[We reproduce below an article on the contributions of Eugene Merle Shoemaker in the study of impact cratering in Australia, which we hope will be of great interest to our readers The article is reproduced from the Australian Journal of Earth Sciences, v 52, no 45, 2005, pp 477-479 with the permission of the Geological Society of Australia Our grateful thanks are due to A E Cockbain, Editor-in-Chief of the Journal for the permission accorded – Editor]

THE SHOEMAKER LEGACY TO THE AUSTRALIAN IMPACT RECORD

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'Gene always wanted to use his rock hammer to study impact craters on the Moon When he realized that wasn't possible, he chose Australia'

The Australian continent offers one of the best places on Earth for studies of impact cratering The low relief, aridity, and extensive Precambrian basins which dominate the Australian outback maximise the preservation potential and expression of both recent and ancient impact effects Subdued topography also facilitates exploration of these features Recognising this, starting in the mid-1980s, Gene and Carolyn Shoemaker visited impact structures in Australia for 12 seasons, studying more than 20 different impact craters, eroded impact structures and ejecta fallout units, as well as numerous 'false alarms' Yet, to date only a fraction of this work has appeared in print or is accessible to the public Gene Shoemaker was of the philosophy that he should gather as much data as he could while he was able to, feeling he could always write reports and papers at a later date However, Gene's tragic death in a car accident in Australia in 1997, while traveling to the Goat Paddock impact crater, prevented publication of much of this work This body of research currently is archived at the US Geological Survey in Flagstaff, Arizona Rocks sampled from the numerous impact sites have been sent to the Natural History Museum of the Smithsonian Institution, and may be borrowed there for study

Impact cratering is a fundamental geologic process throughout the solar system The lunar surface reveals the most complete record of impact cratering in the

neighbourhood of Earth during the last several billion years. From his study of the lunar impact record, Gene estimated the present production rate of terrestrial craters up to 10 km in diameter from Earth-crossing asteroids Further, Jupiter's satellites also carry a record of impact cratering during late geologic time, allowing an estimate of cratering rates from asteroid and comet impacts In 1983, Gene and Carolyn started the Palomar Asteroid and Comet Survey (PACS), a long-term project aimed at evaluating populations and fluxes of Earth (and other planets)-crossing asteroids and comets, resulting in an increase in the number of known objects In 1984 Gene and Carolyn began surveying Australian impact structures, with the aim of establishing the terrestrial flux of impacting bodies during ancient times For more than 12 years their astronomical and geological efforts were enthusiastically synthesised Newly catalogued asteroids and comets, fresh data on lunar craters, and discoveries of craters and impact debris layers on Earth permitted a reassessment of Earth's bombardment history, stretching back some 3 5 billion years

In 1984, when the Shoemakers first arrived in Australia, only about 10 Australian impact structures were known Because very few geologists were studying impact craters, or were interested in such, an empty niche existed which the Shoemakers filled without impinging on the work of Australian geologists One exception was the multidisciplinary study of Gosses Bluff impact crater by Milton, Glikson, Brett and others, started in 1968 By the end of their fourth field season in 1987, some 18 structures of known or probable impact origin had been identified While earlier geologists were the first to notice and to mention many circular structures, definitive evidence for an impact origin was in the main identified by Gene and Carolyn It could be said that their interests spurred on many Australian geologists and geophysicists to look for impact structures, and that this increased activity led directly to remarkable refinements in their geological record Recently, with results from regional geophysical surveying programs, and with more people tuning their eyes for the distinct signatures of impacts, many more structures have been discovered Several of these impact structures were identified only after Gene's death, including Woodleigh, Gnargoo (probable), Yarrabubba, Matt Wilson, Foelsche, Barossa Valley, Amelia Creek, Gulpuliyul (probable) At the

time this issue goes to print, the Australian impact record includes seven small impact craters or crater clusters associated with iron meteorites or tektites, 25 eroded or/and buried impact structures, nine possible impact structures and eight impact ejecta fallout units, some with associated tsunami effects. Gene's goal of acquiring a complete dataset of impact sites in Australia's Proterozoic basins may yet be realised.

Most members of the relatively small community of impact geologists require evidence for target shock effects or for meteoritic chemical traces, to verify a suspected impact site. Detailed structural features often receive less attention. However, many factors influence the development, preservation and detection of shock or contaminant features. Microscopic shock lamellae (planar-deformation features) are best formed in crystalline rocks and quartzite, and to a lesser extent in other quartz-bearing sedimentary rocks. Impact structures may contain shatter cones, those distinct striated 'horse tail'-like fractures that are experimentally verified as field criteria of shock history, but shatter cones may be scarce in other impact structures. Finding an alternative way to test an impact hypothesis may be necessary. Gene believed that impact structures could be identified by their structural characteristics. Hypervelocity impact events are so strikingly different from any other geological process, that the deformation and damage done to target rocks should be unique. Consequently, instead of concentrating on petrography and geochemistry, Gene mapped the geology. Through his mapping, he was able to better characterise the deformation of simple craters. These are characterised by the unique forms of their buckled and overturned rims, and complex structures with circumferential shortening folds collaring a semi-chaotic zone where strongly distorted rocks vied for space. In this way, not only was he able to provide evidence for the impact origin of several structures, but also, his mapping constitutes three-dimensional structural analysis that is fundamental for the understanding of the cratering process. Of special importance are development of central uplifts, effects of oblique collisions on structure and ejecta, influence of different impactor speeds and compositions, and the structural manifestations of target lithology.

Gene negotiated the Australian impact record as a geologist with hammer in hand. He was interested in both small craters and larger complex structures. Each season, he and Carolyn would pore over the early Landsat spacecraft images looking for circular features worthy of investigation. Sometimes topographical maps would show something unusual. By giving talks to groups or by discussing the attributes of impact with other geologists, they often would learn of puzzling features they should visit. Word of mouth and letters often described new possibilities. Road maps sometimes showed 'meteorite craters', although field checking seldom confirmed impact signatures and, more often, clearly indicated an alternative origin. Many craters that the Shoemakers visited proved to be, under close examination, sink holes, collapse structures, round spots, or animal burrows. Some of the true impact craters had been briefly described; some had been searched for meteorites or shatter cones; some had been mapped with little detail. Whatever had not been done, the Shoemakers worked on. Sometimes Gene mapped on air photos; sometimes the two made topographic maps from scratch using rod and staff and a time-honoured alidade on a tripod. Sometimes they searched for impact glass and meteorites; sometimes they made gravity or magnetic surveys. Many of their sites were only poorly located on early geological or topographic maps and had never been flown for aerial photography. When they began their Australian work, the Global Positioning System (GPS) had not yet been developed, so they shot in locations with a theodolite, triangulating from stars and becoming familiar with the night-time sky down under.

In the process of all this activity, Australia became as familiar and beloved as their home in Arizona. Each season on arrival from the United States, they would load their little Hilux pickup with a field library, camping gear, tools, food, water, and extra fuel, batteries and tyres. Starting their work in the north, they travelled southward as the Australian winter eased. Their first three field seasons were spent in Western Australia, and then they moved to Northern

Territory and South Australia before progressing onward to Queensland. Many structures were visited a number of times for extra field work or for field checking earlier data. Occasionally, other geologists, geophysicists, geochemists, and friends went along with the Shoemakers for a few weeks or more. At one time or another, camp members included Glen Beere, Alan Wilson, David Roddy, Jeff Plescia, Kuni Niishizumi, Candace Kohl, Mark Caffee, Bob Finkle, Mike and Carole Dence, Glenn and Gretchen Izett, and Ralph and Herta Uhlherr. During one season, even their grandson Sean Woodard was part of the team, but more often they travelled the Outback alone. It was not until 1996 that they carried a GPS and a satellite telephone. Computers, phones and other electronic devices were not part of their typical field equipment, and they were seldom in touch with the rest of the world.

It was difficult to say which crater was their favorite, for each was quite different from another with its own unique geology and with its own special challenges. The Shoemakers' first season took them to the Spider structure

in the Kimberley, and a period of adventure. They tried to drive into the structure but were constantly blocked by quartzite ridges. Knowing that others had been to Spider before them, they concluded those visitors must have accessed the structure from the east via the Hann River. From the Gibb River Road, they turned into the river bed of the Hann and headed downstream but, only a short distance farther, their Hilux sank. Unloading the entire vehicle onto the riverbank, they succeeded in winching the pickup out on to a shallow ledge, which enabled them to drive farther on higher ground, but still not into the crater. Finally, through the good graces of Stockdale Mining, the Shoemakers were helicoptered into the centre of Spider for a week of mapping. Each day they would climb the 'spider's legs' and observe the smoke of a bush fire coming ever closer. Toward the end of the week, seeing the matter of their departure or the arrival of the fire as touch and go, they made plans for escape into the billabong by which they were camped. Fortunately, the helicopter arrived the afternoon before the fire swept over the area. Another year, determined to continue mapping the remaining large area of Spider by use of their vehicle, the Shoemakers spent two days circumnavigating the structure. Finally they drove over the rim by cutting trees, hauling boulders out of the way, and winching the truck over some steep, rough places. Of course, after mapping was completed, they discovered the easier route which included crossing their nemesis, the Hann River.

Teague Ring, posthumously named Shoemaker, is one of the larger structures that the Shoemakers mapped. As they visited the structure several seasons, they became friends with owners Ken Shaw and Dawn Martin, and often stayed with them before and after their field work. Ken and Dawn are progressive ranchers and always had fascinating stories to tell, both of their ranching practices and of the adventures and misadventures of those traveling the famous Canning Stock Route across Cunyu Station. Often the whole region was decorated with the wild flowers that covered the paddocks following the rainy season. The ring lakes that highlight the structure were typically filled with colourful brackishwater. Despite being completely unpotable, they held a mirage quality and were beautiful to behold after months in the dry desert. It was in this structure that the Shoemakers saw their first herd of brumbies, which were curiously racing to catch up with them and observe their actions. Well-exposed, the rim exhibited exquisite circumferential folding and was a pleasure to map in detail. Shatter cones present in the Frere iron-formation were also of special interest. Only about half of the structure's central region was mapped during their visits, but the Shoemakers intended to spend portions of several more seasons amongst the wildflowers and alkaline waters of Lake Teague.

Liverpool Crater at the top end of the Northern Territory was one of the last to be studied by the Shoemakers. York Films of England desired footage of the Shoemakers at a crater not commonly filmed, and Gene cagily suggested that if their group could get access from the Northern Land Council, Liverpool in Arnhem Land would be ideal. York Films succeeded, and after Gene and Carolyn helicoptered in with them for filming, they were able to drive back two weeks later to map the crater. When the footage was shot, the setting was very attractive with swimming holes around the rim, verdant eucalypts, and a beautiful arch in one exposure of impact breccia. During the interval when they were away, a bush fire swept across the region, and the Shoemakers arrived with their Aboriginal guides amidst still-smoldering timber. Two of the Aborigines, brothers Johnny Maurirundjul and Jimmy Njimimjuna of the Kurulk tribe, were famous bark painters, who interrupted their schedule of preparing for a show in Germany to go out to this structure where their parents had once lived. At their request, five of their sons piled into the back of the pickup in order to see this place they had never visited. While Jimmy, joined by his son, took a gun to go water buffalo hunting, Gene started his mapping. The other brother, Johnny, remained at the meeting site to ask Carolyn about the 'star' that had fallen from the sky to make the crater. They exchanged their stories of the origin of Liverpool. In the Aboriginal culture, the crater was made as the nest of a giant catfish. Later, on the wall of one of the rock shelters at the crater, the Shoemakers found several pictographs including a depiction of the giant catfish.

Gene always wanted to use his rock hammer to study impact craters on the Moon. When he realised that wasn't possible, he chose Australia. The Shoemakers' legacy to the planetary impact record was to impart a geological perspective and, following suit, many others have begun to examine Australian craters as geological structures rather than morphological features. The Shoemakers' work also has demonstrated that planetary geology can be studied on the ground: perhaps the closest you can get to the surface of another planet here on Earth is by standing on an Australian impact crater. Very few of us will be able to travel to the Moon or Mars, but perhaps we can experience the impact-evolution of a surface in the inner solar system by looking at the rock record in the Australian Outback from the Shoemaker perspective. After all, a four-wheel drive vehicle is much more affordable than a space shuttle.