplied each delegate with a copy of the Geological Survey of Western Australia Report 82 by Franco Pirajno, detailing the geology of the structure and including his mapping dated from 2002. Consequently the following general description is brief.

The Shoemaker Impact Structure (SIS) is located at 25°52'S, 120°53'E, about 100 km northeast of Wiluna, and 850 km north-northeast of Perth (Figure 1a). The structure is at the southern edge of the Paleoproterozoic Earaheedy Basin close to the exposed northern margin of the Archean Yilgarn Craton. It consists of a central core, about 12 km across, of predominantly granitic rocks, surrounded by a complex ring syncline about 20-25 km across in Paleoproterozoic sedimentary rocks (Figure 1b).

The structure interrupts prominent lines of hills of the northwest-trending Frere Range, which rise about 50 – 70 m above the surrounding plain. Two concentric rings of low hills, formed by iron-rich sedimentary rocks of the Frere Formation, define the shape of the structure. Ephemeral playas of Lake Nabberu, Lake Teague, and Lake Shoemaker occupy the poorly exposed areas between the two rings and in the area of the central uplift (Figure 2, and see also the front cover of this guide).

The SIS was first described by Butler (1974), who named it the Lake Teague ring structure. He suggested it might have formed as either the result of granite intrusion or an impact event. Bunting et al (1980, 1982) carried out systematic mapping in the area and described evidence for shock metamorphism, including shatter cones and planar deformation fabrics (PDF) in quartz. On geological grounds they concluded that the structure was caused by a cryptoexplosive event that was non-random and therefore may not have been caused by a meteorite impact. During 1986 and again in 1995 Eugene and Carolyn Shoemaker conducted fieldwork and confirmed the presence of shock metamorphism, concluding that the structure was formed by extraterrestrial impact (Shoemaker and Shoemaker, 1996). Sadly, Eugene died in a car accident on 18th July 1997 during a geological field trip that had included another visit to SIS. In commemoration of his life and contribution to astrogeology, the Lake Teague ring structure was renamed the Shoemaker Impact Structure (Pirajno and Glikson 1998). Pirajno (2002, 2005) and Pirajno et al. (2003, 2004) reported detailed investigations of the structure, following 1:100,000-scale mapping by the Geological Survey of Western Australia (Pirajno, 1998).

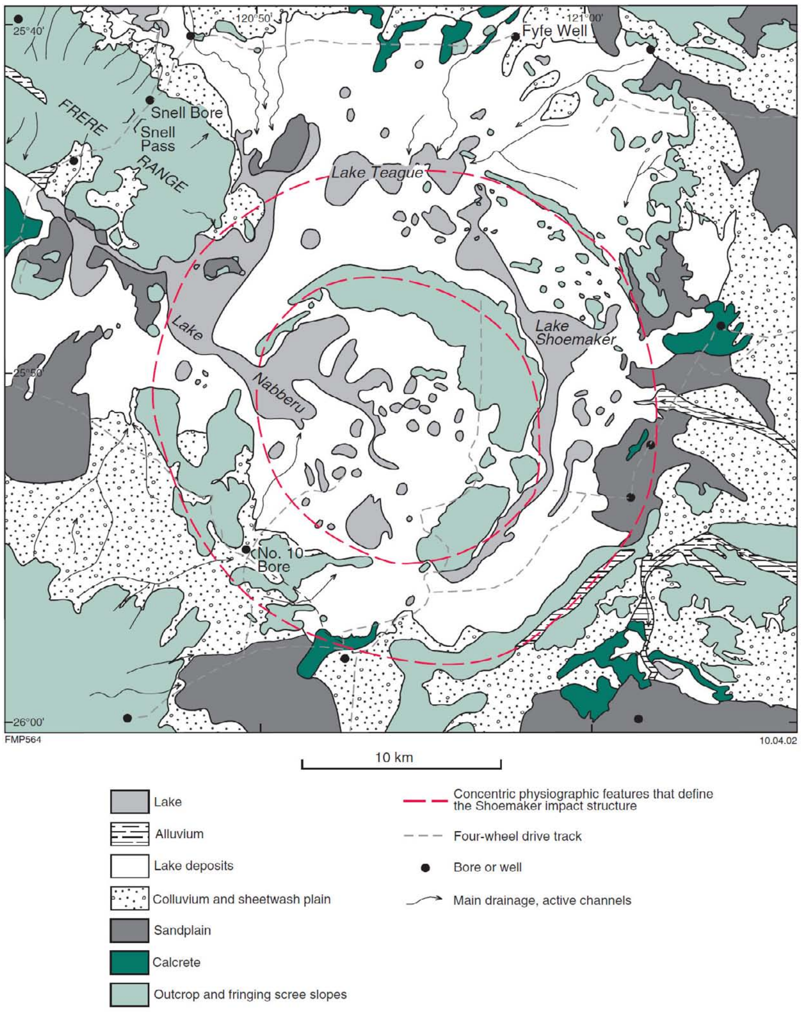

Figure 2: Physiographic map of the area around the Shoemaker impact structure. From Pirajno (2002).

The Shoemaker Impact Structure is a deeply eroded structure. Pirajno (2002) suggests that 2-3 km of overlying rock may have been removed by erosion. Estimates for the original crater diameter range from 36 to 90 km, depending on how it is defined (Glikson, 2002). The structure has been formally assigned a diameter of 30 km, which corresponds to its visible extent. The structure is asymmetrical, with an apparent tilt to the northeast, probably by post-Earaheedy Group but pre-impact tectonism. Pirajno (2002, 2005) notes an east-west asymmetry in the higher magnetic intensity and hydrothermal alteration on the eastern side of the central uplift.

Regional setting

The pre-impact regional geology involves two principal components: the Archean granite-greenstone terrane of the Yilgarn Craton and the Paleoproterozoic sedimentary sequence of the Earaheedy Basin (Earaheedy Group).

Dolerite, possibly a sill, outcrops on the northeast inner rim of the SIS. The emplacement age of the dolerite is not known, but the most likely affiliation is with the numerous dolerite sills of the 1.07 Ga Warakurna Large Igneous Province (Wingate et al., 2004), numerous examples of which intruded the Mesoproterozoic Bangemall Superbasin some 100 km north and northeast of the SIS. Aeromagnetic data show several linear features that are almost certainly mafic dykes. Pirajno et al. (2004) suggest that the sill and dykes post-date the impact.

Yilgarn Craton

Archean greenstones are exposed in a NNW-trending belt about 30 km southwest of the centre of the SIS. Evidence from geophysical interpretation and exploration drilling suggests that greenstones unconformably underlie the Earaheedy Group along the southwest and southeast margins of the SIS. The main rock types are metamorphosed mafic and felsic volcanic rocks, with minor metasedimentary and ultramafic rocks. The greenstones form part of the Laverton Domain of the Kurnalpi Terrane of the eastern Yilgarn (Cassidy et al., 2006). The major mafic-felsic magmatic event in the Laverton Domain has been dated at around 2.81Ga. The central uplift of the SIS contains outcropping remnants of schistose mafic/felsic/sedimentary rocks within the Teague Granite, and Pirajno (2002) interprets an unexposed NW-trending greenstone wedge in the southern part of the Teague Granite.

Granite in the Kurnalpi Terrane is mainly biotite monzogranite and syenogranite ranging in age from 2.7-2.65 Ga. Granite south and southwest of the SIS is mostly hornblende quartz monzonite and hornblende monzogranite. It is coarse grained, consisting of orthoclase, microcline, oligoclase, quartz and dark green euhedral hornblende, with minor biotite, epidote and titanite. Nelson (1999) determined a SHRIMP U-Pb age of 2664 Ma for the hornblende quartz monzonite. Archean granite, including alkaline leucogranite and pyroxene-bearing quartz syenite, collectively termed the Teague Granite, is present in the central core of the SIS, but it been considerably modified by the impact (see below).

The greenstone belt to the southwest of the SIS, near Horse Well, contains some small historical gold workings and some uneconomic gold resources (<100,000 ounces), mainly in shear-hosted veins. Elsewhere the Laverton Domain has significant deposits of gold, nickel, copper-zinc and rare-earth elements.

Earaheedy Group

Subgroup	*Formation*	*Lithology*	*Thickness*	*Comments*
Miningarra Subgroup	Chiall Formation	Siltstone, shale, with glauconitic sandstone and mature quartzite beds in the upper part.	100+ m	In the SIS area, only present in the northeast part of the rim syncline. Not visited on the excursion.
Tooloo Subgroup	Windidda Formation	Shale, mudstone and stromatolitic limestone.	0-300? m	Only present east of the SIS. May be unexposed in eastern rim syncline.
	Frere Formation	Granular iron-formation, shale, ferruginous chert, BIF, dolomite.	600 m	Mainly GIF and shale at SIS. Locally Fe and Mn rich.
	Yelma Formation	Basal sandstone/conglomerate, shale, stromatolitic dolomite.	20-300? m	Limestone commonly silicified (in and outside the SIS). MVT deposits.

Table 1: Stratigraphy of the Earaheedy Group in the area of the Shoemaker impact structure.

The Earaheedy Group, which sits unconformably on the Yilgarn Craton at Shoemaker, occupies the Earaheedy Basin and is a thick package of shallow-marine clastic and chemical sedimentary rocks. In total it is about 5000 metres thick, but only the lower three formations (the Yelma, Frere and Chiall Formations) are involved at the SIS (although a carbonate/shale unit, the Windidda Formation, has been mapped between the Frere and overlying Chiall Formations to the east of the SIS). A summary of the formations is given in Table 1.

Figure 3: Ironstones of the Frere Formation.

The Earaheedy Group was deformed by the Capricorn Orogeny (~1.8 Ga), which created a gentle northeast tilt in the southern part of the basin, but intense folding, faulting and cleavage in the northern part. Good recent summaries of the Earaheedy Group and its tectonic setting in the Capricorn Orogen are given by Pirajno et al. (2009) and Muhling et al. (2012).

Until recently the maximum depositional age of the Earaheedy Group was poorly constrained by dating of detrital zircons between 2.0 Ga in the lowermost part of the sequence and 1.8 Ga near the top (Nelson, 1997; Pirajno et al., 2009). Rasmussen et al. (2012) have now dated volcanic zircons from tuff beds in a drill hole in the basal Frere Formation about 40 km northwest of the SIS. The SHRIMP Pb-Pb data give a depositional age of 1.89 Ga for the basal Frere Formation. Muhling et al. (2012) reported minimum depositional ages from the underlying Yelma Formation. Authigenic monazite intergrown with primary sulphide minerals gave a SHRIMP Pb-Pb age of about 1.81 Ga, and xenotime outgrowths on detrital zircon an age of about 1.83 Ga.

Description of the impact structure

The two components that define the Shoemaker Impact Structure are the concentric ring syncline/anticline structures, formed mainly in Frere and Chiall Formations, and the central core of Archean, mainly granitic rocks (Bunting et al, 1980; Pirajno, 2002).

The ring structures consist of an outer ring anticline and an inner ring syncline. Because of the asymmetry of the structure the folds on the northeast side are much wider, and it is here that the main ring syncline contains shale and sandstone of the Chiall Formation. The outboard ring anticline is absent from the southwest side of the structure. There is a complex pattern of faults, some of which contain quartz veins. In the eastern portions, thrusting and shearing introduce additional complexity. Outside the structure, radial quartz veins appear to converge towards the centre.

The central core (Figure 4) contains various granite types, principally syenite, quartz syenite and leucocratic granite (Bunting et al., 1980; Johnson, 1991; Pirajno, 2002), collectively named the Teague Granite (Pirajno, 1998). These have been uplifted relative to the enclosing Earaheedy Group and are now considered to be within the central uplift of the impact structure. The following descriptions are from Pirajno (2002; 2005).

Figure 4: Teague Granite in the centre of the structure.

The syenite is medium grained, pink to brick red, and contains about 55% orthoclase phenocrysts and 15% zoned alkali pyroxene (sodic hedenbergite or aegirine augite), with 25% albite in the groundmass. Accessories include green fibrous amphibole, zircon and andradite garnet. The quartz syenite is similar to the syenite in grain size and colour but has a polygonal and granoblastic texture. Albite and quartz, in roughly equal proportions, are overprinted by perthitic microcline. Accessories include alkali pyroxene, amphibole, zircon and titanite. The leucocratic granite consists of quartz and microcline, +/- albite, biotite and sericite. Unlike the syenitic rocks the texture of the leucocratic granite is distinctly cataclastic.

Pirajno (2002, 2005) concluded that the various rock types in the Teague Granite, along with alteration assemblages and veins in remnants of greenstones, resulted from deformation, alkali metasomatism and hydrothermal alteration of Archean rocks by the impact. A possible candidate for the pre-impact precursor of the pyroxene-bearing alkaline rocks is the hornblende quartz monzonite outside the SIS.

Age

The age of the Shoemaker Impact Structure is poorly constrained, largely because the rocks have undergone a complex sequence of thermal events over time. The impact must post-date deposition of the Earaheedy Group, and a recently reported Pb-Pb (SHRIMP) age of 1.88 Ga on volcanic zircon from the Frere Formation therefore gives a maximum age of the impact (Rasmussen et al., 2012). A number of different dating methods have been used on samples of the Teague Granite, and these provide widely varying ages. SHRIMP U-Pb dating of zircons extracted from the granite returned 2648 ± 8 Ma, which is interpreted to be the magmatic age of the granite (Nelson, 1997). Rb-Sr dating on whole-rock granite samples returned ages of 1630 and 1260 Ma (Bunting et al., 1980), which are now interpreted to be 'resetting' by thermal events at 1630 Ma and intense weathering at 1260 Ma (Pirajno and Glikson, 1998; Pirajno et al., 2003). Ar-Ar dating returned disturbed apparent ages of about 1300 and1000 Ma, the latter age possibly being related to the emplacement of a dolerite sill on the northern edge of the inner ring at about 1070 Ma. K-Ar analyses on clay minerals from the granite provided ages of 694 ± 25 and 568 ± 20Ma.

The K-Ar technique has previously been successful at determining the tectonic and thermal histories of sedimentary basins, and Pirajno (2002, 2005) therefore takes 568 Ma as the most likely age of the impact; however the two K-Ar ages are inconsistent, and there is no certainty that the clay minerals sampled were the direct result of processes associated with the impact. Pirajno et al. (2004) describe the dolerite in the northeast inner ring as undeformed and possibly post-impact. If this is correct, and if the dolerite is part of the 1.07 Ga Warakurna Large Igneous Province, then a late Paleoproterozoic to early Mesoproterozoic age of impact is more likely.

Evidence for impact

Circular structure:

The most striking feature of the Shoemaker Impact Structure is the two concentric rings of iron-rich rocks, which mark a well-defined circular structure around a 12 km diameter core of Archean granitic rocks (Figures 1, 2 and front cover of this guide). There is evidence of uplift of the granitic core accompanied by faulting and generation of ring syncline and anticline.

Shatter cones:

Shatter cones up to 30 cm long occur in the granular iron-formation of the Frere Formation (Bunting et al., 1980; Pirajno, 2002). Sandstone of the Chiall Formation contains shatter cones up to 0.5 m in length about 15 km northeast of the centre of the SIS (Figure 5), and poorly developed shatter cones have been described from silicified carbonate rocks of the Yelma Formation immediately east of the central uplift (Pirajno, 2002). With the eye of faith, shatter cones can be identified in the Teague Granite.

Figure 5: Shatter cones in the Chiall Formation.

PDFs:

Planar deformation features, mainly of the decorated variety defined by lines of fluid inclusions, are present in quartz in the leucocratic portion of the Teague Granite (Figure 6) (Bunting et al., 1980; Pirajno, 2002). They appear to be absent (or rare?) in the syenitic phases.

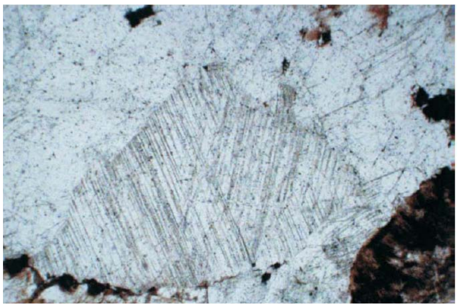
Figure 6: PDFs in quartz of Teague Granite. From Pirajno (2002)

Planar fractures:

Planar fractures are found in quartz grains of Chiall Formation sandstone, near the location of the shatter cones.

Pseudotachylite veins:

Bunting et al. (1980) describe narrow (<1mm) pseudotachylite veins, consisting of quartz and feldspar fragments in a devitrified glassy matrix, in the granite and syenite. (e.g. Figure 7). In the same thin sections plagioclase crystals are shattered and twin lamellae disrupted.

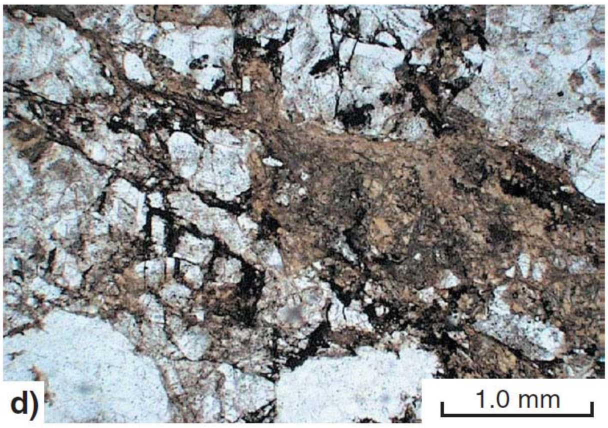

Figure 7: Pseudotachylite veinlets cutting across an albite–quartz assemblage and infilled with sericite Plane-polarized light. From Pirajno (2002).

Fracturing and brecciation:

Much of the granitic rock in the central core is intensely fractured. About 15 km NNE of the centre of the SIS is a lag deposit of centimetre- to metre-sized rounded and angular boulders of sandstone. Pirajno (2002) suggests that the fragments represent reworked lithic breccia ejecta or crater-fill allochtonous breccia, although Bunting et al. (1982) considered them to be a lag deposit from Permian glacial rocks.

Geophysical signatures:

Pirajno (2002) describes gravity lows and demagnetized aeromagnetic patterns that are consistent with similar patterns from other impact structures. He suggests that an inner circular magnetic high along the eastern side of the core could be enhanced magnetic susceptibility caused by hydrothermal alteration of hematite to magnetite after impact.

Metasomatism and hydrothermal alteration:

Pirajno (2002, 2005) ascribes numerous features of the SIS to impact-related metasomatism and hydrothermal alteration, including sodic pyroxene, potassium enrichment of feldspar, and silicification in the Teague Granite.

Excursion localities (Figure 8)

Because of the scale of the SIS and difficulties of access (such as playa lakes and poor tracks) the excursion will concentrate on the exposed eastern core, adjacent parts of the inner ring, and the iron formations along the northern inner ring. Access is via Millrose homestead and station tracks to Billabong Bore (MGA 287500E 7126700N), thence NE along a moderately good track for about 13 km to Locality 1 at MGA 293735E 7135257N.

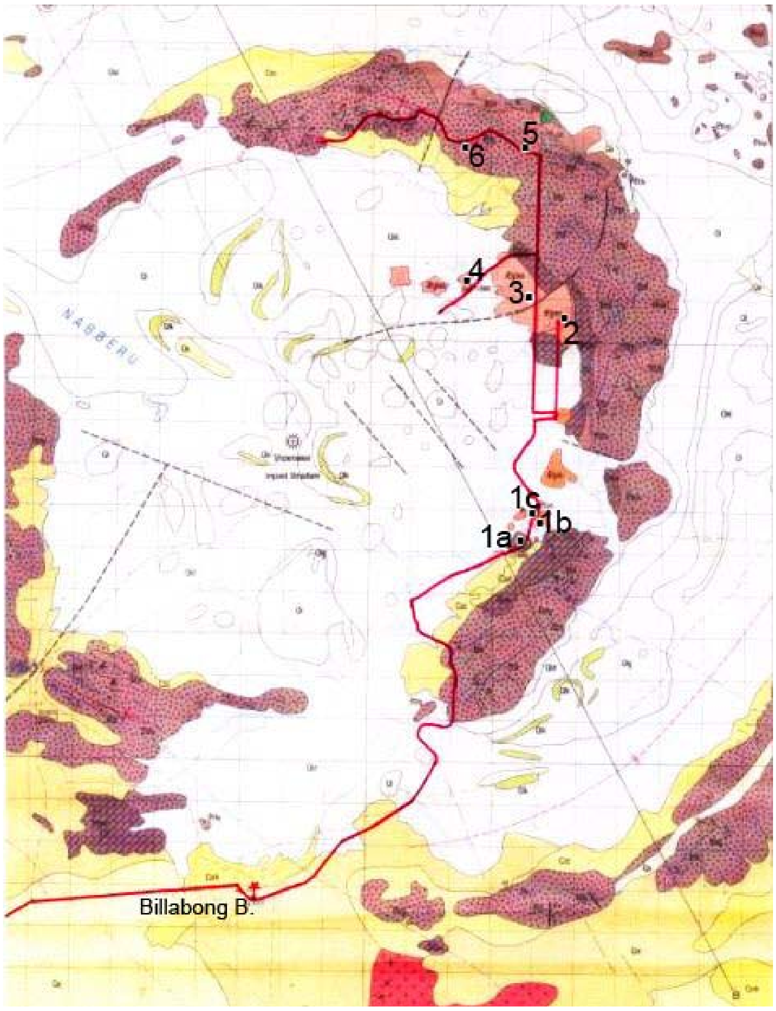

Figure 8: Excursion localities. For geology, see Figure 1. Base map from Pirajno (1998). Grid squares are 1 km.

Locality 1a: Leucogranite, silicified stromatolites and mineralization

Outcrop near the track is leucogranite of the Teague Granite. The composition is quartz, plagioclase, pale pink alkali feldspar and rare biotite. The texture looks recrystallized, and there is closely spaced fracturing – both probably related to the impact event.

Figure 9: Stromatolites (*Asperia digitata*) in silicified dolomite of the Yelma Formation.

To the west there is poorly outcropping chert (silicified carbonate) of the Yelma Formation. The chert has a wavy lamination with well-preserved stromatolites of the form *Asperia digitata* (formerly *Yelma digitata*) (Figure 9) – a form characteristic of the dolomitic Sweetwaters Well Member of the Yelma Formation (Grey, 1984, 1994). Silicification of carbonate is common in the Yelma Formation throughout the Earaheedy Basin, although here it is particularly severe. Rare float of chert breccia has a sulphurous smell and oxidised material that may be oxidised base-metal sulphides. However preliminary analysis using a Niton portable XRF indicates no anomalous base metals. The rock is essentially silica (analysis courtesy of Don Boyer). Base metal mineralization is common in the Sweetwaters Well Member near the top of the Yelma Formation. At Sweetwaters Well, 60 km northwest of Locality 1, fresh galena is present in outcropping stromatolitic dolomite (Bunting, 1986). Exploration drilling of the Sweetwaters Well Member, mainly by Renison Goldfields Consolidated, defined several prospects with zinc, lead and copper sulphides in Mississippi Valley-type (MVT) mineralization (Pirano et al, 2004).

Walk/drive 600m northeast along the track, then to a low outcrop about 100m southeast of the track.

Locality 1b: Quartz arenite – Yelma Formation?

This outcrop of mature, fine- to medium-grained quartz arenite is presumably Yelma Formation; however it is somewhat enigmatic. The rock type, shallow-marine features and stratigraphic position are typical Yelma, but there is no evidence of the deformation that we would expect within the central uplift of a major impact structure. Petrological examination might show evidence of shock effects (e.g. PDFs). If there are none, then it is possible, if unlikely, that the shock waves concentrated in zones of weakness that bypassed this locality. Alternatively, is this evidence of a post-impact, transgressive, shallow-marine sequence that flooded the crater?

Walk/drive about 500m along the track to a low outcrop at MGA 294090E 7136040N.

Locality 1c: Granite, greenstone and Yelma Formation

Near the track is outcropping leucogranite of the Teague Granite. The granite is pervasively shattered and fractured. About 40m to the west poorly exposed mafic schist, with a WNW-trending vertical foliation, is probably a selvage of metamorphosed Archean greenstone caught up in the granite.

To the west, about another 100m, a narrow outcrop of immature sandstone strikes north-northeast, with a shallow easterly dip. The sandstone may originally have been glauconitic, another typical feature of the Yelma Formation. The eastern contact with the granite is probably a fault, but at the western contact the sandstone could be unconformable on the granite. The sandstone can be followed for at least 300m to the southwest where it thickens and contains poorly exposed beds of carbonate (probably originally dolomite, but now largely secondary calcrete). The sandstone, especially on the eastern side of the outcrop, is severely shattered.

Drive north for about 2.4 km to a fence, turn right and after 600m turn left and follow the track on the east side of the fence north for about 2.4 km to a small creek at MGA 294600E 7140500N. [If time is short Locality 2 might be omitted or visited later in the excursion.]

Locality 2: Shattering in leucocratic Teague Granite

Walk northeast along a small creek. The leucocratic variant of the Teague Granite is fractured and shattered by the impact. At MGA 294705E 7140585N the shattering is intense, and includes some possibly poorly developed shatter cones near a very fractured quartz vein (Figures 10a and 10b).

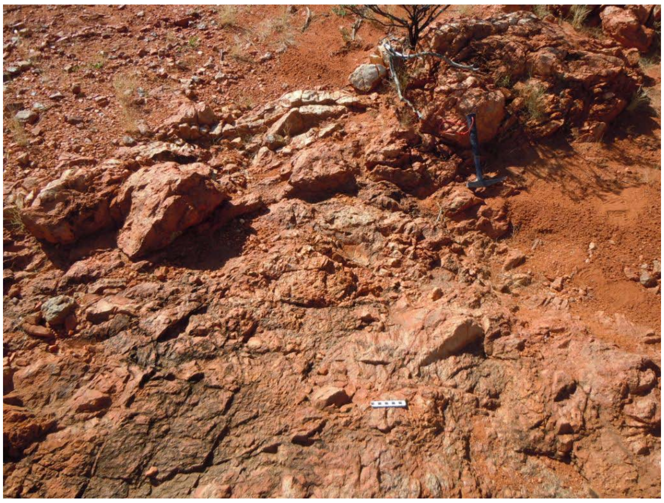

Figure 10a: Shattered granite at Locality 2. Scale: 10cm. Figure 10b: Detail of shattered granite at Locality 2.

Return south for 2.4 km, and just before the fence corner go through the gate. Turn north along the west side of the fence for 150m, turn left and go west for 600m. Turn right and follow the track north for 2.9 km to MGA 294100E 7141100N.

Locality 3: Leucocratic granite and quartz syenite of the Teague Granite

A traverse west for about 600 metres crosses patchy outcrop of Teague Granite. Much of it is leucocratic, but some has been defined as quartz syenite by Pirajno (2002). Much of the outcrop and subcrop is very fractured, and there are some poorly developed shatter cones. Quartz in thin section shows well developed PDFs (Figure 11). Pirajno's sample GSWA 152613 is located near here at MGA 29616E 7413460N. It is described as quartz-microcline-albite granite by Pirajno and albite–K-feldspar-quartz syenite by A. Y. Glikson (Appendix 2 in Pirajno, 2002), and was one of the samples that gave indeterminate Ar-Ar ages (D. Phillips, Appendix 3 in Pirajno, 2002).

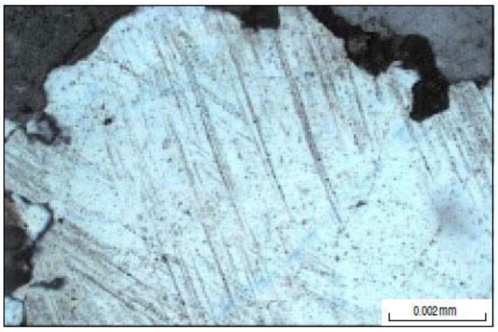

Figure 11: PDFs in quartz of Teague Granite. From Pirajno (2002).

Continue north along the track for 1.1 km to MGA 294100E 7142200N, turn left onto an old track and follow it west then southwest for 1.9 km to MGA 292460E 7141630N, about 200m north of the track.[Note that this locality was not visited during the preparation for this excursion, and there is no guarantee that access will be possible.]

Locality 4: Syenite of the Teague Granite

This is the site of sample GSWA 118996 from which Nelson (1997) obtained a SHRIMP U-Pb igneous crystallization age of 2648 +/- 8 Ma. Nelson described the rock as a pink, medium-grained equigranular syenite, composed of subequal amounts of microcline and albite with minor quartz (3-5%) and hornblende (2-3%). About 300m to the west at MGA 292150E 7141595 (coordinates from Pirajno, 2002) Johnson (1991) described one of several samples as aegirine-augite syenite.

Return 1.1 km to the north-south track and head north for 2.4 km to MGA 294100E 7144600N and turn left. Drive for about 200m.

Locality 5: Panorama view

With a very large structure and relatively low relief there is little opportunity to see the whole feature. From here

Figure 12: Panorama from near the centre of the Shoemaker impact structure, looking towards the rim. Note the line of hills (Frere Formation) and playa lakes.

there are views of much of the inner ring of hills of resistant Frere Formation, and the flat 12-km-diameter central uplift in more-easily eroded Archean rocks covered by playa lakes (Figure 12).

Continue west along the track for 1.8 km to MGA 292134E 7144740N.

Locality 6: Shatter cones in Frere Formation

South of the track outcrops of steeply dipping granular iron formation display some of the best shatter cones in the SIS (Figures 13 and 14). Some of the cones have large apical angles whereas others are more of the horsetail variety. Although secondary iron enrichment obscures some of the detail it is still possible to see the granular texture of the iron-formation, with rounded peloids of jasperoidal chert, generally 0.5-1.0 mm across, in a matrix of fine hematite and cryptocrystalline silica. Larger, more-tabular fragments, on a centimetre scale, are rip-up clasts (intraclasts). The peloids and intraclasts indicate a shallow-water environment above wave base. Elsewhere in the basin the granular iron-formation has an oolitic or pisolitic texture and, rarely, oncolites (large grains with concentric algal layering and abundant microfossils), indicating even shallower, shoal-like conditions. In the northern part of the Earaheedy Basin some banded iron-formations formed in deeper water.

If time permits the excursion will continue west along the track to investigate other outcrops of iron-formation with shatter cones, and examples of iron and manganese enrichment.

This then completes the Shoemaker part of the excursion. Retrace the track to the south, via Billabong Bore, to Millrose homestead and Wiluna.

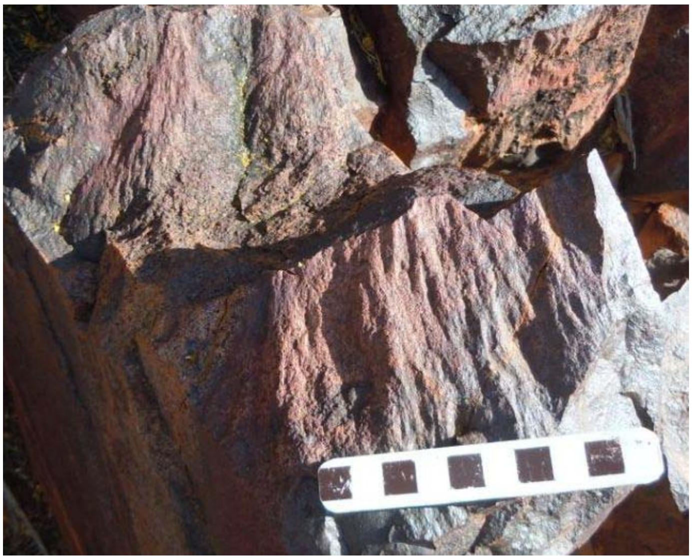

Figure 13: Horsetail structure on a shatter cone at locality 6. Scale is 10cm across.

Figure 14: Horsetail structure on a poorly-developed shatter cone in the Frere Formation. Scale is 10cm across.

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Notes

Figure 1: The "discovery" Google Earth image of the Hickman Crater. The crater is around 260m in diameter.