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Notes

The Western Australian Museum meteorite collection

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Abstract: The first meteorites recovered from Western Australia were a number of irons, the earliest of which was found in 1884 east of the settlement of York. These were named the 'Youndegin' meteorites after a police outpost. Some of the larger specimens were taken to London to be sold as scrap metal, but were recognized as meteorites and eventually acquired by museums. The main mass of Youndegin (2626 kg) was recovered in 1954 and is retained in the collection of the Western Australian Museum.

Despite a sparse population and relatively recent settlement by Europeans (1829), a number of factors have contributed to the excellent record of meteorite recovery in Western Australia. Primarily, large regions of arid land have allowed meteorites to be preserved for millennia, and these are generally easily distinguished from the country rocks. A less obvious, but significant, factor is that, in antiquity, Australian Aborigines do not appear to have utilized meteorites extensively. Finally, systematic collecting from the Nullarbor Region, has contributed to the large numbers of recoveries since 1969.

The 'Father' of the State's meteorite collection was the chemist and mineralogist Edward Sydney Simpson (1875–1939) who, from 1897 to 1939, recorded and analysed many of the meteorites that formed the foundation of the collection. The first *Catalogue of Western Australian Meteorites* was published by McCall & de Laeter in 1965 (Western Australian Museum, Special Publications, **3**). Forty-eight meteorites were listed, 29 of which were irons (some of which have since been paired). Interest in meteorites increased in the 1960s, so that when the second supplement to the catalogue was published in 1972, 92 meteorites were listed with stones accounting for most of the additional recoveries. Today, the collection contains thousands of specimens of 248 distinct meteorites from Western Australia (218 stones, 26 irons and four stony-irons), and around 500 samples of potentially new meteorites (mostly chondrites from the Nullarbor) that remain to be examined. There are also specimens of 160 meteorites from other parts of Australia and the rest of the world. While numerically the collection is small compared to other major collections in the world, it contains a high percentage of main masses from Western Australia (around 85%), including many rarities, and has an aggregate weight in excess of 20 tonnes. The small proportion of falls to finds (4 : 244) reflects the sparse population of the State. This may change significantly when a network of all-sky fireball cameras is established in the Nullarbor Region.

Covering an area of $2.5 \times 10^6\,km^2$, Western Australia represents approximately one third of the Australian continent. For more than a century, the State has been a rich hunting ground for prospectors and collectors, and has proved a prolific source of meteorite finds (de Laeter & Bevan 1992; Bevan 1992*a*, 1996). However, the early history of meteorite recovery in Western Australia reflects extensive mineral exploration and the clearing of land for agriculture that, serendipitously, resulted in the discovery of meteorites.

As early as the 17th century, Dutch explorers examined the coastline of Western Australia and made some geological observations. Before the establishment of the Swan River Settlement (now Perth, the State capital) by the British in 1829, British and French maritime surveys had returned small collections of rocks to Europe for examination. However, in Western Australia, it was not until the mid- to late 19th century that economic minerals were sought in earnest, and the first meteorite discoveries were made. Moreover, the establishment of a repository for mineralogical collections in Western Australia presents an interesting history in itself, and has contributed significantly to the extensive collection of meteorites that exists at the Western Australian Museum today.

Despite mineral-collecting activity in the mid 1800s, no official repository for the material was established and, for many years, mineral

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and rock specimens gathered by government agencies remained dispersed throughout the offices of the government officials and private individuals concerned. Some were deposited at the 'Swan River Mechanics Institute and Museum', an institute established by public subscription in 1860.

In 1881 the Reverend Charles Grenfell Nicolay (1815–1897), then chaplain to the Fremantle convict establishment and scientific advisor to the government, was authorized by Governor Sir William Robinson to begin a public collection of rocks, minerals and fossils. A self-taught natural historian, Nicolay had previously lectured in geography at King's College, London, and between 1848 and 1856 he had held the positions of Dean, Deputy Chairman and Professor of Geography and Ancient History at Queen's College, London (Playford & Pridmore 1969). This pioneer mineral collection formed the basis of a 'Geological Museum' housed in the Guard Room at the Fremantle convict establishment adjacent to Nicolay's private residence. Nicolay arranged and added to the collections of prominent early workers. Initially, the collection is reported to have fitted into two glazed bookcases.

The establishment of the Geological Museum at Fremantle in 1881 saw it become the first government-funded museum in Western Australia. The institution rapidly underwent several name changes from the 'Registry of Mines and Minerals' to the 'Registry of Minerals' before settling on the 'Geological Museum'. During his tenure as Curator of the Geological Museum (1881–1889), Nicolay acted as a geological consultant to the government on several projects, improved the mineral collection and wrote geological notes.

The first discoveries

The earliest meteorites found in Western Australia were a number of irons, the first of which was discovered on 5 January 1884, when agriculture was being established east of the settlement of York, a small town 80 km east of Perth. These were named the 'Youndegin' meteorites after a police outpost 50 km NW of the find site. However, the meteorites were actually found 1.3 km NW from Penkarring Rock, now known as Pikaring Hill (Fig. 1). The first specimen, designated 'Youndegin I' (11.7 kg), was found by a mounted policeman, Alfred Eaton. Nicolay requested the Commissioner of Police in Perth to send Mr Eaton back to Penkarring Rock to search for additional specimens, three of which had been seen at the time of the initial discovery (designated Youndegin II–IV, 10.9, 7.9 and 2.72 kg, respectively). These fragments, and a substantial amount of weathering products (iron oxides), suggested that the meteorites had lain on the surface for a considerable period, and may represent the disintegration of a single mass.

Reverend Nicolay sent Youndegin II and IV to the British Museum (Natural History) where Fletcher (1887) confirmed their meteoritic nature. Fletcher (1887) also noted a cubic form of graphite that he called 'cliftonite'. This was the first description of a meteorite found in Western Australia. In exchange, Lazarus Fletcher, Keeper of Minerals, sent 85 specimens of minerals from classic European and North American localities, making a significant contribution to the growing mineralogical collection. A sample of Youndegin was exhibited at the Colonial and Indian Exhibition in London in 1886 (Anon. 1886).

Over the succeeding 45 years, numerous other masses of the same meteorite were recovered in the same general area (Fig. 1). Youndegin V and VI (173.5 and 927 kg) were found in 1891 and 1892, respectively. Both of these masses were sold to a mineral dealer in London (Gregory 1892). However, Youndegin V was acquired later by H.A. Ward (Ward 1904) and eventually went with his collection to the Field Museum of Natural History in Chicago, while the Naturhistorisches Museum in Vienna purchased Youndegin VI. In 1929 Youndegin VII (4.1 kg) was found, and a number of fragments collectively known as Youndegin VIII (totalling 13.6 kg), the latter were distributed among private collectors. Evidently, one of these fragments was made into a horseshoe that hung in a blacksmith's workshop in York for many years (Simpson 1938).

Some irons from the district were not initially named Youndegin. Two fragments found to the east of Pikaring Hill in 1892 by Aborigines were named 'Mount Stirling' (92.3 and 0.68 kg) (Cooksey 1897). Buchwald (1975) suggests that Ward may have borrowed the large Mount Stirling mass on his visit to Australia in 1896 in order to cut it. Some 20 kg of material was sold or exchanged in large and small slices from Ward's Natural Science Establishment in Rochester, New York. The bulk of the main mass of Mount Stirling was returned to the Australian Museum in Sydney, where 0.42 kg of the 0.68 kg mass is also preserved.

In 1893 and 1933, respectively, two masses were found north of Pikaring Hill and named Mooranoppin I and II (1.6 and 0.82 kg). The larger of the masses went to the Ward–Coonley

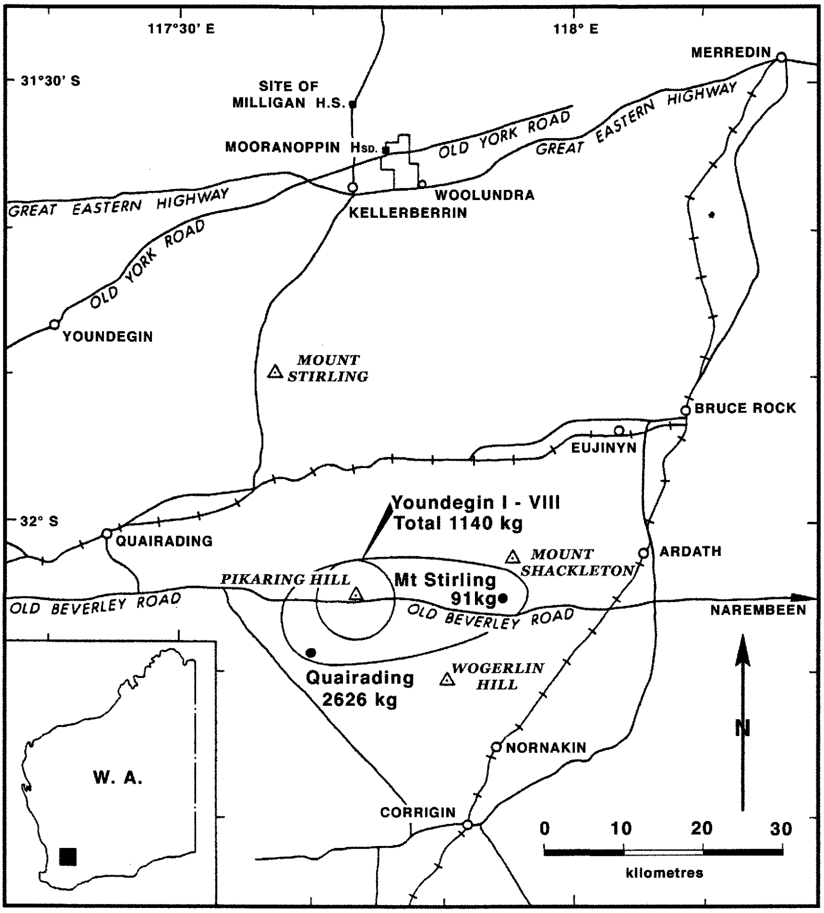

Fig. 1. Map showing the location of masses comprising the Youndegin meteorite shower in Western Australia (after Cleverly & Cleverly 1990).

Collection (Ward 1898), whilst the smaller mass (now 0.725 kg) was retained and is now in the Western Australian Museum Collection. In 1903 the largest mass of Youndegin yet discovered (2626 kg) was found SW of Pikaring Hill (Fig. 2). The mass remained at the site of discovery until 1954 when it was rediscovered and named Quairading. Subsequently, the mass was presented to the then Western Australian Museum and Art Gallery. The common origin of the Youndegin masses was demonstrated by de Laeter (1973*a*) who showed that they belonged to chemical group IAB (Wasson 1974). A comprehensive metallographic description of Youndegin has been provided by Buchwald (1975).

The distribution of fragments of Youndegin on the ground resulted from the atmospheric disruption of a large meteoroid travelling in a SW direction. However, Cleverly & Cleverly (1990) re-examined the provenance of some of the masses in the Youndegin shower and, on the basis of this, delineated a tentative strewn field indicating atmospheric passage in a westerly direction (Fig. 1). In recent years, two more masses of Youndegin have been recognized. A mass weighing 4.66 kg was described by de Laeter & Hosie (1985), now at the High School in Quairading, and a small, unlabelled mass weighing 1.5 kg was discovered by the author in the collection of the E. de C. Clarke Geological Museum at the University of Western Australia. The latter was analysed by Wasson *et al.* (1989) and shown to be part of Youndegin.

In their re-assessment of provenance of the Youndegin irons, Cleverly & Cleverly (1990) noted a small mass of unknown weight, and

Fig. 2. Harry Wheeler (Western Australian School of Mines) with the main mass (2626 kg) of the Youndegin meteorite shower found near Quairading, Western Australia (see Fig. 1).

described it as 'double fist-sized', that was found around 1968 close to the locality of the original Youndegin finds. The mass was taken to a machinery company in Quairading where an attempt was made to cut it. This may be the mass now at Quairading High School (Cleverly & Cleverly 1990). Youndegin is, therefore, a large shower comprised of at least 15 masses with a total weight of more than 3.8 tonnes (t).

The Western Australian Museum

Bringing the Geological Museum to greater public prominence, in 1889 the collection accumulated by Nicolay was transferred from Fremantle to Perth. There the collection was combined with the collection of the Government Geologist, Henry (Harry) Page Woodward (1858–1917) (appointed to a permanent position in 1887), and housed in the room formerly used as the High Court of Justice in the old Perth Gaol, today still a part of the Western Australian Museum complex. Bernard Henry Woodward (1846–1916), Harry Woodward's cousin, was made Curator to the Geological Department. Also, from 1889 to 1895 Bernard Woodward was the government analyst, responsible for almost all assaying in the State. In March 1891 Bernard Woodward was appointed as Curator of the Geological Museum and the institution was constituted as a separate department from that of the Government Geologist (Woodward 1912; Ride 1960; Lord 1979).

The Geological Museum was formally opened at its new site on 9 September 1891 by the Governor, Sir William Robinson, the Premier, Sir John Forrest, the Reverend Nicolay and the new curator, at a meeting of the Western Australian Natural History Society. With the purchase and addition of the collections of the museum of the Swan River Mechanics Institute by the government in June 1892, the Geological Museum quickly diversified and changed its name to the Public Museum embracing zoology, botany and ethnology, as well as geology. In rapid succession, the institution changed its name to the Perth Museum in 1895, and then to the Western Australian Museum and Art Gallery in 1897. Sixty-two years later, in 1959, the Western Australian Museum and the Art Gallery of Western Australia became separately named and independent institutions (Ride 1960).

The early meteorite collection

Following the initial discovery of the Youndegin irons, meteorites were recovered periodically from Western Australia. The Ballinoo iron meteorite (group IIC) weighing 42.2 kg was found in 1892 by G. Denmack, 10 miles south of Ballinyoo Springs on a tributary of the Murchison River. Only one slice of this meteorite (2475 g) is preserved in the Western Australian Museum's collection, and this was accessioned in 1954, the main mass (11 kg) having gone with Ward's collection to the Field Museum of Natural History in Chicago, and significant portions to the American Museum, New York, the Smithsonian Institution, Washington, The British Museum (Natural History) in London and Harvard University, Cambridge, Massachusetts. Division and distribution of meteorites, often by sale, was not an unusual occurrence for early discoveries from the State. For example, only five of the 15 masses (including the main mass) of Youndegin are currently held by the Western Australian Museum, although samples from the other masses of Youndegin have been acquired by exchange from other museums over the years.

During the latter part of the 19th century, and the early part of the 20th century, meteorites from Western Australia were held in a number of institutional collections, and in private hands. In addition to the Western Australian Museum, the principal institutions holding meteorites included the Geological Survey of Western Australia, the former Government Chemical Laboratories (now Chemistry Centre of Western Australia), the University of Western Australia, all in Perth, and the Western Australian School of Mines in Kalgoorlie (now part of Curtin University of Technology).

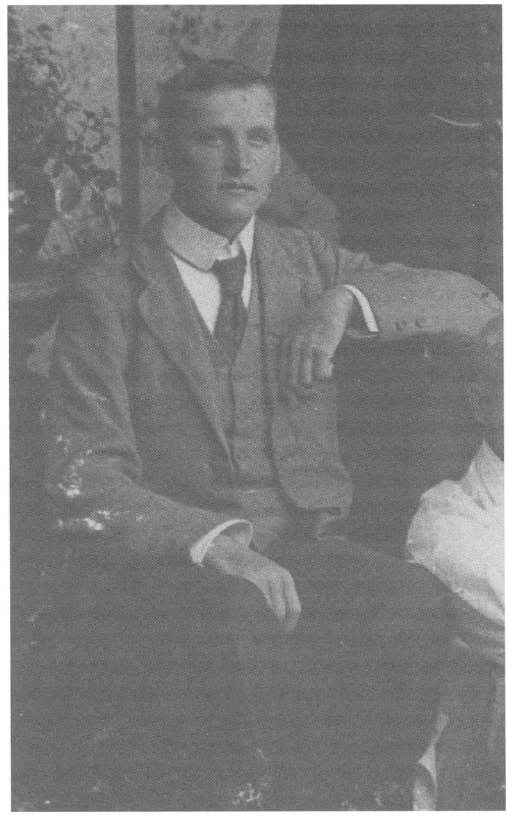

Fig. 3. Edward Sydney Simpson (*c.* 1897) first as Mineralogist and Assayer in the Geological Survey of Western Australia, and then as Government Mineralogist and Analyst (1922), described many of the early meteorite recoveries from Western Australia.

The 20th century

The most prominent scientist involved with the early description of meteorites from Western Australia was Edward Sydney Simpson (1875–1939) (Fig. 3). Simpson was appointed as Mineralogist and Assayer to the Geological Survey of Western Australia in 1897. At the time, the Geological Survey occupied premises on the same site as the museum. A graduate of the University of Sydney, later Simpson enrolled at the University of Western Australia (UWA founded in 1911) (Glover 2003). With a credit from his degree in Mining and Metallurgy from the University of Sydney, Simpson was conferred with his degree in Geology in 1914 after only 2 years and became the first graduate of UWA.

During his tenure, Simpson's contribution to mineralogy was outstanding, and in 1922 he was made Government Mineralogist and Analyst, and head of the combined laboratories of the Health, Agriculture and Mines departments. Simpson recorded an immense amount of data on Western Australian minerals, which eventually earned him a Doctorate of Science from the University of Western Australia (the first awarded by that institution) in 1919. However, he also worked on a number of meteorites. Specimens accumulated during his tenure, eventually known as the Simpson Collection, included some meteorites. *Minerals of Western Australia*, Simpson's famous work, published in three volumes after his death, is still the principal reference work on mineral occurrences in the State (Simpson 1948).

Essentially, in the first 40 years of the last century, Simpson was instrumental in establishing a collection of meteorites from Western Australia. Simpson ensured that new meteorites, wherever possible, were placed in the museum's collection, although many were initially retained by the Geological Survey of Western Australia.

Simpson often retained the small samples of the meteorites on which he worked. By 1912, the museum's collection contained a number of masses (or samples thereof) of distinct iron meteorites, Youndegin, and the first recovered mass of Mount Dooling (group IIC, 31.3 kg, found in 1909). Another mass, Roebourne (group IIIAB, 87.3 kg, found in 1892), had been acquired by H.A. Ward (Ward 1898), whilst main masses of Nuleri (group IIIAB, 120.2 g, found about 1902) and Premier Downs (first found in 1911, and later to be renamed Mundrabilla) were then held by the Geological Survey of Western Australia (Woodward 1912). Most of these meteorites had been analysed and classified by Simpson (see McCall & de Laeter 1965, and references therein). Another iron, Yarri (group IIIAB, 1.52 kg), had reportedly been found before 1908 and was later held in the WA School of Mines (Cleverly & Thomas 1969). From September 1935 until his death in 1939, Simpson was a Trustee of the Western Australian Museum and Art Gallery, and he continued to contribute greatly to its mineralogical collections.

The earliest comprehensive listings of Australian meteorites were published by Cooksey (1897) and Anderson (1913). Anderson (1913) recorded that Western Australian meteorites then comprised seven irons, together with numerous masses of Youndegin. The total number of distinct meteorites from Australia then held in various collections totalled 46, including 29 irons. The next major listing of Australian meteorites was prepared by Hodge-Smith (1939). Twenty irons (comprising 27 separately named specimens), one stony-iron and four stony meteorites were listed from Western Australia. All of these meteorites were finds, except for Gundaring which was found in 1937 but had been linked to a fireball seen in 1930. However, the preservation of this mass indicates prolonged terrestrial residence, and suggests that it is highly unlikely to have been an observed fall.

The first comprehensive catalogue of Western Australian meteorites was published by McCall & de Laeter (1965). The number of iron meteorites had increased by then from 20 to 29, the number of stony-irons from one to four (including Bencubbin, later to be reclassified) and the number of stones from four to 15. However, only one substantiated observed fall, Woolgorong (L6, fell 1960), was listed.

During the 48-year period between 1912 and 1960, a number of important meteorites were recovered, some of which were deposited at the Western Australian Museum. The most important of these was Bencubbin. The first mass (54.2 kg) of Bencubbin was discovered in 1930 during ploughing (Fig. 4). A second, larger mass (64.6 kg) was found in 1959, and a third mass (15.76 kg) was found in 1974. Bencubbin has subsequently proved to be of extreme rarity and scientific importance. Originally classified as a 'stony-iron' (McCall 1968), today it is recognized as the type specimen of a new group of carbonaceous chondrites (CB) or 'Bencubbinites' (Weisberg *et al.* 1990, 2001; Rubin *et al.* 2001). Bencubbin is a breccia enclosing clasts of material from other chondritic groups (both carbonaceous and ordinary), and the meteorite remains the subject of extensive ongoing research.

Fig. 4. Cut face of the first mass of Bencubbin found in 1930. A large ordinary chondritic inclusion (dark patch) has been sampled by coring.

Other masses recovered during this time include two masses of Mount Edith (IIIAB, 160.6 kg found in 1913, and 165.1 kg found in 1914), Youanmi (IIIAB, 118.4 kg found in 1917), Tieraco Creek (IIIAB, 41.6 kg found in 1922) and Mount Magnet (chemically anomalous, 16.6 kg found in 1916 comprising two interlocking fragments) (McCall & de Laeter 1965).

Another significant discovery was the recognition from the air in 1947 of the Wolfe Creek Crater measuring 880 m in diameter (Reeves & Chalmers 1949). In 1949 the crater was visited and numerous masses of iron shale weighing several thousands of kilogrammes in total weight were recovered (Guppy & Matheson 1950; Cassidy 1954; La Paz 1954; McCall 1965*a*). Taylor (1965) described unaltered iron meteorite material located near Wolfe Creek Crater that has been classified as a group IIIAB iron (Scott *et al.* 1973). More recently, Buchwald (1975) has provided a modern metallographic description of the Wolf Creek[1] iron meteorite. Fresh meteorite material was later used by Shoemaker *et al.* (1990) to derive a terrestrial age for the impact event of approximately 300 ka.

The only other crater associated with meteorites known in Western Australia at that time was Dalgaranga. First noted by an Aboriginal stockman, Billy Seward, in 1921, the Dalgaranga crater was recognized as meteoritic in origin by the station manager, Gerard E.P. Wellard, in 1923. Numerous small fragments of meteorite were found in and around the crater that measured 25 m in diameter. Only one fragment weighing 40 g appears to have been preserved in Simpson's collection. Simpson (1938) described and analysed the meteorite that later proved to be a mesosiderite (Nininger & Huss 1960; McCall 1965*c*; Wasson *et al.* 1974; Hassanzadeh *et al.* 1990). Dalgaranga was the first impact crater to be recognized in Australia. The meteorite formerly known as Murchison Downs, reportedly found in 1925 (McCall & de Laeter 1965), has been shown by Bevan & Griffin (1994) to be a transported fragment of Dalgaranga (see also Wasson *et al.* 1989).

In Western Australia there are three meteorite impact craters (Wolfe Creek Crater, Dalgaranga and Veevers) with associated meteoritic fragments. Of these, Veevers Crater is the most recently recognized. The Veevers meteorite impact crater is situated between the Great Sandy and Gibson deserts in Western Australia at co-ordinates 22°58′06″S, 125°22′07″E. The bowl-shaped, circular structure, measuring 70–80 m in diameter and 7 m deep, was recognized as a possible impact crater in July 1975 (Yeates *et al.* 1976). Yeates *et al.* (1976) surveyed the crater but did not find any meteoritic material. Subsequently, in August 1984, the American astrogeologist Eugene M. Shoemaker (1928–1997) and his wife Carolyn S. Shoemaker visited the locality and recovered several small fragments of iron meteorite from two localities immediately to the north of the crater. The material comprised irregular, weathered fragments, the largest weighing 8.9 g. In July 1986, during a further visit to carry out a detailed survey of the crater (Shoemaker & Shoemaker 1988), an additional 32 metallic slugs and fragments of meteoritic iron were recovered, the largest weighing 36.3 g. Most of this material was found just to the east of the crater, on the flanks of the crater rim and adjacent plain. A precise age for the crater has not yet been published, although Shoemaker & Shoemaker (1988) estimated that it was formed around 4000 years ago. Wasson *et al.* (1989) analysed the meteorite and showed it to be a normal member of chemical group IIAB. Bevan *et al.* (1995) described the Veevers fragments showing that they were the disrupted remnants of a crater-forming projectile, and thus confirmed the origin of the crater. Subsequently, additional material has been recovered from the vicinity of the crater by private collectors, the total weight of which is unknown.

In parallel with the growth of space science and exploration, the late 1950s and early 1960s saw a heightened interest in meteoritics in Western Australia, and the museum's collection grew steadily. Four main factors contributed to the new impetus. First, a research group of physicists at the University of Western Australia, led by Dr Peter M. Jeffery (1922–1990), was searching for isotopic anomalies in meteorites (e.g. see de Laeter & Jeffery 1965). This group encouraged Dr G. Joseph H. McCall, a geologist then at the university, to classify the many accumulated and undescribed stony meteorites in the Western Australian Museum's collection, including the newly fallen Woolgorong meteorite (McCall & Jeffery 1964), whilst de Laeter (1973*b*) undertook to classify the iron meteorites. An X-ray fluorescence spectrometry technique was established at Curtin University of Technology to measure the Ni, Co, Ga and Ge contents of irons to determine their chemical classification (Thomas & de Laeter 1972; de Laeter 1973*b*).

Secondly, owing to the lack of a permanent curator, under the auspices of the Trustees, the Western Australian Museum formed an ad hoc Meteorite Advisory Committee to oversee the management of the meteorite collection, arrange exchanges with other institutions and provide research material when requested. A well-known meteoriticist, Dr Ray A. Binns, later became Chair of the Meteorite Advisory Committee. His international contacts proved invaluable in arranging for meteorite exchanges, and in amending the names of some Western Australian meteorites to conform to guidelines laid down by the Nomenclature Committee of the Meteoritical Society. During this time Dr Duncan Merrilees (Curator of Palaeontology), Dr Colin Pearson (Conservation), Dr Leigh F. Bettenay (temporary Assistant Curator of Meteorites) and Dr Kenneth J. McNamara (born

1950) (Curator of Palaeontology and Merrilees' successor) acted consecutively in the capacity of 'Curator of Meteorites' to effect the decisions of the Advisory Committee. It was not until 1985 that the Western Australian Museum appointed the author as the institution's first permanent Curator of Mineralogy and Meteoritics.

Role of the Western Australian School of Mines

The third contributing factor was the existence of an active group of scientists interested in meteorites at the Western Australian School of Mines in Kalgoorlie. The principal meteorite researchers were Mr M. Keith Quartermaine and Mr William (Bill) Harold Cleverly (1917–1997), both of whom undertook meteorite collecting fieldwork post-1960. Additional support was provided by Harry W. Wheeler, R.P. Thomas, M.E. Moriarty and T.G. Bateman. During the decade of the 1960s nearly a tonne of meteorite material passed into the Western Australian School of Mines collection, or via the school into other collections in the State and elsewhere. The material included parts, often main masses, of 37 new meteorites representing an addition of about 2% to all meteorites known in the world at that time (Cleverly 1993). This period also saw the gradual recognition of the Nullarbor Region of Western Australia as a potentially abundant source of meteorite finds.

A visit to Western Australia in 1959 of the American Harvey Harlow Nininger (1887–1986), the world renowned meteorite collector, resulted in some important consequences. Nininger exchanged material with the Western Australian School of Mines, also he visited Dalgaranga crater and collected an additional 9.1 kg of meteorite fragments (Nininger & Huss 1960). However, perhaps the most significant outcome of Nininger's visit was his introduction to Mr Albert John Carlisle (1917–1993). Carlisle was a professional bushman who had spent most of his life living and working on the Nullarbor Plain. Nininger acquired two meteorites from Carlisle, one of which, from the Nullarbor, proved to be the only pallasite (formerly Rawlinna (pallasite) now Rawlinna 001) so far recorded from Western Australia.

Prior to his meeting with Nininger, Carlisle had recovered a number of meteorites, notably Cocklebiddy, an H5 ordinary chondrite weighing 19.5 kg, that he found in 1947 on the Nullarbor (McCall & Cleverly 1968). Evidently, Carlisle was inspired by Nininger, and his interest in meteorites rekindled. Subsequently, Carlisle, his wider family and others influenced by him donated large numbers of meteorites either to the Western Australian School of Mines or, after 1969, to the Western Australian Museum. Among the meteorites Carlisle first brought in from the Nullarbor to the School of Mines was the North Haig (964 g) ureilite that had been found in 1961 by R.F. Kilgallon, then only the fourth of its kind known in the world. Another was the L6 chondrite Sleeper Camp (weighing 1.25 kg) found by H. Carlisle in 1962. Both of these meteorites were found approximately 70 km north of Haig railway station on the Trans-Australian Railway (Cleverly 1993). In 1965 Carlisle found another distinct ureilite, Dingo Pup Donga (122.7 g), in the close vicinity of the North Haig discovery. Both ureilites were shown by Vdovykin (1970) to contain diamonds.

The first stony meteorite recorded from the Nullarbor is Naretha (L4 chondrite), which was found in 1915 (McCall & Cleverly 1970). From the 1960s to the present time, the Nullarbor Region has dominated as an area of importance for meteorite recoveries in Western Australia; however, it is not the only region of the State in which meteorites have been found. In early 1964, the Warburton Range iron (group IVB, 57 kg) was brought to the Western Australian School of Mines in Kalgoorlie by two Aboriginal prospectors where it was recognized as a nickel-rich ataxite (McCall & Wiik 1966). The acquisition of the mass was negotiated for the Western Australian Museum where it resides today. In April of the same year, a fragment of a mesosiderite was identified by Cleverly. A field excursion to the site of discovery on Mount Padbury Station (25°40′S, 118°6′E) resulted in the recovery of more than 285 kg of fragments, including several large masses, the largest of which weighed 88 kg (Cleverly 1965*b*; McCall & Cleverly 1965; McCall 1966*a*; Mason 1974).

In 1963 an expedition funded by the National Geographic Society set out from Sydney to search for meteorites and tektites throughout Australia. The party consisted of Dr Brian H. Mason (then of the American Museum of Natural History, New York), Dr Edward P. Henderson (Smithsonian Institution, Washington) and Mr R. Oliver Chalmers (Australian Museum, Sydney). In Western Australia the party sought the find-sites of two meteorites (Mount Egerton and Dalgety Downs) that had been discovered in 1941 and reported in the 1942 annual report of the Government Chemical Laboratories (Mason 1968). Through the help of Mr A.P. Healy, the finder of the Dalgety Downs L4 chondrite, the site was relocated and approximately 214 kg of additional material was recovered. In a later search of the locality by Cleverly, a further 40.9 kg of fragments was found (McCall 1966*b*). A search for the find-site of the Mount Egerton meteorite on Mount Clere Station by the National Geographic expedition was unsuccessful.

A description of the original 1.7 kg of fragments of Mount Egerton was provided by McCall (1965*b*). The meteorite is a rare mixture of metal and enstatite, and, although it was originally described as an anomalous mesosiderite (Grady 2000), the meteorite is more closely related to the enstatite achondrites (aubrites) (Hutchison 2004, and references therein). In June 1966, with the help of the original Aboriginal finder, M.T. Gaffney, Quartermaine relocated the find-site and more than 3000 additional fragments of Mount Egerton were recovered, totalling approximately 20 kg (Cleverly 1968).

Intensive prospecting for nickel during the 1960s led to a number of discoveries in the Eastern Goldfields. In 1967 the Credo L6 chondrite, a 10.8 kg flight-orientated stone, was found about 75 km NW of Coolgardie, and the Fenbark H5 chondrite was found 7 km west of Broad Arrow in May 1968 (McCall & Cleverly 1969*a*). Other meteorites found in the 1960s, 1970s and 1980s include the Baandee (H5), Jeedamya (H4), Wooramel (L5), Mount Margaret (L5), Nimberrin (L6) and Millrose (L6) ordinary chondrites (Bevan *et al.* 1990).

In 1960 a small mass of iron meteorite weighing 1.6 kg was found about 4.8 km east of Gosnells (32°05′S, 116°01′E), an outer suburb of Perth, and about 400 km from the 1909 find-site of Mount Dooling (group IC, 31.3 kg). Based on structural and chemical evidence, de Laeter *et al.* (1972) showed that this latter mass was undoubtedly a transported fragment of the original Mount Dooling meteorite to which the 'Gosnells' fragment could be fitted. A third mass, weighing 701 kg, was found in 1979 at a site (30°0′S, 119°40′E) 3 km east of the Mount Manning Range, about 50 km SE of Diemal, 30 km SW of Johnson Rocks and about 10 km SSW of the 1909 find (Fig. 5). Although this mass was originally named 'Mount Manning', de Laeter (1980) showed that the meteorite is chemically identical to Mount Dooling and is evidently the largest known mass of the same fall. In 1997 Mr John Emmott brought a mass of meteoritic iron weighing 29.2 kg to the Western Australian Museum for examination. The meteorite was reportedly found in the area of the Mount Manning Range many years ago, and chemical data (J.T. Wasson pers. comm.) show that it is another mass of Mount Dooling. This latter mass was not acquired by the museum and, under the

Fig. 5. The 701 kg main mass of the Mount Dooling group IC iron meteorite with the finders, and J.R. de Laeter (left).

terms of the State's meteorite legislation, ownership passed to the finder.

Meteorite legislation in Western Australia

The last major factor influencing meteorite collecting in Western Australia was the introduction, in 1969, of legislation concerning meteorites as part of the Museum Act, which is the enabling legislation of the Western Australian Museum. From that time on, meteorites found (or observed to fall) in Western Australia belong to the Crown, and ownership is vested in the Trustees of the Western Australian Museum. In the legislation, provision is made for expenses and rewards for finders delivering meteorites to the Trustees. The legislation was amended in 1973 as the Museum Act Amendment Act 1973.

More recently, Australian Federal legislation under the Protection of Movable Cultural Heritage Act (1986) prohibits the unauthorized export of meteorites (along with other listed scientific and cultural materials) from Australia. Both State and Federal legislation does not prevent recognized collecting institutions, like state museums, from undertaking normal curatorial transactions such as exchanges, and providing material to foster scientific research. To facilitate scientific interaction between Australia and other countries in the world, institutions like the Western Australian Museum operate under a general permit. Essentially, they are allowed to operate under standard curatorial guidelines common to every major museum in the world.

The promulgation of legislation concerning meteorites in Western Australia had both positive and negative effects. For the first time, the Western Australian Museum was recognized as the repository for meteorites in the State. However, other institutions in Western Australia effectively had their meteorite collections 'frozen', and this caused a general decline in interest, largely on regional grounds, to support meteorite collecting. Nevertheless, a large number of meteorites have come into the Western Australian Museum's collection over the 35 years of the operation of the Act.

Eventually, most, but not all, of the important meteorite masses held at the Western Australian School of Mines, Geological Survey of Western Australia and Government Chemical Laboratories were transferred to the Western Australian Museum's collection. The Geological Museum at the University of Western Australia retains the mass of the Duketon iron (group IIIAB, 118.3 kg found in 1947), and a small number of main masses and a moderate collection are still retained by the Western Australian School of Mines.

The Meteorite Advisory Committee

From 1986 there was a full-time curator in charge of the collection, and the Meteorite Advisory Committee was eventually disbanded in 1989. During its nearly 30 years of operation, the Committee co-opted many local scientists to serve in an advisory capacity to the Trustees, these included Dr Ray A. Binns (then of the University of Western Australia), Dr D. Russell Hudson (CSIRO), Cleverly (WA School of Mines), Mr Michael Candy (The Government Astronomer, Perth Observatory), Mr Joe H. Lord (1919–1999) and Dr Alec F. Trendall (born 1928) (former directors of the Geological Survey), Professor John R. de Laeter (born 1933) (Curtin University of Technology), McCall, Professor Peter G. Harris, Jeffery and Dr Neal J. McNaughton (all of the University of Western Australia).

Observed meteorite falls

Owing to a sparse population, recovered observed meteorite falls are rare in Western Australia. Only four authenticated observed falls are currently recorded, Woolgorong (1960), Millbillillie (1960), Wiluna (1967) and, most recently, Binningup (1984).

In October 1960 a bright fireball was observed by station workers F. Vicenti and F. Quadrio, and a meteorite appeared to fall on the spinifex plain to the north of the boundary fence on the Millbillillie–Jundee track in the Wiluna district. No search was initiated at the time, but two stones were found there later by an Aborigine named 'Louis' and D. Vicenti in 1970 and 1971, respectively. The largest mass, weighing approximately 20 kg and measuring 25 × 26 × 18.5 cm, found in 1970 was taken by Mr J. Finch of Lorna Glen Station to the University of Western Australia where it was recognized as a meteorite and named Millbillillie.

Many other stones from the Millbillillie shower have since been recovered by local Aboriginals, including masses of 8.5, 4.75 and 3 kg. Currently, the Western Australian Museum holds approximately 30 kg of material. From material held in private hands, a crusted mass weighing 368 g was purchased by C.V. Latz. This mass, originally named Nabberu, was described by Fitzgerald (1980). A comprehensive analysis of the Millbillillie eucrite is given by Mason *et al.* (1979). Since 1990 large numbers of additional stones, said to have totalled more than 300 kg, have been recovered over an area close to the original finds. Amongst this material, the first lunar meteorite found outside of Antarctica, Calcalong Creek, was found and exported to the United States (Hill *et al.* 1991).

On 2 September 1967 at 10:46 p.m. local time, following the appearance of a bright fireball accompanied by sonic phenomena, a shower of stones estimated to be between 500 and 1000 in number, and with a total weight estimated at 250 kg, fell approximately 8 km east of Wiluna township. The ellipse of dispersion measured approximately 6.7 × 3.2 km elongated NW–SE. The largest stones of Wiluna (H6) were collected from the NW end of the ellipse indicating an approach from the SE. Masses ranged from 10 kg to 2.2 g and the meteorite was described by McCall & Jeffery (1970). The Western Australian Museum holds 179 meteorite masses, 140 fragments and numerous small masses collected from the SE end of the shower, totalling 145.7 kg.

The Woolgorong L6 chondrite was seen to fall around 20 December 1960, but was not recovered until 1961. Numerous masses, including five large fragments totalling 32–36 kg, were recovered and the main mass is retained at the Western Australian Museum. Several fragments interlock, and about one third of the entire mass can be reassembled (McCall & Jeffery 1964).

More recently, at 10:10 a.m. on the 30 September 1984, after the appearance of a brilliant fireball accompanied by sonic phenomena, a single crusted stone (H5 chondrite) weighing 488.1 g fell within 4–5 m of two women sunbathing on Binningup beach. The locality lies approximately 20 km north of Bunbury and 130 km south of Perth (Bevan *et al.* 1988). The Binningup meteorite (Fig. 6) was the first observed fall from Australia on which short-lived radionuclides were measured within a few months of its fall.

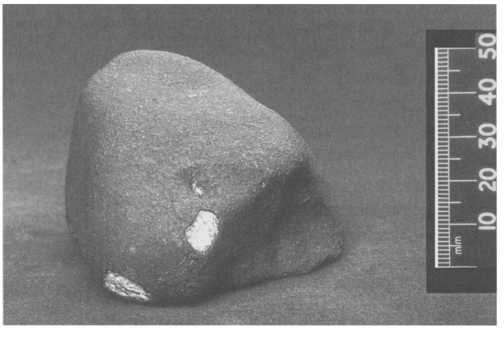

Fig. 6. The Binningup H5 chondrite (weighing 488.1 g) that fell at 10:10 a.m. on the 30 September 1984, after the appearance of a brilliant fireball accompanied by sonic phenomena.

On average, the southern part of Western Australia enjoys 243 days per year with clear skies. Fireballs with the potential to yield meteorites are frequently reported; however, the recovery rate has been extremely low. In an attempt to improve the recovery rate of observed falls, a network of all-sky cameras is to be established in the Nullarbor Region. A single prototype camera has been in operation in the Eastern Goldfields since October 2003. In the first 6 months of operation, the camera detected 37 events, six or seven of which were very likely to have deposited meteorites. With a fully operational network, it is hoped to double the current number of recovered observed falls worldwide (six) with orbital information in the first 2 years. A clean storage facility is to be established at the Western Australian Museum for sample retrieval (Bland 2004). This project heralds a new era of meteorite collection in Western Australia.

The Nullarbor Region

The full potential of the Nullarbor Region as a source of meteorite finds was not realized until the mid to late 1960s (see Bevan 2006). A number of meteorites had previously been collected from the Nullarbor, the first of which were the two small irons weighing 116 and 112 g, and originally named Premier Downs I and II. These were found in 1911 by H. Kent (a railway surveyor) approximately 12.8 km apart near the 357 mile peg on the Trans-Australian Railway Line. Both masses were sent to the Geological Survey of Western Australia where they were described and analysed by Simpson (1912) and Simpson & Bowley (1914). A third mass of the same meteorite weighing 99 g (designated Premier Downs III) was found by A. Ewing before 1918 (Simpson 1938). A fourth mass, reputedly found by a Mr Harrison, was recovered from a site NE of Loongana Station before 1964, and listed under the name Loongana Station by McCall & de Laeter (1965). The find was reported by D.J. Ritchie and was said to have been part of a very large mass. Additional small masses weighing 94.1, 45 and 38.8 g were found in 1965 by W.A. Crowle at a site 10 miles (*c.* 16 km) north of Mundrabilla siding on the Trans-Australian Railway Line.

Earlier, in 1963, a prospector, Mr T. Dimer, claimed that he could locate an enormous iron meteorite that was reputed to be 'as big as a motor car'. Rumours of a large meteorite on the Nullarbor had evidently circulated since at least 1944 (Cleverly 1993). Two unsuccessful expeditions to locate it were conducted during the 1960s involving Cleverly, Quartermaine and McCall. In April 1966, close to the site of the material recovered by W.A. Crowle, two large masses estimated to be 10–12 and 4–6 t, later named Mundrabilla, were found approximately 200 yards (*c.* 183 m) apart and described by the finders R.B. Wilson and A.M. Cooney (Wilson & Cooney 1967*a*, *b*) (Fig. 7). Later, in 1967, W.H. Butler found a 66.5 g fragment that was originally named Loongana Station West by McCall & Cleverly (1970) but proved to belong to Mundrabilla.

The smaller of the two large Mundrabilla masses, weighing 6.1 t, was shipped to Germany for cutting at the Max-Planck Institut für Kernphysik in Heidelberg, and was described by Ramdohr & El Goresy (1971). Eight or nine slabs were cut in 1973–1974, each approximately 4–5 cm thick. The wire-cutting technique was the same as that pioneered by V.F. Buchwald when dividing the Cape York (Greenland) mass (Buchwald 1975). Slabs of Mundrabilla measuring approximately 135 × 70 cm are on display at the Western Australian Museum and the Natural History Museum in London.

Two additional masses weighing 840 and 800 kg, designated Mundrabilla No. 3 and No. 4, respectively, were found by Carlisle in 1979 at a location 20 km east of the find-site of the two large Mundrabilla masses, and around 100 small irons totalling 3.97 kg were discovered by the same finder in 1978, 3.4 km SSW from Tookana Rock Hole (31°41′S, 128°21′E) (de Laeter & Cleverly 1983). In total, at least 12 masses of the Mundrabilla shower (group IAB–IIICD) (including a 3.5 t mass found by Carlisle in August 1988) and hundreds of small irons, altogether totalling more than 22 t, have been recovered to date from a large area between Loongana and Forrest sidings on the Trans-Australian Railway (de Laeter 1972; Bevan & Binns 1989*a*; McCall 1998). A metallographic description of Mundrabilla is given by Buchwald (1975), and the meteorite has been the subject of extensive research (Grady 2000). The meteorite is an unusual mixture of metal and troilite, and has been shown by Choi *et al.* (1995) to belong to group IAB–IIICD.

Between 1963 and 1971 searches on the Nullarbor by staff from the Western Australian School of Mines (joined by Drs Brian H. Mason and Edward P. Henderson in 1967) recovered 809 stony meteorites, with an aggregate weight of 21 kg, in four overlapping strewn fields from an area approximately 100 km NNE of Haig (Cleverly 1972). The material comprised 781 fragments of the H6 chondrite Mulga (north) in a dispersal ellipse measuring 6 × 1 km, 24 fragments of highly weathered H4 chondrite Mulga (south), three pieces of the L6 chondrite Billygoat Donga (Cleverly 1986) and a single stone (found in 1971) of the then-unique C5

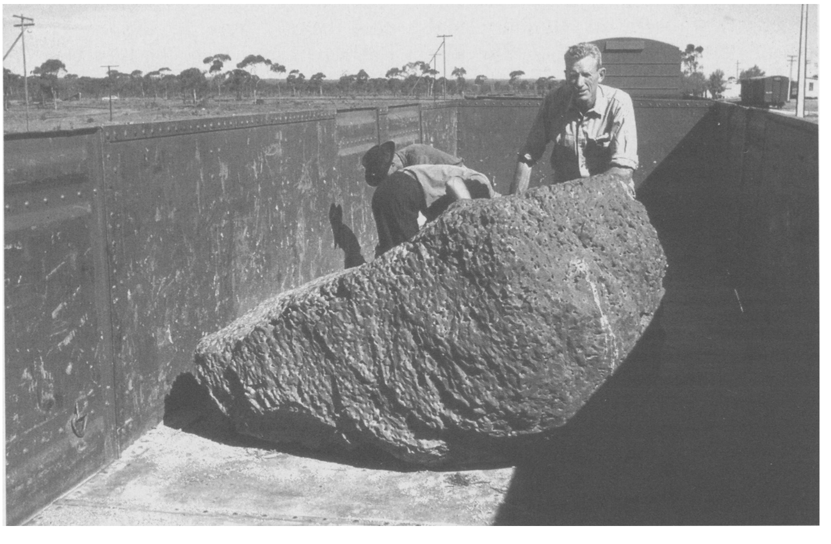

Fig. 7. Main mass (11.5 t) of the Mundrabilla meteorite on route to the Western Australian Museum (W.H. Cleverly centre).

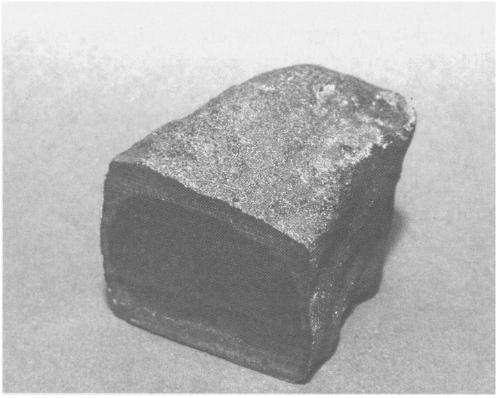

Fig. 8. Main mass of the unique Mulga (west) C5 chondrite, the first carbonaceous chondrite found in the Nullarbor.

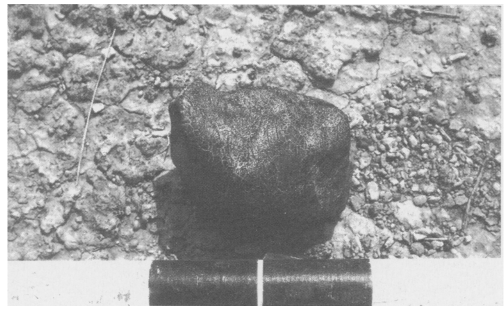

Fig. 9. Mass of the Camel Donga eucrite shower as found on the Nullarbor Plain (5 cm scale).

chondrite Mulga (west) (McCall 1972; Binns *et al.* 1977). Mulga (west) was the first carbonaceous chondrite found in the Western Australian Nullarbor (Fig. 8). Shortly after, in 1974, Carlisle found the small (16.55 g) flight-orientated mass of the CM2 chondrite Lookout Hill on the Nullarbor.

Between 1967 and 1969 nine distinct ordinary chondritic stones found on the Nullarbor were received from Carlisle. These were the H5 chondrite Forrest 001, Webb (L6), Oak (L5), Nallah (H), North Forrest (H5), Reid (H5), North Reid (LL5), North East Reid (H5) and West Reid (H6) (McCall & Cleverly 1969*b*, 1970).

Throughout the 1970s and 1980s, Carlisle continued to recover numerous meteorites from the Nullarbor. Amongst the more notable was the Carlisle Lakes chondrite weighing 49.5 g found in 1977 (Binns & Pooley 1979). For a long time this stone was considered unique, but has since been shown to belong to the R-group of chondrites named for the Rumuruti meteorite, which fell in Kenya in 1934 (Rubin & Kallemeyn 1989, 1993). In 1982 Carlisle was awarded the Order of Australia Medal for his services to meteoritics.

In July 1985 Cleverly and Mason (then a visiting Gledden Fellow at UWA) were guided to the find-site of the Camel Donga eucrite (a fresh crusted stone weighing 503.5 g first found in 1984) by Mrs Jill Campbell. At the site, which is about 75 km NNE of Nurina on the Nullarbor Plain, 11 additional individuals and fragments (weighing 14.9–504 g) of this shower were collected (Cleverly *et al.* 1986). Systematic searching of the Nullarbor for meteorites commenced again in 1986, and further searches of the Camel Donga strewn field during the period 1985–1993 resulted in the recovery of more than 650 stones totalling more than 30 kg (Fig. 9; see also Fig. 5 on p. 9). The completely crusted stones range in weight from 1 to 1456.5 g. The mapped distribution of the stones indicates a flight path towards the NE, and a history of multiple fragmentation in the atmosphere. The condition of the material and ground evidence suggests that the meteorite fell shortly before the original discovery (Bevan *et al.* 1998).

Since 1986 the Meteorite Recovery Programme of the Western Australian Museum (WAMET) was initiated by the author and, in combination with other groups (e.g. EUROMET – a pan-European group of research institutions devoted to meteorite research), has proved extremely successful in recovering meteorites from the Nullarbor (see Bevan *et al.* 1998, and references therein). In 1988 Carlisle found the third largest mass of Mundrabilla weighing 3.5 t, which is currently on display at the Albany branch of the Western Australian Museum (Fig. 10). In all, several thousands of fragments from about 200 distinct meteorites, representing about half of all meteorites known from Australia, have been described from the Western Australian Nullarbor to date (Grady 2000), and many hundreds of specimens of potentially new meteorites remain to be classified (Bevan & Binns, 1989*b*; Bevan *et al.* 1998). Systematic searches by joint teams from WAMET and EUROMET (Bevan 1992*b*) recovered more than 600 specimens of meteorites (totalling approximately 17 kg) during some 10 weeks of searching on four expeditions between 1992 and 1994 in the Western Australian Nullarbor (Fig. 11). Since 1995, however, unusually high precipitation leading to vegetation growth in the

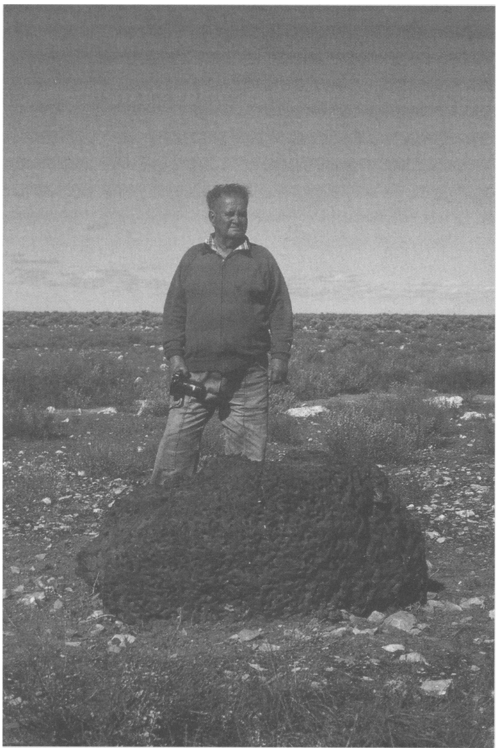

Fig. 10. The 3.5 t mass of the Mundrabilla meteorite found on the Nullarbor by A.J. Carlisle in 1988.

Nullarbor has prevented extensive collecting from the region.

The collection from the Western Australian Nullarbor continues to provide rare meteorite types. For example, Camel Donga 040, two stones totalling 55 g collected by the author in 1988, has been shown by Zolensky *et al.* (2004) to be an unique mixture of pre- and post-metamorphic carbonaceous material from the same asteroid related to the CV chondrites (Fig. 12).

Other meteorites in the collection

Since the establishment of the collection there has been an active programme of exchange with other institutions. In 1971 an exchange of specimens was arranged by McCall with the Academy of Sciences in Moscow. Samples of the Russian material were later exchanged for specimens of rare meteorites from the Natural History Museum in London. In line with other museums, the policy pursued is to acquire, for comparative purposes, material from meteorite types that are poorly, or not at all, represented in the collection. The collection contains around 160 meteorites from other parts of Australia and the rest of the world. Of particular note are the main mass (76 kg) of Miles, a IIE iron from Queensland (found in 1992), approximately 0.5 kg of Murchison (CM2) (fell in Victoria, 1969) and a sizeable sample (660 g) of Peña Blanca Spring (aubrite) (fell in Texas, USA, 1946). Overall the collection contains a high percentage of rarities including samples of three Martian meteorites, Nakhla (fell in Egypt, 1911), Zagami (fell in Nigeria, 1962) and Dar al Gani 476 (found in Libya, 1998), and a sample of the lunar meteorite Dar al Gani 400 (found in Libya, 1998). Other rarities include samples of the ungrouped carbonaceous chondrite Adelaide (found in South Australia, 1972), the type CK chondrite Karoonda (fell in South Australia, 1930) and the main mass of another CK4 chondrite, Cook 003 (found in 1986), from the South Australian Nullarbor.

Summary

Through a combination of physical and human factors, Western Australia has proved a prolific area for meteorite finds. Large tracts of semi-arid–arid land, which constitute much of Western Australia, have allowed meteorites to be preserved for long periods after their fall, and these are more easily recognized than in heavily vegetated terrains. Extensive mineral exploration, and large areas of land turned over to farming and periodic ploughing, have led to the discovery of meteorites. The Nullarbor Region, with its lack of vegetation and contrasting limestone country rock, has proved ideal for the recognition of meteorites and many continue to be recovered from that area by systematic searching (Bevan *et al.* 1998).

Another, less obvious, factor is that the Aboriginal people of Australia do not appear to have utilized meteorites extensively, either for tools or for amuletic purposes (Bevan & Bindon 1996). This is in contrast to other countries with ancient civilizations where meteorites have been collected and used for a variety of purposes over thousands of years.

Currently, the Western Australian Museum meteorite collection holds samples of 248 distinct meteorites from Western Australia, samples of 30 meteorites from the rest of Australia and samples of 130 meteorites from the rest of the world, making a total holding of 408 described and named meteorites. While numerically the collection is small compared to other major collections in the world, it contains

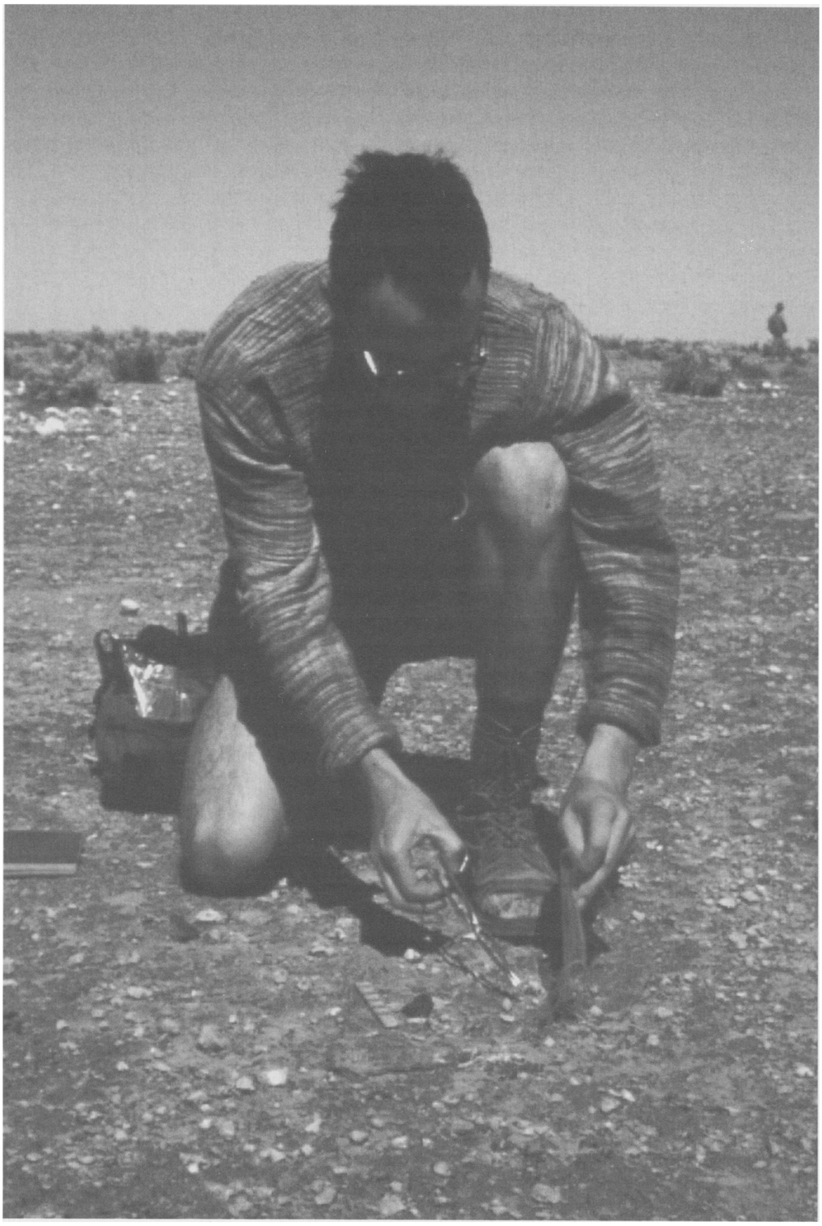

Fig. 11. P.A. Bland on a joint WAMET–EUROMET expedition collecting meteorites on the Nullarbor Plain in 1993.

a high percentage of main masses from Western Australia (around 85%), many rarities and has an aggregate weight in excess of 20 t. The material already in hand from the Nullarbor (around 500 registered but unclassified stones) has the potential to more than double the number of distinct meteorites held in the collection. A small proportion of falls to finds (4:244) from Western Australia reflects the sparse population of the State. This may change significantly when a network of all-sky fireball cameras is established in the Nullarbor Region.

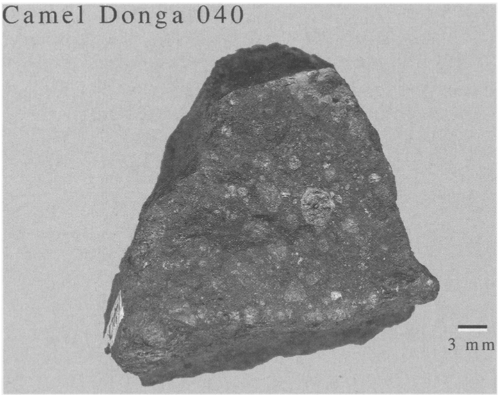

Fig. 12. Camel Donga 040, a unique mixture of pre- and post-metamorphic lithologies related to the CV chondrites.

Notes

[1]Historical research has revealed that the name of the person after whom the crater was named was 'Wolfe' not 'Wolf'. Consequently, the structure has been renamed Wolfe Creek Crater. However, according to the rules of meteorite nomenclature, the previously published name of Wolf Creek is retained for the meteorites found at the site.

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