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The significance of extraterrestrial impacts with reference to Australia

Emeritus Professor Robert S. Dietz, 1914–1995

An impact by an asteroid or comet on the surface of a planet or Moon is the closest natural answer to the physical conundrum as to what happens when an irresistible force collides with an immovable object: the strata open up like a giant flower with a central crater eye and petal-like streaks of ejecta. Whereas plate tectonics outline ongoing mantle–crustal processes, cosmic impacts are the wild cards that perturb both terrestrial crustal history and the evolution of life; they result in the paradigm of astrocatastrophism, and link Earth science with astronomy. Over the aeons, the face of the Moon has looked down on Earth with a fixed stare, while mother Earth has constantly modified her smile through plate tectonics.

The role of extraterrestrial impact in Earth history with its catastrophic scenario has been and remains an anathema to many geologists who follow uniformitarian Lyellian views. The British astronomer H.A. Proctor in 1873 was probably the first to offer an impact interpretation of the lunar craters, but withdrew the idea because such craters were not evident on Earth. In 1893, G.K. Gilbert, chief geologist of the United States Geological Survey, described the lunar craters as meteoritic in origin, but in 1896 opined that the Barringer crater, Arizona, was of volcanic origin. In 1969, G.J.H. McCall wrote: 'It is not in dispute that impact explosions have had some role in geology, though it must appear to most geologists, weighing the geologic record without sentiment, that their role has been very insignificant'. McCall regarded the Wolfe Creek Crater in the Kimberley region of northwest Australia, as of volcanic origin. The Apollo missions, initially biased toward a volcanic interpretation of the lunar craters, resulted in a ringing victory for 'impactology'. More recently, clear distinctions have been made between impact and volcanic features on Venus.

The gradual recognition between 1930 and 1950 that the Barringer crater (Meteor crater) was truly a prototype asteroidal crater aroused much interest, and by mid-century eleven craters associated with meteoric debris had been recognised, four of them in Australia — namely Dalgaranga, Henbury, Boxhole, and Wolfe Creek. The 24-m-diameter Dalgaranga crater was first discovered in 1923, but fifteen years passed before E.S. Simpson published in 1938 a description of this crater and the associated mesosiderite fragments, which contrasted with the nickel–iron fragments associated with craters elsewhere. In 1932, the Henbury cluster of craters was described by A.R. Alderman. The 152-m-diameter Boxhole crater was identified by C.T. Madigan in 1937. Most remarkable of all was the Wolfe Creek crater (averaging 880 m across, and 45 m deep), discovered from the air in 1947. A decade would pass before the first of the astroblemes — ancient eroded impact structures — would be identified from their structural type and shock indicators. To date, some 23 putative craters and astroblemes have been verified on the Australian continent (see compendium, this issue).

The reality of planetary impacts by cosmic bolides was emphasised by the apparition of the 1994 comet Shoemaker–Levy 9, which had been disrupted into a 'string of pearls' by Jupiter's tidal attraction. As calculated, the fragments slammed into Jupiter's southern hemisphere over several days in July 1994, at 60 km s^{-1}, creating immense explosions. These impacts resulted in the greatest recorded display of celestial fireworks since the telescope was invented by Galileo. Within ten seconds of impact of each fragment, an immense fireball rose above the horizon and into telescopic view. The plumes of debris arced in ballistic trajectories expanding to thousands of kilometres. The end result of this impact series amounted to Earth-size dark splotches which persisted for several months. Had such impacts impinged on Earth, the effects would compare with those of the 65 Ma Cretaceous/Tertiary boundary events when over two-thirds of terrestrial species were wiped out by the effects of an asteroid that formed the Chicxulub crater in Yucatan.

The role of mega-impact in earliest planetary history is manifested for example by the probable extraction of the Moon from Earth by a Mars-size body, and by the interpretation of Miranda, Saturn's satellite, as a churned body coalesced from fragments blown apart by impact. The retrograde rotation of Venus is possibly explained by early capture of a satellite about half the size of the Moon. Space probes reveal that impact craters dominate the surface morphology of most of the terrestrial planets and their 27 satellites; some of the best examples engrave the surface of Venus and the Moon, where the near-absence of erosion ensures the pristine structure of these scars. Earth is exceptional among the planets since its volcanic–tectonic activity and severe surface erosion over the aeons eliminate or extensively mask the effects of impacts. Nevertheless, some 160 impact scars are revealed by the morphological and geological record, and each year several more are discovered.

Planets and satellites have been bombarded by cosmic debris for 4.6 Ga; evidence of the first 600 Ma of this process is furnished by the 30 000 craters on the Moon, testifying to an asteroid/comet flux about two orders of magnitude greater than at present. Scant terrestrial evidence for this period — the Hadean — includes relict 4.27-Ga zircon grains in sediments in the Gascoyne Province of Western Australia, 3.96-Ga tonalite gneiss and amphibolite of the Acasta gneiss (Slave Province, Northwest Territories, Canada), and gneisses of similar age in Antarctica.

Comparative planetology offers new perspectives on the history of the Earth; sometimes we must leave home to learn from whence we came! Remnant Hadean surfaces of Mercury, Mars, and the Moon hold clues to the Earth's earliest history. Yet Earth remains unique, thanks to its surface temperature range allowing the preservation of liquid water and thereby the evolution of life. Mars lacks sufficient atmospheric pressure to hold liquid water, while the Venusian mantle was probably catastrophically degassed. The Goldilocks paradigm prevails: Earth is stressful, but this hastens the arrow of evolution. Remarkable discoveries lie ahead.

The lunar record reveals early accretionary growth through impacts, culminating in saturation bombardment ending about 3.9 Ga when the giant maria basins were blasted out. The 1994 Clementine mission to the Moon has greatly enhanced the knowledge of this satellite. Even more important was the grand tour of the Solar System by Voyager 1 and 2, followed recently by the Magellan mapping of Venus. Venus reveals three impact craters larger than 150 km across (Mead, Meitner, and Isabella), as does the Earth (Vredefort, 2.0 Ga; Sudbury, 1.85 Ga; and Chicxulub, 65 Ma). Remarkably, although impact ejecta have been identified at the Cretaceous–Tertiary boundary in over 100 sites worldwide since 1980, it took another decade to find Chicxulub — in 1990 —buried beneath a kilometre of limestone in the Yucatan Peninsula, Mexico. How many more covered or deformed impact structures await discovery? The crater count on Venus is about 1000, and Earth should have at least a similar number of craters. The scattered pages of Precambrian stratigraphy might have preserved some impact effects — including diamictites, microtektites (spherule beds), superheated magmas, and impact-related deformational events. Shatter cones and mineral planar deformational features may be preserved locally.

The first fall recognised as meteoritic in origin occurred in 1803, when 3000 fragments fell at L'Aigle, France. On Kitt Peak near Tucson, Arizona, a program called Spacewatch uses a special telescope for detecting meteoroids passing near the Earth. Eighty-two small objects had been discovered over five years to the end of 1994. On 8 December 1994, a 10-m rock designated '1994xM1' hurtled past Earth at 43 000 km h^{-1} at a record-setting close approach of 102 000 km — about one-quarter the distance between the Earth and the Moon. Had this cosmic cannonball struck Earth, a 150-m-diameter crater would have resulted. Although crater-forming impacts are historically rare, recent examples include the Sikhote–Alin event, which showered 23 t of nickel–iron fragments on Kamchatka, Siberia, in 1947. In 1954, at Sylacuaga, Alabama, a 3.86-kg chondrite crashed through the roof of a house and ricocheted to hit a woman on the hip. In 1984, a 1.5-kg chondrite knocked a mailbox off its post in Claxton, Georgia, USA. In 1991, a 1-m iron created a 10-m percussion crater at Sterlitamak, Russia. Two cars have been hit recently by small meteorites: one at Peekskill, New York (1992); the other in Japan (1995). No deaths have been reported to have been caused by meteorites, but a gram-size fragment soft-landed on the head of a small boy during the 1992 M'bali fall in Uganda.

My own principal contact with Australian impact structures was a one-week study of Gosses Bluff in 1967, while en route to join the US Coast and Geodetic survey's research vessel *Oceanographer* in Perth (Dietz 1967: Nature, 216, 1082–1084). I recognised that it was an astrobleme *par excellence* and one of the world's finest examples. Gosses Bluff is an exhumed circular ring structure of up-ended strata with a 4.5-km central uplift enclosing a central eroded basin. Surrounding the uplift is an annular-ring syncline, providing an overall diameter to the disturbance of 24 km. The structure is truncated by mesas constituting the relics of a Mesozoic peneplain. Gosses Bluff includes a spectacular display of shatter cones created by the impact shock wave. The shatter cones are oriented upwards at high angles relative to the bedding at the centre, and at low angles to the bedding at the peripheries of the structure. These attitudes represent shock effects propagated from the centre at a shallow depth beneath the palaeosurface. Shatter-coned breccia clasts suggest that deformation and uplift immediately followed the passage of a shock front. The structure and scale of Gosses Bluff resemble those of the Sierra de Cangalha astrobleme in Brazil.

Two other Australian astroblemes are of special interest to me. The first is the large late Precambrian Acraman structure. Like Chicxulub, ejecta blankets of the Acraman impact containing shatter cones and shock lamellae are recognised in stratigraphic records located hundreds of kilometres away from the crater. The second remarkable astrobleme is the Spider structure — so named because of the numerous sandstone ridges which radiate from its central uplift. Spider promises to tell us much about the mechanics of central rebound uplift, typical of many astroblemes.

With the exception of Antarctica, Australia with its dry desert climate is the world's finest site for the collection of meteorites. With about 447 Australian meteorites now known, Australia ranks third in meteoritic finds after Antarctica and the USA. The meteorites range from nickel–iron masses to friable stones. They include soft carbonaceous chondrites — even rare pre-biotic organic compounds — and samples from the Moon and the Asteroid Vesta (Eucrites). Australian finds include Calcalong Creek, the only known lunar-derived meteorite, and the Murchison CM2 carbonaceous chondrite. Meteorites offer an insight into the metallic cores of planets, form the basis for determining the age of the Solar System and the Earth, and yield information on cosmic radiation.

The vast Australasian tektite strewn field, which extends northwestward between Australia and southeast Asia, consists of small bits of anhydrous natural glass splashed from a cometary impact about 780 000 years ago from an unidentified locus. These tektites are aerodynamically sculptured by their molten passage through the atmosphere. Flanged buttons are found in Australia. These indicate flight into near space for at least several minutes to allow molten spheres to congeal and then, upon re-entry, partly remelt on their front faces to form flanges. A former interpretation of tektites in terms of impact ejection from the Moon has been discarded on geochemical criteria. It is possible that the comet that generated the Australian tektites broke into several fragments before impact, laying down a swath of small craters or possibly just searing the ground along a path extending from Hainan Island, China, and striking across southeast Asia to Thailand. Large layered blobs of glass termed Muong Nong tektites from a type locality in Laos occur along this path. In 1967, I made the suggestion that the 20-km Elgygytgyn crater in Siberia might be the source of the Australasian strewn field, but subsequent dating of this crater as 4 Ma shows that it is too old to be the source of this field.

A 1961 paper by W.F. Cannon entitled 'Impact of uniformitarianism' examines the role of this principle laid down by Charles Lyell in his 1830 'Principles of geology'. Nowadays a paper entitled 'The impact of impacts' would seem to be in order in view of the catastrophic role played by the collision of bolides with Earth, causing craters, wild fires, and extinctions. As the planetologist and historian of science Ursula Marvin has pointed out, bolide impacts are a geological process of major importance which, by its very nature, demolishes uniformitarianism as a basic principle in geology. To regard bolide impacts as uniformitarianism, imposing a modern usage on an 1830s Lyellian term, would amount to an exercise in 'newspeak'.