Century Zn deposit–the world's largest meteorite impacted orebody

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SUMMARY

We describe how the world-class Proterozoic Century zinc deposit in northwest Queensland has been sculptured by an Ordovician meteorite impact, the Lawn Hill Impact Structure. The deposit is located at the SW edge of the crater, is dismembered by crater-related faults and is overlain by breccias (suevite) related to fall-back and resurge processes into the crater. Using drilling and newly acquired IP data, we interpret a five-fold thickening of slumped Cambrian carbonate breccias in the crater, to a depth of 600 m. The Century deposit is known to have been larger than has been so far discovered. A restoration of the post-ore faults and Zn:Pb metal ratios of the mined Northern and Southern ore blocks, indicates an original enlarged form of the world-class deposit and that parts of the orebody may have spalled into the Cambrian-filled crater. This points to significant discovery potential in an otherwise intensely explored, near-mine setting.

Key words: Century zinc deposit, meteorite impact structure, suevite breccias, post-ore faults

INTRODUCTION

Considered a unique occurrence in the world, the near coincidence of two rare geological entities, a giant Zn-Pb-Ag deposit and a large meteorite crater, and the imprint of one on the other, is described here. The Century deposit had a pre-mining resource of 118 Mt at 10.2% Zn, 1.5% Pb and 36 g/t Ag (Waltho and Andrews, 1993), making it a very significant occurrence by global standards. The orebody is preserved on the edge of an 18km diameter annulus of highly disturbed Cambrian carbonate rocks, surrounding a core of shocked and partially melted Proterozoic rocks, called the Lawn Hill Impact Structure (LHIS, Shoemaker and Shoemaker 1996; Salisbury et al., 2008; Darlington et al., 2016; Figure 1). Investigations by the authors of the relationship of the deposit to the crater are described elsewhere (Lees et al., in press) and this presentation draws on and supplements that paper.

Due to erosion and post-ore faults, it was a once larger orebody (Waltho and Andrews, 1993; Broadbent et al., 1998). We seek to explain this in relation to the adjacent meteorite crater. We describe outcrop and petrographic evidence in breccias overlying the deposit that we interpret as impact-generated. This is supported by mapping and drilling evidence for large scale slumping of the overlying Cambrian sequence, with included Proterozoic slabs, that fill the thickened crater. In the underlying Proterozoic, using 3D modelling constrained by drilling, IP and gravity, we equate the offsets of the deposit to the cratering processes. This promoted large scale translation of an originally intact orebody and, in turn, suggests missing parts of the orebody may have been displaced into the crater.

Previous work on the Century deposit

In the Lawn Hill Platform of the Mt Isa Inlier (Figure 1A), the stratabound Century zinc deposit is hosted in the upper part of Lawn Hill Formation (Hutton and Sweet, 1982; Andrews, 1998). It lies adjacent to a crustal scale structure, the Termite Range Fault (TRF; Figure 1), regarded as the conduit for the metalliferous fluids that formed the deposit (Broadbent et al., 1998). The deposit (Figure 1C) was described by Waltho and Andrews (1993), Broadbent et al. (1998), Broadbent and Waltho (1998), Kelso et al. (2001), Feltrin et al. (2009) and O'Rourke et al. (2017). Its genesis is attributed to replacement processes in a hydrocarbon reservoir (Broadbent et al., 1998). The deposit is truncated by post-ore faults, the Nikkis and Magazine Hill Faults at either end (Figure 1C) and is broken up into Northern and Southern blocks by the Pandoras Fault (Figure 1C). An isolated ore block, called the East Fault Block (EFB; Figure 1C), is detached from the main orebody and located within Cambrian carbonate breccias. The eastern and western edges to the orebody are hematite altered and leached and interpreted to represent a pre-Cambrian unconformity, and locally includes a basal grit along the unconformity surface (Broadbent et al., 1998). Thus, the orebody has been reduced from its original size (Waltho and Andrews, 1993), leading Broadbent et al. (1998) to speculate that it may have been two or three times larger in its original form.

Previous work on the Lawn Hill Impact Structure

The Cambrian filled annulus is an outlier of the Georgina Basin, seen in the Constance Range 12km west of Century, where an undeformed, ca. 120m thick sequence is preserved (Figure 1A; Southgate 1988). Along with its curious shape (Figure 1B), the extensive brecciation, folding and mega-blocks seen within the thickened annulus (Figure 1C) are striking features. Shatter cones and pseudotachylite in the Proterozoic core were identified by Stewart and Mitchell (1987) and Shoemaker and Shoemaker (1996) who interpreted it as a Precambrian impact. Lindsay and Brasier (2006) described it as a Cambrian impact, with carbonate being deposited within a pre-existing crater. Salisbury et al. (2008) suggested a Cambrian impact event into semi-consolidated sediments and, in the Proterozoic core, they identified planar deformation features in quartz, impact spherules and microdiamonds. Darlington et al. (2016) dated the melted Proterozoic material as Ordovician (472 +/- 8 Ma; $^{40}Ar/^{39}Ar$. The lack of shock textures in the overlying Cambrian rocks was explained by their being semi-consolidated, water saturated sediments that absorbed shock waves at the time of

impact (Salisbury et al., 2008; Darlington et al., 2016). An alternative interpretation of the carbonates relates the slumping and mega-breccias to syn-sedimentary processes (Feltrin and Oliver, 2014).

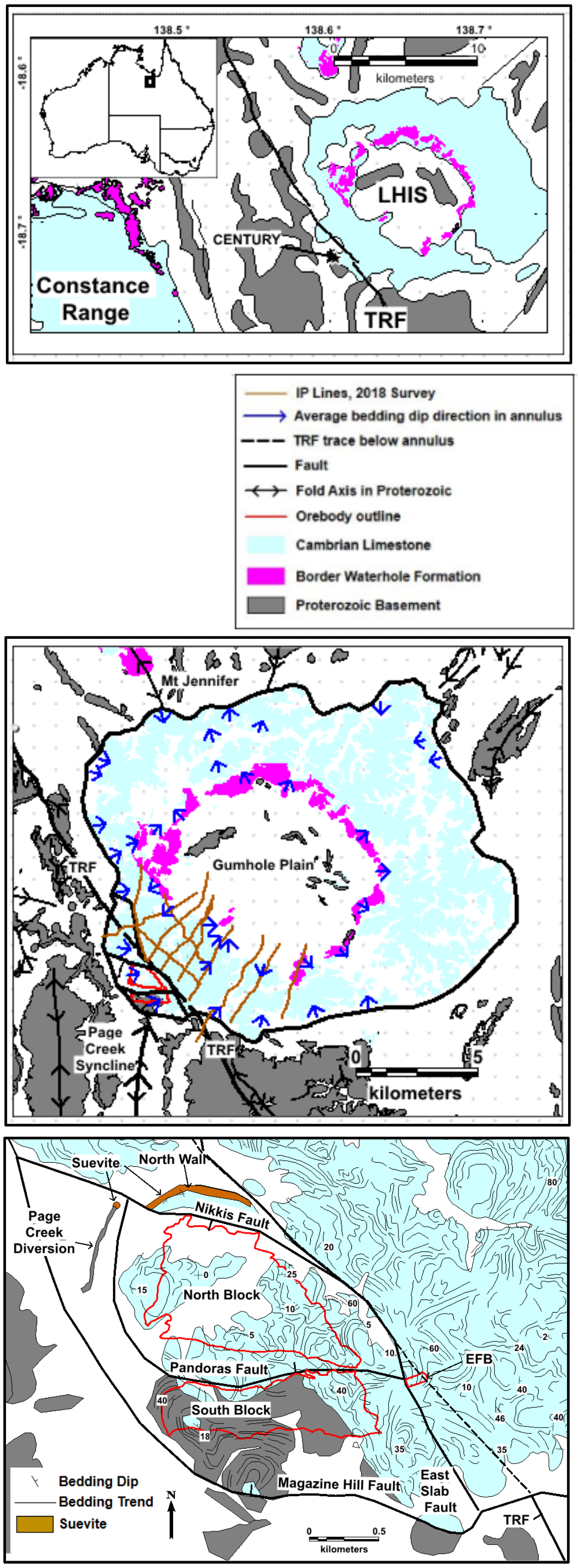

Figure 1. Location maps A. Century deposit and Lawn Hill Impact Structure, NW Queensland, B. Detail of LHIS. C. Detail of Century Mine (adapted from Lees et al., in press). EFB = Eastern Fault Block.

Other than Salisbury et al. (2008), the relationship of the Century deposit to the LHIS was mostly ignored by previous workers. Waltho and Andrews (1993), Broadbent et al. (1998), Kelso et al. (2001) and O'Rourke et al. (2017) recognized the presence of displaced Proterozoic rocks and their incorporation into the overlying Cambrian sequence as fault slices, chief amongst these being the EFB orebody (Figure 1C). Faulting of the deposit was entirely attributed to proximity to the TRF and O'Rourke et al. (2017) interpreted the fault architecture as an extensional flower structure along the TRF, with minor post-Cambrian modification.

METHODS

Exploration and mining since 1990 provided large databases of drill holes, surface and pit geology, geophysics, geochemistry and 3D models. From the earliest observations (Waltho and Andrews 1993), it was recognized that significant modification to the extents of mineralization had occurred. When we considered this in relation to the meteorite impact, this led us to re-examine the orebody geometry, the crater geometry and the basal Cambrian contact and associated overlying breccias in outcrop, drill core and thin section. We find that the breccias contain evidence of an origin as impact-generated suevite (e.g. French 1998). Suevite is a breccia rock that comprises partly of melted material with crystal and/or lithic fragments formed during an impact event.

To constrain the crater geometry, a dipole-dipole Induced Polarization (IP) survey, was carried out in 2018 on eleven lines totaling over 28 km, at ~700 m spacing (Figure 1B). The method relied on the contrasting properties of the highly resistive Cambrian carbonate rocks relative to the low resistance and chargeability of the underlying Proterozoic rocks. Historic drilling were used to constrain the interpreted Cambrian-Proterozoic contact. The overall crater geometry was used to infer the dominant gravitational movement of slump blocks.

The orebody geometry was examined using spatial metal grade estimates to define and extrapolate metal grade contours in each ore block. Pre-faulting restoration of these data allow us to infer the extents of the original deposit prior to diminution through erosion or fault loss. Displacements of the deposit were restored within a 3D space using Maptek Vulcan software.

RESULTS

Impact-related effects are described below with respect to the overlying Paleozoic rocks and the underlying Proterozoic basement (Lees et al., in press). These units had different rheologies and burial depths at the time of impact. The less consolidated Cambrian carbonates were deformed chaotically through sliding and brecciation, while the lithified Proterozoic shales were fractured and displaced on faults as coherent blocks.

Impact response in the Paleozoic cover sequence

The main responses were the formation of breccias, rafts and detachment faults, and structural thickening in the annulus.

Firstly, the breccias comprise of two main types, a basal Proterozoic-sourced, clast-dominated breccia and an overlying Cambrian carbonate-dominated mega-breccia. The basal sequence (i.e. below the Cambrian carbonates) crops out immediately west of the mine, in the Page Creek diversion

channel (Figure 1C) and occurs extensively in drilling across the orebody. The second series of breccias are within and overlying Cambrian carbonates and are best preserved along the north wall of the mine (Figure 1C), north of Nikkis Fault. These are volumetrically the more significant of the two breccia types and effectively fill the annulus.

The basal grit comprises shale-flake fragments derived from weathered and un-weathered Proterozoic shales, similar to what underlies the grit. Although interpreted by Broadbent et al. (1998) as an unconformity-related grit, this sequence displays features indicative of very rapidly deposited and melted material (Figure 2A). The shale flakes show a range of orientations, notably including upstanding clasts. Some clasts show jigsaw fit rotations, others are boudinaged, and have indented, folded margins where they impinge other clasts. This suggests ductile processes were involved, along with brittle fragmentation. Petrographic analysis shows planar deformation features (PDF's) in quartz grains (Figure 2B), devitrified glass fragments (Figure 2C), boudinaged fragments (Figure 2D) and altered rims of some clasts (Figure 2E). These relationships indicate a hot, high energy depositional process, consistent with a meteorite impact origin. Where logged in drilling (Figure 3), the grit is upwards of 10m thick and covers most of the Northern and part of the Southern Block.

The overlying carbonate breccia has angular to sub-rounded clasts (Figure 4) of carbonate and chert, locally in a laminated clay matrix. Several clasts show dropstone features with respect to laminations in the matrix (Figure 4A), indicative of fall-back material from the impact. Other clasts display open fractures and truncated flat edges on their margins (Figure 4B) that we interpret as spall fractures related to tensile fracturing immediately after impact (Kenkmann et al., 2014). Along the north wall of the Century open cut (Figure 1C), the uppermost breccia comprises chaotic, unsorted and poorly consolidated material. We interpret these as "resurge" deposits, formed through fluidization of poorly consolidated material.

Secondly, the Palaeozoic sequence is characterised by detachment faults that bound carbonate rafts and mega-breccia bodies overlying the North and South Blocks of the orebody. Included are rafts of Proterozoic shale. Other Proterozoic rafts are known from drilling in the carbonate annulus to at least 500m depth. These relationships are consistent with a high energy, impact-related environment. One of these is the East Fault Block (EFB) orebody, which is contained within Cambrian carbonate breccias and lies at least 50 m above the main Century ore. Salisbury et al. (2008) interpreted the EFB is a mega-clast of Century ore that was injected into Cambrian carbonate during the impact. Our interpretation confirms this and suggests that, during the impact event, it followed a separate trajectory with respect to the syn-impact extensional collapse along the Magazine Hill and Pandoras Faults (Figure 1C).

Thirdly, a major response to the cratering processes in the Palaeozoic rocks is structural thickening in the annulus. The doughnut-shaped annulus is about 18km across and filled with deformed Cambrian carbonates (Figure 1). Drilling data, supported by geophysical data (deep imaging IP), indicates a depth to the top of the Proterozoic basement of about 500m on the western side, and at least 600 m on the northeastern and southeastern sides (Figure 5) of the annulus. This is highly anomalous compared to the average thickness (ca. 120 m) of the undeformed Georgina Basin (Figure 1) and indicates a five-fold structural thickening of the sequence, inclusive of Proterozoic rafts, within the deepest parts of the annulus. Post-impact slumping from nearby regions into the crater is indicated.

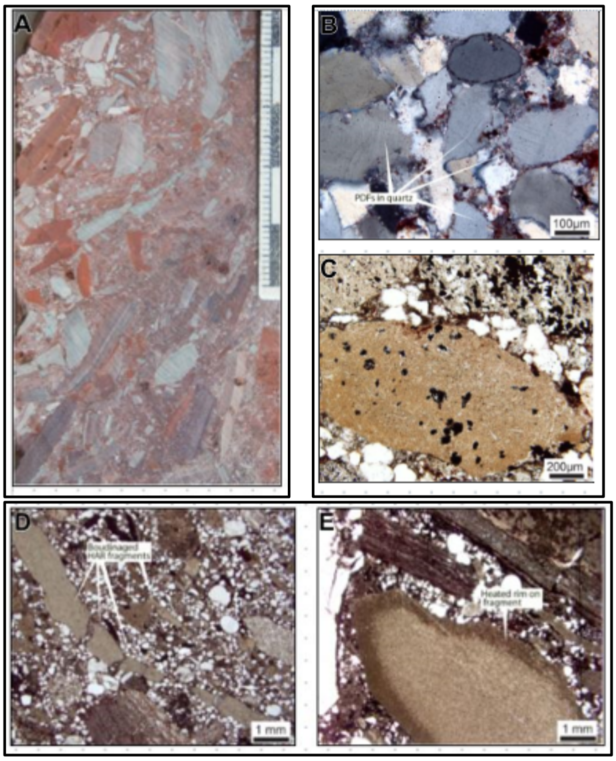

Figure 2. Proterozoic-sourced shale-flake breccia. A. Drill core sample showing in-situ fragmentation and ductile effects. B. Photomicrograph of quartz grains with planar deformation features (PDFs). C. Photomicrograph of devitrified clast. D. Photomicrograph of boudinaged high aspect ratio clasts (HAR). E Photomicrograph of clast with altered rim suggesting reaction with heated matrix. Adapted from Lees et al. (in press).

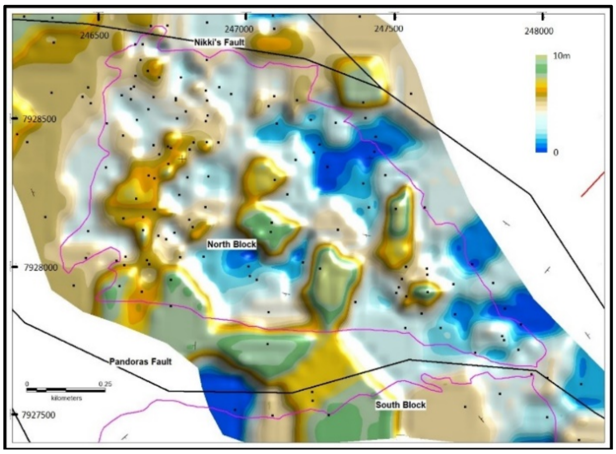

Figure 3. Isopach image of basal grit thickness over the northern part of the Century deposit. Black dots = drill holes containing the logged unit. Thickness scale bar 10 m.

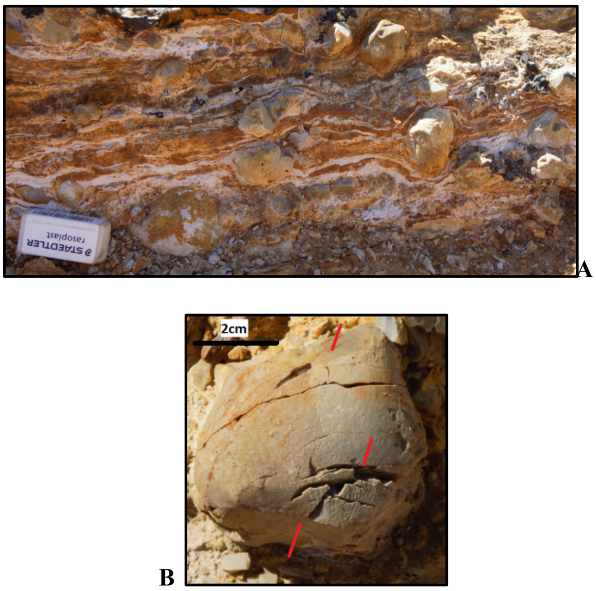

Figure 4. Carbonate-dominated breccia. A. Dropstone clasts in laminated matrix. B. Spall-fractured clast (red arrows).

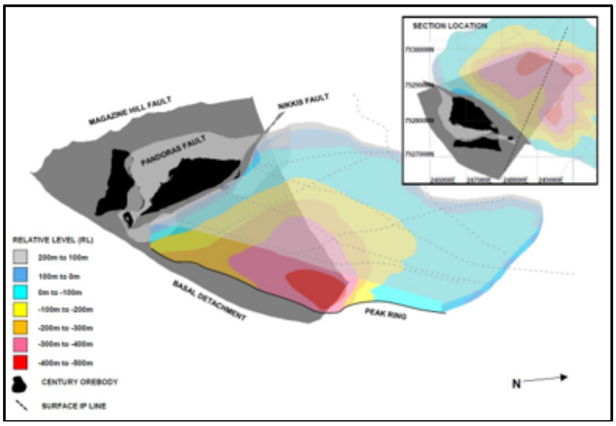

Figure 5. 3D perspective model of crater depth, major faults and ore blocks (from Lees et al., in press)

Impact response within Proterozoic basement

In the open cut mine, the responses that we equate to impact are fracturing in the ore horizons, downward penetrating carbonate dykes that intrude the orebody, and large-scale rotational faults that offset the orebody.

Firstly, there are numerous transgressive galena and sphalerite veins proximal to the hanging wall, and pervasive small-scale fracturing of the orebody associated with sulfide remobilisation (Salisbury et al., 2008). This indicates a significant post-ore fracturing event possibly due to a rapidly propagated deformation.

Secondly, a swarm of carbonate breccia dykes occurs deep in the Proterozoic basement at Century (Salisbury et al., 2008; Feltrin and Oliver, 2014). Where the dykes cut ore horizons, the ore is brecciated and the sulfide remobilized. Following Salisbury et al. (2008), we interpret the dykes and small-scale faults as impact-related, being a tensile response to impact-related forces (Kenkmann et al., 2014). Critically, it pins the presence of carbonate above the orebody at this moment in the Ordovician and it ties the location of the orebody as proximal to the impact crater.

Thirdly, the orebody is cut by post-ore faults (Figure 1C). At the southern end, the Magazine Hill Fault is north-dipping with a dip-slip displacement of 400 m, but possibly up to 700 m. It appears to be a major detachment, with a shallow dip towards the crater. Its down dip extension is uncertain (O'Rourke et al., 2017); it may be listric or could steepen towards the crater with a similar geometry to Kenkmann et al.'s (2014) crater rim model. Through the center of the mine, the Pandoras Fault is a listric, north-dipping structure (Figure 1C). Its displacement is pinned in the east with near zero offset increasing to 500m extensional displacement in the west. The displacement gradient indicates rotational block movement towards the crater. At the northern end, Nikkis Fault is a complex structure. It mostly dips southwards and swings in orientation from west to east across the deposit and is likely to link to the northwest trending East Slab Fault (Figure 1C), being the eastern margin of the EFB.

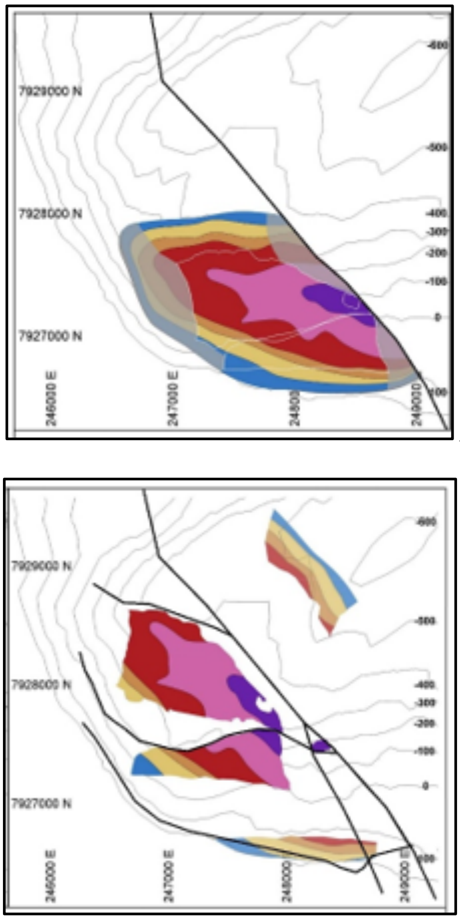

Figure 6. Restoration of Century orebody with respect to crater edge geometry. A. Original orebody form interpreted from grade shells and fault restoration. Grey areas are eroded eastern and western edges. B. Displaced parts of the orebody related to imapct cratering. Contours represent depth to the base of the crater. Adapted from Lees et al. (in press).

Restoration of the Century Orebody

Due to post-ore faults, the current location of Century is not where it was formed. Lateral displacement was constrained by the genetic ore deposit model, i.e. it formed adjacent to the TRF,

while vertical displacement was constrained by the flat-lying basal Cambrian unconformity in the Georgina Basin to the west. Restoration of offsets along faults was accomplished via a translation of marker units within the mine.

Restoration of displacements on the Magazine Hill and Pandora Faults, taking account of the coherence between the grade shells, suggests a translation of the Century deposit from some 1200 m to the southeast and up to 400 m above the final resting position of the North Block (Figure 6).

Extrapolation of the metal grade contours suggests that the deposit at the time of its formation covered approximately double the area of that preserved prior to mining (Figure 6). It is postulated that 25% of the deposit may have been lost through erosion at the eastern and western margins prior to the deposition of the Cambrian carbonate sequence. The fate of the remaining 25% of the original mineralized body remains to be explained. Our reconstruction predicts two other areas of the orebody existed at the time of impact. The first is north and east of the original orebody, across Nikkis Fault. We suggest that this part of the orebody slipped first towards the cater along a low angle detachment, before Nikkis Fault was initiated. It may be preserved in the crater fill. The second area is in the hanging wall to the Magazine Hill Fault, however its preservation potential is considered low, given the overlying resurge deposits.

CONCLUSIONS

We consider Century to be the world's largest impact-modified ore deposit. It is the happenstance of two rare geological features, one a world-class Zn-Pb sediment-hosted deposit, and the other a meteorite impact crater. Linking the two has mostly eluded previous workers. Critically, we ascribe dislocation of the orebody to impact-related processes. We present evidence of suevite breccias overlying Proterozoic host rocks at Century and of slumping of Cambrian carbonates incorporating rafts of the Proterozoic into a deepened annulus. The original form of the Century deposit is unknown due to erosion and post-ore faulting. Restoring the fault offsets of the two ore blocks and reconstructing Zn:Pb metal grade ratios across them brings the deposit back to an inferred formational geometry, about twice the known size, located 1200m to the southeast, prior to impact. The inference is that missing ore blocks may have been displaced towards the crater.

ACKNOWLEDGEMENTS

New Century Resources Ltd allowed publication of this work.

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