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Andrew Y. Glikson • Franco Pirajno

Asteroids Impacts, Crustal Evolution and Related Mineral Systems with Special Reference to Australia

Springer

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The Anunnaki, a group of deities that appear in the mythological traditions of the ancient Sumerians, Akkadians, Assyrians, and Babylonians, some of whom apparently represented the stars, i.e., the zodiac, or “heavenly host” worshipped by the Canaanites and Hebrews. Creative Commons (<https://www.flickr.com/photos/tortuga767/525162235/in/photolist-NpAri-qCtV4W-5YiNuT-7AdeWc-5YiPa6-ArwNvs-qs5Fjk-qawEF1-qavKvm-qawK6U-qawMu1-5YiNzH-bjqDs-c-dX9jVD-9R4bpo-7UKhQP-c5Vys1-NpfYf-LwTdSc-NpfYd-fzHbv9-5Yo3eN-5Yo3sA-3dEmn-y-5YiNMR-5Yo2LC-5YiNo2-5YiNQk-5Yo3a5-5YiNJM-5Yo36m-ecrYj1-n5ZZe-5Yo3xm-5YiNsF-9Wbk1t-5YiP48-5YiPeV-8VVgsj-5YiNEH-7u9hGF-8fAreF-qaEJtx-c3jWJS-ANdC5v-7udbsL-AWUNi1-qYiyFE-fU9Uwt-g3nwHA>)

*In honor of Eugene Merle Shoemaker and
Robert Sinclair Dietz: Pioneers of asteroid
impact research*

Preface

Thanks to their long-term geological stability, Precambrian and younger terrains in the Australian continent contain a large number of impact structures and probable impact structures. These include 38 confirmed asteroid impact structures and 43 ring structures, many of which constitute possible to probable asteroid impact structures. These structures have been the subject of more than half a century of studies by geologists from universities, geological surveys, and related institutions. The structures range from several tens of meter-large craters, such as the Henbury and Veevers craters, to buried structures larger than 100 km in diameter, such as the Woodleigh impact structure and the Warburton probable impact structure. Discoveries and research of many of these structures, notably by Peter Haines, Eugene and Caroline Shoemaker, John Gorter, Robert Iasky, Victor Gostin, George Williams, and others, published in the literature, are reviewed in the present book *“Asteroid Impacts, Crustal Evolution, and Mineral Systems with Reference to Australia.”* The book presents a compilation and a review of Australian impact structures, impact ejecta/fallout deposits, and related mineralization, including discussion of the significance of many of these structures for crustal evolution and for mineralization. The book further reviews asteroid impact ejecta/fallout units, mainly of Archaean age studied in the Pilbara Craton of Western Australia and also the late Proterozoic Bunyeroo impact layer in South Australia. Discoveries of impact fallout units in the Pilbara Craton by the US scientists, including Bruce Simonson, Scott Hassler, Don Lowe, and Gary Byerly, and their students and follow-up discoveries and research by Australian geologists have defined the Pilbara as one of the two best documented terrains where Archaean impact ejecta/fallout deposits are identified, the other terrain being the Kaapvaal Craton in southern Africa. A synthesis of evidence from both cratons indicates periods of large asteroid bombardments during ~3.47–2.48 billion years ago, including peak bombardment about 3.25–3.22 billion years ago. The latter period coincides with an abrupt transformation of an early Archaean granite–greenstone crust to mid- to late Archaean semi-continental crustal regimes, underpinning the significance of heavy asteroid impact events for crustal evolution. Thermal and hydrothermal processes associated with impact cratering bear important consequences for the formation of mineral deposits, such as Ni at

Sudbury and Pb–Zn at Siljan and Kentland. Impact structures may also provide sites for accumulation of hydrocarbons, whereas in some instances fracturing associated with impact structures allows outward migration of oil and gas.

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Introduction

“Nature hides her secrets . . .” Albert Einstein

Humans have been looking at the stars, planets, comets, and falling meteorites and meteorite showers ever since, and much earlier than, the onset of civilization (Frontispiece). The terrestrial planets of the inner solar system—Mars, Earth, Venus, and Mercury—are all affected by asteroids deflected from the asteroid belt and comets falling off the Kuiper belt. However, when viewed from space planet Earth, although located in the trajectory of these bodies, displays little or no cratering. This impression is apparent rather than real, arising due to (1) the extension of the oceans over some two-thirds of the Earth’s surface and (2) the dynamic nature of Earth, including the accretion and subduction of tectonic plates as well as the intensive erosion processes. The asteroid impact record on Earth is thus to a large extent concealed and is the subject of extensive search using structural, geophysical, petrological, and geochemical methods. The cover-up of most oceanic impact records and erosion of orogenic mountain belts leave stable old cratons as the best sites for preservation of impact scars, including craters and their deep-seated roots and rebound dome structures. This book documents the impact records of the Australian continent and marine shelves, including impact ejecta/fallout units (Chap. 2), exposed impact structures (Sect. 4.1), buried impact structures (Sect. 4.2), meteorite craters (Sect. 4.3), and ring and dome geophysical anomalies of unproven origin (Chap. 5). A review of very large impact structures worldwide is given in Chap. 3.

Falling between the disciplines of astronomy, planetary science, and geology, the subject of asteroid impacts is only rarely taught in universities, remaining a focus of research by small teams. In Australia these notably included American scientists such as Eugene and Caroline Shoemaker, Don Lowe, Gary Byerly, Bruce Simonson, and Scott Hassler and Australian scientists including George Williams and Victor Gostin; geological survey scientists including P. Haines, P. Hawke, R. Iasky, F. Pirajno, and A. Hickman; and university and museum scientists including M. Dentith and A. Bevan and others. It was not until about 1981 when Louis and Walter Alvarez unearthed a telltale iridium-rich sedimentary horizon at the ~66 million-year-old (Ma) Cretaceous–Tertiary (K–T) boundary at Gubbio, Italy

(Alvarez et al. 1980, 1982; Alvarez 1997), that a paradigm shift took place in terms of the recognition of the significance of extraterrestrial impacts for K–T boundary mass extinction of species (Chap. 1, Fig. 1.9) and the effects of such impacts on terrestrial biological evolution. The spectre of the large dinosaurs extinguished by a large asteroid impact has fired the imagination of people like no extraterrestrial event has done before. The discovery reestablished the idea that much of Earth's history has been shaped by catastrophes, a theory promoted by Georges Cuvier and natural theologians which was preceded, but was largely supplanted, by Darwin's theory of evolution and by Hutton's and Lyell's geological uniformitarian and gradualism theory.

The geological antiquity of Australian land surfaces, in particular platform sediment and volcanic cover over 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 the 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; World Impacts Database) (Table 4.1). In addition 43 examples will be outlined 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 5.1). The discussion will proceed in terms of examples of large geophysical multi-ring features including total magnetic intensity anomalies, circular gravity anomalies, and seismic domes.

The pressure–temperature field of shock metamorphism is distinct from that of terrestrial metamorphism, including the high-pressure eclogite facies. Central to the identification of extraterrestrial impact structures are criteria for shock metamorphism calibrated with laboratory experiments (French 1998) (Fig. 1.17). The static PT field of regional metamorphism is mostly below 10 GPa, whereas shock pressures inducing the graphite to diamond transformation, coesite to stishovite transformation, shatter cones, planar deformation features, diaplectic glass, and shock melting are higher than 10 GPa. Structural signatures of buried extraterrestrial impact structures are identified by cross-cutting relations with older structures, radial and oblique faulting, and tensional faulting at the rims and centripetal dome and thrust structures at the centers. Confirmation of an impact origin has to await petrofabric examination for intra-mineral deformation features, commonly planar deformation features (pdf) in quartz, solid-state vitrification to diaplectic glass, and melting of quartz to lechatelierite (French 1998).

Using these criteria, early discoveries included the Meteor Crater, Arizona (Roddy and Shoemaker 1995), and the Ries Crater, Germany (cf. Chao 1967, 1968). The pioneering studies of Robert Dietz have paved the way for the

identification of giant impact structures, referred to as astroblemes (star scars), including Vredefort (289 km-diameter; $2,023 \pm 4$ Ma) (Dietz 1961) and Sudbury (~ 250 km; 1850 ± 3 Ma) (Dietz 1964). A number of factors militate against an origin of these structures due to deep-seated or cryptoexplosion mantle-derived processes (Nicolaysen and Ferguson 1990). These terrains contain shock metamorphic mineralogy and textures, including shatter cones, planar deformation features in quartz, high-pressure phases [coesite, stishovite], and shock vitrification products such as silica glass (lechatelierite), feldspar glass (maskelynite), impact melting, melt breccia, pseudotachylite veins, microbreccia dykes, and iridium anomalies. While melt rock abound, no volcanic rocks are associated with mega-impact structures. The shock metamorphic features indicate pressures of >10 GPa, exceeding pressures induced by volcanic explosions.

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Authors' Biography

Andrew Yoram Glikson an Earth and paleo-climate scientist, studied geology at the University of Jerusalem and graduated at the University of Western Australia in 1968. He conducted geological studies of the oldest geological formations in Australia, South Africa, India, and Canada and studied large asteroid impacts, including effects on the atmosphere, oceans, and mass extinction of species. Between 1998 and 2014, this work included detailed studies of impact ejecta units in the Pilbara Craton, Western Australia, geochemical studies of impact ejecta units from South Africa, and the identification and study of several Australian buried impact structures, including Woodleigh, Gnargoo, Mount Ashmore, Talundilly, Warburton East and West, Hickman crater, and Lake Raeside jointly with Arthur Hickman, recently a 3.46 Ga twin impact ejecta and possibly the Diamantina anomaly. Currently, he is a Visiting Scientist in Geoscience Australia developing a catalogue and website of Australian confirmed and possible asteroid impact structures. Since 2005 he extended the studies of past mass extinctions to the effects of climate on human evolution, the discovery of fire and global warming.

Franco Pirajno Adjunct Professor at the Centre for Exploration Targeting (CET), University of Western Australia, is an authority on tectonics, ore deposit geology and mineral exploration, with experience in Europe, southern Africa, South East Asia, New Zealand, the southwest Pacific, China, Greenland, southern and eastern Siberia, and Australia. He joined the Geological Survey of Western Australia in 1993, following post-doctoral research at the Vesuvius Volcano Observatory, exploration with Anglo American Corporation, Chair of Economic Geology at Rhodes University, South Africa, with research activity

on precious metals and base metals mineral deposits in the southern African subcontinent. In the last 23 years Franco Pirajno has worked extensively in Western Australia's Proterozoic terranes and was instrumental in the discovery of a new large igneous province in Australia. He was a Visiting Professor at Peking University in 2003, China University of Geosciences, Beijing, in 2004, Distinguished Foreign Professor at Hefei University of Technology during September–October 2012, and Editor-in-Chief of *Ore Geology Reviews* since 2012. His principal research interests include Archaean granite greenstone terrane, Proterozoic intra-cratonic basins, rift associated mineral deposits, layered mafic-ultramafic complexes, metamorphic belts of Proterozoic age, alkaline complexes and an-orogenic magmatism, and carbonate rocks in passive margin settings.