

# A Paleoarchaean impact crater in the Pilbara Craton, Western Australia

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The role of meteorite impacts in the origin, modification, and destruction of crust during the first two billion years of Earth history (4.5–2.5 billion years ago; Ga) is disputed. Whereas some argue for a relatively minor contribution overall, others have proposed that individual giant impactors (>10–50 km diameter) can initiate subduction zones and deep mantle plumes, arguably triggering a chain of events that formed cratons, the ancient nuclei of the continents. The uncertainty is compounded by the seeming absence of impact structures older than 2.23 Ga, such that the evidence for the terrestrial impact flux in the Hadean and Archaean eons is circumstantial. Here, we report the discovery of shatter cones in a complex, dominantly metasedimentary layer, the Antarctic Creek Member (ACM), in the centre of the East Pilbara Terrane, Western Australia, which provide unequivocal evidence for a hypervelocity meteorite impact. The shocked rocks of the crater floor are overlain by (unshocked) carbonate breccias and pillow lavas, stratigraphically constraining the age of the impact to 3.47 Ga and confirming discovery of the only Archaean crater known thus far.

With more than a million craters exceeding 1 km in diameter, and around forty more than 100 km across<sup>1,2</sup>, the Moon preserves an exquisite record of the intense bombardment endured by bodies in the inner solar system during the first billion years or so of its history (Fig. 1a)<sup>3</sup>. On Earth, this early impact record has seemingly been lost, reflecting the destructive efficiency of erosion and subduction in recycling primary (basaltic, oceanic) crust back into the convecting mantle. Nevertheless, the oldest parts of many cratons, the ancient Archaean (4.0–2.5 billion years ago; Ga) nuclei of the continents, formed at or before 3.5 Ga<sup>4</sup>, and should preserve some evidence for an impact flux that would have exceeded that of a similar area of the Moon of comparable age<sup>5–7</sup> (Fig. 1a). However, the oldest recognized terrestrial impact structure, at Yarrabubba, Western Australia, is dated at 2.23 Ga<sup>8</sup>. Where are all the Archaean craters?

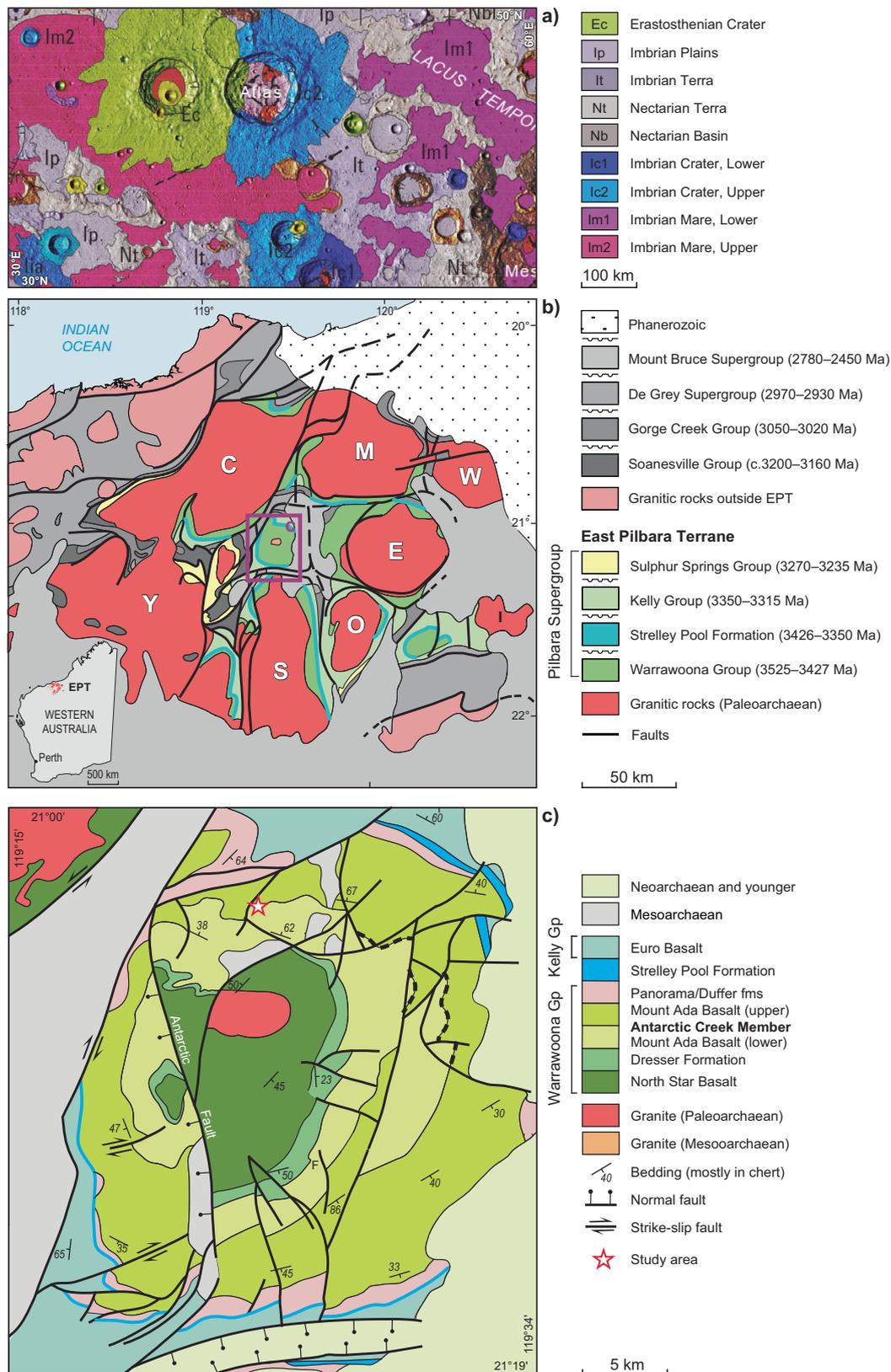
Finding direct evidence for Archaean impacts (i.e., craters or impact structures<sup>9</sup>), and thereby better constraining the Archaean impact flux, is important. Large impactors (here bodies > or >> 10 km

in diameter) travelling in excess of 10 km.s<sup>-1</sup> deliver enormous quantities of kinetic energy, most of which will decay to heat, warming the crust and upper mantle<sup>9</sup>, with potential consequences for plausible tectonic modes on the early Earth<sup>10,11</sup>. Further, numerical models have shown that individual bolide impacts can instigate subduction, mantle upwellings (plumes), and voluminous production of primary (basaltic) crust<sup>12–14</sup>. Moreover, impacts provide a ready mechanism to fracture (brecciate) the crust and, in the presence of a hydrosphere<sup>15</sup>, drive intense hydrothermal alteration of this regolith, concentrating key mineral deposits<sup>16</sup>. Notably, impact craters may have provided the physical and chemical environments required for life to emerge on Earth and elsewhere<sup>17,18</sup>.

The East Pilbara Terrane (EPT), part of the Pilbara Craton of Western Australia, is a near-pristine, approximately 200 km diameter fragment of (mostly) Paleoarchaean (3.53–3.23 Ga) cratonic crust comprising domes of sodic granite (TTG) separated by steeply-inclined greenstone belts dominated by ultrabasic to basic volcanic

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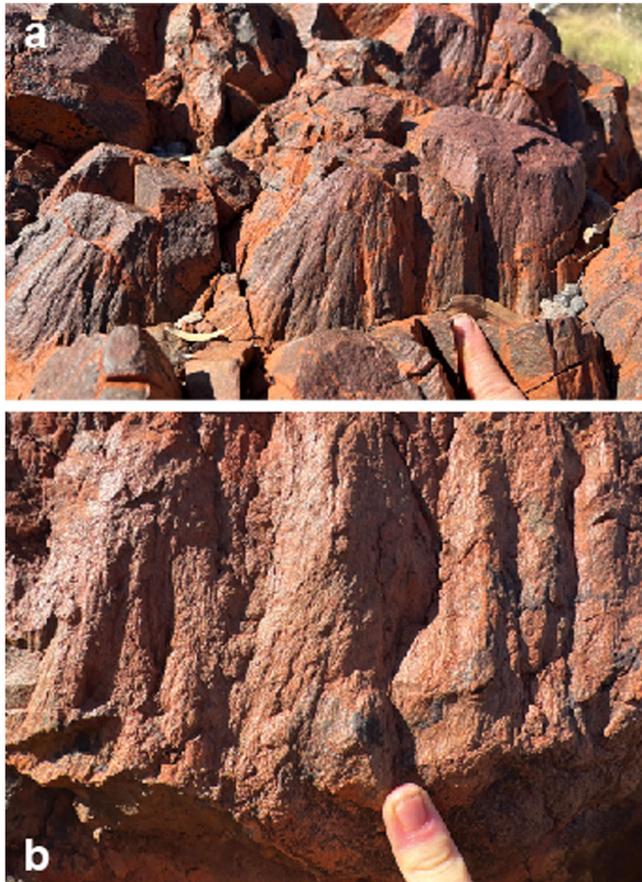


rocks<sup>19</sup> (Fig. 1b). Many interpret the EPT as a long-lived volcanic plateau formed by polyphase plume-driven magmatism, probably involving short-lived episodes of (proto)subduction<sup>19–21</sup>. More recently, it has been argued that the EPT ultimately formed at the site of a large bolide impact<sup>22</sup>, and that such an origin for the initiation of cratons may be generally applicable<sup>22,23</sup>.

Here, we report the discovery of an impact crater at the North Pole Dome, near the centre of the EPT (Fig. 1b, c). Exceptionally preserved shatter cones within a dominantly siliciclastic horizon (Fig. 2a, b), the Antarctic Creek Member (ACM), which has previously been shown to contain spherules (quenched and devitrified impact-melt droplets)<sup>24,25</sup>, provide unequivocal evidence for a hypervelocity

**Fig. 1 | Geological maps and stratigraphy.** **a** Geological map of a (northeastern) part of the Moon around the Atlas crater (from ref. 41), a complex impact structure with a heavily fractured crater floor and a central peak complex<sup>42</sup>. The grey areas are the regolith-covered ancient (Hadean) anorthosite flotation crust. The pink units are approximately 3.6 Ga basalts of comparable age to the oldest basalts in the Pilbara Craton. **b** Simplified geological map of the East Pilbara Terrane (EPT), Western Australia, comprising mostly Paleoproterozoic granite domes and

intervening greenstone belts, at the centre of which is the North Pole Dome. The EPT is about the same size as the  $\leq 3.6$  Ga Atlas crater in (a). **c** Geological map of the North Pole Dome showing the location of the studied stratigraphic section (red star). The ACM follows the boundary between the lower and upper Mount Ada Basalt, and the dashed black line where spherules have been found<sup>24,25</sup>. Panels (b, c) adapted from the Geological Survey of Western Australia under a Creative Commons Attribution 4.0 International licence (see: <https://dasc.dmirs.wa.gov.au/>).



**Fig. 2 | Field photographs of rocks on the flanks on the North Pole Dome.** **a, b** Shatter cones within the Antarctic Creek Member (ACM) arenite.

meteorite impact 3.47 billion years ago. Both spherules and shatter cones are found within the same siliciclastic unit within the ACM, requiring at least two (one proximal, one distal) Paleoproterozoic or earlier impact events<sup>7,26</sup>.

## Results

### The North Pole Dome and Antarctic Creek Member (ACM)

At the base of the Pilbara Supergroup, the 10–15 km thick Warrawoona Group is dominated by weakly metamorphosed ultramafic to mafic volcanic rocks with subordinate felsic volcanic/volcaniclastic rocks and chert<sup>19</sup> (Fig. 1b, c). Pillow lavas near its base are pervasively hydrothermally altered and cut by chert–barite veins and overlain by chemical sediments (mostly chert) containing the oldest known (stromatolite) fossils<sup>27</sup>. At higher stratigraphic levels, within the core of a structural dome (the North Pole Dome; Fig. 1c), a 2–3 km thick sequence of ultramafic–mafic volcanic rocks (the Mount Ada Basalt) contains a thin (up to 20 m) sedimentary unit, the Antarctic Creek Member, which consists of (silicified and carbonate-altered) felsic to mafic volcaniclastic rocks, chert, argillite, arenite and jaspilite intruded by dolerite<sup>19,28</sup>.

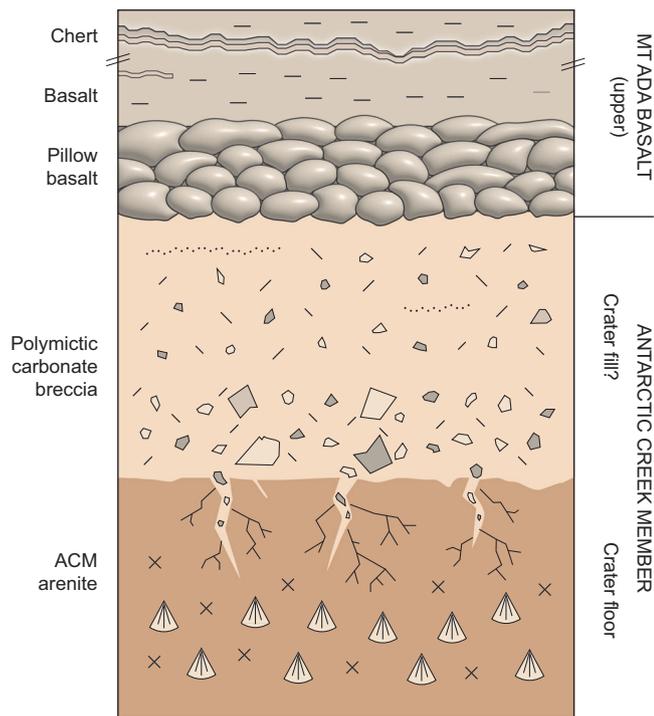
The ACM preserves evidence for the oldest known meteorite impact in the form of one or more layers containing spherules<sup>19,24</sup>, interpreted by most as globally-distributed airfall impact ejecta<sup>19,24,25,29,30</sup>, but whose petrogenesis is debated<sup>31,32</sup>. It contains detrital zircon grains with  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of  $3470 \pm 2$  Ma<sup>24</sup>, providing a maximum depositional age, but has not been dated directly. However, underlying felsic rocks near the base of the Mount Ada Basalt ( $3469 \pm 3$  Ma), and at the base of the overlying sequence of felsic volcanic rocks (the Duffer Formation;  $3468 \pm 2$  Ma) constrain deposition of the ACM to around 3470 Ma ( $3469.2 \pm 1.8/-1.2$  Ma; ref. 19).

Fieldwork in 2021 in a small area of the North Pole Dome identified shatter cones throughout most of the thickness of the ACM (Fig. 2a; Supplementary Fig. 1). The shatter cones crop out more-or-less continuously for at least several hundred metres extending broadly northeast from where the ACM crosses the track at  $21^\circ 02' 54''$  S,  $119^\circ 23' 35''$  E (Fig. 1c). At outcrop, the variably curved surfaces of the shatter cones are smooth, with divergent and branching ribs and a mean apical angle of around  $90^\circ$  (Fig. 2a; Supplementary Information Fig. 1a–d; see also a 3D model at: <https://sketchfab.com/3d-models/shatter-cone-2-cd89206c6d6b4765be766659a6e377da>), similar to the average of literature values<sup>33</sup>. Although the orientation of individual cone axes varies, almost all are steeply inclined and splay (the ribs diverge) downwards (Fig. 2a; Supplementary Fig. 1a–d)<sup>33</sup>, consistent with a right-way-up stratigraphy<sup>19</sup>. On a larger scale, the cones are clearly visible as hut-like structures, some several metres tall, which extend across the hillside (Supplementary Fig. 1e).

Immediately overlying the shocked (shatter cone-bearing) ACM is a 5–10 m thick stratabound sequence of polymictic carbonate breccias (occupying the more strongly eroded gully in Supplementary Information Fig. 1e) containing angular fragments of underlying rocks, conspicuously chert (Supplementary Information Fig. 2). The stratabound layer of carbonate breccias is clearly distinct from the (very recent) calcrete deposits that cover the surface of many exposures, and includes distinctive orange dykes up to a metre thick (Supplementary Fig. 2b) that extend for many tens of metres into the footwall. Directly overlying the carbonate breccias are hydrothermally altered basalts (the upper part of the Mount Ada Basalt), which are pillowed near their base (Supplementary Fig. 1e, f) and contain layers of chert at higher stratigraphic levels. We have found no shatter cones in either the pillow basalts or carbonate breccias/dykes.

## Discussion

Shatter cones are the only unequivocal macroscopic indicator of a hypervelocity bolide impact<sup>33–35</sup>. Those discovered at the North Pole Dome (Fig. 2a, b; Supplementary Fig. 1), a structure interpreted by some as a volcanic edifice<sup>27</sup>, are exceptionally well preserved, retaining delicate features including striated and ‘horse-tailed’ conical fractures that rival those at the type locality at Steinheim, Germany<sup>36</sup>. The shatter cones occur within a lithologically and structurally complex, dominantly (at least locally) siliciclastic unit, the ACM, with very low zircon yield<sup>24</sup>, which we interpret as (subsequently silicified and lithified) subaqueous regolith formed by disaggregation of the uppermost basaltic crust (locally the lower Mount Ada Basalt) by impacts, of which portions were likely reworked, possibly by later impacts or their consequences (e.g., fall out, debris flows, tsunamis).



**Fig. 3 | Schematic stratigraphic log through North Pole Dome crater and overlying sequence.** The shatter cone-bearing Antarctic Creek Member directly underlies the polymictic carbonate breccias, which are generally 5–10 thick.

Importantly, the 3.47 Ga ACM dips away from the core of the (aptly named) North Pole Dome (Fig. 1c), which we interpret to represent the central uplift of a large impact crater and its fill (Fig. 3), consistent with the spatial distribution of shatter cones in younger terrestrial complex craters<sup>37,38</sup> (Fig. 3). If future work confirms that shatter cones occur throughout the mapped extent of the ACM, the 40–45 km diameter of the North Pole Dome (Fig. 1b, c) implies a crater with a diameter of at least 100 km<sup>37</sup>.

The studied sequence of Paleoproterozoic strata exposed in the North Pole Dome, from the shocked rocks of the crater floor to the (unshocked) carbonate breccias that penetrate the fractured footwall rocks (Fig. 3; Supplementary Figs. 1, 2), bears a remarkable similarity to sections through other large terrestrial impact structures<sup>35,37–39</sup>. We speculate that the carbonate breccias represent the lithified and hydrothermally-altered products of impact-related deposits<sup>29</sup>.

The 3.47 Ga age of the North Pole impact is statistically indistinguishable from that of the oldest spherule beds from the Kaapvaal Craton in South Africa<sup>24</sup>, suggesting that the North Pole Dome may have produced deposits (impactites) of global extent<sup>19,24,25,29,30</sup>. At higher stratigraphic levels within the EPT, a spherule layer within layered 3.46 Ga cherts (the Marble Bar Chert Member; Fig. 1)<sup>40</sup> implicates another large (but distal) impact 10 million years or so after the North Pole impact.

Despite the high modelled frequency of bolide impacts in the early Archaean (see Fig. 1a), the rarity of verified impact craters of Archaean age ( $n = 1$ ) suggests that: (a) the impact flux was much less than predicted by lunar data; (b) the evidence has been eradicated, or (c) that we have failed to recognise them. On a young Earth covered in primitive (mafic–ultramafic) crust, identifying shatter cones or impact breccias may represent the best chance of finding other large Archaean impact structures. However, these highly fractured rocks will be the first to undergo (presumably intense) weathering and erosion. Notwithstanding their fragility, we believe many more Archaean craters await discovery.

## Methods

We combine field observations and deductive reasoning with published geochronological data from the Geological Survey of Western Australia GSWA, as summarized in ref. 19.

## Data availability

Data supporting the findings of this study are available within the paper and its supplementary information. More detailed information regarding the regional geology, geochronology and whole rock geochemistry are freely available through the online systems at the Geological Survey of Western Australia (GSWA) website: <https://www.dmp.wa.gov.au/geological-survey/geological-survey-262.aspx>.

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## Author contributions

C.L.K., J.K., and T.E.J. discovered the shatter cones in May 2021. We showed them briefly to RHS in June 2024. C.L.K., J.K., B.V.R., A.Z., and B.M. characterized the samples. T.E.J., C.L.K., and J.K. wrote the first draft with input from all coauthors. All authors were involved in revisions leading to the published version.

## Competing interests

The authors declare no competing interests.

## Additional information

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