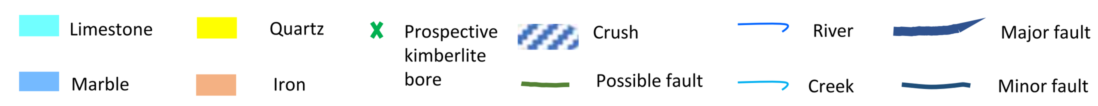
Kurianda - a Potential Meteorite Impact Site:
Revised Interpretation of a Specific Historical Meteorite Impact in the Adelaide Hills

RMIT UNIVERSITY

Robert Moore, RMIT University, Victoria Australia

robertbruce.moore@rmit.edu.au,
science@academicmail.org



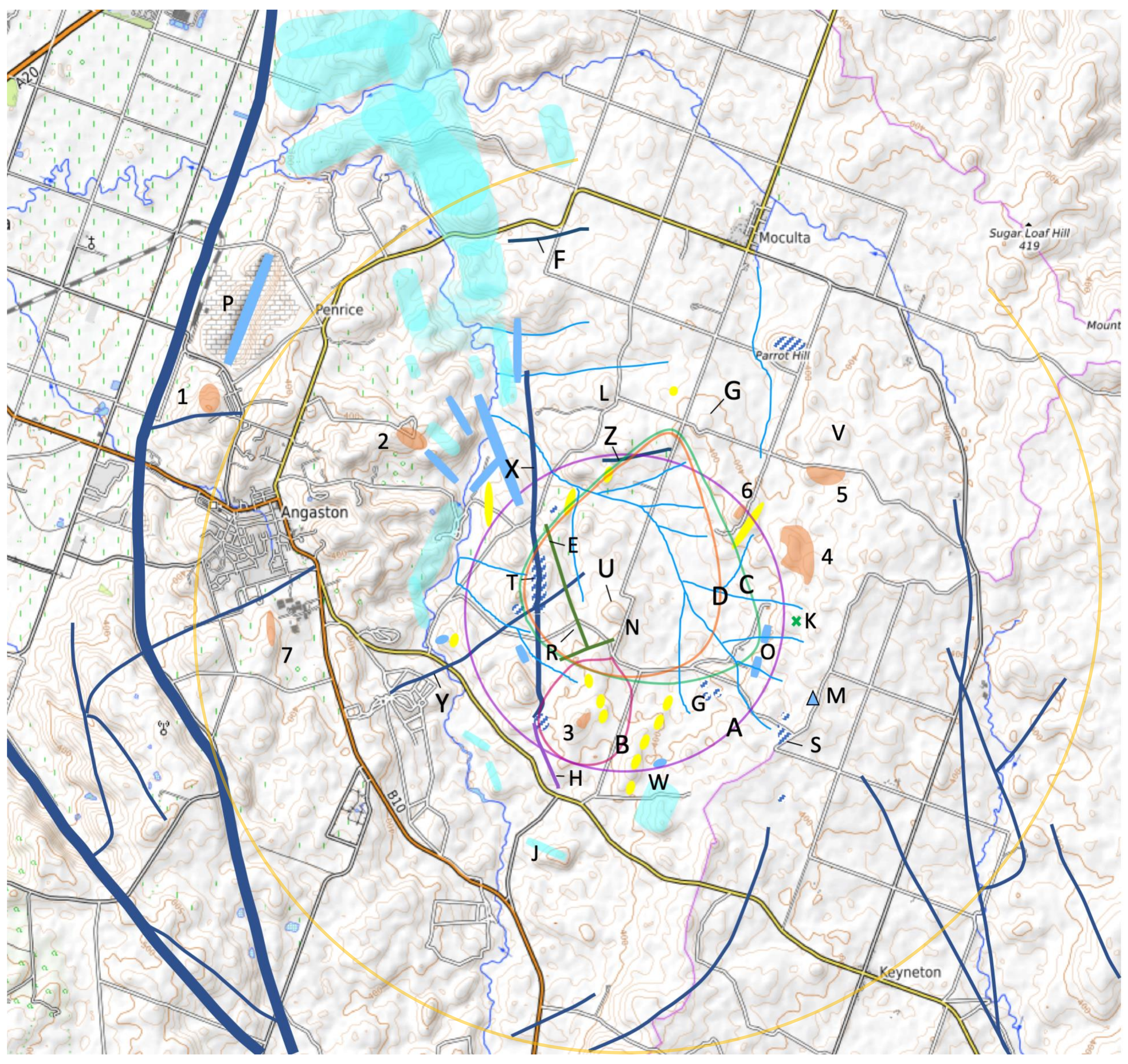


Figure 1. Map of proposed Kurianda structure at Angaston showing 10 metre topographic contours, finds, and sites of rock strata related to the finds. Meteoritic iron from site 2 compares well to similar pieces found weathered at sites 1 and 2. Reported iron caps at sites 3 through 7, may also be related to the at sites 1 and 2. An initial circular mapping [circle A] of a proposed crater with diameter 3 km, around a potential central uplift [U] does not adequately take weathering into consideration, but does establish a floor to rim depth of 80 metres. The entire western rim is missing and the floor of the site currently slopes to the west. Post impact faulting and drainage are discussed in the text in this respect. An oblique impact model is represented in outlines C and D, involving a meteor approaching from N-NE, with banking [B] proposed at the south wall. A find of marble blocks impregnated with iron, at M, may indicate they stemmed from the marble beds at site O or from marble beds that are no longer observable, lying within the crater. The diameter of oblique impact structure D is ~2.5 km x 2 km.

Overview:

This study examines Kurianda, near Angaston, an additional candidate site in a previously proposed multiple impact in the Southern Mt Lofty Ranges, South Australia. A nearby proposed impact in the Mt Crawford (Teetaka) forestry area was already described, along with a proposed ricochet in the Flaxman Valley. The original proposal for the Crawford and Flaxman valleys by Haines *et al.* (1999) and Haines (2000) was of a multiple impact in a SSW-NNE corridor but did not consider sites as far north as Angaston. Principal data given by Haines *et al.* (1999) was in the form of Planar Deformation Features in quartz. The chief data for the additional candidate site Kurianda currently described here involves extensive unmelted chondrite fragments, local topology, iron-rich melt nearby, and macro data concerning shatter-related target materials. Multiple impacts that form craters greater than 2 km in size have not been verified anywhere else on earth, given that Ries and Steinheim craters were recently suggested to not be twin events (Buchner *et al.* 2020). Also, worldwide no similar site to Kurianda has yet been documented with significant iron-rich deposits in the tens to thousands of tons, and that potentially originate from the bolide itself. This study adds to these emerging fields, and will be followed up by further data collection and collaborative analyses. Material so far to hand from the Kurianda area, may already corroborate the modelling of Pierazzo and Melosh (2000) whereby extensive portions of unmelted fragments of a large meteorite with a very low-angle impact, may disperse, and that vaporization does not dominate in these cases, rather seismicity may dominate when impact angle is particularly low (15-30 degrees from horizontal).

Acknowledgement of Country and Special Places – Kurianda and Teetaka

Peramangk dreamtime figures included heavenly bodies which fell to earth, and were considered by Peramangk to have generated aspects of the Southern Mt Lofty Ranges upon impact. This scientific investigation respects and acknowledges that the Kurianda bowl is on land frequented by first nations peoples of the Peramangk, but also Kaurna, Ngangurku, Ngadjuri-Wilyakali-Andynamathana, and other first nations of surrounding areas such as the Ngaywang, Ngarkat, Nukunu, Ngarrindjeri, and Ramindjeri. Specifically that the Kurianda site was frequented annually as a group conference (corroboree) ground. This investigation also respects the European settlers of South Australia and their descendants, their rights, customs and laws, and their relationship to the first peoples listed. Settlers recorded that a particular Peramangk clan of the Kurianda area identified as the Tarrawatta (steep-land) people. A first nations campsite existed ~4 km north of Kurianda on the North Para River, at the junction of Duck Ponds Creek. Similarly, the nearby Teetaka (Mt Crawford) crater and Flaxman valley are also on Peramangk country. At a site on the South Para River, less than 1 km southwest of Mt Crawford, was a campsite of the Poonawatta clan of the Peramangk. As well as being a campsite, the South Para site was also used for first nations exchange/trade (tittanga). The choice of position of the camps near Kurianda and Teetaka may have respected the geological sites, since physical evidence of teaching exists. Beyond that, the wider Peramangk nation includes descendants of at least 8 to 10 separate clans, having ranged the Southern Mt Lofty Ranges and part of Murraylands.

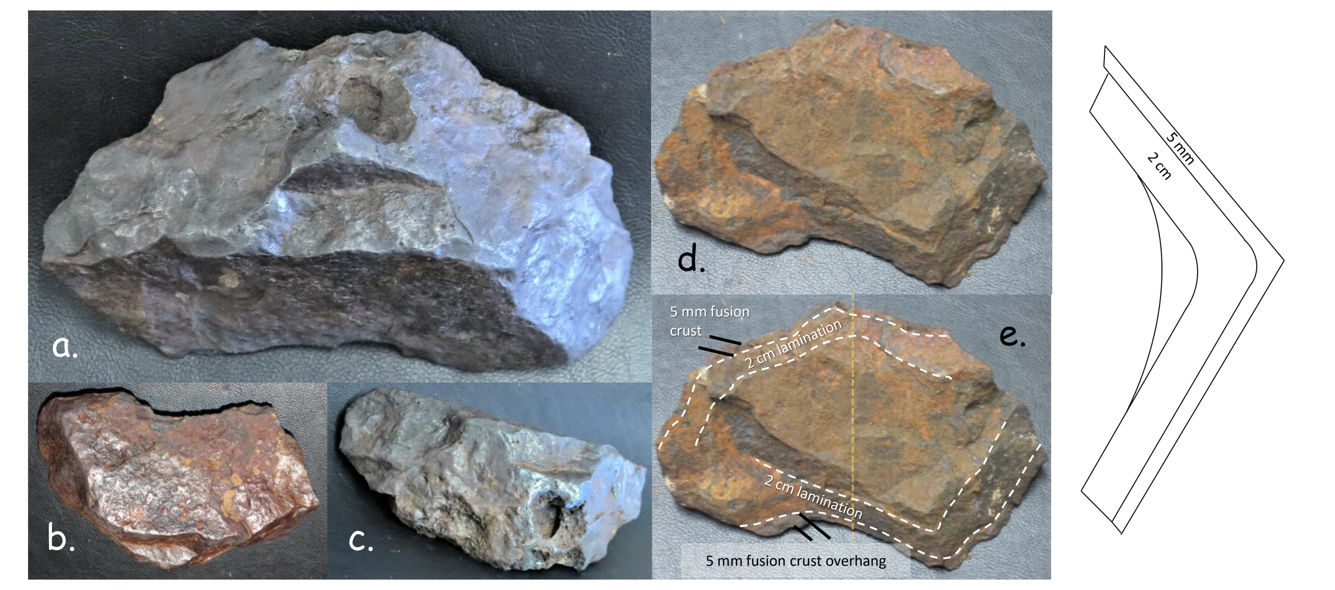


Figure 2 (above). Smoothed magnetic specimen found at site 2 on Figure 1, displaying 5 mm fusion crust and layering. (a) Front face, blackened fusion crust surface, showing features. (b) sheen and smoothness showing very limited oxidation of the fusion crust. (c) alternate view. (d) Back. (e) Back face with cross sectional plane indicated. 5 mm fusion crust delineates front from back, and in places overhangs. (f) schematic in cross section indicating 5 mm fusion crust and 2 cm lamination.

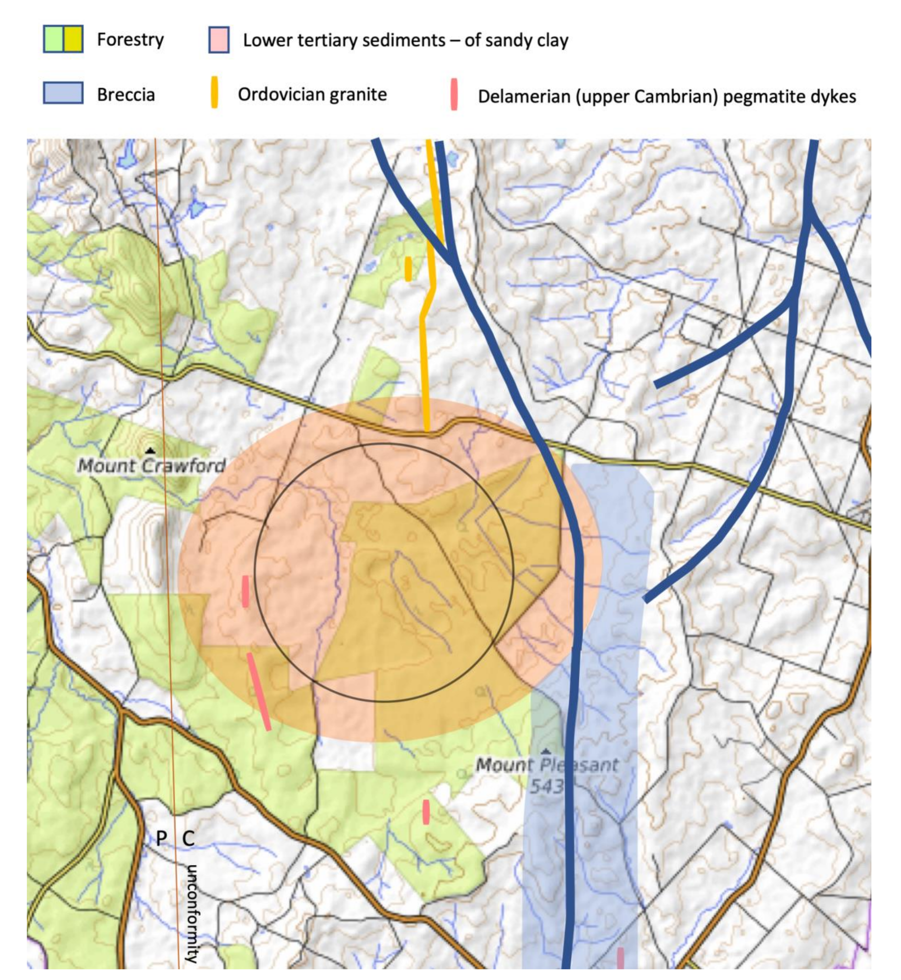


Figure 4 (right). Topographic map at 10 metre intervals showing flatness of the separate Teetaka (Mt Crawford) site.
The approximate maximum radius of crater is circled, and approximate extent of known tertiary infill in shown. The area is mostly used for forestry purposes owing to clayey sand. Uncoloured areas and forestry areas comprise strata as follows: Target rocks to the east of the designated unconformity are Cambrian (C) metasiltstones; Non-target strata west of the unconformity are Proterozoic (P) comprised of shales and dolomites. For relationship to Kurianda see Fig 5.

Iron-rich bolide fragments

A magnetic, and iron-rich, putative meteorite fragment has been newly found at site 2 (Figure 1). The fragment is smoothed on one side, has a 5 mm black fusion crust on that side, and appears to have a layered internal structure (Figure 2 a-e). Other than these outer appearances, the find has not been further analysed because it was found on private land, and returned to the owner. However, it subsequently led to a search for the history and occurrence of iron in the Angaston area.

Several other pieces from the wider site 2, which are by contrast highly weathered due to long term burial, were characterized according to magnetism and density, then split to expose internal relatively unweathered surfaces. A ceramic magnet was used for the magnetism test. The weathered pieces found at site 2 were each magnetic, and showed abundant visible submillimeter presumed iron-nickel inclusions (Figure 3a and 3b). The density of the pieces was 3.4 g/cc consistent with ordinary chondrite. Cutting revealed the coloration of the nonmetal mineral content is mid gray, and grain size of the metallic inclusions is on the order of 0.1 to 1.0 mm. Chondrules are not visible with the naked eye, indicating the finds are potentially of the H chondrite type (H for High iron), which is a type of meteorite that has an average density of 3.4 g/cc, is grey, and appears without visible, large or varied chondrules. Occasional, possible troilite polyhedra of larger size up to 1 cm that are embedded deep inside one of the weathered pieces (Figure 3c) were removed, and are magnetic.

The iron-rich finds are proposed to have originated as dispersal fragments of an ordinary chondrite meteorite. Many iron finds attributed as dispersal fragments occur at a smaller crater site, Barringer in Arizona. It is known that such dispersal of meteorite fragments can occur for instance due to a shockwave travelling in the reverse direction of the strike at the moment of impact. Detailed modelling was done by Pierazzo and Melosh (2000) albeit for a much larger meteorite, and it was found that low angles of impact between 15 and 30 degrees leave much of the meteorite unvapourised. Putative dispersal fragments from the Kurianda impact may follow a similar model. Of fragments photographed at site 1 (Figure 3d) and mined in the 20th century, some are intact and some are melted, but all are loosely surrounded by kunkar and clay. Melted fragments at site 1 may have a higher % of iron than intact fragments. Iron-rich fragments at sites 1 and 2 may represent the types of iron at uninspected sites 3-6, which were characterized by Fleming. Site 7 on private land was described in colonial literature as heavy iron-rich rock.

In the South Australian geological literature, massive iron has not been documented as occurring in the Barossa Range outside the circle currently defining the dispersal proposed here (yellow circle in Fig 1), except Mt Bessemer iron, which is 25 km to the southwest, and is widely regarded as a separate large deposit than that of the Angaston district. Beyond the Barossa, a very large deposit is at Mt Cone (75 km SW of Mt Crawford), and a smaller deposit at Mt Jagged very near Mt Cone is related to the Mt Cone deposit. Further assessment of the detailed characteristics of these iron deposits is needed.

Shocked rocks?

Finds at two sites, close to the Kurianda structure described here, may indicate an anomalous shock. This is especially so given the otherwise weathering-driven history of the region since the Delamerian (Upper Cambrian) orogeny. The orogeny is known to have raised the majority of the beds in the Southern Mt Lofty ranges that themselves date mainly from the Paleozoic and Lower Cambrian, with subsequent periodic but very localized introgression of sediments since.

The first in this category of shock-related finds are marble prisms located at site M (Figure 1) which were presumably uncovered by grading of the road during its construction, or may have been already exposed leading the grader to skirt around them. The most striking of these prisms is a 1 m tall rectangular prism (Figure 3f) albeit with a missing vertex, a vertex that may have been hammered off by preceding geological investigations. Three sides of the prism are coated with weathered iron-impregnated marble to about 8 mm thickness, while the fourth side being uncoated may indicate subsequent cleavage such as by roadworks. The iron-impregnated marble coating on the prisms is not necessarily "rock varnish" owing to its thickness being in millimetres not micrometres, so indicating a new phenomenon. Other blocks at M are similar. By analogy to shattercones, if the shape of the marble prisms, being pointed, were to correlate with a shock event that occurred on pre-existing marble, then the iron impregnation could have occurred either during that same event or after. It is suggested here that the impregnation accompanied shattering. A second proposed impact-related find is a four-sided pointed formation of siltstone from Lambtail Corner Road site R (Figure 1) shown in Figure 3g.

Metamorphic considerations and seismicity model

The cause of metamorphosis of limestone to marble west of fault X is unclear. Contact metamorphism may have occurred on contact with a below ground igneous intrusion known as the Truro volcanics (Cobb and Farrand 1984) attributed to the lower Cambrian. Good evidence of subsurface intrusion is displayed in Segui (2010), being a very strong positive gravity anomaly, distributed broadly throughout the hills nestling Angaston and east to Fault H (Figure 1), though the anomaly is of an undisclosed depth focus. In contrast, the white marble beds at Penrice marble mine (P in Figure 1) are hundreds of feet thick, and occur close below the surface with little or no overlying burden.

Similarly, no adequate metamorphic influence has been described at specific marble locations shown here east of fault X, which do not have any similar gravity signature as the main Angaston hills. At one site (K in Figure 1) in the immediate vicinity of the proposed crater, a putative kimberlite pipe of ~200 m diameter contains minerals of high pressure metamorphic origin. Pressures having occurred in the lower depths of the pipe were attributed as 10 to 30 kbar, and the site is known as the Angaston xenolith. The age of the Angaston xenolith minerals was estimated as Ediacaran of 594 ±71 mya (Segui 2010). Such xenoliths are thought to be generated from the lithosphere-asthenosphere boundary. Chemical analyses cited in Segui showed that a subsequent additional high-pressure exposure of the same xenolith occurred in the Triassic or Jurassic at 206 ±44 mya. Anecdotally, diamonds were never obtained from the xenolith, though two companies have prospected decades ago at the bore K, even including the digging of trenches to determine extent (Segui 2010).

A localised metamorphic role of an impact cannot be ruled out. However, pre-existing Cambrian marble also occurs in two bands, each band being tens of kilometres long, one extending northward from the site towards Truro, and the other extending N-NW from the site towards Kapunda. Accordingly impact metamorphosis need not be invoked *per se*. The marble prisms at site M, are assumed to have already been marble at the moment of proposed impact otherwise they could hardly have cleaved in the way they have if they were limestone at the moment of proposed impact. Metamorphosis to create marble, and then cleavage of marble in the way indicated, need to be separated in time. However, alteration of marble, from a non-oriented crystal structure to a planar crystal structure via impact is suggested by visual inspection.

The modelling by Pierazzo and Melosh (2000) established that for very low-angle impacts, a proportion of the energy of collision does not go into vaporization of the projectile. By necessity then, for a very low angle impact, a substantial proportion of energy goes into some form of shock, distributed between metamorphosis, and seismicity. Landforms invoking seismic circularity are apparent in the landforms of the district, surrounding the proposed impact. If any of these are indeed seismicity-related, and derive from the interval of the impact event, then similarly, microscopic shock features should also be readily observable in the immediate area of the crater rim as studies become mature. Until then, it is arguably premature to discuss shock metamorphism with regard to the marble blocks M in Figure 1 and Figure 3.

Faulting as alternate model, or evidence of banking?

Features concordant with the model of an impact at Kurianda have been outlined above. The feature most contradictory to a high angle impact is the proposed slump or banking, within shape B in Figure 1. Due to the forms present within feature B, the only model that fits the data is a very low angle impact. These features include mutually disoriented but individually traceable outcrop lines (not shown).

For example, in a high angle impact model, some relatively undamaged laminar beds at R in Figure 1, and feature U in particular, would need to have been raised since, such as by a potential complex fault E suggested by Thompson. The strike of the raised beds at R, has an orientation which follows the angle of previously proposed fault E (Figure 1) for which no geological age of occurence has yet been suggested. Exposed rock features in the proposed central uplift have beds oblique to the proposed impact, and the unshattered nature of these beds is inconsistent with central uplifts that have been observed inside complex craters from orthogonal impacts.

If feature U is impact related, then its form may indicate that a short crater diameter such as that of crater D (Figure 1) is most likely, and that U is potentially the equivalent, for an oblique-impact crater, of a central uplift in an orthogonal-impact crater. On the other hand, if U is not impact related, then faulting along L-N, proposed by Thompson may have been responsible for its uplift, presumably well after the currently proposed impact event.

In a non-impact model, the entire circular structure A would have been formed by drainage of the North Para River, but the difference in height of the floor and the eastern rim has not been well explained other than that. The cause of an initial incision is open to question. Fleming (1965) implied that a fault he proposed from V-W is the cause of the 50 metre difference in height between site M and site O. Fleming also proposed that fault X may loop at its southern end via point J to join with the further fault he proposed V-W. Putative fault V-W in turn was proposed partly in respect of crush at S. In such an alternative model, loop faulting may have lowered the central circle, but that model lacks evidence for how the south rim was raised, why the flatness of the present floor is restricted in area, and why the floor is bounded by unexplained raised elements on the northwestern rim, being Little Parrot Hill (site 6) and Gnadenberg Hill (G) in Figure 1. Finally, in relation to alternate models, the crush comprising the entirety of Parrot Hill itself has not been given any hypothetical cause by any researcher.

An alternative to the banking model for how the south bank (including but not limited to area B in Figure 1), along with uplift U can have become raised gradually since the event, is that a hypothetical fault from U to J, may have been initiated by the proposed impact. An even longer potential fault L-J, parallel to fault X, and deriving by the same tectonic and local forces as fault X may be a reasonable suggestion, since L-N was already proposed previously by Thompson. However, Fleming did not concur on L-N, X, Y or complex fault E, not even after 8 weeks field work in the area. As long as no consensus is provided by researchers on exactly where the local minor faults lie, no clarity will surround models that comprise alternatives to the impact scenario. Larger faults in the Southern Mount Lofty are long, curved in places, and generally oriented NNE to SSW, though exceptions occur.

General absence of melt breccia: crush dominates instead

A known characteristic of the area is the presence of "crush", tumultuously mixed rocks uncemented, in particular a large cache comprising the entirety of Parrot Hill. Parrot Hill is otherwise known as Moculta and gives the nearby town its name. Crush is effectively an uncemented breccia, so does not strictly qualify as breccia. Crush at Parrot Hill and S should be thoroughly investigated further as to potential shock features.

Crush present at T was ascribed by Fleming as due to late tertiary activation of fault X (Figure 1). Crush at T may therefore be unrelated to the proposed impact, and is consistent with the erosion of the western rim of a crater, so fault X may constrain the date of a proposed impact to before the time of that fault activity.

Ages of the Kurianda target-rock strata and surrounding beds

The floor of the currently proposed crater, hence the deepest target rock, was previously suggested by Thomson to be Proterozoic, specifically Sturtian, although no strata are exposed on the flat. Hence Thomson raised that dating as a question. Bedrock has not been reached within the crater floor area, rather only the 30 m peak of the central uplift U contains any exposed rock, if little. Siltstone of that peak appears have been used to obtain the age stated in Thomson (1968), while older Proterozoic Torrensian material was given from fault Z to fault F. Encircling essentially the proposed crater then, a succession of concentric, ovoid-mapping bands of younger Proterozoic strata stretching N-S were determined in the Thomson study to successively surround the Torrensian ellipse (southern tip of the inner ellipse focused on U, northern tip at F), namely Sturtian then Marinoan strata, in turn bounded by Cambrian beds including limestone and marble. Beds just west of faults X and Y were characterised by Thomson as a distinctive Marinoan strata younger than the other Marinoan strata in the area. The beds extending from area B in an eastward arc through G to are of a slightly older Marinoan age than those. Thompson proposed that the Cambrian beds of the Angaston hills also extended continuously through to J-W-O.

The exposure of Proterozoic material may be partly related to the impact. Cambrian strata that lay above the current floor level may have been blown out by impact, in which case, for 10 km north and about 2km south, Cambrian strata may be partly covered over by a Proterozoic ejecta blanket, or else the impact angle was so oblique that pneumatic force removed top material north of the impact site, even without contact. In the Proterozoic south bank as a whole there is significant exposure of several mutually parallel strikes heading SSE from the proposed southern rim. Uplifted or exposed Proterozoic beds at H dip strongly, a bedding orientation which may entirely or partially predate an impact. Geologists concur with each other that a semicircular arc of Cambrian beds J-W-O lies around but does not include deposit 3 (Fig 1).

In Figure 1"iron caps" (chemically deposited iron) were proposed by Fleming at 3-4-5-6. Beds underlying the iron caps 1-2-4-5-7 are not Marinoan or Sturtian, unlike under deposits 3 and 6, and so iron caps 1-2-4-5-7 are not necessarily due to snowball earth conditions (Hoffman *et al.* 2011). Rather the iron caps at 1-2-4-5-7 overlie Lower Cambrian beds. That being said, in the Lower Cambrian a waning polar ice cap did affect Gondwana. If these are "iron caps", then a constant gentle weathering at their local points of elevation would be needed to rationalize why little to no material overlies any of these iron caps even after >500 my.

Figure. 3. Putative meteorite fragments and impact-related shocked rocks. (a) 1 mm presumed Fe-Ni inclusions in a matrix comprised of 0.1 mm Fe-Ni inclusions and presumed grey silica, from site 2, consistent with H chondrite [weathered, cut, magnetic]. (b) external of same showing frequency of 1 mm inclusions. (c) polyhedra of possible troilite, extracted from a. (d) Fe-rich rocks amongst kunkar at site 1 of Figure 1 [limited access]. (e) acid-resistant metamorphosed-marble, impregnated with iron at site M of Figure 1. (f) top view of a 1 m high rectangular prism of this type of impregnated marble at site M, being coated on three sides. (g) prismatic fracture [side and top view] of siltstone from site R of Figure 1.

Previously published potential impact sites: Flaxman and Crawford

A previous model of proposed impacts in the area has led to this study, although that model did not examine the Angaston area. Haines *et al.* in 1999 and Haines in 2000 described a model whereby several low-angle (oblique) impacts may have occurred stretching the length of the Southern Mt Lofty Ranges from Mt Crawford to Kangaroo Island, the bolide entering the atmosphere from the S-SW, then breaking up before the series of impacts.

A good candidate impact site was suggested to lie east of Mt Crawford (Figure 4) and a less obvious impact site was suggested at Flaxman Valley (Figure 5) which lies just south of the current study site near Angaston. Flaxman was suggested to be related secondarily to Crawford via a proposed richochet event, the projectile having impacted the Crawford area from the S-SW (Haines 2000). Evidence in quartz at the Flaxman and Crawford sites included Planar Deformation Features (PDFs) grain mosaicism, pseudotachylite veins and maskylnite (Haines et al. 1999). Thirdly a good candidate marine impact site at Pelican Lagoon on American River, Kangaroo Island tentatively corroborated a low angle impact hypothesis when coupled with evidence of a tsunami (Haines 2000) related to the Chinaman's gully formation on Fleurieu Peninsular.

The current work adds to this body of data and tentatively supports a multi impact model, however no firm dates have been obtained by any group at any site, except stratigraphic inference at Chinaman's gully which is an indirect dating since it is not a proposed impact site. The topology of Kurianda suggests a N-NE entry rather than from S-SW. If the proposed Kurianda and Teetaka impacts are related by a multiple event, then several corroborating observations on surface processes tend to support a date of the mid to late Eocene for the multiple impact. Firstly, tertiary lacustrine sediments have filled in a cavity east of Mt Crawford, a cavity that is otherwise unexplained in the literature even though the Adelaide hills are very well studied geologically. Secondly, uplift of the Southern Mt Lofty Ranges to their current form is discussed by Priess (2019) as being mainly tertiary, largely involving reactivation of older faults and raising of older strata, hence these hills are currently in a new weathering phase. Weathering that occurred before the existing uplift of the Southern Mt Lofty Ranges, had progressed to a thorough extent, and is likely to have obliterated any older candidate impact forms. Thirdly, drainage patterns in the two proposed craters Mt Crawford (Teetaka) and Kurianda concord well enough with those that could be expected for relatively recent structures. Finally, the fault X that is here suggested to have demolished the western wall of a crater at Kurianda, is a fault known to have been active in the late tertiary or thereafter, constraining a proposed impact to before that, not after.

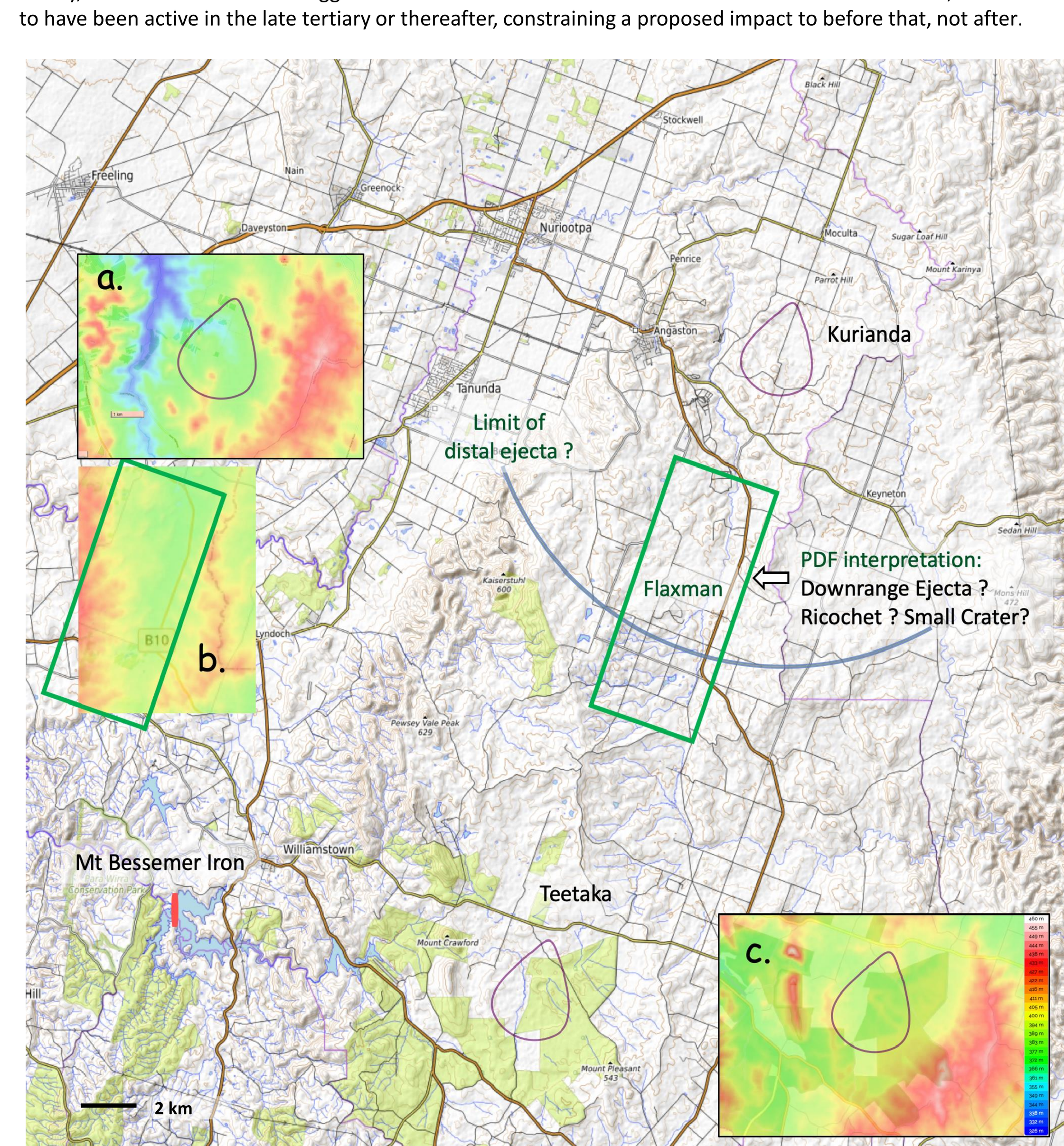


Figure 5. Geographic relationship between Kurianda/Angaston (Upper), Teetaka/Crawford (lower) and Flaxman (middle) areas, showing various alternate origins of the Planar Deformation Features previously observed in Quartz at the Flaxman Valley, as well as showing the closest other iron lode, and a digital elevation model at each site (insets: [a] Kurianda; [b] Flaxman; [c] Teetaka with approx. scale). The overall topographic map is at 20 metre intervals. Mt Bessemer iron 25 km SW of Kurianda, was mined for a long period very close to the surface, yielding ~100,000 tons of ore with a grade of 45% Fe. Published prospective estimates of a further equivalent lode at depth at Bessemer, were contradicted by others. Landscapes north and well south of this map are under re-investigation in relation to potential impacts, while the provenance of the Mt Bessemer deposit should be treated with caution. No other current observations of the immediate Mt Bessemer area, other than iron veining into rock (hence possible melt or other causes), would currently point to an impact origin of that lode.

Multiple impact model: A rubble pile meteor?

One model which suits the data for Kurianda and Teetaka involves the "rubble pile" model for a compound asteroid, a model in which the components of the rubble pile are held together only by gravity (Richardson *et al.* 2002). Such a bolide can potentially break up into its component parts upon entering the atmosphere, each part being a solid large meteor. Given that ~40% of meteorite falls globally are ordinary chondrites, the current study invokes the possibility of a rubble pile meteorite comprised of ordinary chondrites, or comprised of ordinary chondrites and other meteorite types held together loosely by the gravity of the rubble pile. An incident rubble pile meteor appears to have "ungrouped" upon entering the atmosphere. Ries and Steinheim craters were recently suggested to not be twin events (Buchner *et al.* 2020) as previously thought, so making the current proposal perhaps novel to date. No clear data has yet been obtained in this study regarding which type of meteorite impacted Teetaka although magnetic iron pisoliths are abundant there and in several parts of the Southern Mt Lofty Ranges.

Acknowledgements: This study is preliminary. The author thanks C.K & P.H. for critical discussions, & Kaurna, Peramangk & Ngadjuri elders for first nations background. The South Australian Govt owns all minerals in SA.

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