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Geophysical and structural criteria for the identification of buried impact structures, with reference to Australia☆

Andrew Glikson [a,b,*], I. Tonguç Uysal [b]

[a] Planetary Science Institute, Australian National University, Australia
[b] Queensland Geothermal Energy Centre of Excellence', The University of Queensland, Australia

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ABSTRACT

The discovery of large asteroid impact structures, likely and possible impact structures, onshore and offshore the Australian continent (Woodleigh [120 km; ~360 Ma], Gnargoo [75 km; Lower Permian — upper Cretaceous], Tookoonooka [55–65 km; ~125 Ma], Talundilly [~84 km; ~125 Ma], Mount Ashmore [>100 km; end-Eocene] and Warburton twin structures [>400km; pre-end Carboniferous]) requires re-examination of the diagnostic criteria used for their identification. Bouguer anomalies of established impact structures (Chicxulub [170 km; 64.98 ± 0.05 Ma], Woodleigh impact structure and Gnargoo probable impact structure display a unique structural architecture where pre-impact structural ridges are intersected and truncated by the outer ring of the circular structure. Seismic reflection data outline circular central uplift domes, basement plugs and rim synclines. Sharp circular seismic tomography anomalies indicate low velocity columns under both the Woodleigh impact structure and Warburton probable impact, hinting at deep crustal fracturing. Deformed, curved and clouded intra-crystalline planar deformation features in quartz (Qz/PDFs), displaying Miller indices ({10–11}, {10–12}, {10–13}) diagnostic of shock metamorphism, abound around exposed established impact structures (Vredefort [298 km; 2023 ± 4 Ma], Sudbury [~250 km; 1850 ± 3 Ma], Charlevoix [54 km; 342 ± 15 Ma], Manicouagan [100 km; 214 ± 1 Ma]), Tookoonooka and Talundilly). Deformed Qz/PDFs allow recognition of shock metamorphism in buried impact structures, where original Qz/PDFs were bent, recrystallized and/or clouded during formation of the central uplift and hydrothermal activity triggered by the impact. Planar deformation in quartz can also occur in explosive pyroclastic units but are limited to Boehm lamella (Brazil twins) with single lamella sets {0001}. It has been suggested that a class of microstructures in quartz, referred to as metamorphic deformation lamella (Qz/MDL), occur in endogenic tectonic–metamorphic terrains. However, no type locality has been established for Qz/MDL of non-impact origin.

Contents

1. Introduction

The discovery by Robert Dietz (1914–1995) of large asteroid impact structures, originally referred to as 'astroblemes', including Vredefort (298 km; 2023 ± 4 Ma) (Dietz, 1961) and Sudbury

☆ In honor of Robert S. Dietz, 1914–1995.

* Corresponding author. Planetary Science Institute, Australian National University, Australia. Tel./fax: +61 2 6296 3853.
E-mail addresses: Andrew.glikson@anu.edu.au (A. Glikson), T.uysal@uq.edu.au (I.T. Uysal).

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(250 km; 1850 ± 3 Ma) (Dietz, 1964), heralded a new era in the study of the asteroid impact history of Earth. Since that time the advent of geophysical exploration and drilling has uncovered a number of large buried impact structures identified by large circular gravity and magnetic anomalies and confirmed by diagnostic hallmarks of shock metamorphism. Such discoveries included Chesapeake Bay (90 km; 35.5 ± 0.3 Ma) (Poag, 1996), Chicxulub (170 km; 64.98 ± 0.05 Ma) (EID — Earth Impact Database, 2011) and Manson (35 km; 73.8 ± 0.3 Ma) (Koeberl and Anderson, 1996). In Australia Woodleigh (Carnarvon Basin, Western Australia — 120 km; ~360 Ma) (Glikson et al., 2005a,b; Uysal et al., 2005), Tookoonooka (Eromanga Basin, Queensland — 55–65 km; ~125 Ma) (Gorter et al., 1989; Gostin and Therriault, 1997) and Talundilly (Eromanga Basin, Queensland — 84 km, 125 Ma) (Longley, 1989; Gorter and Glikson, 2012) impact structures were documented. In addition a number of probable[1] impact structures, including Gnargoo (north Carnarvon Basin, Western Australia; Iasky et al., 2001; Iasky and Glikson, 2005), Mount Ashmore (Timor Sea; Glikson et al., 2010), and Warburton (northeast South Australia) (Glikson and Uysal, 2010; Glikson et al., 2013) remain to be confirmed.

The discrimination of structural and microstructural diagnostic features of shock metamorphism from those of endogenic terrestrial origin has been the subject of extensive debate (Carter and Friedman, 1965; Carter, 1965, 1968; Carter et al., 1986; Alexopoulos et al., 1988; Lyons et al., 1993; Grieve et al., 1996; Vernooij and Langenhorst, 2005; Spray and Trepmann, 2006; Ferriere et al., 2009; French and Koeberl, 2010; Hamers and Drury, 2011). Central to the recognition of diagnostic features of buried impact structures is their unique geophysical and structural characteristics, including presence of a central uplift and a rim syncline, distinct circular and radial fault patterns, microstructural shock metamorphic effects and extraterrestrial geochemical and isotopic signatures, as distinct from structural features associated with tectonic domes, salt domes or volcanic uplifts.

This paper aims at discussion of the nature of diagnostic criteria for definition of extraterrestrial impacts, with reference to Australian confirmed, probable and possible buried impact structures, using the wealth of geophysical data from Australian sedimentary basins. It is hoped that the clarification of these criteria will help in further investigation of seismic, magnetic and gravity data from sedimentary terrains with the aim of extending the impact database, with implications for the effects of extraterrestrial impacts on crustal evolution.

2. Identification of buried impact structures

2.1. Geophysical criteria

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

1. Intersections by the external rings (commonly but not invariably near-to 360°) of older pre-impact structural elements, as displayed by the Chicxulub impact structure, the Woodleigh impact structure and Gnargoo probable impact structure (Fig. 1). Whereas structurally discordant intersections are also displayed by volcanic diatremes and by salt domes, the combination of these features, presence of a central uplift core or central dome, and a ring syncline, is consistent with diagnostic features which militate for an impact origin.
2. The central uplifts of impact structures are best defined by seismic reflection sections where the basement uplift is commonly associated with thrust faults (Fig. 2a, b). Where the core of the structure consists of sedimentary strata, a structural dome is outlined, whose core may contain chaotically disrupted core zones displaying a loss of seismic markers due to mega-brecciation, as in the Mount Ashmore probable impact structure (Fig. 2c). By contrast to thrust faults around and within the central core zone, ring synclines and outer rims of impact structures feature inward-dipping normal faults (Fig. 2a, b). These structural patterns represent centripetal to upward block movements which involve compression around the uplifted core, extension within the ring syncline and inward collapse of the crater rim, evident in the Woodleigh, Gnargoo and Talundilly structures (Figs. 1 and 2). In addition, some impact structures and probable impact structures display uplift of crystalline basement below impacted sediments, as in the Woodleigh impact structure (Fig. 2) and the Mount Ashmore probable impact structure (Glikson et al., 2010).
3. An intersection of the top of the dome or basement uplift by unconformably overlying post-impact sediments is typical of impact structures, as demonstrated in the Woodleigh, Gnargoo, Mount Ashmore and Tookoonooka structures (Fig. 2). Post-impact isostatic vertical movements are indicated where the central uplift pierces through the unconformity, as in the Mount Ashmore structure (Fig. 2c).

2.2. Microstructural criteria

The distinction between Planar Deformation Features in quartz (Qz/PDFs) indicative of shock metamorphism within established impact structures on the one hand, and proposed Metamorphic Deformation Lamellae (Qz/MDL) of supposed purely endogenic origin on the other hand, is extensively discussed in the literature (Carter and Friedman, 1965; Carter, 1965, 1968; Carter et al., 1986; Alexopoulos et al., 1988; Lyons et al., 1993; Grieve et al., 1996; Vernooij and Langenhorst, 2005; Spray and Trepmann, 2006; Ferriere et al., 2009; French and Koeberl, 2010; Hamers and Drury, 2011). The following criteria have been suggested in this regard:

A. Qz/PDF lamellae are defined by diagnostic Miller indices correlated with specific shock levels, in particular the {10–11}, {10–12} and {10–13} planes (French, 1998). By contrast planar features referred to as Qz/MDL show a wide scatter, including low $C_{OA}Qz$^P_{PDF} angles (angle of the Optic Axis to the pole of planar deformation features) on frequency distribution plots (Lyons et al., 1993; French, 1998, Fig. 4.25).
B. Qz/PDFs form multiple planar sets in shock metamorphosed rocks (Robertson et al., 1968; Stoffler and Langenhorst, 1994; Grieve et al., 1996). Planar features referred to as Qz/MDL consist mostly of only one set of lamellae within any one quartz grain (French and Koeberl, 2010), commonly form basal {0001} planes, representing ~8–10 GPa shock pressures (French, 1998, Table 4.2), including in explosive volcanic units such as at Toba ignimbrites (Carter et al., 1986).
C. Qz/PDF lamellae can be <1–2 μm-thick whereas planar features referred to as Qz/MDL consist of segments usually 2–4 < μm thick.
D. Qz/PDFs are originally perfectly planar whereas planar features referred to as Qz/MDL commonly display undulation, bending and wavy patterns.
E. Transmission Electron Microscopy (TEM) studies indicate little-deformed segments of Qz/PDFs displaying optical continuity between bordering intra-crystalline segments, namely these segments display no subgrain boundaries. By contrast planar features referred to as Qz/MDL display irregular/undulating boundaries and optical discontinuities between separate subgrains, where optic orientations depart by ≤5° from each other and from the orientation of the host quartz (Glikson et al., 2013).
F. TEM studies indicate Qz/PDFs are either amorphous or composed of quartz with low dislocation densities. By contrast planar features described as Qz/MDL are more commonly altered and display high dislocation densities (Goltrant et al., 1991).

[1] In this paper the term “probable impact structure” pertains to documented structures which display a number of features consistent with those of established impact structures but have not been to date included in the Earth Impact Database (EID: http://www.passc.net/EarthImpactDatabase/index.html). The term “possible impact structure” pertains to structures suspected to be of impact origin but which are not known to include diagnostic structural and shock metamorphic signatures.