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Meteorite impacts to gold and nickel deposits (*continued*)

The discovery of *prima facies* evidence for impact structures in the Eastern Yilgarn, Western Australia

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A large circular feature was observed by the author in gravity data of the Yilgarn region of Western Australia in May 1999. The discovery in August 2013 of *prima facies* evidence on many of the documented rings associated with this structure confirmed it to be of impact origin. The rings of this impact structure (Watchorn Impact Structure) extend 560 km north–south and 480 km east–west diameter. From the impact structure's relationship with geological features the age of the impact is estimated at between 2.7–2.64 Ga. This is one of the largest and oldest impact structures worldwide. There are numerous other probable impact structures observable from Kalgoorlie right through to west of Wiluna.

In the Eastern Yilgarn there is an empirical correlation between the largest nickel, gold, copper, silver–lead–zinc and rare earth deposits and the rings of the impact structures. The age of the mineralisation is between 2.7 Ga and 2.62 Ga.

This observed relationship means a paradigm shift is needed for studying the genesis of mineralisation in the Yilgarn and the exploration methods required for success. This may apply to Archaean Cratons worldwide.

This paper is divided into three sections:

A. Examination of impact structures in the Yilgarn (previous issue: *Preview* 166, p. 35).

B. Exploration trip to verify the geology, mineralisation and morphology of the Watchorn Impact Structure (WIS) and to find *prima facies* evidence (this issue: *Preview* 167).

C. Q&A: areas for discussion and further study (next issue: *Preview* 168).

Due to space considerations, Section C shall be deferred until the next issue. In the interim, the author welcomes feedback from readers (Note: opportunity exists for select queries and replies to be published within section C). – Editor

B. Exploration trip to verify the geology, mineralisation and morphology of the Watchorn Impact Structure (WIS) and to find *prima facies* evidence

After discovering the WIS in 1999 an exploration reconnaissance trip was finally undertaken in 2013 to investigate some of the WIS rings that were observed on the gravity, seismic, DEM and most importantly, Landsat data. Notably:

(1) The inner rings were best seen in the gravity data and consisted of two central circular rings of 50 km and 90 km diameter and an outside ring of 250 km diameter. Within these gravity rings and outside them to a diameter of 550 km were circular features observed on Landsat data.
(2) These rings have the morphometric parameters of an impact crater formed by an object of 10–20 km diameter hitting the region just north west of Mertondale 50 km north of Leonora (Figure 1).

These rings were accessible between Menzies and Wiluna and the trip was planned to discover *prima facies* evidence of an impact origin for these specific WIS ring structures.

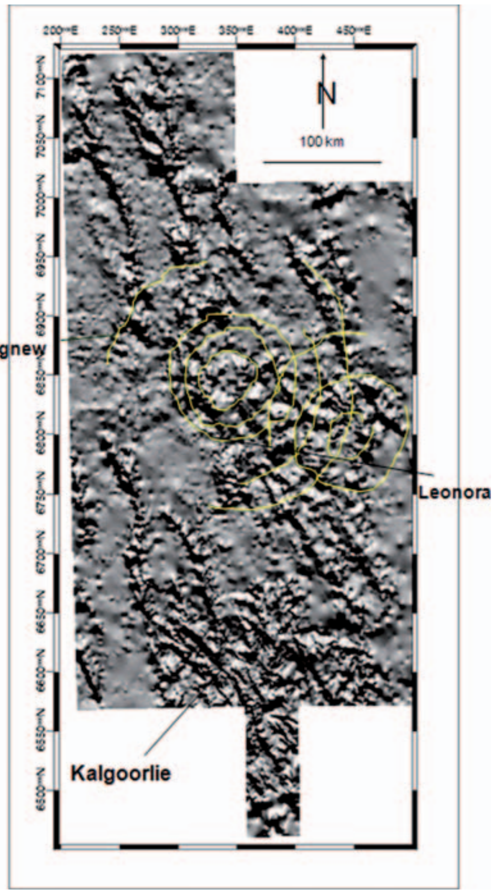

Fig. 1. *Gravity image showing the deeper concentric features and the Watchorn Impact Structure overprinting relationship to the deep Eastern Yilgarn rift structures.*

Prima facies evidence definition

On other planets and satellites morphometric dimensions are used as *prima facies* evidence as they are the only directly observable features. To differentiate impacts from the plethora of other circular features *prima facies* evidence of an impact structure on Earth is reserved to geological features that exhibit shock features. These include shatter cones, shock features in quartz and feldspar grains and rocks believed to be impact melt rocks (Grieve and Pilkington 1996).

Shatter cone. Shatter cones are shock waves preserved or captured in stone. Sudbury shatter cones surround the entire outer perimeter of the impact structure range in size from several centimeters to metres and have distinctive well-defined dominant characteristic deep grooves, converging striations and a narrow V-shape formation.

Shocked quartz. In the mineral quartz the passage of a strong shock wave can cause dislocation of the grain's crystal structure along preferred crystallographic orientations. Thin sections of quartz grains show different sets of planar deformation features (shock lamellae) when rotated.

Impact melt rocks. These rocks are remnants of the impact when rock instantly became fluidal, then cooled to become transformed into many varieties of melt rocks. This material occurs in many states and is associated with only the biggest impacts. **Impactites** are melt glass or melt rock found at the Sudbury impact structure. **Onaping breccias** are quite unusual in the sense that they are composed of small particles and fragments blasted skyward in the conical debris ejection that fell back to earth forming a circular deposit of fallout material. An interesting feature is country rock fragments or quartz, rimmed by fluidal glass, showing well-developed flow lines. Large melt sheets or melt bodies exist around the Sudbury structure (Figure 2).

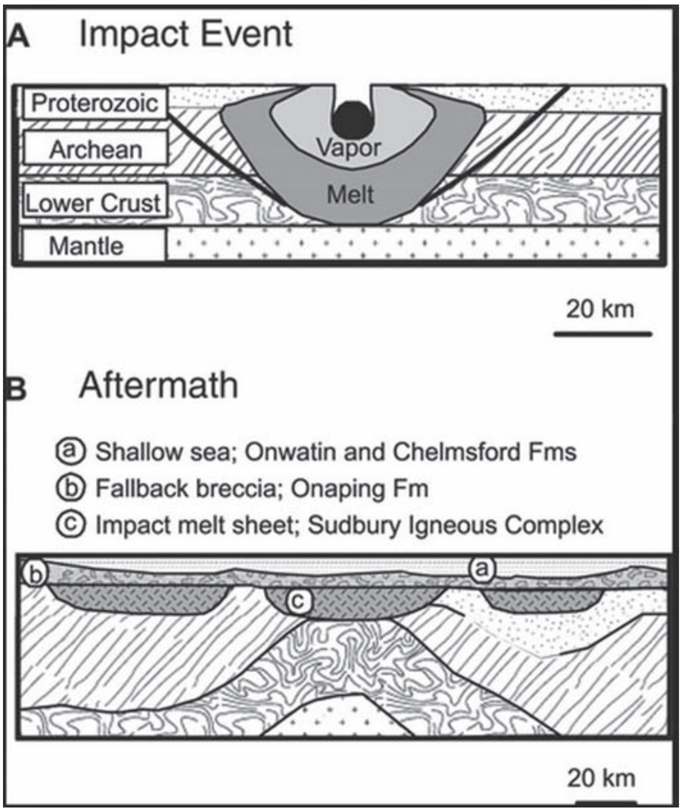

Fig. 2. *Cross-section of the 250 km diameter Sudbury crater showing the dynamics of large crater formation and the major isostatic rebound of the mantle.*

Targeting assumptions and methodology

It was noted that the WIS rings were more strongly developed in the greenstone corridors between the granites. Thus, the main area for the search for the *prima facies* evidence would be along these greenstone corridors, which so happen to be conveniently located amongst the mines and access roads.

Although the central rings were clearly seen on the Gravity and Landsat data the geology and aeromagnetic plans suggest that the area was intensively intruded by later shallower granites and that shock features may have been destroyed there.

The author had also noted that the largest mines, for all metals in the target area were located on or adjacent to the rings. The deposition structures of the gold mines examined reflected the direction of the ring associated with the mine. Thus, the geology of the rings and any mines associated with the rings would be documented to see if this megascopic observation was backed up by field evidence.

The position of the rings was plotted onto a detailed roadmap and an interpreted geology plan of the Yilgarn and the route was planned to visit as many of the sites as possible in three days (Figure 3).

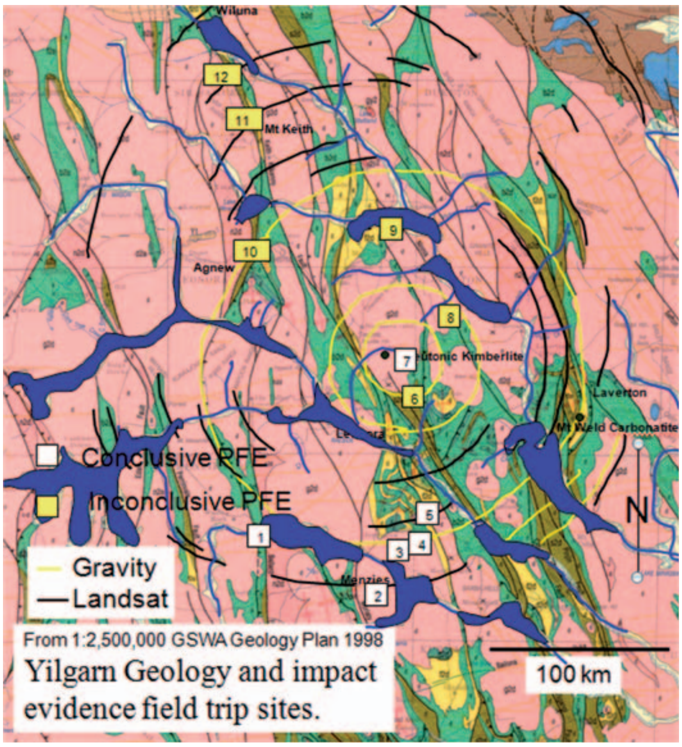

Fig. 3. *Plan of field site locations 1–12 on a plan showing the Yilgarn Geology, Gravity and Landsat rings.*

Field observations

The rings were examined at Sites 1–12 and observed on sites 1–5 as arcuate lines of hills with sheared, mylonitic basalt and granite with abundant quartz float trending along the rings.

Site 1: Agnew Outer Gravity Ring, Iron Statues Island, Lake Ballard. The island in the midst of the Lake Ballard Iron Statues is located on the Agnew ring and is shown on the Landsat as an intermittent dark arc that extends through Mount Ida to Agnew. The island is composed of fine grained spheroidal weathered basalt which has a steep south west dip and strike. There is a line of hills that is arcing parallel to the ring to the NW and, more importantly, to the SE towards Menzies. This ring links the Bardoc fault to the Ballard fault. Generally all other hills and features in this area are NS normal to the ring direction.

Site 2: Agnew Outer Gravity Ring, Lady Shenton Mine, Menzies. This mine also lies near the Agnew ring. The main strike of the orebody in the open pit is parallel to the direction of the not well defined ring at Menzies which is the intersection of the EW ring direction of and the NNW direction of the Bardoc fault.

Site 3: Outer Central Gravity Ring, Niagara. In a road cutting 1 km before Niagara Dam the lithology is comprised of flow banded pegmatite and granites dipping 70° N. The Niagara Mine is EW and is located in an EW line of hills, parallel to the banding in the granites. This banding is parallel to the Kookynie Ring.

Site 4: Landsat Ring, Kooynie. The Kookynie mines are EW, parallel to the Kookynie Ring and dip 40° S. The country rock is basalt, no specimens of shock features observed.

Site 5: Mt Melita Landsat ring 25 km north of Kookynie. After following NS striking hills the next Mt Melita Landsat ring stood out as a line of EW hills composed of mafic intrusives. It became evident that the Landsat features were real on the ground and were comprised of lithologies that were trending EW with EW shearing contrary to the general NNW trend of the country. In general, the rings were also marked by more abundant quartz veins and float. There have not been any unusual or shock structures seen in the quartz or feldspar – yet. Mind you, we are not quite sure what to expect having never seen a shatter cone!

Site 6: Mertondale Inner Gravity Ring, 24 km NE of Leonora. On the Leonora–Mertondale road there was abundant quartz on flat ground at the site of the outer edge of the Mertondale inner gravity ring. Specimens of semi-annealed, shock textured quartz with the appearance of shatter cones were discovered. These were the first examples of what might be *prima facies* evidence seen on the site of a gravity ring. Eureka! These specimens were collected only 16 km from the centre of the Watchorn Impact Structure (WIS).

Specimen 6.3. This shatter cone appeared to have two shatter cones at approximately 30° to each other (Figure 4). This phenomenon was also seen at Sudbury in Canada where it was possible to find shatter cones associated with two impact events in one outcrop. The nose of the Sudbury shatter cones point toward the Sudbury structure, while the nose of the Wanapitei shatter cones point in the opposite direction.

Fig. 4. *Site 6. Specimens 6.3 and 6.4 (inset) showing small shatter cones formed in two directions.*

Fig. 5. *Specimen 6.7. Welded (melt?) quartz rock with a matrix of ever decreasing sized rounded quartz grains with conchoidal fracture and with no shock texture (upper). It contains 2 mm clear unfractured quartz glass grains similar to spherules collected from Chicxulub crater, Mexico (inset).*

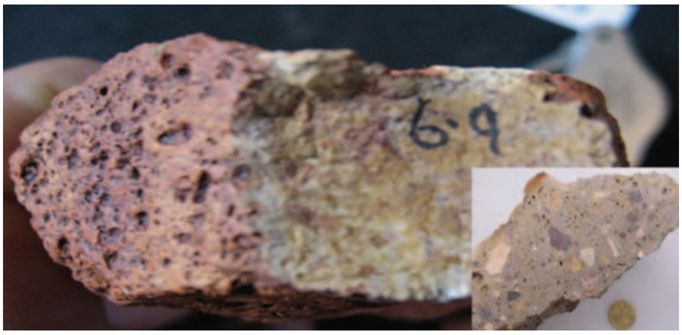

Fig. 6. *Sample 6.9. Mertondale ring, Watchorn Impact Structure, Western Australia. Felsic rock composed of unsorted, welded, rounded and semi-lath shaped clasts. Matrix of fine, glassy felsic material. The specimen has conchoidal fractures and no deformation features. This suggests it is post or syn-impact and is similar to impact melt from Rochehouart Crater, France (inset).*

This is *prima facies* evidence of the WIS, plus another impact in the North Eastern Yilgarn! Shattercones and welded rocks are shown in Figures 4–6.

Site 7: Centre of WIS, The Western Terraces. This is the central area of the WIS. Contorted granite was observed as we intersected the Western Terraces. This graded into massive coarse grained pegmatitic granite 1 km west at the campsite. There were no shock features, indeed no quartz noted. There were zones of granite that were strongly flow banded as is observed in the magnetics of the granite in this area – no samples taken.

Site 8: Leonora Outer Gravity Ring, 8.5 km north of Woolie Bore. The quartz here tended NNW parallel to the NE quadrant of the Leonora Outer Gravity Ring. The quartz was very strained in three directions, possibly once again suggesting more than one close impact (Figures 7 and 8). This area is close to the centre of the Mt Redcliffe Circular Magnetic Feature, which might be a later impact.

Site 9: Darlot Ring, Outer central Landsat Ring, East of the Darlot mine. Once again, there was a line of low hills trending EW in line with the Darlot mine. There were examples of shocked quartz and one specimen (Specimen 9.2) of a quartz shatter cone was found in the short time spent on site (Figure 9). This shatter cone also had two directions of striations – the second very weak.

Site 10: Agnew Outer Gravity ring north from Leinster turn off: *definitive impact shock feature site.* At this site the hills are striking at 50° – parallel to the 250 km diameter Agnew Gravity Ring. The basalt and dolerite stratigraphy is dipping at 50° N. There is an excellent 10 m thick outcrop of rounded shocked quartz. Some sections of this quartz show *in situ* shatter cone structures and striations (Figures 10 and 11).

A small vertical, 50° EW quartz vein was observed 100 m east with *in situ* shatter striations trending 140° towards the centre of the WIS. The dolerite around the shatter cone quartz was also shatter rodded. The shatter zone area appeared localised. Specimens 10.1 and 10.4 are textbook shatter cones (Figures 12–14).

Site 11: Mt Keith Landsat Ring: west and opposite Mt Keith Mine. There is a broad EW quartz vein system on the Mt Keith ring west of the Mount Keith mine that trends towards the centre of the open pit (left of Figure 15 and left of Figure 16).

The Mt Keith ring can be seen on Landsat for many kilometres to the west. Shock striations in the massive quartz are NS and sub horizontal. The alteration associated with this quartz system

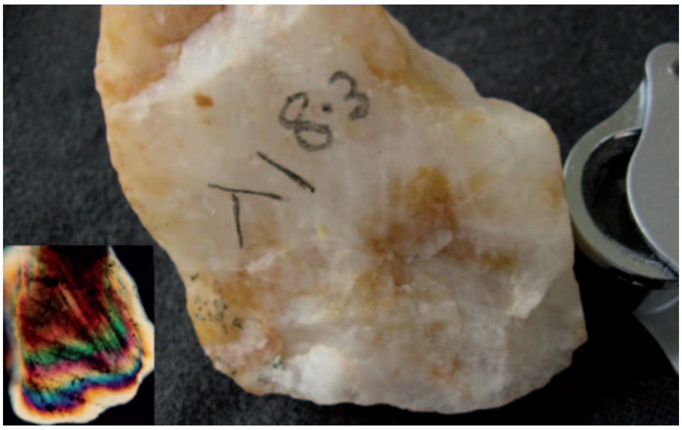

Fig. 7. *Specimen 8.3. Fractured and semi-annealed quartz with three shock fracture directions possibly caused by more than one close impact? Sample from Chicxulub with two directions of Quartz Lamellae (inset).*

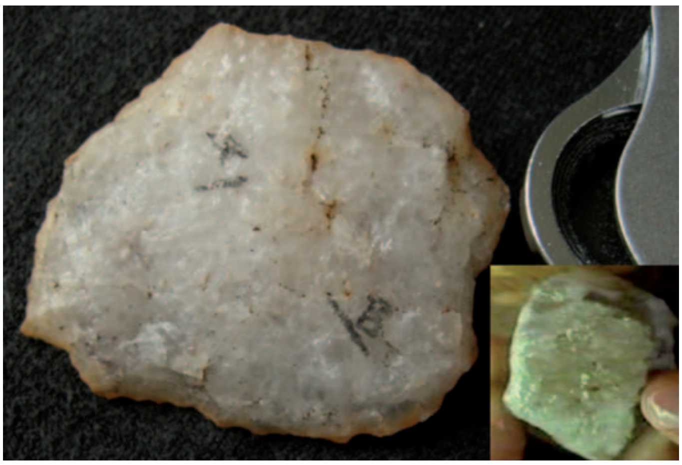

Fig. 8. *Specimen 8.4. Vitreous, slightly fractured quartz with fracture planes in two directions at A & B. Similar rock from Chicxulub Crater, Mexico (Inset).*

Fig. 9. *Specimen 9.2. Specimen of a small shatter cone showing two striation directions.*

Fig. 10. *Site 10. In situ striated shocked quartz (north to right).*

Fig. 11. *Site 10. Shatter cone rocks scattered on ground on Agnew ring.*

Fig. 12. *Site 10, Specimen 10.1. Textbook shatter cone showing deep striation grooves and aggregated rodded structure.*

Fig. 13. *Specimen 10.1. A beautiful example of a single 'knuckle' of a shatter cone. Shatter cone is made up of numerous 'shatter cones' that can be observed all around the perimeter of end A (right) and in photo 9. At end B (left), there is what looks like a later, weaker shatter cone, normal to those at A. Shatter rods B overprint those at A, but with virtually no displacement. Is this evidence of a strong impact over-printed by a later, weaker impact?*

could be seen (Google Earth: http://www.google.com/earth/) as EW–ENE lighter and browner zones in the Mount Keith open pit and is evidence that the WIS occurred after the emplacement of the Mt Keith stratigraphy and granites (Figure 16).

Fig. 14. *Specimen 10.4. Half of a 'knuckle' of a shatter cone. This sample is typical of many of the shatter cone pieces in that there seem to be an equal number of shatter cones in each direction parallel to each other. The combination of these two sets of cones makes up a parallel rod. This parallelism might be the result of the deep formation of the shatter cones (est. 5–10 km subsequent erosion).*

Fig. 15. *Large EW quartz vein at Mt Keith looking west. (Left) This massive quartz vein system, west of the Wiluna road, trends to the centre of the Mount Keith mine. Striations in the massive quartz are NS and 5° N dip. (Right) Detritus of numerous shatter cone segments on ground west of Mt Keith.*

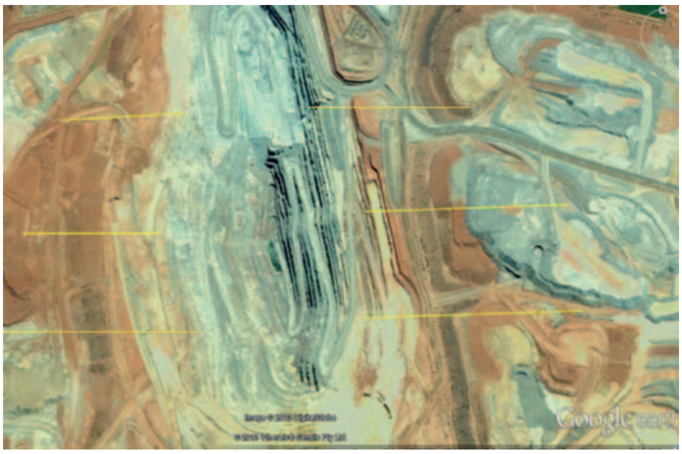

Fig. 16. *Site 11. Mt Keith Open Pit Mine Site. Evidence of the Mt Keith Landsat ring in the Mt Keith open pit.*

West of the Leonora-Wiluna highway *in situ* 500 mm long shatter cones in quartz and adjacent granite (Figure 17) were observed with the same striation direction and plunge as those in the large quartz vein. There are also specimens of shatter cone quartz and rodded feldspar granite (Figures 18–23).

Site 12: Honeymoon Well Landsat ring: tourist stopping point. This site is over 200 km NNW from the Western Terraces which is the centre point of the WIS. The WIS appears to be symmetrical so it is over 400 km in diameter. There are one metre thick quartz veins located south of a granite breakaway that has 40° WNW dipping black mylonitic alteration

Fig. 17. *Site 11. In situ 500 mm long shatter cones in quartz and adjacent felsic granite west of Mount Keith Mine.*

Fig. 18. *Specimen 11.3. Intensely shocked and rodded felsic porphyry that is in line with the in situ quartz shatter cones. It is the intensely shocked medium grained felsic rock that occurs around the site.*

Fig. 19. *Site 11, specimen 11.1. Large annular specimen of shatter cone. Totally granular shattered quartz with deep, incised striations on both sides of the annulus. The diameter of the cone that this specimen is a section of would be about 2 m. Measurements of the amount of spreading indicate that the individual 'shatter cones' that make up the larger composite shatter cone would be about 1.5 m long. (Left) The striations seem to be burnt onto the shattered quartz.*

Fig. 20. *Site 11, specimen 11.1. Shatter cone annulus in quartz. End section showing aggregates of circular rodded structures.*

Fig. 21. *Specimen 11.4. Shatter cone in quartz.*

Fig. 22. *Specimen 11.4. Shatter cone in quartz showing internal smooth sided tube between the rods. How are these formed in such a high shock environment?*

and shearing. Both the quartz and the granite breakaway trend ENE parallel to the ring at a wide angle from the NS regional foliation. There is some rodded feldspar porphyry with NS rods with a sub horizontal plunge. There was some weakly shatter coned and strained quartz with a NS trend shown in Specimen 12.1 (Figure 24).

At Site 12, and at a few previous sites, there are strange, completely undeformed, quartz feldspar rocks (Specimen 12.3), which have a strange quartz/feldspar habit and might be an impact melt rock (Figure 25).

Conclusions of the *prima facies* evidence trip

The rings are real, verifiable geographical and geological features. They were identified from 5–8 km away as one approached them by road and were easily observed on the ground. The field geology and geographic features conformed to that expected from the gravity, DEM, magnetics and Landsat images.

Prima facie evidence of the WIS, discovered at multiple sites, consisted of shatter cones or shock-affected quartz and feldspar, plus welded or melt rocks: Sites 6 and 8 represent the central gravity rings; Site 9 represents a Landsat ring; Site 10 represents the 250 km diameter gravity ring; and Sites 11 and 12 represent the Outer Landsat Rings indicating that if the impact is symmetrical it has a diameter of greater than 500 km.

Two summary composite photos show the *prima facies* evidence from the WIS compared with similar *prima facies* evidence from recognised impact structures (Figures 26 and 27).

Fig. 23. *Site 11, specimen 11.7. Shatter cone 'knuckle' in iron-stained quartz.*

Fig. 24. *Site 12, specimen 12.1. Honeymoon Well shatter cone.*

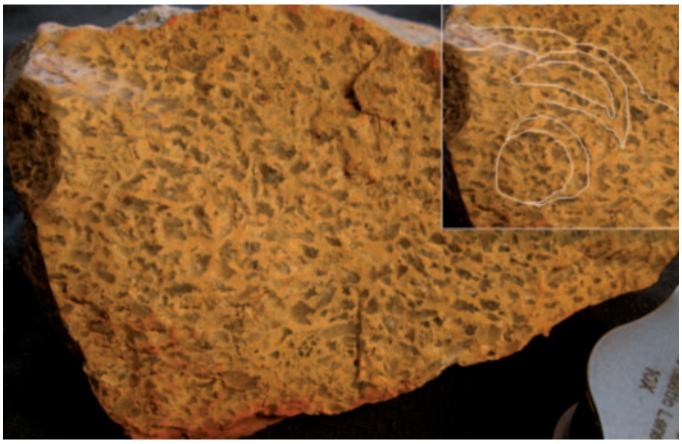

Fig. 25. *Site 12, specimen 12.3. Post-impact glassy (spherules?) conchoidal quartz feldspar rock, completely undeformed. The surrounding granites show moderate deformation either from the impact or regional tectonics. Comprised of angular and rounded 1–3 mm laths of glassy quartz with a light cream coloured aphanitic, waxy, feldspar matrix. Is this an impact generated melt or welded rock? There are concentric rings of laths on the left side and at the bottom (inset). How would these form?*

Fig. 26. *Recognised prima facies evidence from recognised impact structures (left) and Watchorn Impact Structure (WIS), Australia (right). Top row: shatter cones from Cheigau crater, Bavaria (left) and Agnew ring, WIS, Western Australia (right). Middle row: impact Melt Rock, Dagamite Sweden (left). Radial quartz ground mass determines position of laths. Honeymoon Well ring WIS, Western Australia. Radial laths. Bottom row: impact melt or hot gas deposited clastic rocks with unsorted rounded and lath shaped quartz and other minerals. Rochehouart Crater France. Mertondale ring WIS Western Australia.*

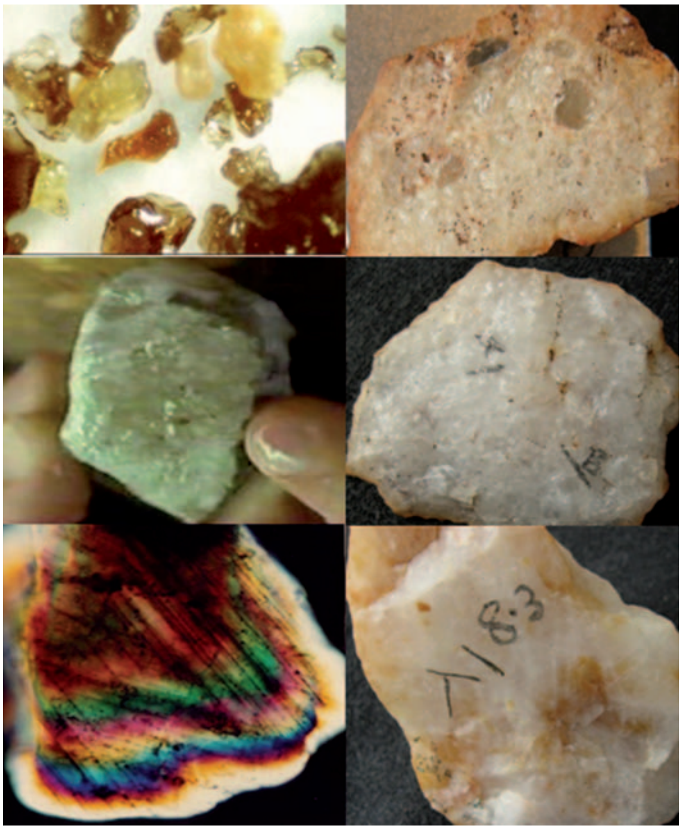

Fig. 27. *Comparison of prima facies evidence from Chicxulub impact structure, Mexico (left) and Watchorn Impact Structure, Australia (right). Top row: melt or welded rocks containing quartz glass Spherulites. Note the similar quartz colours and conchoidal habit. Middle row: shocked glassy quartz with two sets of striations. Bottom row: shocked quartz lamellae (left) and quartz with three planes of striations (right).*

The exploration trip confirmed, with the *prima facie* evidence located on the WIS rings, that at least one, but most likely two major impacts have occurred in the Leonora region (Figure 28).

There are at least eight other suspected impacts in the Eastern Yilgarn (Figure 1) that require field work in the light of the abundant *prima facies* evidence for the WIS.

The WIS rings also have an empirical megascopic and field correlation with the largest nickel, gold, copper, silver–lead–zinc and rare earth deposits. This is particularly evident in the

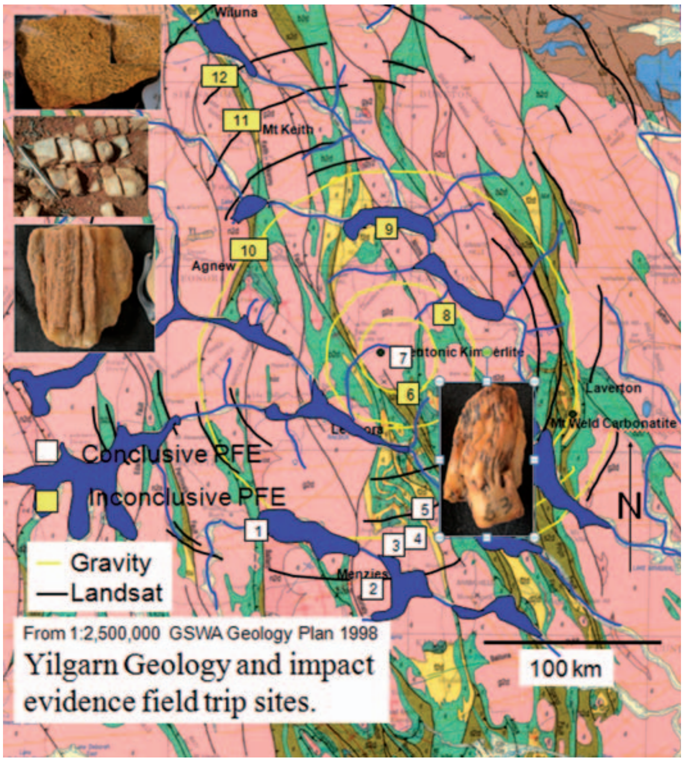

Fig. 28. *Yilgarn Geology and WIS prima facies field evidence trip sites. Plan of field site locations on the Yilgarn Geology, Gravity and Landsat rings with the type specimens found at each location.*

outer rims and the outer central concentric ring. This observed relationship means a paradigm shift is needed for studying the genesis of mineralisation in the Yilgarn and targeting requirements for exploration success. This might apply to the very similar Archaean Cratons worldwide and perhaps the same impact cratering mechanism has operated right up to the present?

This question will be the subject of the next paper.

Reference

Grieve, R. A. F., and Pilkington, M. (1996). The signature of terrestrial impacts. *AGSO Journal of Australian Geology & Geophysics* **16**, 399–420.