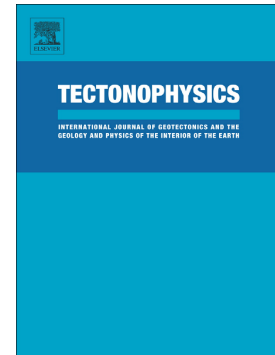


Accepted Manuscript

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PII: S0040-1951(17)30455-9
DOI: doi:[10.1016/j.tecto.2017.11.003](https://doi.org/10.1016/j.tecto.2017.11.003)
Reference: TECTO 127669
To appear in: *Tectonophysics*
Received date: 7 June 2017
Revised date: 30 October 2017
Accepted date: 2 November 2017

Please cite this article as: Andrew Glikson , Structure and origin of Australian ring and dome features with reference to the search for asteroid impact events. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Tecto(2017), doi:[10.1016/j.tecto.2017.11.003](https://doi.org/10.1016/j.tecto.2017.11.003)

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Structure and origin of Australian ring and dome features with reference to the search for asteroid impact events

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ABSTRACT

Ring, dome and crater features on the Australian continent and shelf include (A) **38** structures of confirmed or probable asteroid and meteorite impact origin and (B) numerous buried and exposed ring, dome and crater features of undefined origin. A large number of the latter include structural and geophysical elements consistent with impact structures, pending test by field investigations and/or drilling. This paper documents and briefly describes **43** ring and dome features with the aim of appraising their similarities and differences from those of impact structures. Discrimination between impact structures and igneous plugs, volcanic caldera and salt domes require field work and/or drilling. Where crater-like morphological patterns intersect pre-existing linear structural features and contain central morphological highs and unique thrust and fault patterns an impact connection needs to be tested in the field. Hints of potential buried impact structures may be furnished by single or multi-ring TMI patterns, circular TMI quiet zones, corresponding gravity patterns, low velocity and non-reflective seismic zones.

- A. Examples of crater-form and dome-form features containing elements consistent with an impact origin, though unproven, include *Auvergne, Delamere, Fiery Creek, Monte Christo, Mount Moffatt, Tanami East, Youngerina, Tingha*.

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- B. Examples of buried multi-ring features of possible to probable impact origin include *Augathella*, *Balfour Downs*, *Calvert Hills*, *Camooweal*, *Green Swamp Well*, *Herbert*, *Ikybon River*, *Ilkurka*, *Lennis*, *McLarty Hills*, *Mount Davies*, *Mulkara*; *Neale*; *Sheridan Creek*, *Oodjuongari* and *Renehan*.
- C. Examples of igneous plugs unrelated to impacts include the Monto gabbro and numerous circular granitoid plugs such as *Windinie Hills* granite and *Yataga* granodiorite.
- D. Large circular structures such as *Mount Ashmore* and *Gnargoo* are considered to have convincing structural deformation features warranting classification as probable impact structures.

The origin of very large circular TMI and gravity patterns such as of the *Diamantina* River drainage feature, *Coonamona* anomaly and the multiple TMI ring pattern of the *Deniliquin-Booligal* remain unresolved. The advent of ~40 meters TMI grid coverage promises to further uncover ring and dome features, such as the *McLarty Hills* multi-ring feature, potentially increasing the inventory of ring structures on the Australian continent. Compared with frequency distribution patterns of extra-terrestrial impact structures worldwide, the Australian record displays a relatively common occurrence of large impact structures and relative depletion in small impact structures and craters. This is explained by the better preservation of large structures at deep crustal zones as compared to the erosion of small craters.

Keywords: Australia, ring structure, dome, asteroids, impact

A. Introduction

The geological antiquity of Australian land surfaces, in particular platform sediment and volcanic cover overlying Precambrian cratons in central and western parts of the continent, allows preservation of a range of circular features, including morphological and drainage rings, circular lakes, volcanic craters, tectonic domes, oval granite bodies, mafic igneous plugs, salt diapirs, and magnetic, gravity and seismic anomalies of unknown origin. The criteria applied for recognition of asteroid impact structures and meteorite craters from geophysical evidence (Grieve and Pilkington, 1996; Shoemaker and Shoemaker, 1996; Glikson and Uysal, 2010) and from

petrological evidence for shock metamorphism (French, 1998; French and Koeberl, 2010) allow identification of at least **38** impact structures on the Australian continent and surrounding continental shelf (Gorter, 1998; Haines, 2005; Bevan et al., 2012; Dunster et al., 2014; Glikson, 2017; Earth Impacts Database) (Table H-1). This report lists **42** examples of exposed and buried circular structures and features, including exposed ring and dome features, and circular magnetic, gravity and seismic anomalies of buried features (Table H-2; Fig. 1). The discussion proceeds in terms of examples including (1) circular intrusions; (2) topographic ring and crater features; (3) circular drainage features; (4) total magnetic intensity anomalies; (5) seismic domes, and (6) large gravity multi-ring TMI geophysical features, followed by a synthesis of the distribution of confirmed and unconfirmed impact structures.

B. Criteria for classification of ring and dome features

Circular drainage patterns, round lakes and oval depressions may provide hints of possible underlying ring or dome structures, requiring field tests or drilling where no outcrop occurs (Grieve and Pilkington, 1996; Glikson and Uysal, 2013). Structural domes and near-circular fold structures may initially be mistaken for impact structures, as are basins of approximately circular or slightly elongate pattern and plutonic domes such as oval granite intrusions (Fig. 2, A and B), laccoliths and gabbro plugs (Fig. 2 C and D). In orogenic belts cross-folding may produce dome structures. Diapirs are cored by relatively low-density rocks or magma, an example being granite domes rising in response to the gravity instability of the granitic magma relative to the denser country rocks.

Structural elements of circular features suggestive of an impact origin include:

- Intersections of older structures by external rings of the ring feature, as displayed for example by the *Chicxulub* impact structure (Sharpton et al. 1996), the *Woodleigh* impact structure (Glikson et al., 2005a, b), the *Gnargoo* probable impact structure (Iasky and Glikson, 2005; Glikson and Uysal, 2013) and the *Shoemaker* impact structure (Pirajno, 2002). Whereas structurally discordant intersections are also displayed by volcanic diatremes, igneous plugs and salt domes, a presence of a central uplift core or dome fringed by a ring syncline is consistent with diagnostic features of impact structures;

- The central uplifts of impact structures are well defined in seismic reflection sections where the uplift is commonly associated with inward-verging thrust faults, as in the *Woodleigh* impact structure (Iasky et al., 2001) and the *Spider* impact structure (Abels, 2006).
- An intersection of the top of the dome or a basement uplift by unconformably overlying post-impact sediments is typical of impact structures, as demonstrated in the *Woodleigh*, *Gnargoo*, *Mount Ashmore* and *Tookoonooka* structures. Post-impact isostatic vertical movements are indicated where the central uplift pierces through the unconformity, as in the *Mount Ashmore* structure.

Where the core of the structure consists of sedimentary strata, a structural dome is outlined containing chaotically disrupted core zones which display a loss of seismic markers associated with mega-brecciation, as in the *Mount Ashmore* probable impact structure (Glikson et al. 2010). By contrast to thrust faults around and within central core zones, ring synclines and outer rims of impact structures display inward-dipping normal faults. These structural patterns represent centripetal and upward block movements involving compression around the uplifted core or plug and inward collapse of the crater rim, evident in the *Woodleigh*, *Gnargoo* and *Talundilly* structures. In addition, some impact structures and probable impact structures display uplift of crystalline basement below impacted sediments, as in the *Woodleigh* impact structure (Iasky et al., 2001; Glikson et al., 2005a, b), the *Mount Ashmore* probable impact structure (Glikson et al., 2010) and as magnetic highs at the centres of the *Warburton* impact structures (Glikson et al., 2013, 2015).

However, whereas hints at an impact origin of these structures are offered by the above structural patterns, a confirmation of an impact origin can only be achieved provided shock metamorphic features are identified, including planar deformation features in minerals, shock melt textures and transformation to high density polymorphs such as coesite and stishovite.

The following sections portray examples of circular features classified in terms of several categories, including topographic ring features, circular drainage features, magnetic ring anomalies, gravity ring anomalies and seismic domes.

C. Circular drainage rings

The role of circular structures in the evolution of the Australian continent was highlighted by O/Driscoll (2007). A classic example of a circular drainage feature is the *Diamantina* drainage ring feature, west of Winton, northwestern Queensland: (141.9E22S) (Fig. 3) constitutes an example of a near perfectly circular drainage ring associated with geophysical features, including TMI, Bouguer anomalies and deep seismic transects (Glikson et al., 2016). The *Diamantina* ~120 km-diameter ring feature is manifested by a near-360 degrees circular drainage pattern, radial creeks and a coincident radiometric K-Th-U pattern. A western subdued TMI arc with a ~110 km diameter is offset by ~30 km eastward from the western rim of the drainage ring. Bouguer anomaly data display a gravity low near the centre of the ring structure, but no outer circular pattern. Two recent seismic transects indicate a moderately reflective to weakly reflective crust below flat lying strata of the Jurassic–Cretaceous Eromanga and Permian–Triassic Galilee basins, and above a usually well-defined ~39–45 km-deep Moho. An approximately ~100 km-wide seismically non-reflective to weakly reflective zone overlapping the *Diamantina* ring feature separates crust of different seismic reflection character on either side. The nature of the seismic non-reflective crust is unknown. A potential interpretation of the ring structure in terms of asteroid impact cannot be confirmed or rejected given the present state of knowledge, owing to the near-30 km depth of the seismically non-reflective zone along the transects, and the shift of the TMI part ring zone relative to the circular drainage expression of the Diamantina ring feature. A test of the nature and origin of the Diamantina ring feature requires a cored drill hole near the centre of the TMI ring structure.

The *White Cliffs* half-ring morphological feature (143.1450E30.785S) (Fig. 4a) forms an approximately ~2 km-diameter half-circle depression fringed to the north, east and east-southeast by 2-3 meters thick terraces formed by ferricrete and silcrete capping of probable Cretaceous age. The laterite and weathered rocks are estimated as 100-200 meters thick, are cut to the northwest and southwest by creeks. The base of the low cliffs to the east and north is marked by white eroded material. Samples from the underlying white rock consist of foliated to non-foliated quartz-clay siltstone. No clear TMI signature is associated with the semicircular feature.

Other examples of circular drainage rings include the *Youngerina* ring feature (Fig. 4b), which constitutes a ~2.8 km-diameter morphological ring demarcated by a light rim and associated with a K-Th-U high and a TMI low. No distinct gravity feature is apparent. The *Skirmish* feature, eastern Western Australia (Fig. 4c) (Haines, 2005), is a ~2 km diameter circular structural

anomaly with outward dips resembling an eroded central uplift of a complex impact structure. The feature is situated in otherwise uniformly dipping Early Neoproterozoic Townsend Quartzite. F. Pirajno (pers. comm., 2017) observed a ring of strongly fractured outwardly dipping quartzite with possible shatter cleavage, surrounding a central sand covered region. Petrographic examination reveals common grain fracturing consistent with, but not uniquely diagnostic of, low shock levels. No evidence of igneous or diapiric intrusion is evident and the feature is considered a possible eroded central uplift of a larger ~6 km complex impact structure of post-Early Neoproterozoic age (Haines, 2005).

The *Throssell-Roberts* half-ring topography feature (Fig. 4d) (123.63E27.08S) is an apparent eastern half-circle feature of ~140 km-diameter weakly expressed on shuttle radar images straddling the Roberts and Throssell 1:250,000 Sheet areas, including an apparent central ring, corresponding to the radiometric K-Th-U image. The TMI image displays semi-circular features within the limits of the morphological features. Little correspondence is observed with the gravity pattern.

A. Topographic ring and crater features

Several ring features containing structural, morphological and magnetic elements consistent with those of impact structures are indicated as listed below, including the *Tanami East* (Fig. 5), *Auvergne* (Fig. 6), *Tingha* (Fig. 7), *Monte Christo* (Fig. 8), *Mount Moffatt* (Fig. 9), *Fiery Creek* (Fig. 10) and *Lucas/Yam Hill* (Fig. 11). No impact deformation and shock metamorphic features have been reported to date from these features. However, the multi-ring morphology of some structures (*Tanami East*, *Fiery Creek*) and the intersection by the ring structures of linear morphological and tectonic trends (*Monte Christo*, *Fiery Creek*, *Mount Moffatt*) renders these features potential targets for search of impact deformation and shock metamorphism. In the following the principal features of each of these structures are summarized:

Tanami East, Northern Territory (130.714E19.703S) (Fig. 5) constitutes a central outcrop with a diameter of approximately 150 meters surrounded by multiple rings up to ~600 meters in diameter. The outcrop consists of Middle Cambrian sediments, including dolomite with chert nodules, dolomitic siltstone, sandstone and claystone and is fringed by at least 3 external rings (Fig. 5) consisting of sand, rock fragments, silt, clay and outwash deposits (Tanami 1:250,000

Sheet, 1975). The feature is overlapped by a slightly high TMI values. The *Tanami East* structure requires detailed field examination to assess a possible impact origin.

Auvergne, Victoria Basin, Northern Territory (129.328E15.698S) (Fig. 6): The *Auvergne* ring structure constitutes a well-defined ~1.1 km diameter sub-rounded depression surrounded by sandstone and conglomerate cliffs of the Neoproterozoic Bullo River Sandstone (838±80 - 739±30 Ma). The ring structure is truncated in its WSW flank by a NNW-striking shear zone and on the eastern flank by a NNE-trending fault. A small radiometric K-anomaly is indicated at the centre of the structure. No volcanic rocks are associated with the structure. Subject to field tests the discordant nature of the structure relative to the regional trends and the sub-circularity of a central depression render the Auvergne ring structure a potential target for a search of diagnostic shock metamorphic features.

Tingha, Northern New South Wales (151.114E30.004S) (Fig. 7): The *Tingha* ring feature constitutes a ~21 km-diameter circular body consisting of a core of the Tingha Adamellite (Uralla Plutonic Suite) (Shaw and Flood, 1981) and a mantle of Late Permian granites. The structure is well manifested on TMI and Radiometric images, the latter representing different K-Th-U ratios in the granitoids. Pending further field tests including a search for shock metamorphic features, the structure is regarded as a zoned igneous plug, conceivably a basement uplift of an impact structure?

Monte Christo, Northeast Queensland (148.116E20.404S) (Fig. 8): The ~8 km-diameter topographic ring/crater feature coincides with a TMI low fringed by N-S trending TMI ridges. The ring is cored by Lower Cretaceous igneous units including granodiorite and adamellite and is surrounded by Upper Carboniferous diorite, quartz diorite, tonalite, gabbro, granodiorite, rare adamellite, norite, monzonite, granite (Stephen Johansen, pers.com., 2012). The core consists of much more mafic hornblende quartz diorite or tonalite and is deeply weathered and poorly exposed. The aplitic granite at the rim of the ring structure displays concentric shearing and is topographically elevated relative to the granite-occupied central depression, possibly reflecting silicification of the sheared aplite. The aplite displays higher K-U-Th levels than the internal granite. The ring feature may represent a circular magmatic intrusion emplaced in a sheared Upper Carboniferous igneous complex. Such Cretaceous intrusions become increasingly common toward the coast to the northeast of the Bowen Basin. According to R. Bultitude pers. comm. 2015) the feature consists of granitic rocks ranging from hornblende-biotite granodiorite

to leucocratic biotite syenogranite, all almost certainly of early Cretaceous age. The nearest Cretaceous volcanics are in the Proserpine region >50 km to the east. The origin of the *Monte Christo* ring feature requires field examination for possible features of shock metamorphism.

Mount Moffatt Carnarvon National Park, Queensland (147.913E25.082S) (Fig. 9): The feature constitutes a somewhat NS-elongated crater ~2.8–2.5 km in diameter, surrounded by an circular ridge consisting of Lower Jurassic sandstones displaying an overall NW to NNW structural trend. No corresponding TMI or gravity features are observed.

Fiery Creek, Northwest Queensland (139.228E19.222S) (Fig. 10): The *Fiery Creek* dome structure constitutes a prominent morphological ring feature with an inner northeast diameter of ~10 km and an outer quiet TMI zone defining a structure about ~19 km in diameter formed in Lower Proterozoic arenites of the Myalli Beds which comprises quartzite, sandstone, siltstone, conglomerate and volcanics. The circular structure corresponds to a gravity low and prominent on the K-Th-U image displaying distinctly low levels of the radioactive elements. The intersection of NNW structural trends by the superposed circular feature is consistent with features of impact structures such as *Woodleigh* and Shoemaker. The occurrence of a quiet magnetic mantle around the central dome is analogous to similar TMI-quiet circular mantles observed around some proven impact structures, including *Yarrabubba*, *Acraman*, and *Shoemaker*. However Shoemaker and Shoemaker (1996) did not find evidence of impact in the Fiery Creek structure.

Lucas/Yam Hill, Western Australia (128.7163E20.8408S) (Fig. 11) is a ~70-80 meters-diameter circular multiring knob of possible Permian-Triassic sediments, featuring a central ~20 meters crater, surrounded by a >220 meters-diameter ring consisting of Tertiary calcrete. The LANDSAT image suggests a weakly defined external ring approximately ~400-500 meters in diameter. The origin of the feature requires field examination.

B. Magnetic and gravity ring anomalies

Circular TMI anomalies offer critical evidence in the search for buried impact structure, provided discrimination can be made between anomalies induced by mafic/ultramafic igneous plugs, magnetite-bearing granitoids and impact structures. An example of a multiring mafic-ultramafic intrusion is the *Saturn* Intrusion in the western part of the *Giles Complex*, Western Australia

(Fig. 2C). Where the outer TMI and gravity rings intersect pre-existing structural trends, as in the instances of the *Woodleigh* and *Shoemaker* impact structures, a possible interpretation in terms of impact is enhanced. An example is the McLarty Hills buried TMI multi-ring anomaly, central *Canning Basin*, Western Australia (Fig. E-14). Typically exposed and buried impact structures may display TMI signatures representing re-magnetisation of deformed and recrystallized rocks and radial dykes, such as in the Sudbury offset dikes, Ontario (Ontario Geological Survey, 1997). Disruptions of flat-lying basalts detected on aeromagnetic images may in some instances express uplift and deformation by impact structures, such as in the *Foelsche* (Haines and Rawlings, 2002) and *Glikson* (Macdonald et al., 2005) impact structures detected due to the circular deformation of magnetic layers of the *Antrim Plateau Volcanics* and equivalents (Glass 2002; Haines, 2005).

Aeromagnetic data reveal a significant number of TMI ring and multiring anomalies ranging from 8 to 30 km in diameter. The *Camooweal* structure, Georgina Basin, western Queensland (Fig. 12), is expressed by a well pronounced 21 km-diameter TMI triple-ring pattern (Fig. 12a) which corresponds to gravity, radiometric K-Th-U, and Shuttle- Radar images, expressing concentric and radial drainage features (Fig. 12b). The structure underlies the Camooweal Dolomite of Lower Cambrian or uppermost Proterozoic age, consisting of dolomite with chert nodules and some arenite beds. The TMI image displays a 360 degrees triple ring pattern superposed on a SE-dipping TMI gradient whose northern and eastern sectors are superposed on and intersect WNW lineaments (Fig. 12a). The central ~10 km diameter zone constitutes a quiet magnetic zone or depression and corresponds to a broadly circular gravity high and to a well-defined ~140 degrees circular drainage ring fed by outward radiating creeks (Fig. 12b) representing an original morphological elevation of a central dome. The above features of the Camooweal TMI ring structure are consistent with those of a buried impact structure. (Grieve and Pilkington, 1996). The low radiometric values of the drainage pattern suggest the creeks are occupied with winnowed quartz-dominated alluvium depleted in K, U and Th relative to the central dome.

Other buried structures identified by their ring and multi-ring TMI features include *Killarney* (Fig. 12c), *Neale* (Fig. 13a), *Herbert* (Fig. 13b), *Lennis* (Fig. 13c), *Ilkurka* (Fig. 13d), *Oodjuongari* (Fig. 14a), *Wessell* (Fig.14b), *Calvert Hill* (Fig. 14c), *Mount Davies* (Fig. 14d),

Renehan (Fig. 15a), *McLarty Hills* (Fig. 15b), *Augathella* (Fig. 15c), *Green Swamp Well* (Fig. 15c) (K. Kaljnik, pers. comm., 2017).

Renehan (Fig. 15a), a circular aeromagnetic anomaly 10 km in diameter, displays a central magnetic high with evidence of radial folds. A topographic high overlapping a TMI high overlapping uplifted Palaeoproterozoic Tomkinson Creek Group (Dunster et al., 2014). Remotely sensed data, including satellite imagery suggest this outcrop might be atypically chaotically folded and faulted. The 1st vertical derivative magnetic image shows features suggestive of a complex impact structure, including a demagnetised outer annular zone and central magnetic high. Haines (2005) interpreted the feature as disrupting *Kalkarinji* Suite volcanic rocks in the sub-surface, which would suggest it must be younger than early Cambrian. A magnetic transect across this feature shows a near horizontal magnetic body about 400 m above magnetic volcanic rocks. The structure may be interpreted as an intrusion (sill), an impact melt sheet, or possibly a remnant of volcanic rocks displaced upwards around the outer part of a central uplift. An outcrop of silicified marine quartz sandstone at the centre of the central magnetic anomaly requires examination for possible shock metamorphic textures. The high degree of circularity of the structure and the existence of a central morphological and TMI uplift suggest a probable impact structure.

Delicate multi-ring TMI ring and multi-ring patterns are identified by close spaced (20 and 40 meters) patterns such as at *Connolly Basin, Western Australia, the McLarty Hills multi-ring* (Fig. 15b), *Augathella* ring, Queensland (Fig. 15c) and *Green Swamp Well*, NT (Fig. 15d) (Table 2).

The *Neale* TMI circular feature, northeast of the Fraser Range, Western Australia (Fig. 13a), which forms a somewhat NS-elongated (NS - 6 km-diameters; EW - 5 km-diameter) ring structure surrounded by a ~1.5 – 4 km wide subdued TMI rim. The geological map suggests the structure intersects Proterozoic granite overlain by Cambrian volcanics (Fraser Orogen, 2014). The structure coincides with a gravity low, may be suggestive of a ~10 km-diameter impact structure. The ring structure intersects a NW-trending lineament, probably a fault, and is superposed on an uneven TMI relief. The central magnetic ring of the Neale structure may represent a central uplift accentuated by up-folded basaltic sheet whereas the outer quiet zone may represent an outer ring syncline. The geology of the basement in the vicinity of the *Neale* ring structure remains subject to further interpretation. The *Neale* ring structure may represent a

potential buried impact structure. To the west of Neale is a near-360 degrees circular feature, *Plumridge*, of yet unresolved origin, possibly a granite plug. To the north is a magnetically quiet NS-elongated area of unknown nature.

The Officer Basin, Western Australia, displays several TMI multiple rings anomalies, including the ~16 km-diameter *Herbert* feature (Fig. 13b), the ~20 km-diameter *Lennis* feature (Fig. 13c), and the ~12 km-diameter *Ilkurka* feature (Fig. 13d), displaying magnetic signature characteristic of impact structures. Gravity data coverage in the area (GA national grid of 11 km) is too sparse to verify a gravity signature. The *Lennis* and *Ilkurka* features were investigated by CRA as possible kimberlitic or lamproite igneous intrusions by shallow drilling, but no intrusions were discovered. CRA interpreted the ring features as possible fracturing of Cambrian tholeiitic *Table Hill Volcanics* (Compston, 2007), with the circular magnetic anomaly being caused by tholeiitic flood basalts. However, the dimensions of these structures are larger than those of typical alkaline igneous intrusions, and drilling on the annular magnetic high anomaly of the northern structure verified highly dipping beds, consistent with deformation caused by a central uplift from an impact. The largest magnetic anomaly was drilled by five shallow drill holes by CRA and intrusions were not discovered. No samples from these drill holes have been recovered.

Herbert (Fig. 13b) is a multi-ring TMI feature including ~16, 8, and 5 km diameter magnetic rings underlying Cenozoic sediments including quartz sandstone fragments, clay, silt, colluvium and minor alluvium, overlying Cambrian to Cretaceous sediments. The Proterozoic basement is located at a depth of >4500 meters. The 360 degrees multi-ring TMI anomaly is strongly suggestive of a buried impact structure. Another example is a possible impact structure is the *Oodjuongari* Structure, Northern Territory (Fig. 14a) (Gorter et al., unpublished report), expressed on aeromagnetic data and poor quality seismic reflection profiles. From the regional geology, the age of a possible impact is considered as post Cambrian based on the interpretation of the Cambrian Tindal Limestone within the interpreted impact structure.

A weakly manifested circular TMI signature is displayed by the *Wessell* feature, Davenport Ranges, Northern Territory, a 2.5 km doughnut-shaped aeromagnetic low coincident with a topographic low or crater. The feature is pronounced in the 1st vertical Derivative magnetic data (Fig. E-8) and has been noted as a geophysical anomaly by Arafura Resources and as a possible impact structure by Macdonald and Mitchell (2004). Pre-existing structures include highly folded Proterozoic dolerites and siltstones. Similar features are displayed by the *Calvert Hills* probable

impact structure (137.466E17.354S) (Fig. 14c). The *Calvert Hills* structure, identified by Peter Haines from aeromagnetic images, aerial photos and ASTER imagery, possibly represents an exhumed impact crater partly exposed in otherwise flat-lying rocks of the McArthur Basin (Dunster et al., 2014; Macdonald and Mitchell, 2004). Aeromagnetic images show a circular magnetic low 4 km in diameter, truncating the high frequency signature of the magnetic Gold Creek Volcanics. Radial and circumferential folding is consistent with impact deformation. The structure is considered of probable impact origin and inferred as of late Palaeoproterozoic to earliest Mesoproterozoic age. A semicircular drainage pattern may indicate isostatic uplift of a ~11 km-diameter zone.

Another example is the *Sheridan Creek* circular structure noted by Haines (2005) and Dunster et al. (2014), a ring like positive aeromagnetic anomaly, 3 km in diameter, hosted by Mesoproterozoic rocks and disrupting a reversely magnetised dolerite sill. The source of the anomaly is buried beneath younger cover, representing a possible impact structure in view of its resemblance to aeromagnetic signature of known impact structures (*Foelsche, Glikson*).

The *Mulkara* feature, Eromanga Basin, South Australia, a geophysical feature defined by a weak TMI high located in flat-lying Mesozoic sedimentary rocks of the Eromanga Basin. The geophysical anomaly is in part overlapped by semi-circular topographic expression. The structural anomaly was initially identified from seismic surveys and first reported by Flynn (1989), who considered it to be a 9 km diameter simple bowl-shaped crater within a broader disturbed zone. A petroleum exploration well, *Crater-1*, was drilled about halfway between centre and rim in 1993, but did not provide definitive information on the origin of the structure (Gorter, 1998). Subsequent gravity studies indicate a gravity low at the centre of the structure leading Plescia (1999) to reinterpret the feature as a complex crater with a diameter of ~20 km and a central peak ring with diameter of 9 km. The age of the structure is interpreted as 105±3 Ma based on seismic stratigraphic evidence (Flynn, 1989). If an impact origin is correct, the impact occurred in an active sedimentary basin, which subsequently buried the crater.

A potential impact identified as the *Pemberton* feature, indicated by John Myers (pers. com., 1980) is a roughly circular magnetic quiet zone approximately 10 km-diameter located at the hinge of ENE to SSE linear TMI ridges forming a flexure of the Albany-Fraser high-grade metamorphic terrain (Fig. 16). In this area the linear TMI features are markedly disrupted and subdued, yielding the appearance of an apparent circular feature. The subdued ~10 km-diameter

sub-oval region is located between two terrains distinguished by contrasting TMI and gravity characteristics. A northern terrain and a southern terrain are distinguished on shuttle radar image and less so on radiometric images. The northern terrain consists of mostly linear though bent TMI features forming a large flexure and coinciding with a gravity high. The southern terrain appears to be dominated by fractured and less linear features (Fig. 16) which occur at high angles to the linear northern and western terrain and coincide with a gravity low. The southern terrain is dominated by granitoids whereas the northern terrain is more heterogeneous.

C. Seismic domes

Extensive seismic reflection surveys and drillings for oil and gas have delineated dome structures some of which display features consistent with internal brecciation, uplift and unconformable truncation and erosion by younger formations. A type example is the *Woodleigh* proven impact structure in the Carnarvon Basin, Western Australia (Iasky et al., 1999; Mory et al., 2000; Glikson et al. 2005a, 2005b). *Gnargoo*, a 75 km-diameter structure identified from seismic and gravity datasets in the northernmost Carnarvon Basin, Western Australia, displays close similarities to the *Woodleigh* impact structure. *Gnargoo* was interpreted by Iasky and Glikson (2004, 2005) as a possible complex impact structure with an age constrained between the Early Permian age of deformed rocks and unconformably overlying undeformed Lower Cretaceous strata.

The *Mount Ashmore* seismic dome (Glikson et al, 2010), approximately 50 - 70 km in diameter displays characteristics rendering it a probable impact structure. The structural dome, located below a major pre-Oligocene post-Late Eocene unconformity and above a ~6 km-deep-seated raised basement high, indicated by marked gravity and magnetic anomalies, displays chaotic deformation at its core and a centripetal kinematic deformation pattern. A study of drill cuttings of Lower Oligocene to Lower Jurassic sedimentary rocks reveals micro-brecciation and extreme comminution and flow-textured fluidisation of altered sedimentary material. The dome is interpreted as the core of an asteroid impact structure.

A major controversy has been raised in connection with the origin of the *Bedout* seismic dome located offshore the north-western Australia (Fig. 17) The *Bedout* structure constitutes a dome of

Permian volcanics and sediments truncated unconformably by Cretaceous sediments. The dome was proposed as a possible impact structure by Gorter (1996, 1998) due to the discordant relations between the dome and overlying sediments as revealed in a seismic transect, typical of eroded central uplift structures. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of feldspar from the breccia in Lagrange-1 well gives an age of 251.1+4 Ma, approximately coincident with the Permian – Triassic boundary. Becker et al. (2004) claimed to have identified shock metamorphosed impact breccia in samples from the drill hole, inferring a possible impact crater ~200 km large. However, further examination of *Bedout-1* core samples found no evidence of shock metamorphism and the breccia was interpreted as an altered mafic volcanic breccia (Renne et al., 2004; Glikson, 2004; Wignall et al., 2004).

G. Large geophysical multiring features

The Australian continent contains a number of large geophysical anomalies, some of which contain features consistent with impact deformation, but to date lacking in the definitive evidence for such origin. Two of these features are the Warburton twin seismic anomalies, each approximately ~200 km in diameter, where low seismic tomography velocities, deep seated magnetic cores and planar deformation features in quartz from drill cores suggest an impact origin (Glikson et al., 2013, 2015), although seismic transects are required to confirm this suggestion. Deformation features (Boehm lamellae), implying tectonic stresses, also occur in quartz from these rocks, but are distinguished from deformed planar deformation features due to the multiple cross-cutting nature and closer spacing of the latter (Glikson and Uysal, 2013). The Diamantina River ring feature, discussed above, contains TMI and seismic elements consistent with impact deformation, although the centres of a morphological ring, a TMI half ring and a seismic hinge are displaced relative to each other.

***Deniliquin-Booligal* TMI and gravity ring structure**

A large >400 km-diameter TMI (Figs 18, 19) and gravity (Fig. 20) multi-ring structure in southern New South Wales, the *Deniliquin-Booligal* structure (***D-B*** structure) (Hallett et al., 2005), studied in detail by A.N. Yeates (Yeates et al., 2000), has been interpreted in terms of a

possible impact structure. Circular magnetic lineaments define a >130 degrees multi-ring pattern with an approximate diameter of ~430 km NE-SW and ~415 km NW-SE. The concentric ring structure is truncated in the northeast and in the southeast by the Bootheragandra Fault which separates the *D-B* ring structure from the NS-trending Wagga Metamorphic Zone of the Lachlan Fold Belt. The TMI rings are well expressed in the western part of the structure and are truncated at about 15-20 degrees by a major NNW-trending ~290 km-long linear magnetic anomaly (<565 nT). It is noted that mobile belts may partly wrap around cratons and produce arcuate regional structures, as for example around the northern Gawler Craton.

The centre of the *D-B* concentric TMI structure is occupied by a ~125 km diameter-large magnetic zone showing relatively smooth TMI pattern values ranging between -46 nT and +157 nT (Figs 18, 19). . This zone is surrounded by markedly circular TMI patterns which attain an overall width of ~124 km in the northwest and ~115 km in the southwest. Cross sections through the north-western and north-eastern sectors of the circular TMI and gravity rings display fine circular ridge and trough zones. TMI values of this zone in the northwest range between -2.5 nT and 62 nT. This markedly lineated annular zone is fringed to the northwest and the southwest by an arcuate up to 70 km-wide TMI trough with values as low as -43 nT. The outer TMI troughs are fringed in the southwest and the northwest by strongly magnetic linear zones where TMI values reach ~300-560 nT.

The overall circular ridge pattern which characterizes the Deniliquin-Booligal TMI ring structure is overprinted by younger magnetic anomalies, including:

1. Probable granitic intrusions showing narrow well-defined magnetic outlines overprinted on the DB anomalies.
2. Probable younger sub-horizontal volcanic formations suggested by sharp magnetic signatures beneath the Permian-Triassic Oakland Basin.

Probable granitic intrusions are expressed as well defined annular aureoles, in particular in the south-western part of the *D-B* ring. Irregular high-amplitude strongly magnetic features superposed on the *D-B* ring may constitute sub-horizontal volcanic units. (cf. a ~110 km-long NNE-trending strongly magnetic anomaly of ~198 nT, a ~45 km-long NW-trending body and irregular NNW-trending anomalies (A.N. Yeates, pers. com.). A search for shock metamorphic textures in basement drill holes. marked in Fig. 18, encountered Bohm lamella in quartz

signifying overpressures but no shock metamorphic textures (Glikson and Yeates, unpublished results, 2015).

***Coompana* circular gravity and TMI anomaly**

The western Gawler Craton, forming the basement for the Eucla Basin, South Australia, displays a number of circular gravity and TMI anomalies, the largest of which is the *Coompana* structure, with a diameter of ~44 km defined by a gravity anomaly and ~50 km defined by a strong TMI anomaly (Fig. 21). The TMI feature represents reverse magnetism of a positive TMI anomaly (Foss et al., 2016a, b). Magnetization intensity estimates for the investigated anomalies range from 0.1 to 0.5 SI units. A small subsidiary magnetic ring is located on the southern rim of the structure. The deeper magnetization is well correlated with a negative gravity anomaly, suggesting that the material generating the main magnetic anomaly has a relatively low density. In view of the highly magnetic nature of the *Coompana* anomaly its origin from a granite body is open to question. The effects of mafic volcanics intersected in marginal bore holes at depth of 302-340 m (CD-1, KN-1) (Foss et al., 2016a) are uncertain. An interpretation in terms of an impact structure needs to be tested by a drill hole near the centre of the anomaly.

Distribution patterns of ring and dome features

Estimates of the temporal cratering flux are complicated by the difficulty in determining the age of impact structures (Jourdan et al., 2012). Based on crater size vs cumulative frequency plots for the post-LHB (Late Heavy Bombardment) (3.8 Ga) impact flux in the Earth–Moon system the cratering rate is estimated as $5.9 \pm 3.5 \times 10^{-15} \text{ km}^{-2} \text{ year}^{-1}$ for craters of diameter $D \sim 20 \text{ km}$ (Barlow, 1990; Shoemaker and Shoemaker, 1996) (Figs 22, 23). This estimate is consistent with the ~20 km-diameter crater production rate of $6.3 \pm 3.2 \times 10^{-14} \text{ km}^{-2} \text{ year}^{-1}$ for the last 120 years based on impact structures in Europe and North America (Grieve and Shoemaker, 1994), which is higher than the post-3.2-Ga lunar cratering record. Based on the above cratering size-frequency rates it was estimated that approximately 450 craters of diameter $\geq 100 \text{ km}$ were produced on Earth since ~3.8 Ga (Glikson, 2001). The preferential preservation of large impact craters, due to the preservation of deep crater root zones at mid-crustal levels, as well as the detection of large impact structures on geophysical maps, allows estimates of the minimum impact flux of large craters from direct observations.

Shoemaker and Shoemaker (1996) showed that the cumulative size-frequency distribution of six Australian Proterozoic impact structures (Figs 22, 23) is consistent with the flux of Earth-crossing asteroids and long-period comets. Plots of cumulative size frequency of 38 confirmed Australian impact structures (Table 1) for the range of diameters of 10 to 100 km fall approximately parallel to this trend (Fig. 22) while the cumulative size frequency of craters <5 km in size diminishes, which is likely due to the higher rate of erosion and removal of small craters. A similar size frequency distribution and petering out of small craters applies to the plot of 42 ring and dome structures of unconfirmed origin (Table 2). Compared with frequency distribution patterns of extra-terrestrial impact structures $N_D \sim D^{-1.8}$ (Grieve and Shoemaker, 1994), the Australian trend displays a relatively more common occurrence of large impact structures and depletion in small impact structures, a trend explained by the better preservation of large as compared to small structures.

The oldest asteroid impact ejecta deposits on the Australian continent are represented by ejecta fallout units intercalated with sedimentary units in the Pilbara Craton, Western Australia, including ejecta units dated as 3.47, 3.46, 2.63, 2.57, 2.56, and 2.48 Ga (Lowe and Byerly, 1986; Simonson et al., 1990; Glikson, 2013, 2014; Glikson et al., 2016). However, since the originating impact sites may have pre-existed at locations removed from the present position of the Australian continent, these impacts are not considered in the present paper.

Detailed field research of Australian impact structures by Eugene and Caroline Shoemaker during the 1980s and 1990s have recovered a wealth of impact observations, including the *Teague Lake* (renamed as *Shoemaker*), *Spider*, *Kelly West*, *Strangways* and *Lawn Hill*. Comprehensive documentation of the Australian impact record has been presented by Haines (2005), for the Northern Territory by Dunster et al. (2014) and for Western Australia Bevan (1996) and Boxer (2014).

Many of the 43 rings, domes and crater features of unconfirmed origin indicated in this paper (Table H-2) display structural attributes consistent with an impact origin, including high degrees of circularity of multiple ring features. The agreement between diameter vs cumulative diameter plots of these features with impact trends (Fig. 23) is consistent with this observation. The preservation of impact structures and of ring and dome features depends on the extent to which these structures are exposed, eroded, shallow-buried or deeply buried, complicating their

recognition and estimates of their original diameters. The difficulty in precise age determinations of impact events (Jourdan et al., 2012) renders estimates of impact age frequencies uncertain. Examples are the contrasts between (1) deeply buried relatively well dated Phanerozoic impact structures such as *Woodleigh*, *Talundilly*, *Tookoonooka* and *Yallalie*, and (2) deeply eroded poorly dated impact structures such as *Yarrabubba*, *Shoemaker*, *Strangways* and *Spider* (Table 1).

Table 1. 38 Confirmed and probable impact structures and craters on the Australian continent and continental shelf.

Name	Long/Lat	province	Diameter km	Age	Notes	Reference
<i>Acraman</i>	135.44E32.019S	Gawler Craton, SA	40-90	580 Ma	Confirmed impact structure	Williams,1986; Williams and Wallace, 2003
<i>Amelia Creek</i>	134.83E20.92S	Davenport Ranges, NT	~20x12	1640–600	Confirmed impact structure	Macdonald et al. 2005
<i>Boxhole Crater</i>	135.1952E 22.613S,	NT	~0.17	5.4+1.5	Confirmed impact crater	Madigan ,1937
<i>Calvert Hills</i>	137.466E;17.344S	McArthur Basin, NT	≥4	Post-Mesoproterozoic	TMI ring, confirmed impact structure	Macdonald and Mitchell 2004; Dunster et al., 2014
<i>Cleanskin</i>	137.937E18.163S	NT-Qld border	15	post 1400 Ma pre-Cretaceous	Tmi, Radiometric, morphology; Confirmed impact structure	Haines et al., 2012
<i>Connolly Basin</i>	124.758E23.537S	Gibson Desert, WA	~9	Paleocene	Confirmed impact structure	Shoemaker & Shoemaker, 1986
<i>Dalgaranga</i>	117.283E27.634S	WA	0.02	0.27 Ma	Confirmed impact crater	Nininger & Huss, 1960
<i>Darwin</i>	145.665E 42.308S	Tasmania	1.2	0.816±0.007	Confirmed impact crater	Fudali & Ford, 1979
<i>Flaxman & Crawford</i>	139.056E34.611S 139.033E34.724S	South Australia	3.5-8.5	Late Eocene to early Oligocene?	Presence of shock metamorphic features	Haines et al. 1999
<i>Foelsche</i>	136.783E16.672S	McArthur Basin	~6	Neo-Proterozoic	Confirmed impact structure	Haines & Rawlings, 2002
<i>Glikson</i>	121.56E23.982S	Savory Basin, WA	14	<508	Confirmed impact structure	Shoemaker & Shoemaker., 1997; Macdonald et al.

						2005
Gnargoo	114.026E23.626S	Carnarvon Basin, WA	~75	<300	Structure near-identical to Woodleigh including a central uplift	Iasky & Glikson, 2005
Goat Paddock	126.675E 18.336S	West Kimberley, WA	~5	Early Eocene	Confirmed impact structure	Milton & Macdonald 2005
Gosses Bluff	132.308E23.817S	Amadeus Basin, NT	12	142.4±0.8 Ma	Confirmed impact structure	Milton et al., 1972
Goyder	135.043'E 13.468'S,	McArthur Basin, NT	9-12	1325–150 Ma	Confirmed impact structure	Haines, 1996
Henbury Craters	133.148E24.572S	Amadeus Basin, NT	0.06 – 0.18	4.2±1.9 kyr	Confirmed impact craters	Alderman, 1932; Milton, 1972
Hickman	119.683E23.037S	Hamersley Basin, WA	0.36	Quaternary	Confirmed impact crater	Glikson et al., 2008
Kelly West	133.957E19.931S	NT	8-20	1640 – 550 Ma	Confirmed impact structure	Tonkin, 1973
Lake Raeside	120.964E28.792S	Yilgarn Craton, WA	~11	Tertiary	Confirmed buried impact crater	Glikson et al. 2016
Lawn Hill	138.647E18.69S	NW Qld	18	Post-Cambrian	Confirmed impact structure	Stewart & Mitchell, 1987
Liverpool	134.0476E12.396S	Northern NT	1.6	NeoProterozoic	Confirmed impact structure	Guppy et al., 1971; Shoemaker et al., 2005
Matt Wilson	131.181E15.498S	Gregory National Part, NT	5.5	NeoProterozoic	Confirmed impact structure	Sweet et al. 2005
Mount Ashmore	123.2075E12.5586S	Timor Sea	>>50	Eocene-Oligocene boundary	seismic dome, probable impact structure	Glikson et al, 2010
Mount Toondina	135.359E27.944S		3 - 4	Cretaceous to Paleogene	Confirmed impact structure	Youles, 1976
Piccaninny	128.43E17.42S	Kimberley, WA	7	<360 Ma	Confirmed impact structure	Beere 1983
Renehan	132.664E18.309S	South Lake Woods, NT	≥10	Post-Middle Cambrian	TMI ring; probable impact structure	Dunster et al., 2014
Shoemaker	120.888E25.859S	Nabberu Basin, WA	29-31	<568 Ma	Confirmed impact structure	Pirajno, 2003
Spider	126.091E16.742S	Kimberley, WA	11-13	900-600 Ma	Confirmed impact structure	Abels, 2005
Strangways	133.59E15.203S	McArthur Basin, NT	25-40	642±46 Ma	Confirmed impact structure	Zummersprekel & Bischoff, 2005.
Talundilly	144.482E24.862S	Eromanga Basin, Qld	84	125±1	Confirmed impact structure	Gorter & Glikson, 2012
Tookoonooka	142.681E27.105S	Eromanga	55	125±1	Confirmed impact	Gostin & Theriault.

		Basin, Qld			structure	1997.
Veevers	125.3727E22.9699S	Canning Basin, WA	70m	~4 kyr	Confirmed impact crater	Yeates et al., 1976
Warburton East	140.407E27.656S	Warburton Basin east	<200	~300	Probable impact structure	Glikson et al., 2013
Warburton West	138.799E26.434S	Warburton Basin west	<200	~300	Probable impact structure	Glikson et al., 2015
Wolfe Creek	127.795E19.171S	Kimberley, WA	0.88	30 kyr	Confirmed impact crater	Guppy & Matherson 1950
Woodleigh	114.840E26.803S	Camaron Basin, WA	120	359.2±2.5	Confirmed impact structure	Iasky et al., 2001
Yallalie	115.76E30.446S	Perth Basin, WA	12	Cretaceous	Confirmed impact structure	Dentith et al., 1999
Yarrabubba	118.83E27.183S	Murchison, Yilgarn Craton, WA	>30-70	Proterozoic	Confirmed impact structure	Macdonald et al., 2003

Table 2. 42 Ring, dome and crater structures of unknown origin or possible impact origin

Name	Long/Lat	province	Diameter (km)	Age	Notes	Reference
Augathella	146.60E 26.00S	Charleville, Qld	3	Devonian to Lower Cretaceous?	Buried TMI ring	K. Klajnik, pers. com. 2017
Auvergne	129.328E 15.698S	Victoria Basin, NT	≥1.1	Post-739 Ma?	Sub-rounded depression, discordant to the regional structure; unknown origin	This report
Balfour Downs feature	120.14E 22.40,S	East Pilbara, WA	~4		TMI ring anomaly Unknown origin	K. Klajnik, pers.com.
Bedout	118.94E 17.97S	Off Pilbara Coast, WA	~200	251.1±4	Seismic dome capped by unconformity	Gorter, 1996; Becker et al., 2004
Camoowial	138.204E 19.245S	Georgina Basin, Qld	≥21	Post-Cretaceous	TMI and drainage signatures; probable impact structure	Glikson, 1996; Haines, 2005
Coompana	129.7E 31.1S'	SW South Australia	44 - 50	Pre-Eocene	circular Gravity low and positive TMI anomaly	GA and SADME surveys; Foss et al., 2016a,

						b.
Cummins Range craters	127.3898 E 18.887S	Kimberley	4 craters: the largest: ~38x28m		Small craters	BMR Record 1966/218
Delamere	131.175E 15.775S	Victoria Basin, NT	4.5	4.6NSx4.4 EW	Elliptical morphological ring of Antrim Plateau volcanics/ Possible impact structure	A. Whittaker, pers. com.
Eurowie Creek	136.007E 22.45S	East NT	1	Post-Cambrian	TMI anomaly	Dunster et al., 2014
Fiery Creek	139.228E 19.222S	NW Qld	19	Post-lower Proterozoic	Morphological, TMI, gravity and K-Th-U data consistent with impact structure but no evidence for impact was detected.	Shoemaker & Shoemaker, 1996
Green Swamp Well, NT	133.20E 19.48S	NT	3		TMI ring; Small depression	K. Klajnik pers. com. 2017
Gulpulyul, NT	134.001'E 13.316S,	McArthur Basin, NT	0.5 – 0.8	1600-1500	Probable impact structure, structure and drainage features	Plumb, 2005; Dunster et al., 2014
Haines	120.7E 16.9S	Timor Sea, offshore Canning Basin	2.5	Post-Eocene	Seismic disturbance	Jones et al., 2010
Herbert	124.394E 25.056S	Officer Basin, WA	8.5 – 9.0	Post-Cambrian	TMI ring; probable buried impact crater	Haines, 2005
Ikybon River	131.02E 15.174S	Antrim Plateau volcanics, NT	3.67x2.79	Post 513 Ma	Morphological ring/crater, TMI and radiometric features. Possible impact structure	A. Whittaker, pers. com.
Ilkurka	127.426E 28.354S	Officer Basin, WA	≥12	Tertiary	TMI ring; probable impact structure	Iasky & Glikson, 2004
Killarney	131.948E 16.159S	Victoria Basin, NT	1 – 1.5		Several TMI and LANDSAT ring features.	klajnik krisztián, pers. Com.
Lennis	126.945E 27.56S	Officer Basin, WA	≥20	Tertiary	TMI ring; Probable buried impact structure	Iasky & Glikson, 2004
Lucas/Yam Hill	128.7163 E 20.8418 S	Canning Basin, WA	>0.2 – 0.5	Post-Triassic	Round hill, origin unknown	This paper

Maningrida	134.242E 11.802S	Offshore, NT	8	Post- Neoproter ozoic	TMI feature, Probable impact structure	Haines, 2005
McLarty Hills	123.46E 19.375S	Canning Basin, W.A.	~10	Post-late Ordovici an	Multiring TMI	K. Klajnik pers.com. 2017
Mercury	114.33E 19.66S	Timor Sea	30 +	Late Cretaceo us	Gravity feature	Gorter 1998; Haines, 2005
Mingobar	145.91E 21.08S	NE Qld	>15	late Middle Devonian		Gorter 1998
Monte Christo	148.116E 20.404S	NE Qld	≥8	Post- lower Cretaceo us	topographic ring	S. Johansen, pers. Com.2012
Monto (Goondicum Gabbro)	151.4194 E 24.863S	Qld	≥6.5	Early Cretaceo us	Gabbro plug	Huerner, 2013, pers.com.
Mount Davies	121.104E 25.217S	Nabberu Basin, WA	4 - 5	post 1460	TMI multiple ring. Probable impact structure	This paper
Mount Moffat	147.913E 25.082S		≥2.5 - 2.8		topographic ring	This paper
Mulkara	138.878E 27.705S	Eromang a Basin, SA	≥9	Mesozoic	Geophysical feature	Plescia, 1999
Neale	125.637E 28.946S	Fraser Range, WA	≥6	Post- Cambrian	TMI ring; probable impact structure	This paper
Oodjuongari	134.2E 16.637S	McArthur Basin	~5	Post-Early Cambrian	TMI ring; probable impact structure	Gorter et al. (unpublished)
Pemberton	116.051E 34.557S	Albany- Fraser, WA	5		Magnetic anomaly	
Puka	132.708E 24.0S	Palm Valley, Amadeu s Basin, NT	0.28	Post- Palaeozoi c	Bowl shaped crater, no impact deformation observed	Dunster et al., 2014; Hamacher and Norris, 2009
Sheridan Creek	135.101E 13.079S		≥3	Post- Mesoprot erozoic	TMI anomaly	Dunster et al., 2014
Skirmish	128.466E 26.435S	WA	≥6	Post early Neoproter ozoic	topographic ring	Haines, 2005

Spear Creek	135.83E1 7.26S	Carpentaria Basin	0.6 – 1.0	Post-Cretaceous	Topographic, K-Th-U and TMI ring	K. Mitchell, pers. Comm.
Spring Range	134.3E 21.85S	Georgina Basin, NT	0.3	Post-Cambrian	Possible impact structure	Haines, 1989; Dunster et al., 2014
Tanami East	130.714E 19.703S		~600 m	Post-Cambrian	Possible impact structure	This paper
Throssell-Roberts	123.63E2 7.08S	East Yilgarn	<140		Apparent Eastern half circle and central uplift on shuttle-radar	This paper
Tingha	151.114E 30.004S		≥21	Post late Permian	topographic ring	This paper
Youngerina	145.08E 29.522S	North NSW	≥2.8		Morphological, radiometric and TMI ring	This paper
Wessell	135.081E 20.608S	Davenport Ranges, NT	2.5	Proterozoic or Post-Proterozoic	TMI ring; possible impact structure	Dunster et al., 2014
White Cliffs	143.1450E 30.785S	W NSW	≥2		topographic half ring	This paper
Yilgalong	120.893E ;21.4817S	East Pilbara	18.2x 17.5	Quaternary	Probable impact crater	Williams, 2007

Impact crater size frequency distribution patterns on Earth and Moon (Fig. 24) suggest a high incidence of craters larger than 100 km in diameter (red frame in Fig. H-3) in the order of near- 10^2 craters larger than 100 km and near 10 craters of near-500 km in diameter. Combining the number of the ≥ 100 km impact craters discovered to date (Vredefort, Sudbury, Chicxulub, Manicouagan, Maniitsoq, Popigai, Woodleigh, Warburton) with that of ejecta layers signifying large impacts (a minimum of 13 units), more than 20 very large impacts of $D_c \geq 100$ km have been identified to date, namely approximately one fifth of those expected from the Earth-Moon system size frequency incidence.

Summary and Conclusions

Australian ring, dome and crater features include 38 confirmed asteroid impact structures and meteorite craters and 42 ring, dome and crater features of unconfirmed origin. A large number of the latter features include structural and geophysical elements consistent with those of impact

structures. Pending field investigations and/or drilling, and in some cases seismic surveys, such an origin cannot be established. Exposed ring structures include morphological crater-like forms which intersect pre-existing linear structures. Such features contain central morphological highs and unique thrust and fault patterns. Buried circular features with affinities to impact structures include single or multi-ring TMI patterns, circular TMI quiet zones, corresponding gravity patterns, low velocity and non-reflective seismic zones.

The discrimination between impact features and igneous plugs, volcanic caldera and salt domes can commonly be made on the basis of rock types. Examples of crater-form entities containing elements consistent with an impact origin and which require field investigation include Auvergne, Delamere, Fiery Creek, Monte Christo, Mount Moffatt, Tanami East, Youngerina and Tingha. Examples of igneous plugs which are unlikely to have an impact origin include the Monto gabbro and numerous circular granitoid plugs such as Windinie Hills granite and Yataga granodiorite. Examples of TMI ring and multi-ring features of possible to probable origin as buried impact structures include Augathella, Calvert Hills, Camooweal, Green Swamp well, Herbert, Ikybon River, Ilkurka, Lennis, McLarty Hills, Mount Davies, Mulkara; Neale; Sheridan Creek, Oodjuongari and Renehan.

Large circular structures such as Mount Ashmore and Gnargoo are considered to have convincing structural and deformation features to warrant preliminary classification as probable impact structures. The origin of very large circular TMI and gravity pattern of the Diamantina River drainage feature and the multiple TMI ring pattern of the Deniliquin-Booligal remains unresolved. The advent of ~40 meters TMI grid coverage promises to further uncover ring and dome features, such as the McLarty Hills multi-ring feature, potentially increasing the inventory of ring structures, including confirmed impact structures, on the Australian continent. Comparisons of diameter distribution trends of confirmed impact structures and ring and dome features of unconfirmed origin display close similarities, including prevalence of large as compared with small structures suggesting better preservation of former and loss of the latter by erosion. The delicate nature of ring anomalies identified by 20-40 meter TMI grids, listed above, suggests many more such features may be identified, while evidence for impact origin would require drilling.

Acknowledgements

The research on which this paper is based was supported by Geoscience Australia. I am grateful to Richard Blewett, Chris Pigram and Alan Whittaker for their support of this research. I am grateful to Alastair Stewart, Clive Foss, Arthur Hickman, Peter Haines, Franco Pirajno and Tony Yeates for helpful comments and suggestions, to Russell Korsch, Peter Milligan, Tony Meixner and Michael Doublie for discussions, and Krisztian Klajnik for drawing attention to TMI ring features including Killarney, McLarty Hills, Augathella and Green Swamp Well.

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FIGURES

1. Distribution of confirmed impact structures and ring and dome features of undetermined origin, igneous origin and possible to probable impact origin on the Australian continent and continental shelf. Red circles – confirmed impact structures; green circles – confirmed impact craters; orange circles – circular features of undetermined, igneous and possible to probable impact origin. Credit: Google Earth with additions based on Tables H-1 and H-2.
2. Plutonic ring and dome structures: **A.** Total magnetic intensity image of *Windinie Hills* circular granite, Yalgoo Goldfield, Murchison Province, Western Australia; **B.** Geological map of the *Yataga* Granodiorite, northern Queensland; **C.** TMI image of the Saturn mafic-ultramafic magnetite-bearing multi-ring intrusion, Giles Complex, Blackstone region, Western Australia (Maier et al., 2014; GSWA with permission); **D.** Google Earth image of the Monto, Goondicum gabbro plug, NE Queensland. Credit: GA (CC²), NASA
3. Google Earth image of the *Diamantina* River circular ring, western Queensland.
4. **A.** Google Earth image of the *White Cliffs* semi-circular morphological feature, western New South Wales (143.145E30.785S); **Fig. B.** The *Youngerina* circular drainage feature, northern New South Wales (145.08E29.522S); **C.** Skirmish feature, Western Australia; **D.** Throssell-Roberts half circular feature. The thin discontinuous white circle demarcates the approximate limits of the apparent feature. Credit: NASA, GA (CC)
5. Google Earth image of the *Tanami East* probable impact structure. Note the triple rings of the central dome and the faint outlines of an outer rim. Credit: NASA
6. Google Earth image of *Auvergne* sub-rounded depression, Northern Territory. Credit: NASA

² GA-CC – Geoscience Australia Creative Commons

7. *Tingha* ring feature: (A) superposed TMI and shuttle radar; (B) superposed Landsat-YM and shuttle radar; (C) combined K-Th-U radiometric image and shuttle radar, Credit: GA-CC
8. *Monte Christo* ring feature: (A): Google Earth image; (B) Combined topographic and TMI radiometric image. Credit: NASA, GA-CC
9. *Mount Moffatt* ring feature: (A) Combined LANDSAT and shuttle radar image; (B) superposed geological map and shuttle radar image. Credit: NASA, GA-CC
10. *Fiery Creek* structure, Queensland: (A) Landsat-TM; (B) K-Th-U radiometric image; (C) Total Magnetic Intensity. Credit: NASA, GA-CC
11. *Lucas/Yam Hill*, Western Australia. Note the apparent multiple rings. Credit: NASA
12. **A.** TMI image of the Camooweal buried structure; **B.** Shuttle Radar image of the Camooweal area. **C.** TMI image of the Killarney feature, Northern Territory; **D.** Google Earth image of the Killarney feature, Northern Territory.
13. **A.** Neale TMI multi-ring structure; **B.:** Herbert TMI multi-ring structure; **C.** Lennis triple ring TMI structure; **D:** Ilkurka double ring structure
14. **A-**Oodjuongari TMI feature; **B-**Wessell TMI feature; **C.** Calvert Hills feature; **D.** Mount Davies combined TMI and shuttle radar image.
15. **A.** The Renehan probable impact structure, displaying a TMI ring pattern including a partly exposed central dome; **B.** McLarty Hills TMI multi-ring feature; **C.** Augathella TMI multi-ring feature; **D.** Green Swamp Well TMI feature
16. The Pemberton TMI feature, Albany-Fraser belt, Western Australia.
17. A NW-SE seismic section through the Bedout dome, offshore Pilbara coast, Western Australia.
18. TMI features of the Deniliquin-Booligal ring structure, southern New South Wales and northern Victoria, showing locations of drill holes from which basement cores were derived.

19. A northwest-southeast TMI section through the Deniliquin-Booligal ring structure, New South Wales.
20. Deniliquin-Booligal structure - Bouguer gravity anomalies.
21. The Coompana gravity and TMI circular anomaly, southwest South Australia.
22. log cumulative size distribution vs log diameter of confirmed and probable impact structures on the Australian continent. Red open circles – Australian impact structures; discontinuous line – regression; triangles – six Proterozoic impacts (Shoemaker and Shoemaker, 1996). $N_D \sim D^{-1.8}$. The cumulative size distribution of terrestrial impact structures according to Grieve and Shoemaker (1994) for structures larger than 20 km in diameter.
23. log cumulative size distribution vs log diameter of Australian ring, dome and crater features of unknown origin. Red open circles – ring, dome and craters; discontinuous line – regression; triangles – six Proterozoic impacts (Shoemaker and Shoemaker, 1996). $N_D \sim D^{-1.8}$: The cumulative size distribution of terrestrial impact structures according to Grieve and Shoemaker (1994) for structures larger than 20 km in diameter.
24. Crater size vs. cumulative frequency plots for post-LHB times in Earth–Moon system. MpLHB—post-lunar maria craters and post-Martian plains craters (after Barlow, 1990). NEA—crater distribution extrapolated from observed Near-Earth Asteroids ($D_c=20 D_p$). PHAN—Phanerozoic impact rates after Grieve and Dence (1979), showing loss of smaller craters. EpLHB—average Earth cratering rate based on Table 1 and extrapolated to the entire Earth surface on basis of number of 520 km-diameter craters and cumulative crater vs size-frequency relationships parallel to those of MpLHB; CONT—mean cratering rate on time-integrated continental crust (~20% of Earth's surface). OCEAN—mean cratering rate on time-integrated ocean crust (~80% of Earth's surface). E-LHB—Late heavy bombardment of Earth, extrapolated from lunar data of Barlow (1990).

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1

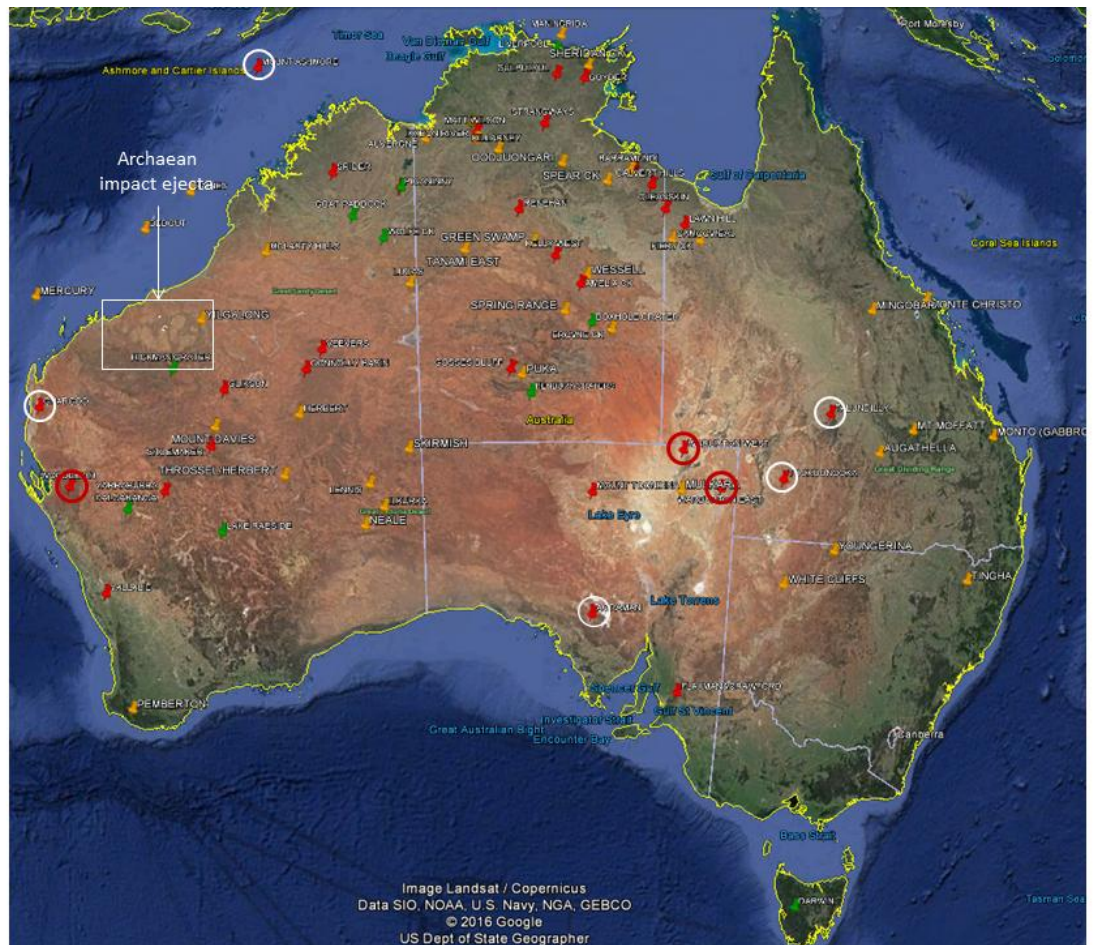


Figure 1

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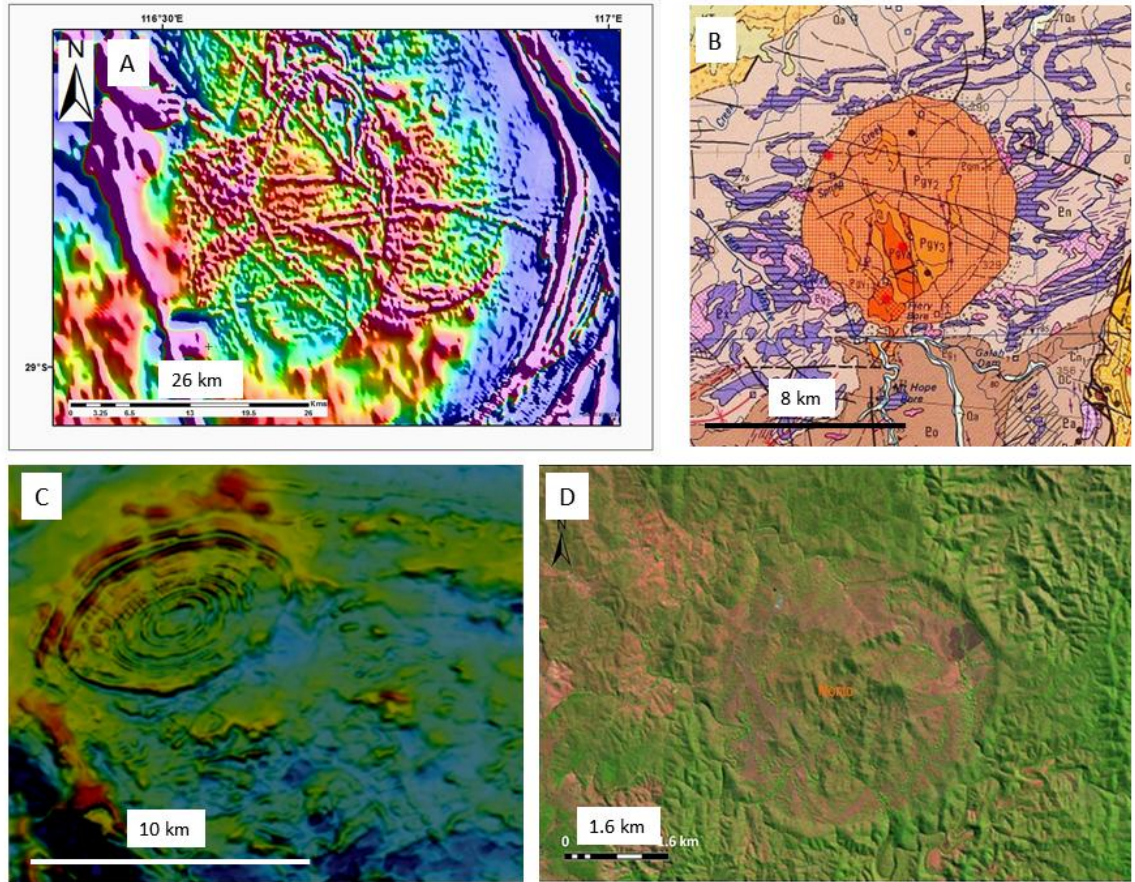


Figure 2

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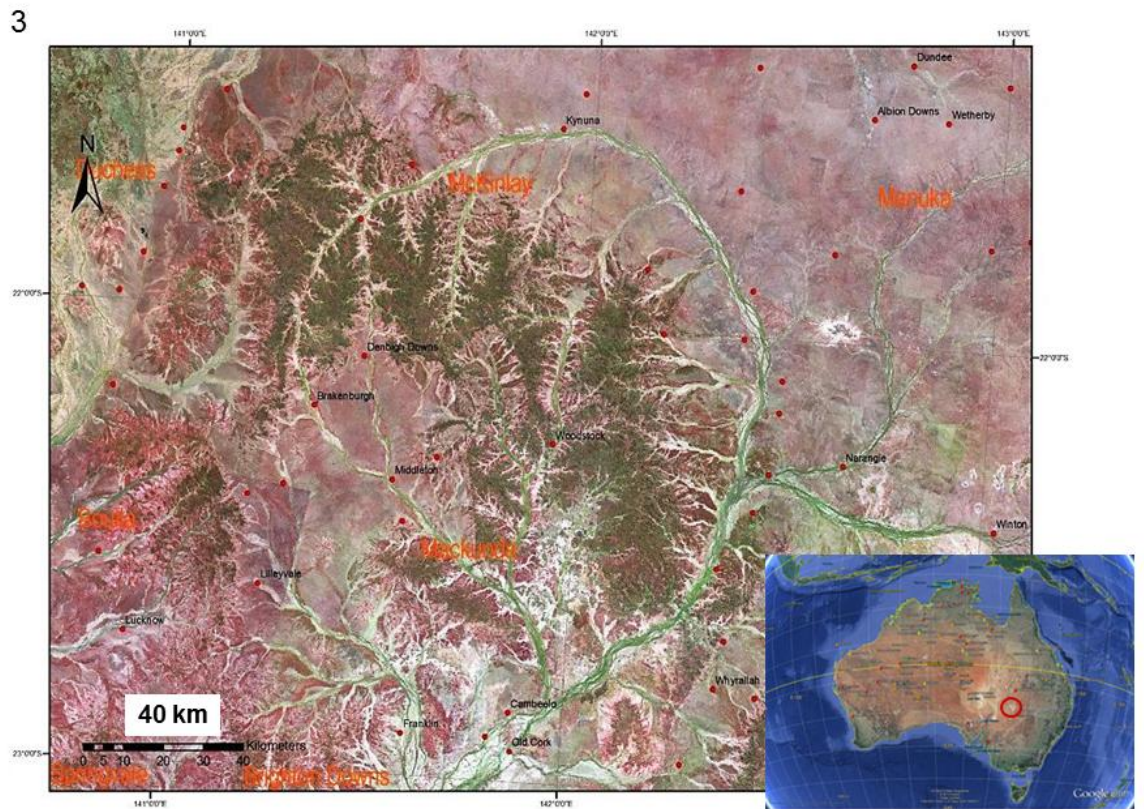


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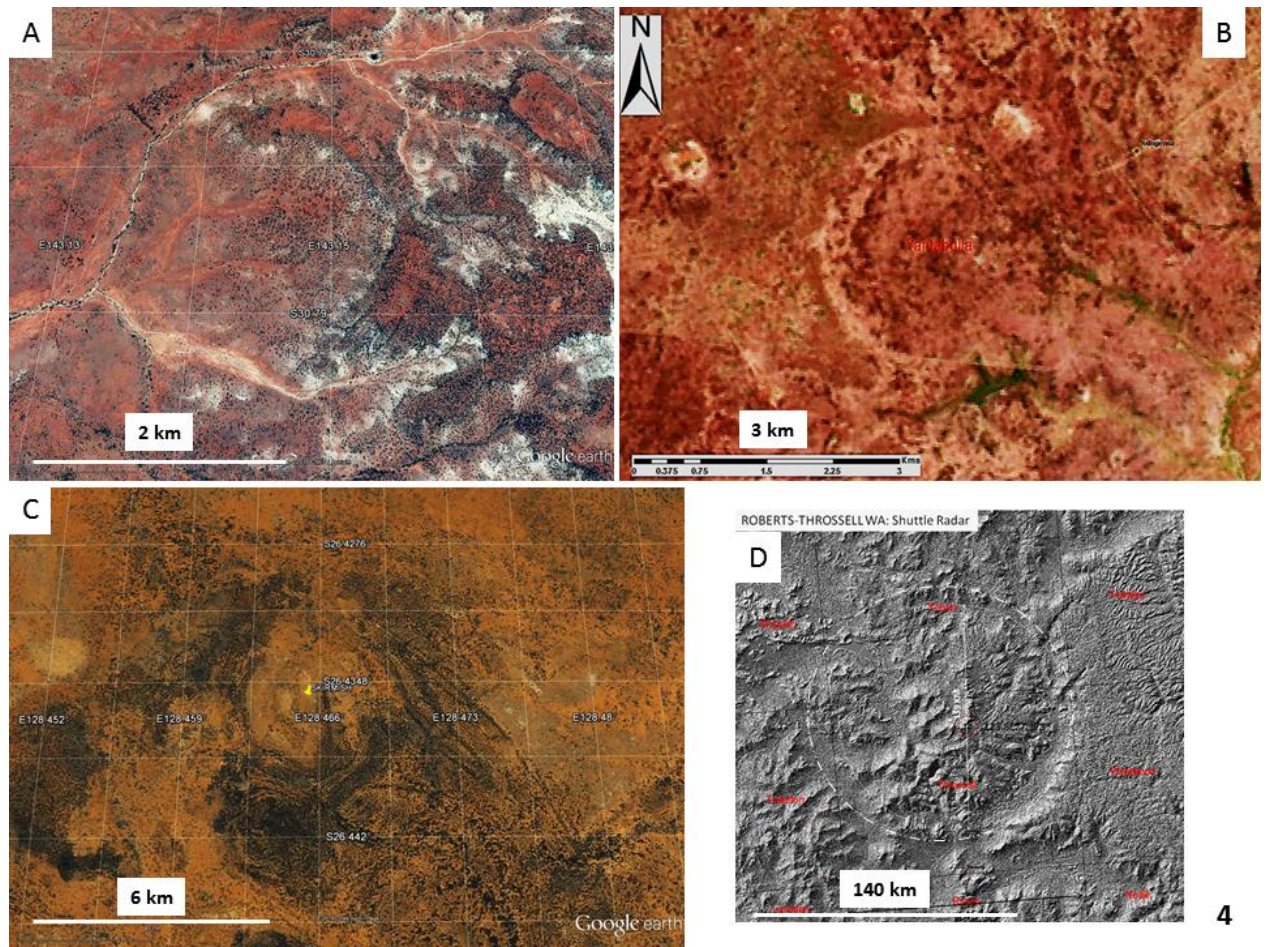


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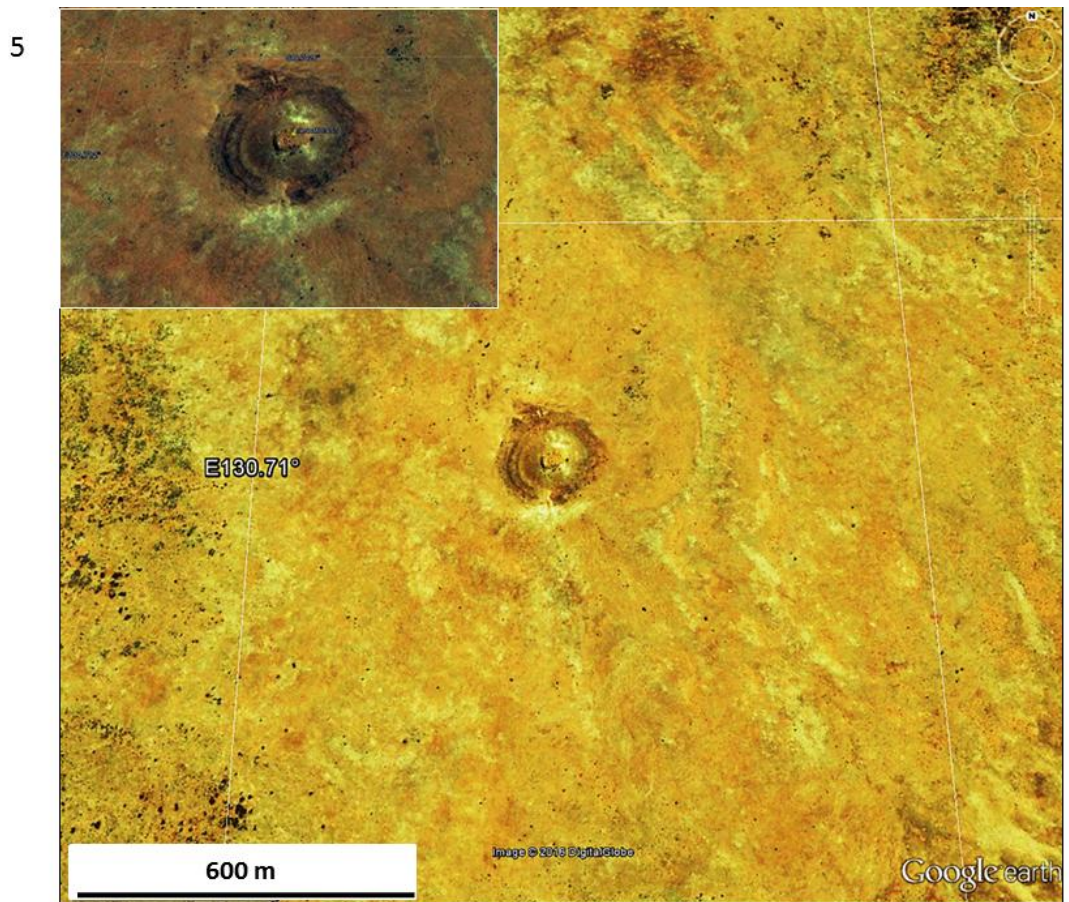


Figure 5

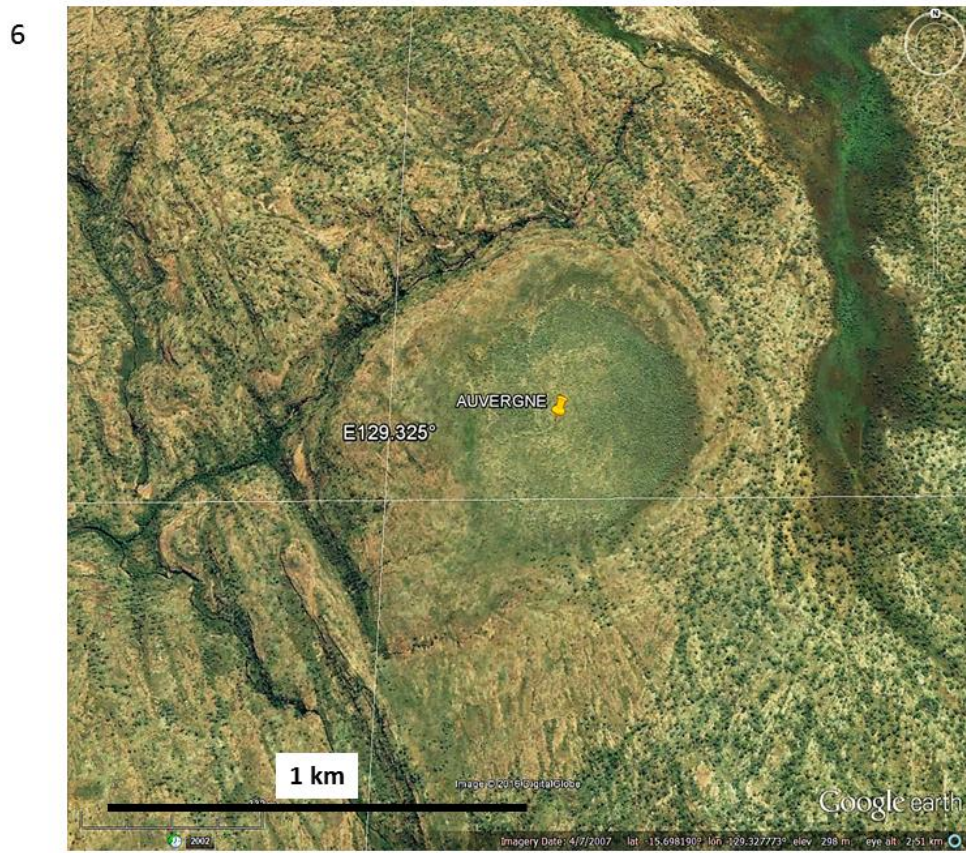


Figure 6

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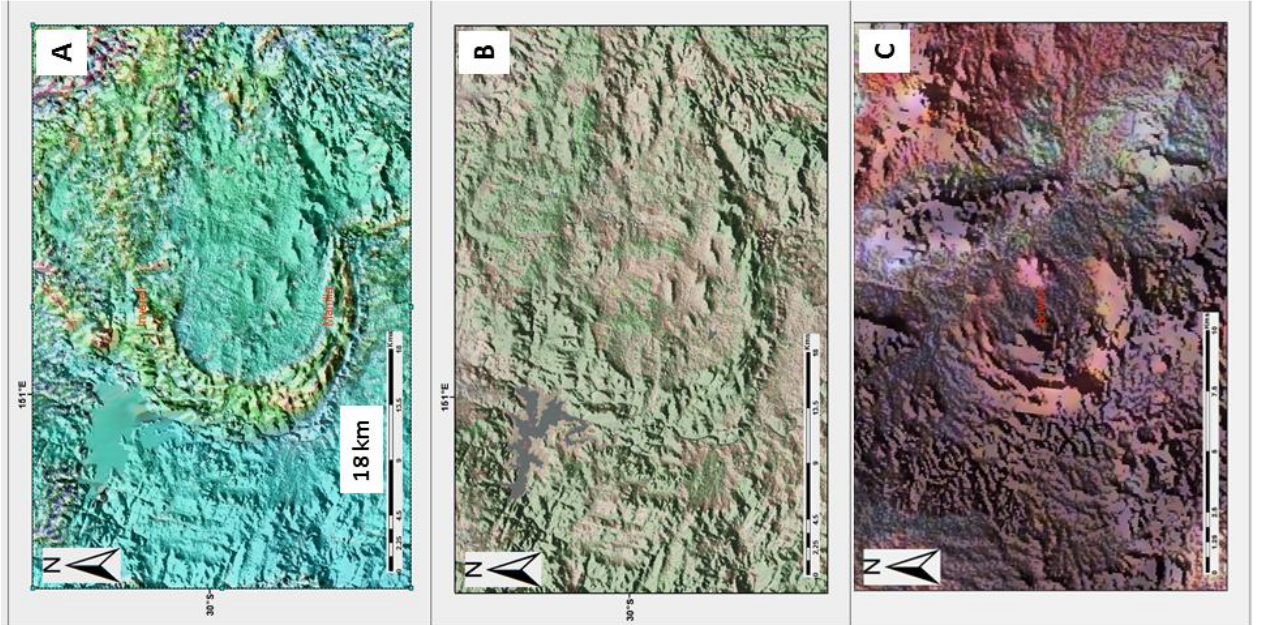


Figure 7

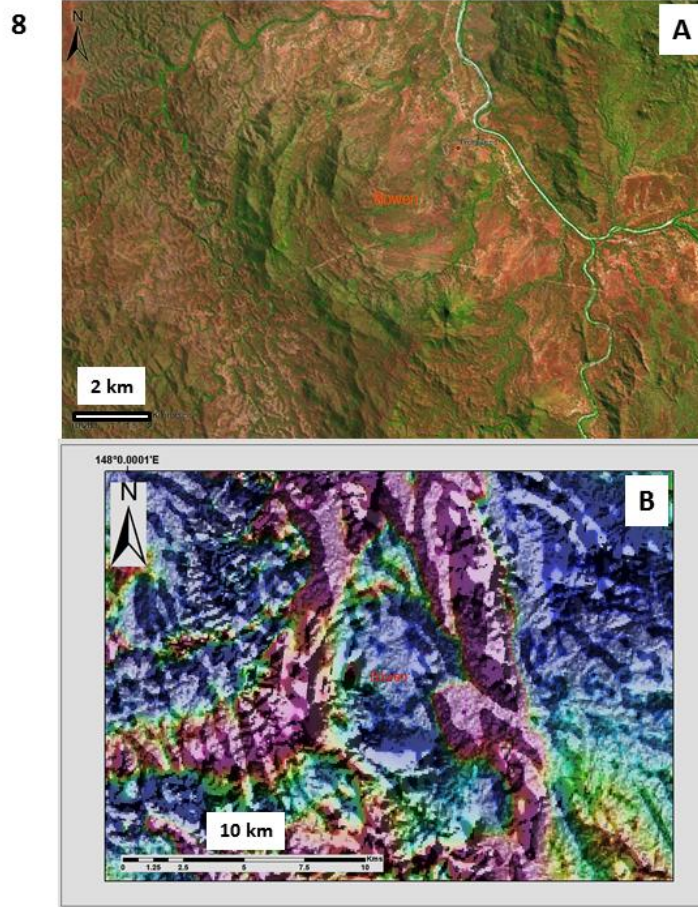


Figure 8

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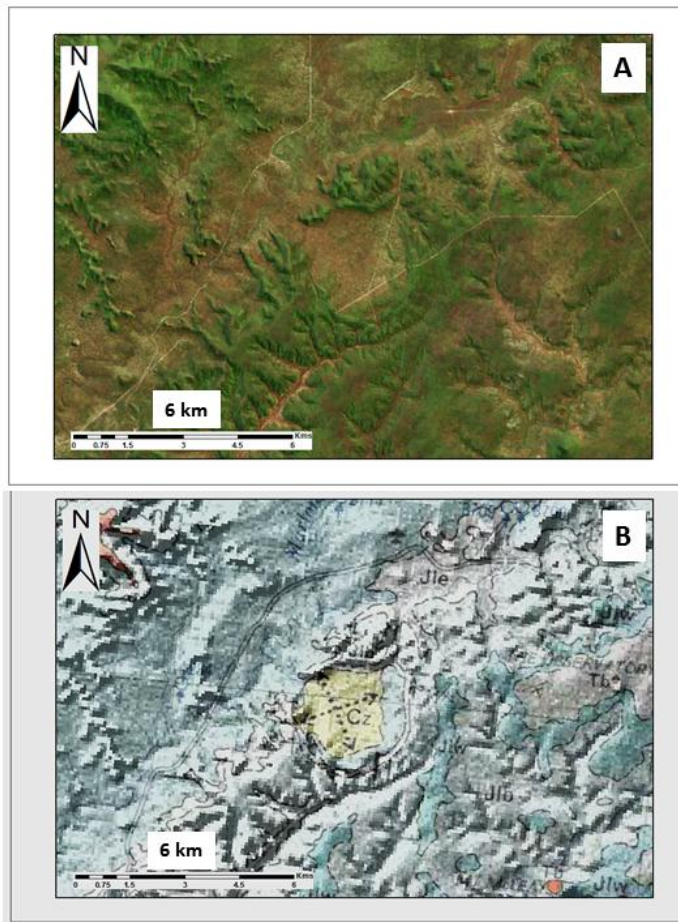


Figure 9

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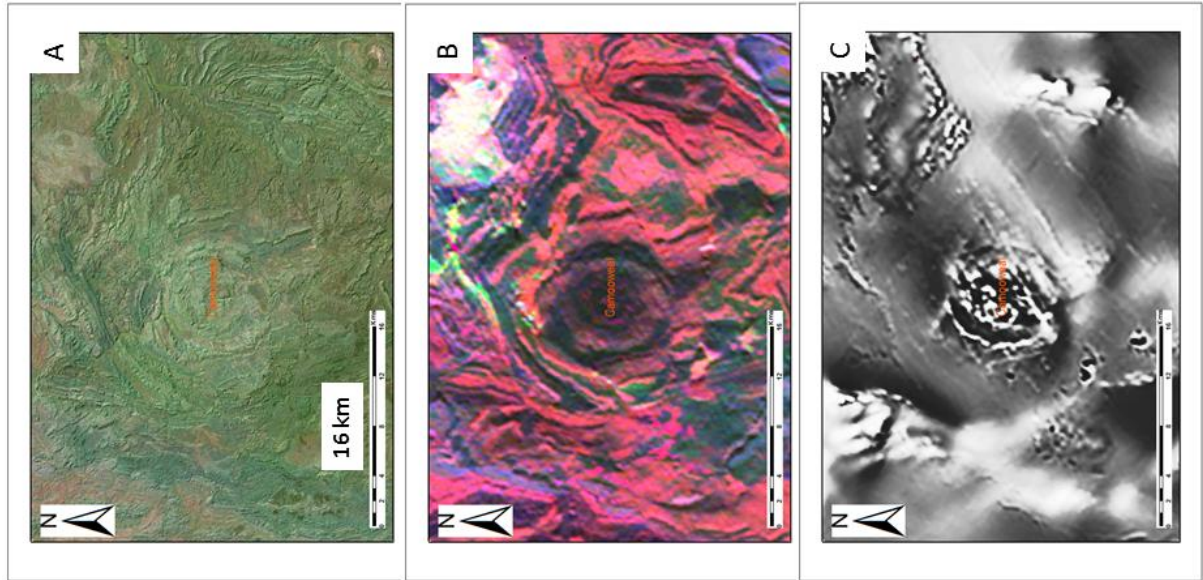


Figure 10

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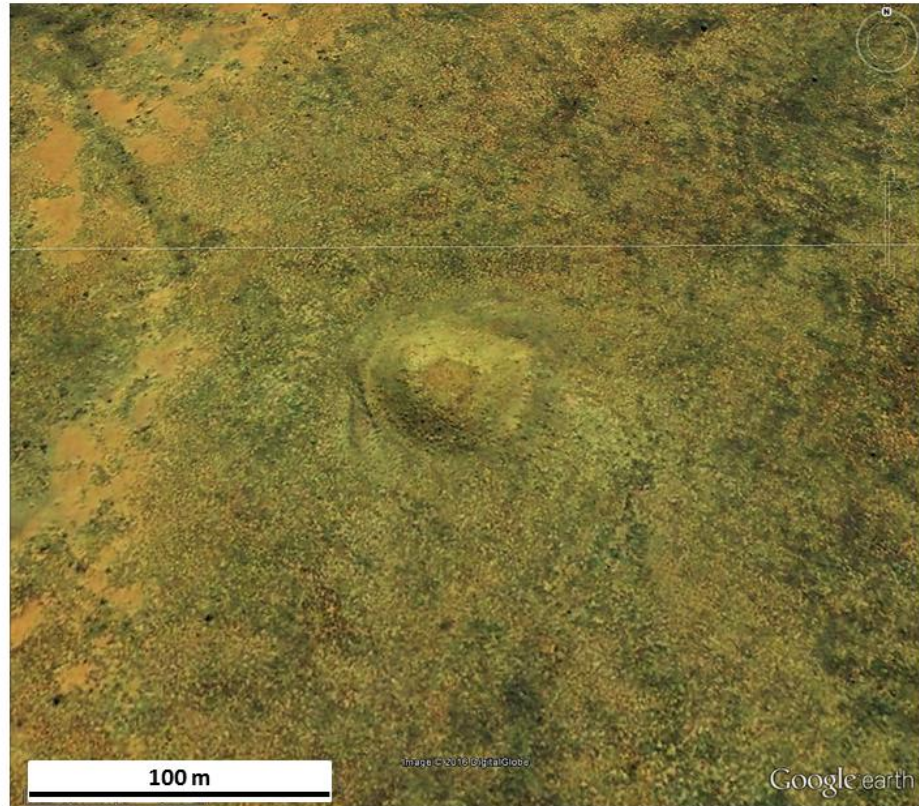


Figure 11

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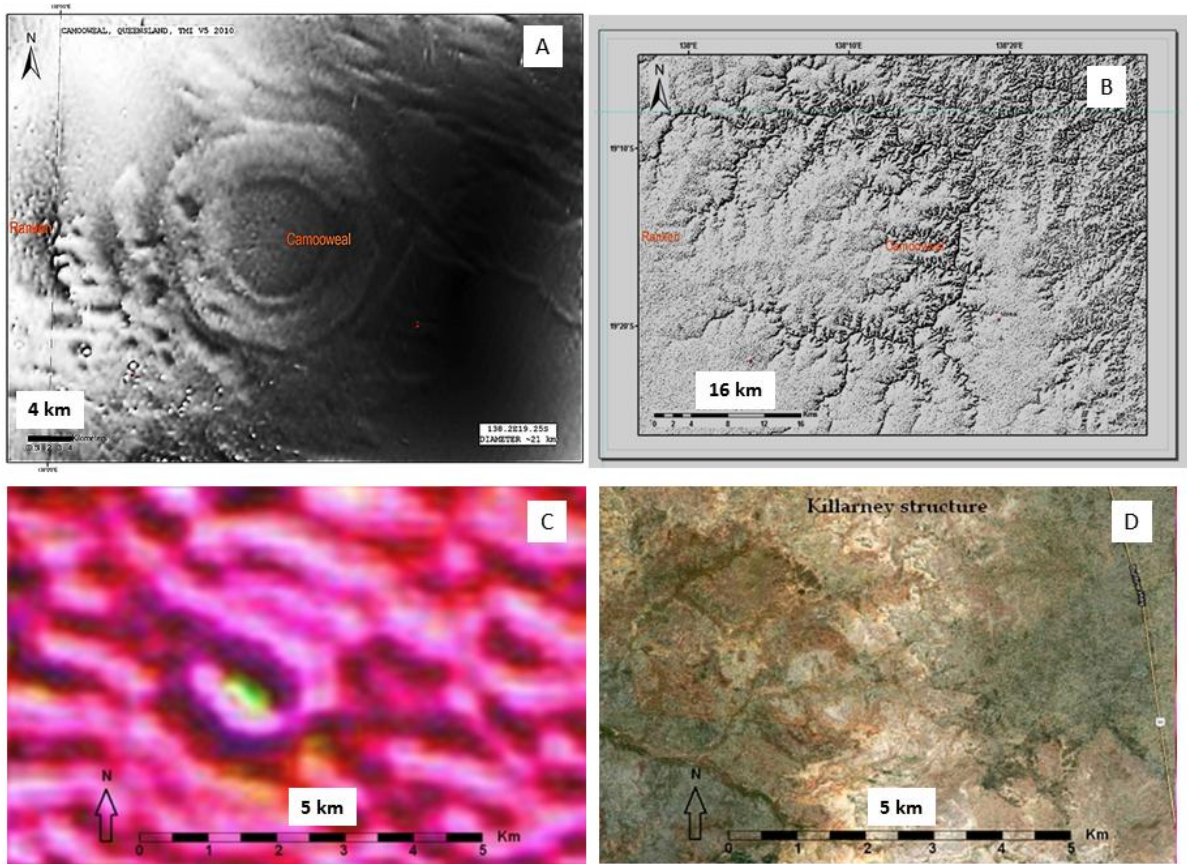


Fig. E-1 – E-4

Figure 12

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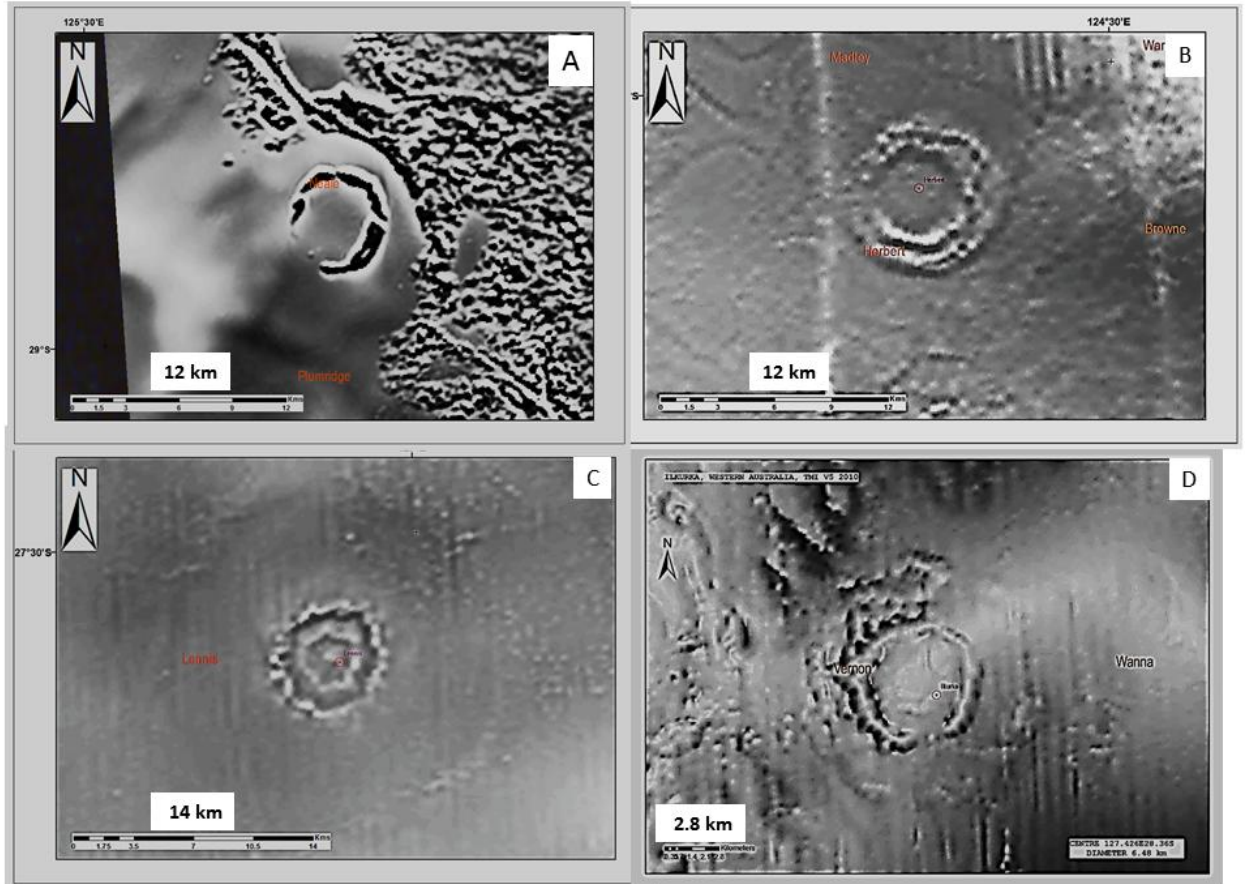


Figure 13

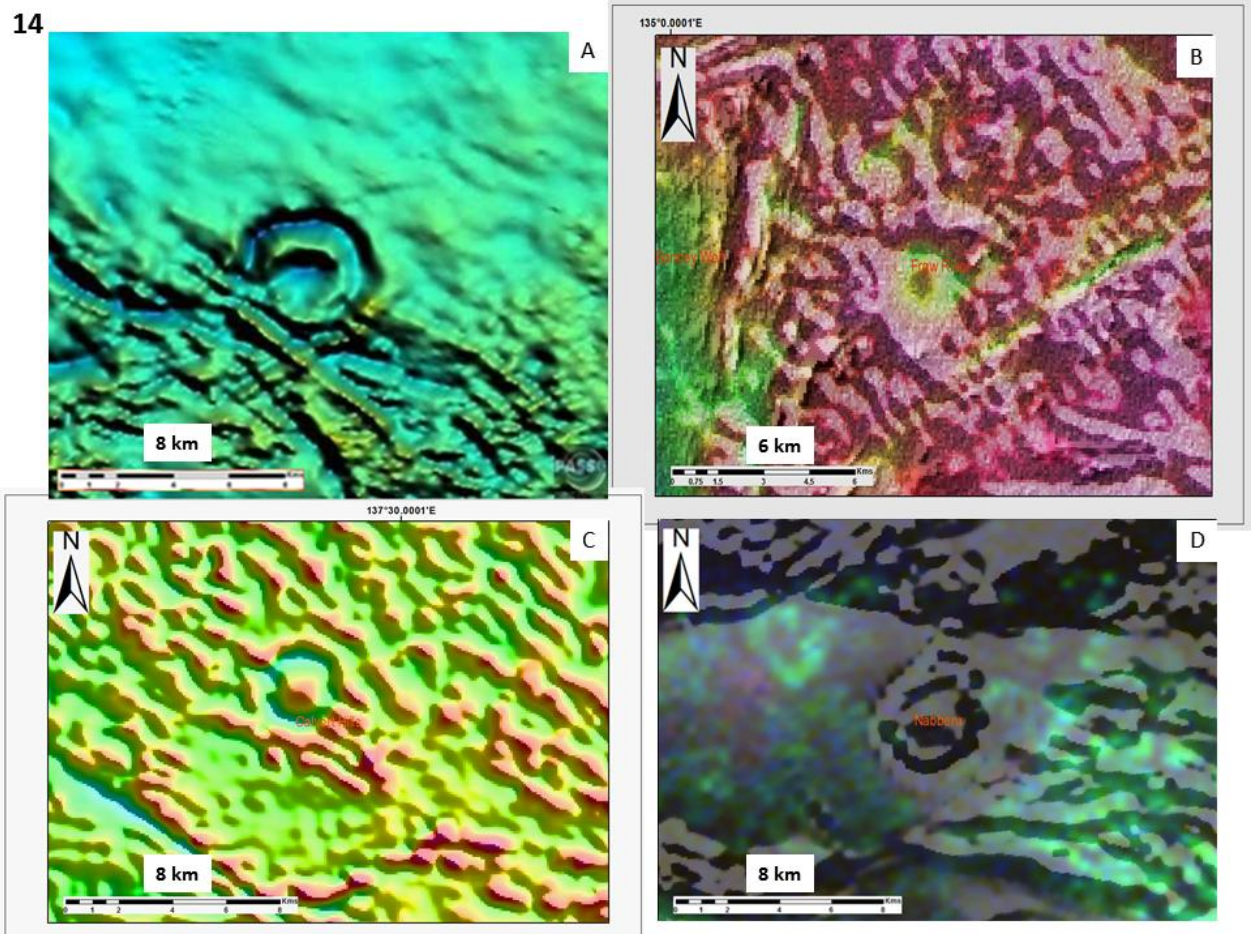


Figure 14

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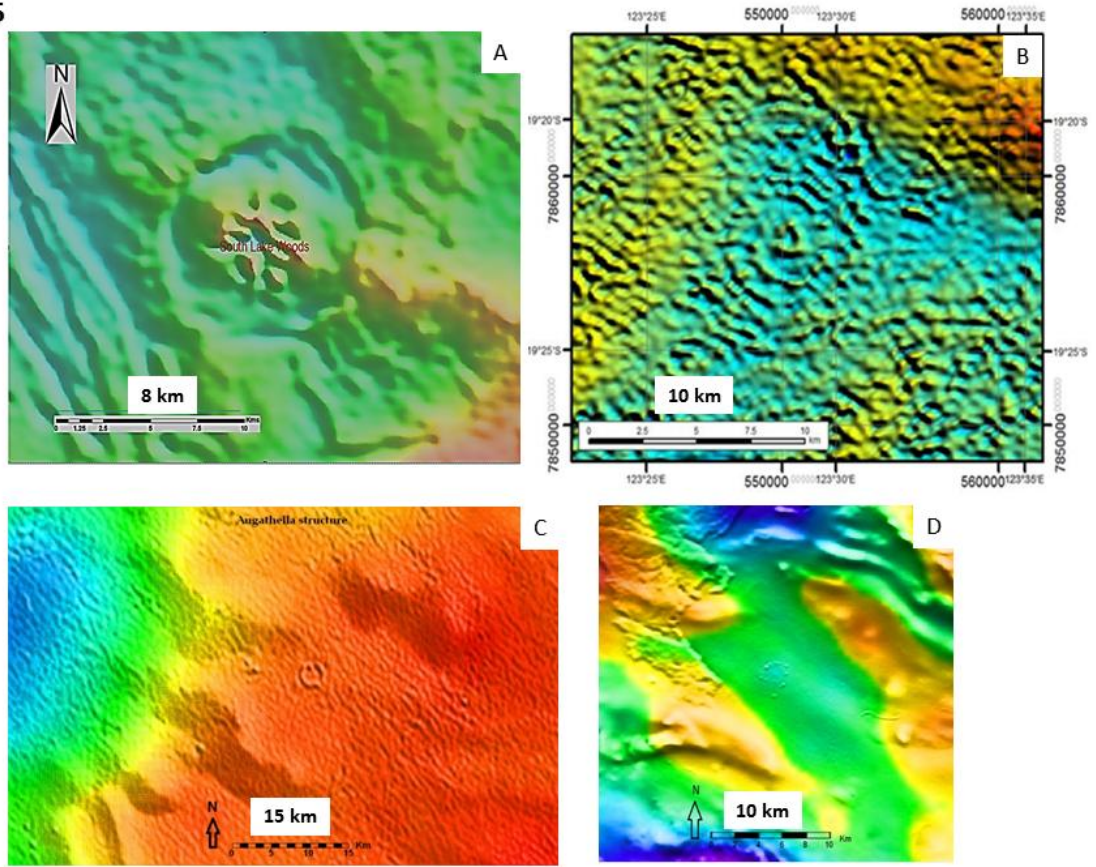


Figure 15

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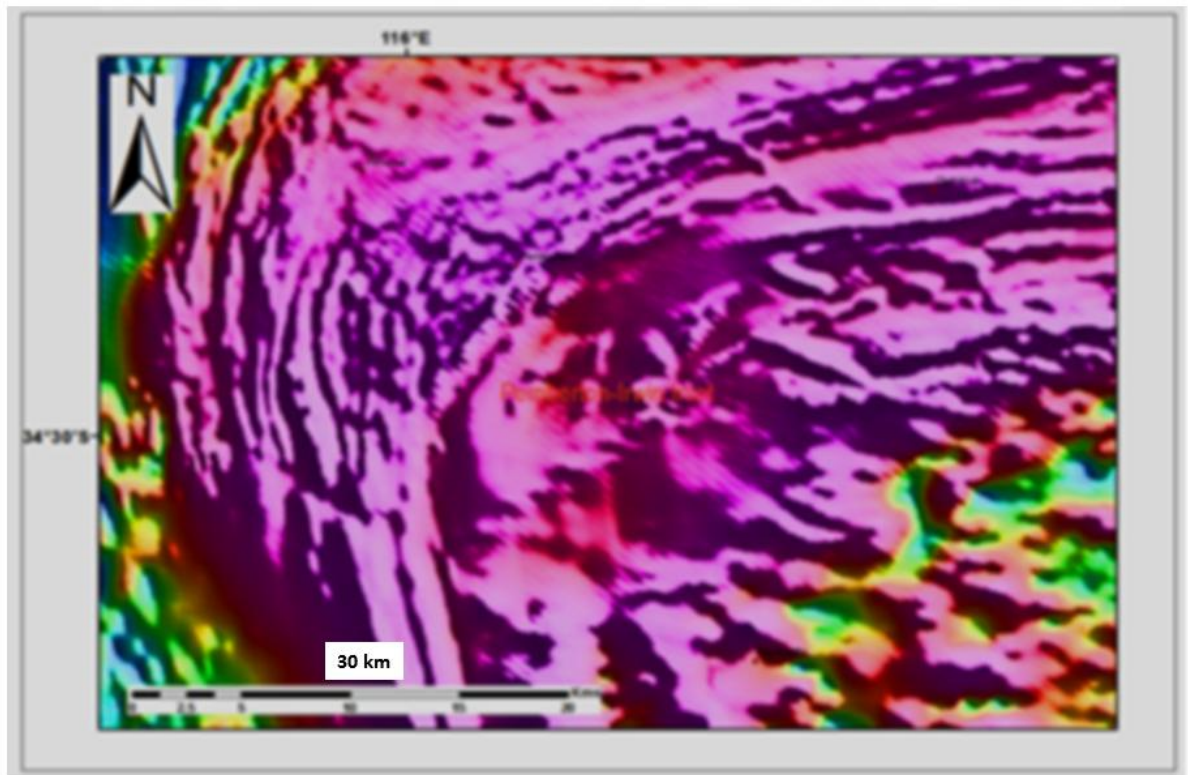


Figure 16

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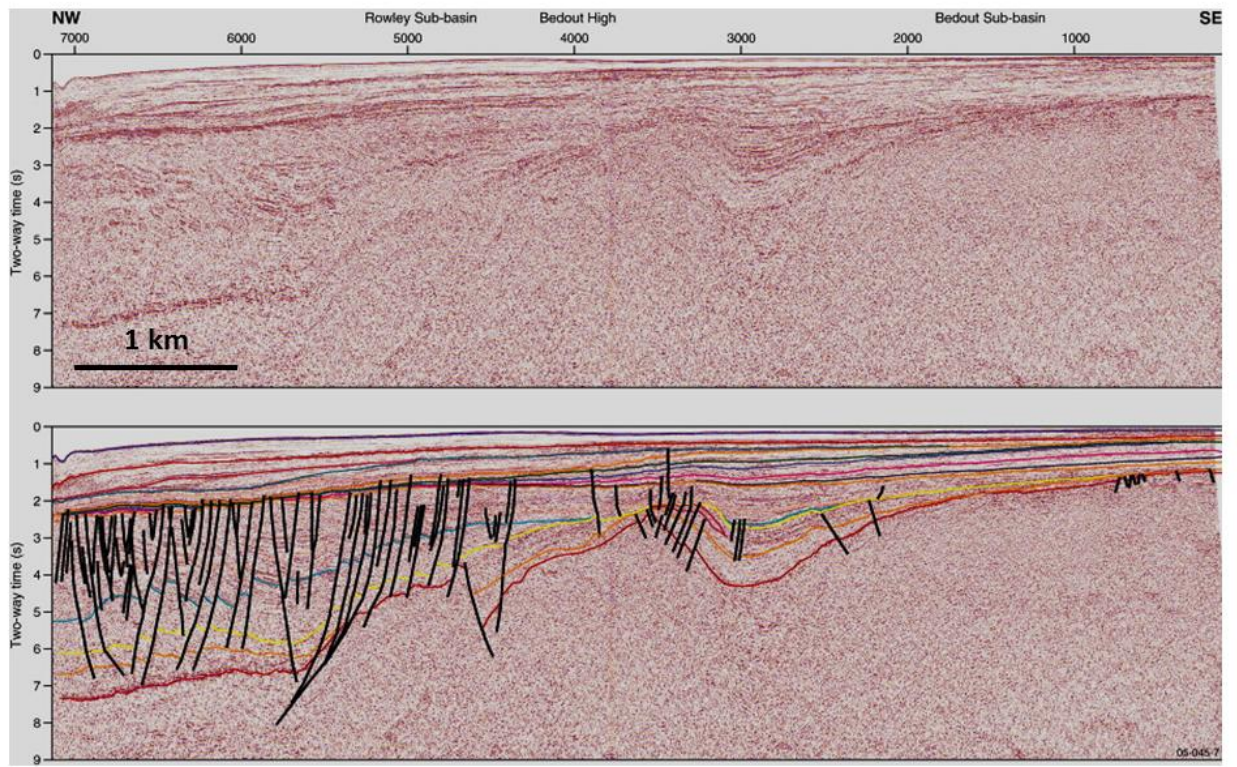


Figure 17

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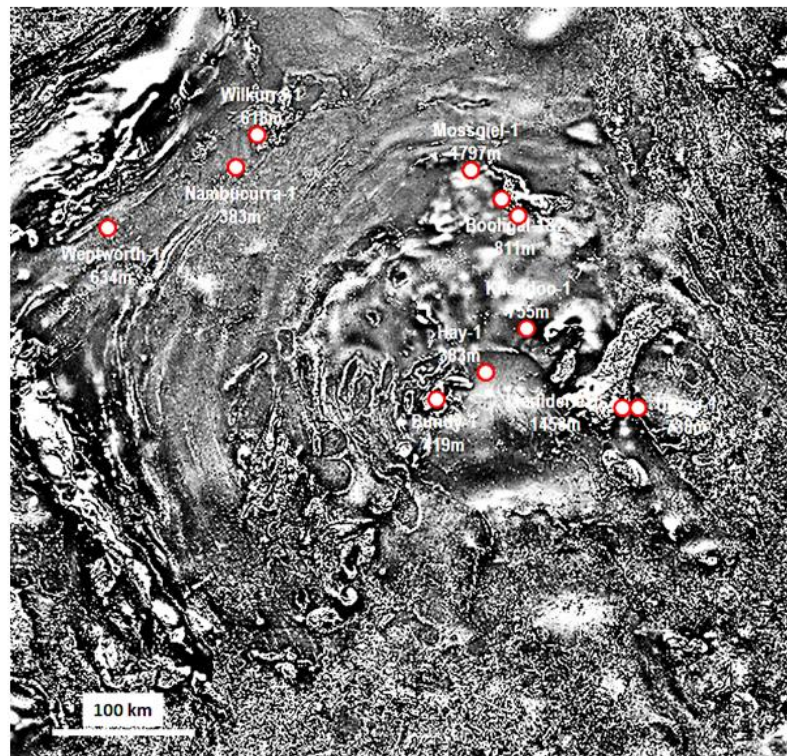


Figure 18

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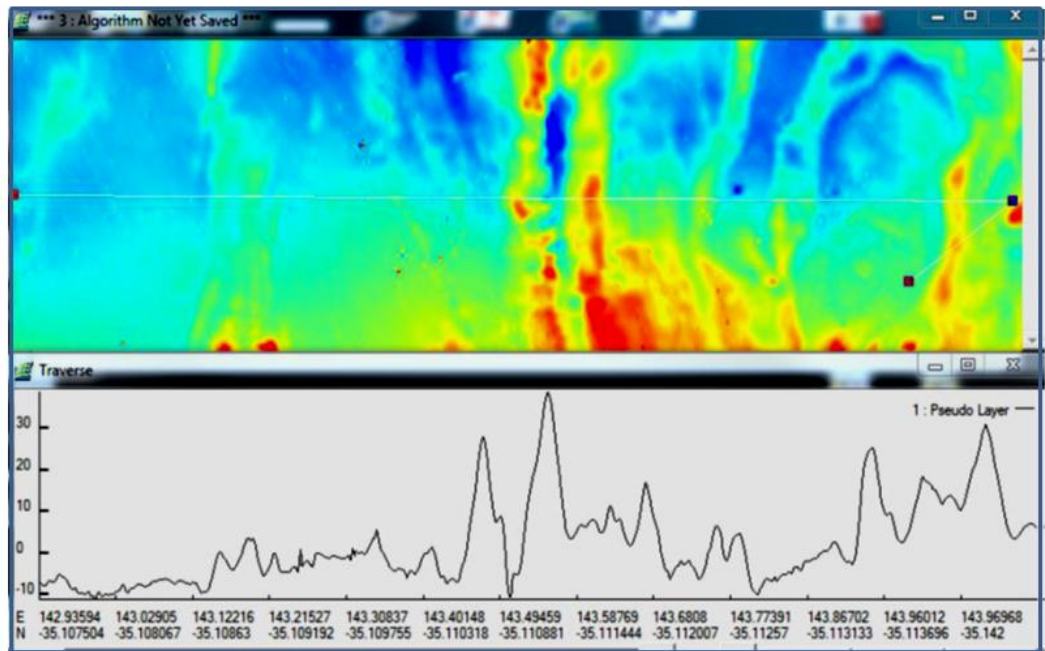


Figure 19

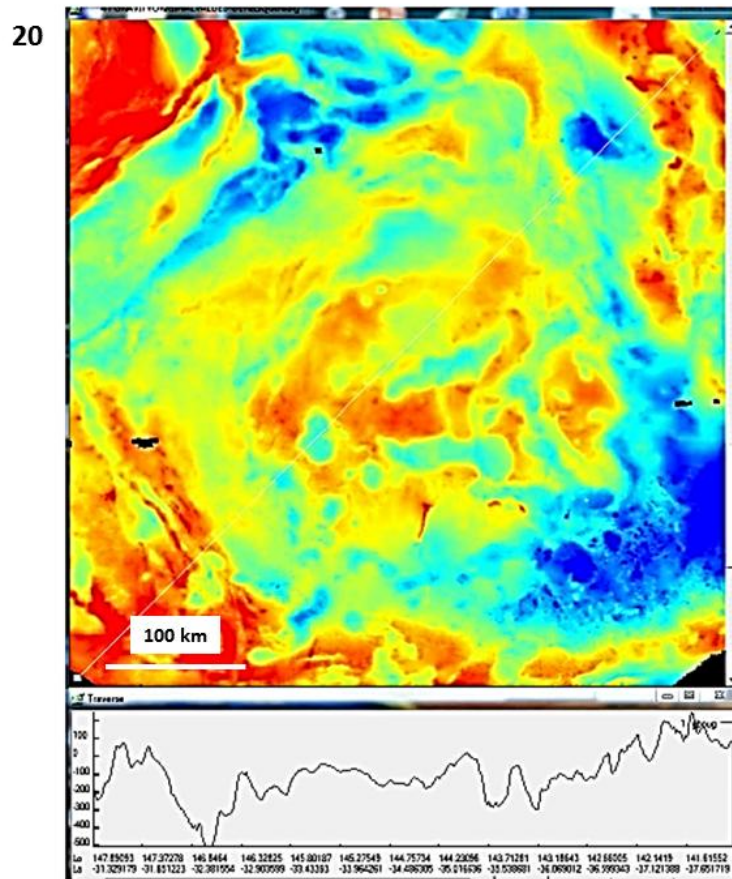


Figure 20

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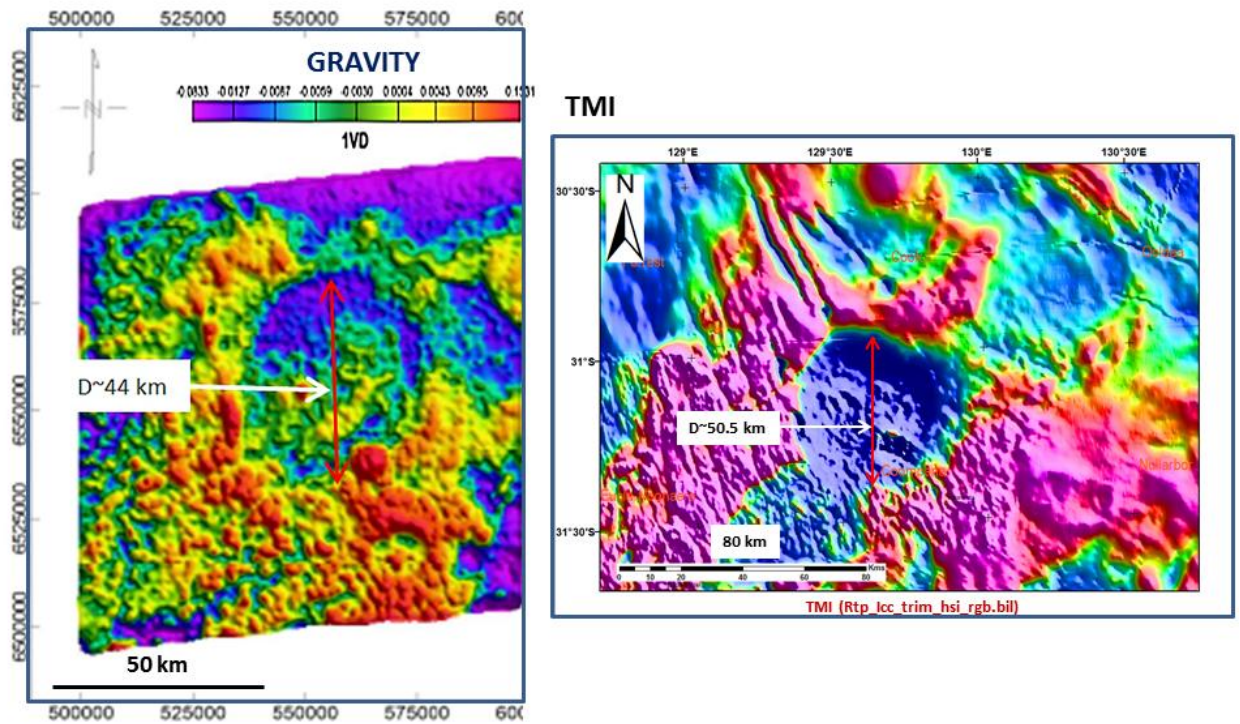


Figure 21

22

Confirmed impact structures

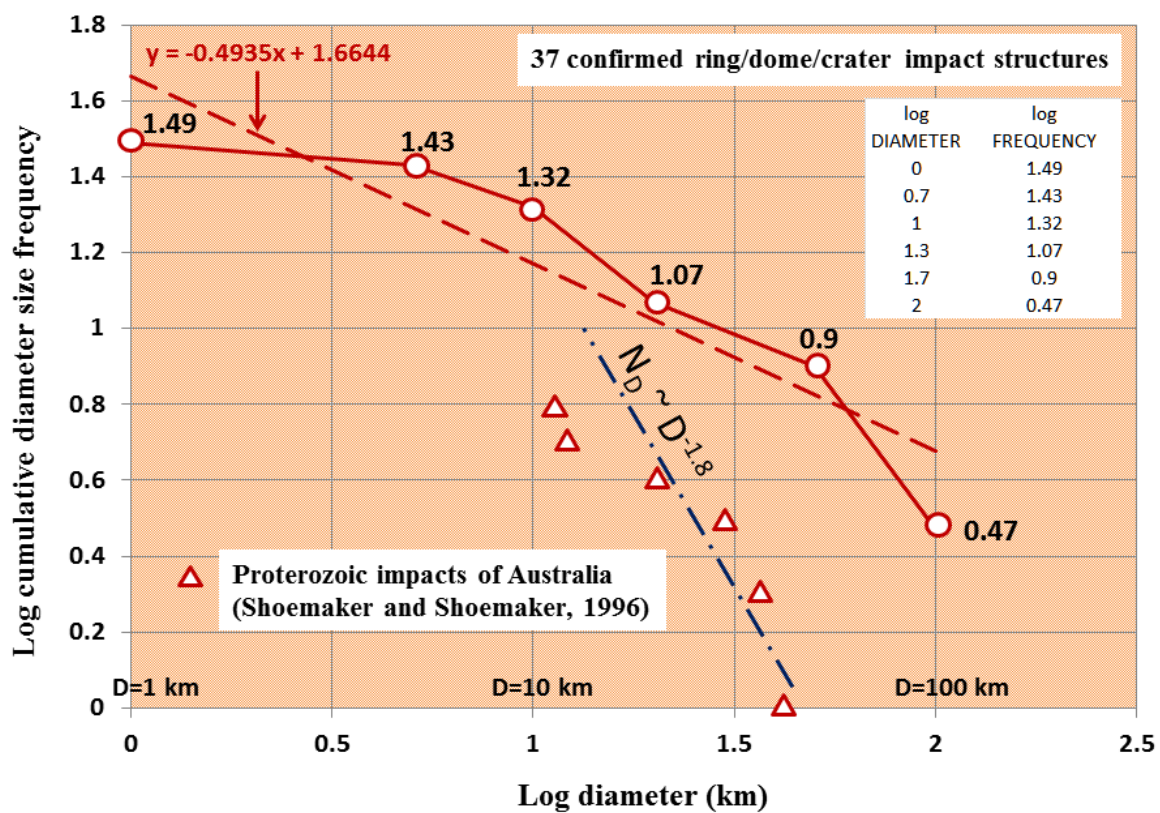


Figure 22

23

Ring and dome structures of unconfirmed origin

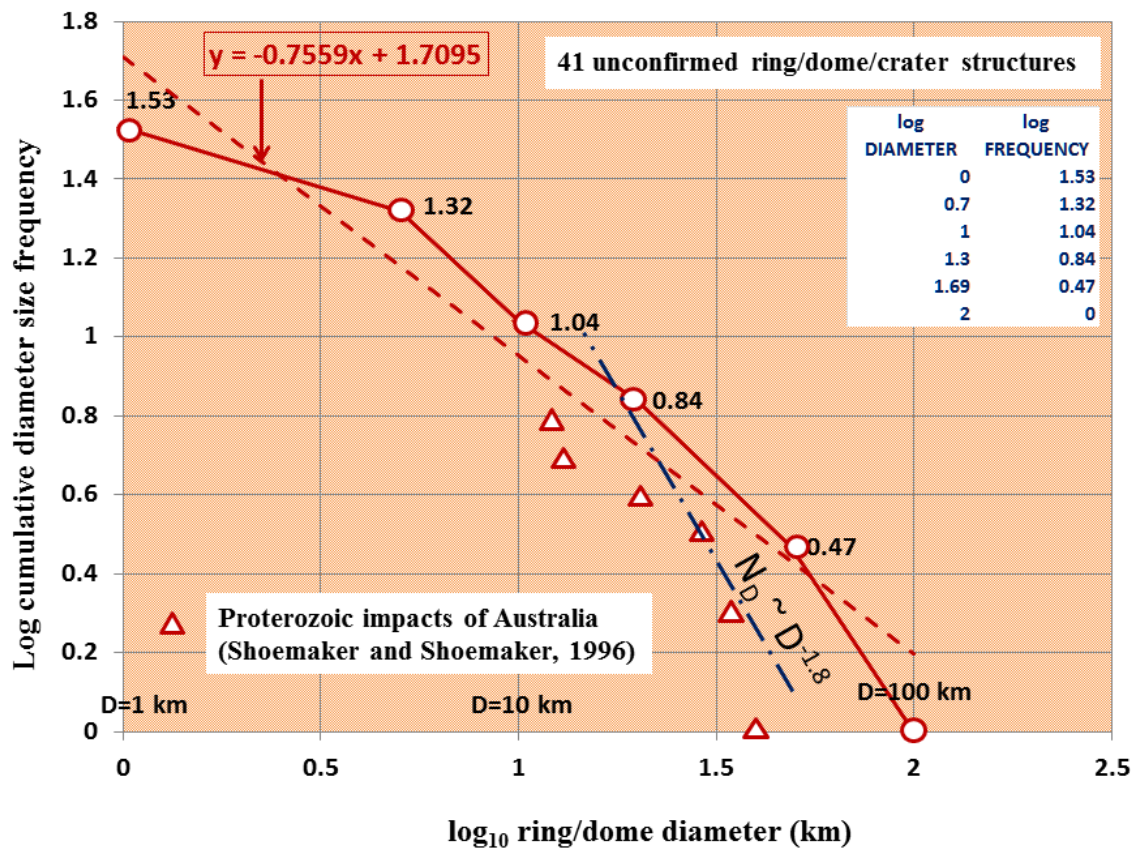


Figure 23

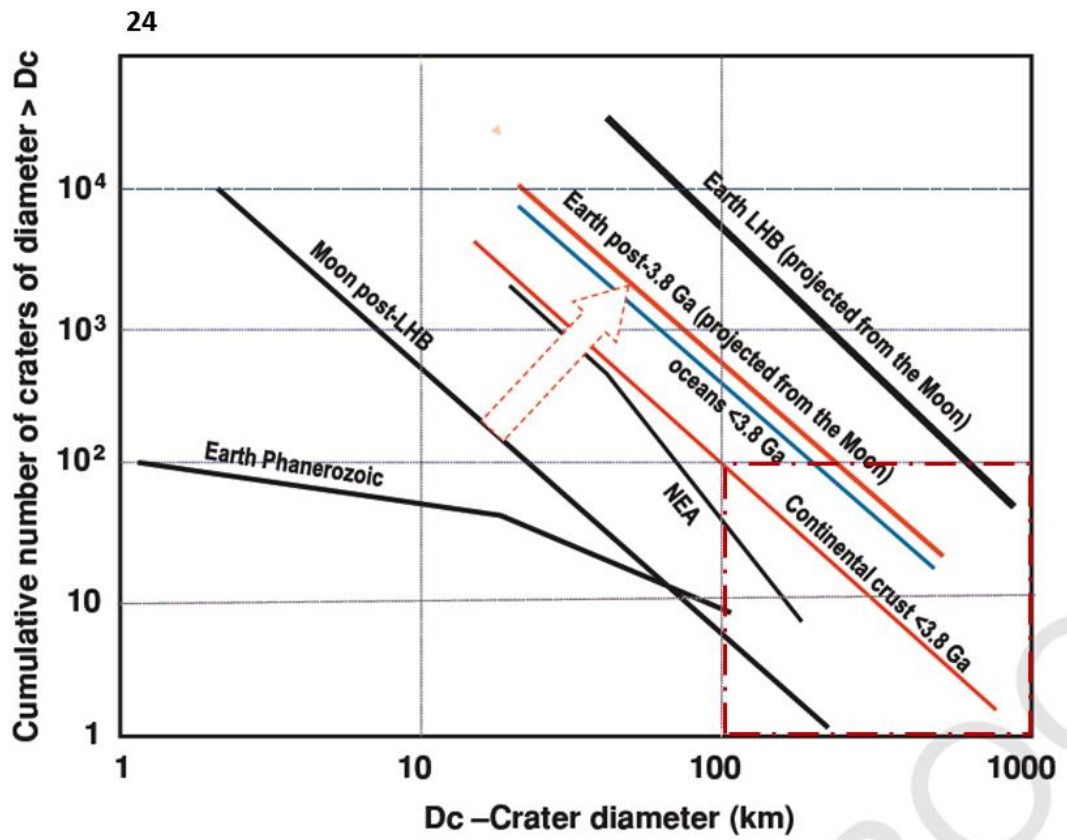


Figure 24

HIGHLIGHTS

- Ring, dome and crater features on the Australian continent and shelf include 38 structures of confirmed to very likely asteroid and meteorite impact origin and numerous buried and exposed ring, dome and crater features of undefined origin.
- The paper discusses and identifies criteria for discrimination between ring and dome features of morphological, structural, igneous origin, geophysical anomalies of unknown origin and features of possible impact origin.
- 43 ring and dome features are discussed in terms of their origin, similarities to or difference from impact structures.
- The Australian record displays a relatively common occurrence of large impact structures and relative depletion in small impact structures and craters, interpreted in terms of good preservation of large structures at deep crustal zones as compared to the erosion of small craters.