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The Asteroid Impact Connection of Planetary Evolution

With Special Reference to Large Precambrian and Australian Impacts

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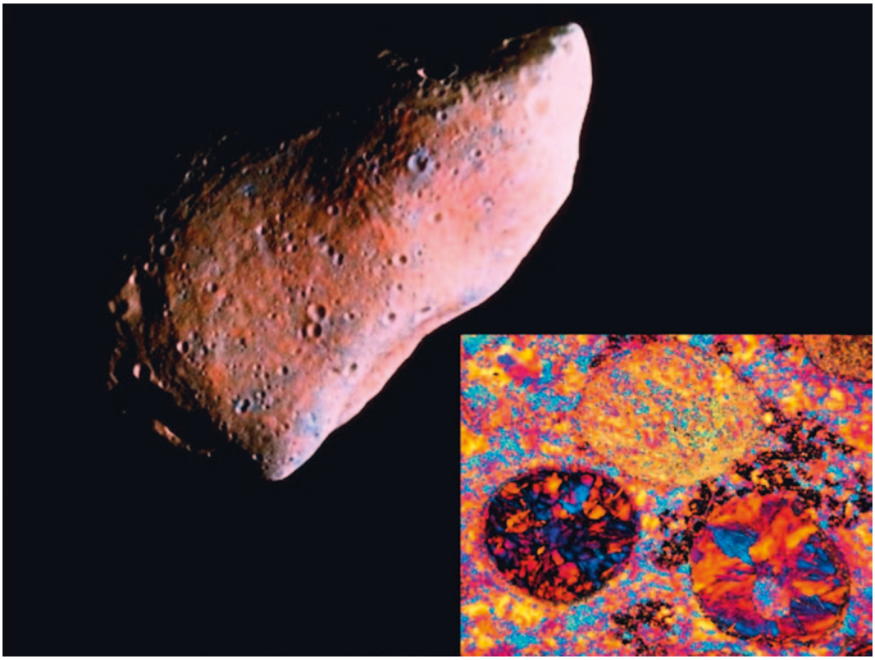

The asteroid Eros (34.4 × 11.2 × 11.2 km) (NASA) and S3 impact microkrystites, Barberton Greenstone Belt (courtesy G. Byerly)

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In honor of Eugene M. Shoemaker,
Carolyn S. Shoemaker, Robert S. Dietz,
David H. Green and Ian Williams

Preface

A paradigm shift according to Thomas Kuhn (1962) constitutes a change in the basic assumptions within the ruling theory of science. It is not a term to be used lightly, except in relation to major breakthrough in the understanding of nature. In the field of Earth Science this term can be used in connection with the conception of gradualism in terrestrial evolution by James Hutton (1788) and Charles Lyell's (1830), sea floor spreading and plate tectonics by Harry Hess, Bruce Heezen, Robert Dietz, and Sam Carey, and the identification of meteorite craters and astroblemes ('star scars') by Eugene Shoemaker and Robert Dietz, both having been my mentors. My introduction to extraterrestrial impacts in 1968 was related to the study of Gosses Bluff Structure, Central Australia, where the United States Astrogeology Branch, led by Eugene Shoemaker, was planning a study of Moon-like landscapes in preparation for the Apollo program (Fig. 1.1). At the time few geologists realized the role of asteroid impacts. In subsequent years, the sea-change discovery by Walter and Louis Alvarez of the KT asteroid impact boundary and associated mass extinction of species has changed this attitude. This was followed by the identification of the relations between the 580 Ma-old Acraman impact structure, the Bunyeroo ejecta, and radiation of Acritarchs by George Williams, Victor Gostin, and Kath Grey. Based on geological studies of Archaean terrains during the 1980s and 1990s I raised doubts whether many Precambrian Earth features were triggered exclusively by internal mantle and crust processes. A breakthrough came in 1986 and following years when Don Lowe, Gary Byerly, Bruce Simonson, and Scott Hassler and their students began to discover millimeter scale impact spherules (microkrystites) in Archaean sediments, overlain by tsunami deposits, initiating a paradigm shift in the study of early crustal evolution. Given the difficulty in identifying spherule units in the field, impact frequencies documented to date inherently represent only a minimum flux, namely the 'tip of the iceberg', yielding support to an extension of the Late Heavy Bombardment. This monograph, focusing on impacts craters larger than 20 km in diameter, is based on research of Archaean and younger terrains during 1964–2012, including studies of impact ejecta units and large buried impact structures on the Australian continent. Notably detailed research in the Pilbara Craton, with the support of Arthur Hickman of the Western Australian Geological Survey and my field mate John Vickers, enabled follow-up of discoveries by Lowe, Byerly, Simonson and their students. Suggestions that Archaean extra-terrestrial impacts acted as triggers of internal mantle-crust events will meet with resistance by proponents of uniformitarian schools of thought. Traditionally, geology—the study of Earth—focuses on internal crust, mantle, and core process, taking little account of the effects of large asteroid impacts. However, the two are not mutually exclusive. Whereas purely endogenic mantle-crust dynamics and plate tectonic cycles are manifest, the intermittent triggering of thermodynamic events by large extra-terrestrial impact clusters constitutes a combination of Cuvier's catastrophism and Lyell and Hutton's gradualism throughout Earth history.

Reference

Kuhn TS (1962) The structure of scientific revolutions. The University of Chicago Press, Chicago

Acknowledgments

This book is based to a large extent on my field and laboratory investigations of impact ejecta units in the Pilbara, Western Australia, on laboratory studies of impact ejecta from the Barberton Greenstone Belt, South Africa, during 1998–2007, and on studies of Australian buried impact structures during 1999–2012. The book was invited by Petra Van Steenbergen and edited by Hermine Vloemans of Springer SBM NL. I am grateful to Don Lowe, Gary Byerly, Franco Pirajno, Victor Gostin, Hugh Davies, Miryam Glikson, Peter Haines, and Arthur Hickman for their comments on the book manuscript. I am indebted to John Vickers, my field mechanic and laboratory technician, for consistent help and geological interest in our investigations. Field work in the Pilbara would not have been possible without the long-term support and interest of Arthur Hickman of the Geological Survey of Western Australia. I thank Robert Iasky, Franco Pirajno, Peter Haines, Martin Van Kranendonk, and John Gorter for their interest and numerous discussions. I am grateful to Bruce Simonson and Scott Hassler for introducing me to impact ejecta exposures in the Hamersley Range, to Gary Byerly and Don Lowe for providing ejecta samples from the Barberton Greenstone Belt. Tonguc Uysal and Hal Gurgenci collaborated in the study of the Warburton shock metamorphic terrain. David Green and Ian Jackson facilitated my research at the Research School of Earth Science, Australian National University. I thank Charlotte Allen, Harry Kokkonen, Frank Brink, Stephen Eggins, John Fitz Gerald, and Tony Eggleton for help and advice with analytical work. I thank David Jablonski for collaboration with the Mount Ashmore study. I thank Alan Whittaker, Elinor Alexander, Rodney Boucher, John Bunting, Prame Chopra, Chris Klootwijk, Nick Lemon, Tony Meixner, Martin Norvick, Hugh O'Neill, Bruce Radke, Erdinc Saygin, John Veevers, Xiaowen Sun, and Doone Wyborn for discussions regarding the Warburton structure, and Les Tucker, David Groom, Karen Groom, and Michael Willison of PIRSA for help with examination and sampling of drill cores, Elaine Appelbee for drafting. I am grateful to the following people for permission to use figures in this book: Alessandro Montanari, Alex Shukolyukov, Anita Andrews, Karen Ballen, Gary Byerly, Sherry Cady, Bevan French, Richard Grieve, Duane Hamacher, Scott Hassler, Arthur Hickman, Alan Hildebrand, Michael Jones, Gerta Keller, Don Lowe, Victor Masaitis, Mustafa Mincel, Victor Gostin, Reg Morrison, Franco Pirajno, Bruce Simonson, Caroline Shoemaker, John Spray, Claudia Trepmann, Martin Van Kranendonk, and Jim Wark.

Contents

Chapter 1
A Paradigm Shift in Earth Science

Abstract This section suggests the evolution of Earth progressed through a combination of internal core-mantle-crust dynamics and extraterrestrial large impacts which triggered seismic, tectonic, volcanic and tsunami processes as well several mass extinctions of species.

When, in 1981, Louis and Walter Alvarez, the father and son team, unearthed a tell-tale Iridium-rich sedimentary horizon at the ~65 million years-old (Ma) Cretaceous-Tertiary (KT) boundary at Gubbio, Italy (Alvarez et al. 1980, 1982; Alvarez 1997), the find heralded a paradigm shift in the study of terrestrial evolution. The discovery re-established the idea that much of Earth's history has been shaped by catastrophes, a theory promoted by Georges Cuvier and natural theologians which preceded, but was largely supplanted by, Darwin's (1859) theory of evolution and by Hutton (1788) and Lyell's (1830) geological gradualism (Fig. 1.1).

The KT boundary (64.98 ± 0.05 Ma[1]) corresponds to the 2nd largest mass extinction of species recorded in Earth history, when some 46 % of living genera were extinguished (Keller 2005) (Figs. 1.2, 9.3 and 9.4). Since the parent craters of the KT event have been identified, including *Chicxulub* (170 km-diameter, Yucatan Peninsula, Mexico) and *Boltysh* (~25 km-diameter, 65.17 ± 0.64 Ma, Ukraine), other large asteroid impact craters and impact ejecta units have been associated with mass extinction and biological radiation boundaries (Grey et al. 2003; Grey 2005; Glikson 2005, 2009), underpinning the vulnerability of species to catastrophic events.

The Earth conceals its secrets well, not least buried scars of meteorite impacts and thin, commonly hardly detectable, spherule layers within sedimentary sequences. Based on shock metamorphic criteria calibrated with laboratory experiments (French 1998), the pressure–temperature field of shock metamorphism is distinct from that of terrestrial metamorphism, including that of high pressure eclogite facies (Fig. 1.3). Whereas the PT field of eclogite is below 10 GPa, the graphite to diamond and coesite to stishovite transformations, shatter cones, planar deformation features, diaplectic glass and shock melting occur well above 10 GPa (Fig. 1.3).

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[1] Impact structure ages and diameters are after the Earth Impact Database [EID] (http://www.passc.net/EarthImpactDatabase/index.html) and information by the author. Where two figures are cited (cf. 130 < 260 km) the lower value represents an estimate of the diameter of the collapsed crater whereas the higher value is the diameter of the outer ring.

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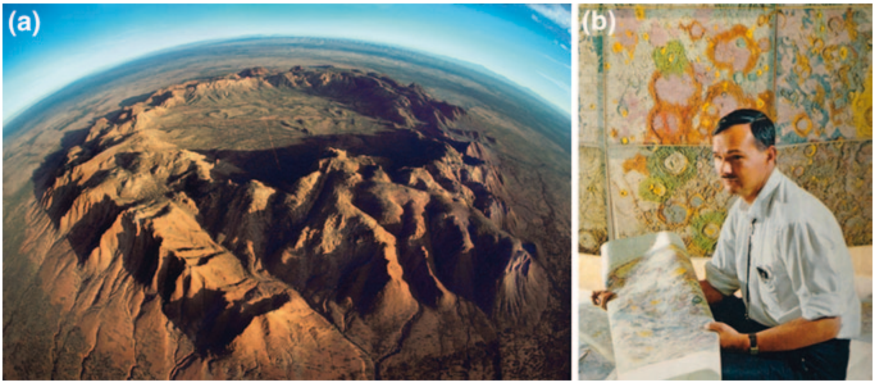

Fig. 1.1 Gosses Bluff impact structure, central Australia, and Eugene Merle Shoemaker compiling the first comprehensive geologic moon map http://users.tpg.com.au/users/tps-seti/planets.html. In 1968 the joint Gosses Bluff study by the U.S. Geological Survey, headed by Eugene Shoemaker, and the Australian Bureau of Mineral Resources, opened my eyes to the significance of large asteroid impacts and their diagnostic hallmarks, to be followed years alter by systematic studies of Archaean impactites and buried impact structures on the Australian continent. **a** Aerial view of Gosses Bluff, looking from the south (courtesy Reg Morrison); **b** Eugene Shoemaker studying lunar maps (courtesy Carolyn Shoemaker)

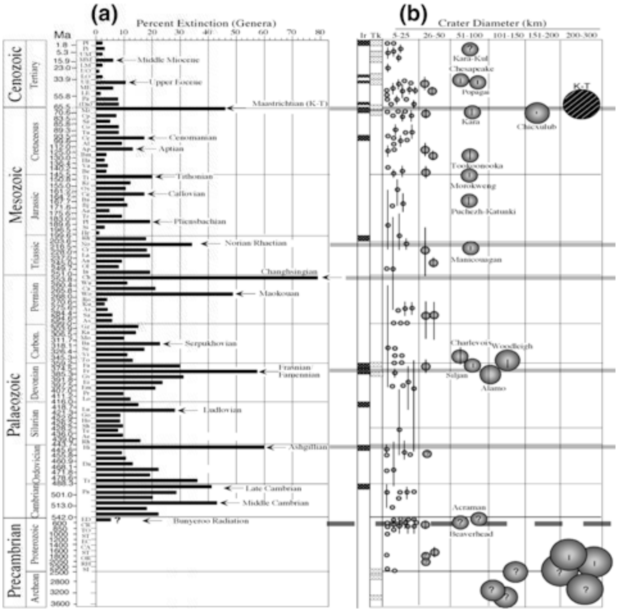

Fig. 1.2 Phanerozoic mass extinctions, asteroid impacts, and large igneous provinces. **a** Extinction intensity; **b** Impact events; **c** Volcanism. Stratigraphic subdivisions and numerical ages are after Gradstein et al. 2004). The extinction record is based on genus-level data by Sepkoski (1996). The number of impact events, size and age of craters follows largely the Earth Impact Database (2005), with modification by the author (AG). (Keller 2005, by permission)

Where signatures of buried extraterrestrial impact structures are found, their structure and composition needs testing by geophysical and geochemical methods, while confirmation often has to wait for years before their origin can be established. Until the 1960s, the apparent scarcity of large impact basins on Earth, as contrasted with the large lunar mare basins, constituted a major objection to theories advocating catastrophic extraterrestrial collisions. Several scientists, including Alt et al. (1988), Oberbeck et al. (1992) and Abbott and Isley (2002), proposed genetic connections between large impacts and geodynamic events. Following the establishment of criteria for shock metamorphism at Meteor Crater, Arizona (Shoemaker and Kieffer 1979; Roddy and Shoemaker 1995) and the Ries crater, Germany (cf. Chao 1967, 1968), the pioneering studies by Robert Dietz have paved the way for identification of giant impact structures, referred to as *astroblemes* (star scars). This included Vredefort (289 km-diameter; 2,023 ± 4 Ma) (Dietz 1961) and Sudbury (~250 km; 1,850 ± 3 Ma) (Dietz 1964). Alternatively these structures were regarded as crypto explosion features consequent on volcanic gas explosion (Nicolaysen and Ferguson 1990). However, shock metamorphic parameters indicate pressures of >10 GPa, exceeding pressures induced by volcanic explosions, nor are contemporaneous volcanic rocks associated with mega-impact structures. It has taken more than 20 years to establish the asteroid impact origin of these structures, identified by shatter cones, planar deformation features in quartz, high pressure phases [coesite, stishovite], shock vitrification [such as produce silica glass (Lechatelierite) and feldspar glass (maskelynite)], impact melting, melt breccia, pseudotachylite veins and dykes, iridium anomalies and numerous other features diagnostic of shock metamorphism).

Despite acceptance of the diagnostic hallmarks of impact outlined above, few suspected that, following the Late Heavy Bombardment of the Moon (LHB ~3.95–3.85 Ga) (Ryder 1990, 1991, 1997), extraterrestrial impacts continued to play a

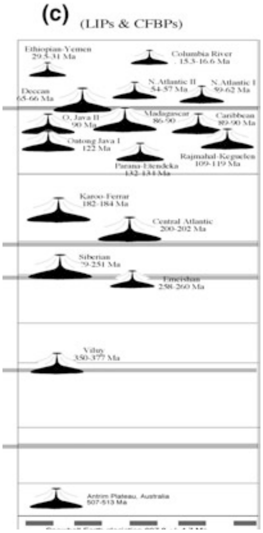

Fig. 1.2 (continued)

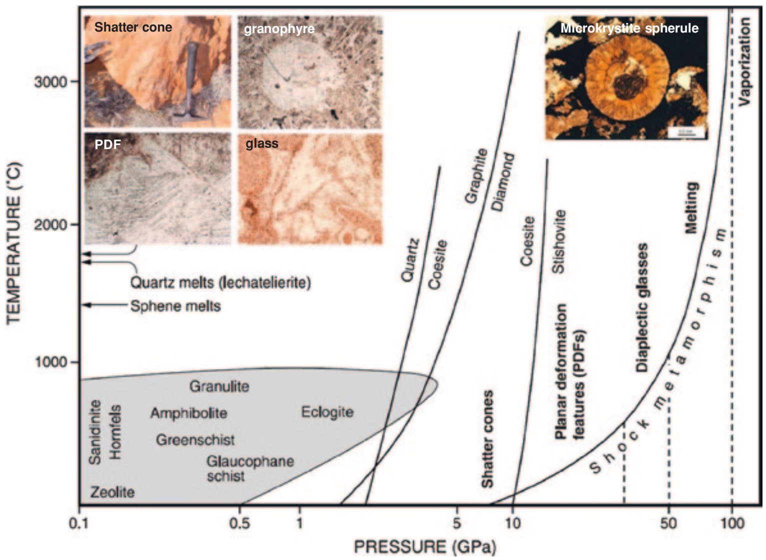

Fig. 1.3 Pressure–temperature diagram comparing conditions of shock metamorphism and conditions of endogenic crustal metamorphism. The shock-metamorphic field (from ~7 to >100 GPa) is distinct from the endogenic field is (P < 5 GPa, T < 1,000 °C). Stability curves for high-pressure minerals (coesite, diamond, stishovite) are shown for static equilibrium conditions (after French 1998, Fig. 4.1; by permission). Inset microphotographs display (1) a shatter cone; (2) granophyre core and radiating crystallites; (3) planar deformation features in quartz; (4) devitrified glass (1–3 from the Yarrabubba impact structure) and (5) a microkrystite spherule formed by condensation of impact-released vapor (Jeerinah Impact Layer)

major role in the history of Earth. However, since the 1980s geological field work in the ancient cratons of South Africa and Western Australia by Don Lowe, Gary Byerly, Bruce Simonson, Scott Hassler, the present author and other have identified major asteroid impact ejecta units within sedimentary and volcanic sequences, recording repeated impact clusters by asteroids tens of kilometers in diameter between ~3.5 and 2.5 Ga (Lowe et al. 2003; Simonson and Glass 2004; Glikson 2008; Glikson and Vickers 2010). This breakthrough was allowed by the identification of millimeter-scale originally glassy spherules in sediments of the KT impact boundary termed microkrystites (Fig. 9.4), characterized by inward radiating quench crystallites, chromium spinels and platinum group element anomalies, markedly high iridium levels (Glass and Burns 1988). Geochemical calculations and spherule size frequency analysis suggest asteroids as large as 20–50 km across (Melosh and Vickery 1991; Byerly and Lowe 1994; Shukolyukov et al. 2000; Kyte et al. 2003; Glikson and Allen 2004).

Microkrystite spherules form when vapor, ejected from craters upon large impact, condense in the atmosphere. On impact, target rocks are fragmented, shattered, fused and vaporized. The crust underlying the crater rebounds elastically, forming a dome, a process analogous to the upward ejection of a water drop when a stone is thrown into a pond. The impact vapor is dispersed with the winds, cools and condenses as myriad melt droplets which solidify as tiny glass spheres, preserved in sub-marine sediments (Fig. 1.4).

Since the 1990s no fewer than 18 microkrystite-bearing ejecta and fallout units have been detected in Archaean Pilbara and Barberton greenstone belts, overlying sediments of the Hamersley Basin and Transvaal Basin (Simonson 1992) and younger sediments. Pilbara ejecta units are dated as about ~3.47 Ga (2 units), ~2.63 Ga, ~2.57 Ga, ~2.56 Ga (2 units) and ~2.48 Ga-old, and Barberton ejecta units about 4.482, 3.472, 3.445, 3.416, 3.334, 3.256, 3.243 and 3.225 Ga (2 units) (Lowe and Byerly 2010). Several of these units represent multiple impacts (Glikson 2004a, b). A spherule unit 1.85–2.13 Ga-old is reported from Greenland (Chadwick et al. 2000) and spherule units ~1.850 Ga-old are reported from Ontario, Minnesota and Michigan (Addison et al. 2005; Jirsa et al. 2008; Cannon et al. 2010). The frequency of impact ejecta units in the Barberton greenstone belt suggests frequent intermittent bombardment of the Earth since the LHB (Lowe and Byerly 2010). Given the difficulty in identifying spherule units in the field, impact frequencies documented to date inherently represent only a minimum flux, namely the 'tip of the iceberg', yielding further support to an extension of the LHB.

The question arises, what were the effects of impacts by asteroids ~10 km and larger on the Earth's crust, its structure, tectonics, magmatic activity and

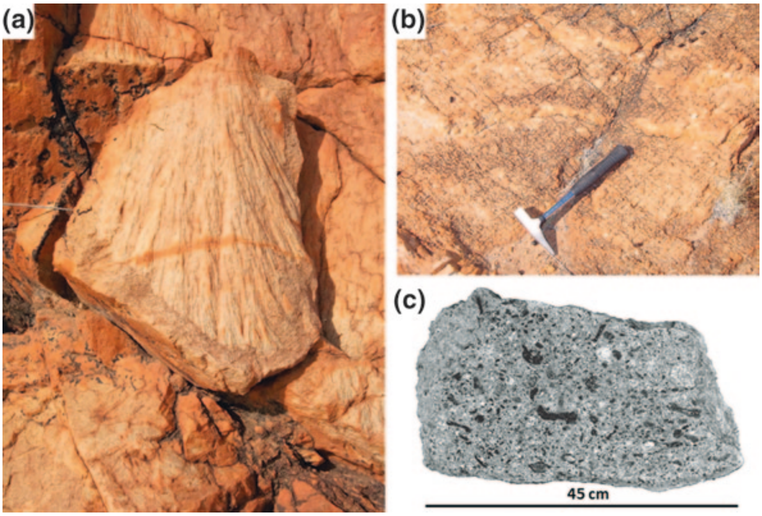

Fig. 1.4 Outcrop-scale (mesoscopic) features diagnostic of asteroid impact. **a** Shatter cone from the Gosses Bluff impact structure, central Australia, forming penetrative conical radiating horse tail-shaped striated fracture pattern (courtesy Duane Hamacher); **b** Rhombohedral fracture patterns associated with shatter cones, Yarrabubba impact structure, Western Australia; **c** Suevite—crater-fill melt breccia. Large hand specimen, about 45 cm-long, of typical fresh suevite from the Ries Crater (Germany). The specimen consists of irregular and contorted individual fragments of glass (*dark*) with roughly parallel elongation and crystalline rock fragments (*light*) in a fine clastic matrix. (From French 1998, by permission)