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# Some Australian contributions to meteoritics from the 19th to the 21st Centuries

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Meteorites are fragments of natural debris that survive their fall to Earth from space, and meteoritics is the science of their study. Meteorites are fundamental to our understanding of the origin and early evolution of the Solar System. Many have remained virtually unaltered for 4.56 Ga and represent some of the original materials from which the planets were constructed. From the 19th Century onwards contributions to the understanding of planetary materials have been made by Australian scientists in the fields of meteorite recovery, mineralogy, petrology and metallurgy of meteorites, meteorite classification, isotopic studies, geochronology, impact cratering and Solar System formation. This paper documents some of the significant achievements that have been made.

**KEYWORDS: chondrites, geochronology, irons, isotopes, meteorites, mineralogy, petrology, stony-irons.**

## INTRODUCTION

Meteorites are a fundamental source of information on the origin and early evolution of the Solar System, and meteoritics is the science of their study. The majority of meteorites are fragments broken from asteroids in solar orbits between Mars and Jupiter, although few specific asteroids have been identified as possible sources. Other meteorites are fragments from the Moon and Mars. Many asteroidal meteorites have remained virtually unaltered for 4.56 Ga and provide evidence of the earliest formative processes of the Solar System, ranging from stellar evolution of the nearby galactic region, condensation and melting of early materials, nebula and preplanetary disk formation, and the accretion, differentiation and disruption of planetesimals and protoplanets.

While meteorites have been studied for over 300 years, with the successful NASA (Apollo) and Russian (Luna) sample recovery missions from the Moon from 1969 to 1976, the mid-20th Century saw a rapid expansion in planetary science world-wide. Significant contributions to our understanding of the early Solar System have been made by Australian scientists working both in Australia and overseas, and by overseas scientists working in Australia. This paper documents some of the significant discoveries that have been made from the recognition, recovery and study of planetary materials. In addition, the development of ever more sensitive and sophisticated analytical equipment through the 20th Century parallels the heightened interest in planetary materials, and was largely driven by it.

## METEORITIC MATERIALS

Three main groups of meteorites are recognised, determined by the relative amounts of metallic Fe–Ni and ferromagnesian silicates they contain. Irons are composed almost entirely of metal; stones are made predominantly of silicates (olivine, pyroxene and feldspar) similar to those occurring in terrestrial basalts, but may also contain appreciable amounts of metal; and stony-irons are mixtures of metal and silicates in roughly equal proportions. Stony meteorites are the most common, accounting for more than 95% of those observed to fall, whereas irons and stony-irons are rare, accounting for around 4% and 1% of the meteorite flux, respectively.

Two groups of stones are recognised; chondrites and achondrites. Chondrites contain millimetre-sized beads made essentially of silicates that are called chondrules (Greek *chondros* = grain) (Figure 1). The origin of chondrules remains enigmatic, but they are accepted as some of the early solids in the Solar System. Chondrites are gas-borne agglomerates, of both high- and low-temperature materials whose individual components and whole rocks have been variably altered by retrograde (aqueous alteration) and prograde (recrystallisation) metamorphism. In many chondrites, secondary (metamorphic) processes have been overprinted by tertiary (shock metamorphic) events.

Essentially, there are only two major categories of meteorites: meteorites that contain chondrules, the *chondrites*, and the *non-chondritic meteorites* that do not. The non-chondritic meteorites include those meteorites that lack chondrules and have textures and chemistries that show that they formed by partial, or complete igneous differentiation on their parent bodies, or are breccias of igneous debris. They include two kinds of stony achondritic (silicate-rich, but lacking chondrules) meteorites; primitive achondrites (those that retain a chemical signature of the precursor chondritic material from which they were made), and excluding meteorites from the Moon and Mars, highly differentiated asteroidal achondrites. Of the metal-rich meteorites, there are iron meteorites with essentially igneous histories; and two distinct groups of igneous stony-irons, mesosiderites and pallasites. In addition, there are a number (~60) of meteorites (mainly irons) that do not fit into any of the recognised groups and are termed ungrouped.

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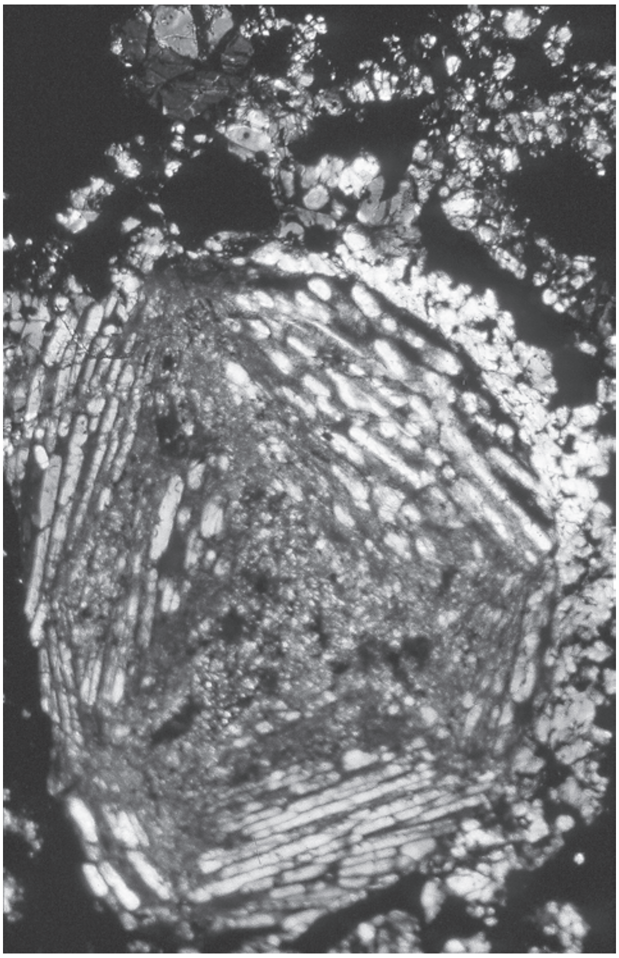

**Figure 1** Barred olivine chondrule in the Allende CV3 carbonaceous chondrite (field of view 2 mm).

In the modern classification of meteorites 15 groups of chondrites, three groups of primitive and seven groups of highly differentiated asteroidal achondrites, four groups of martian achondrites, lunar achondrites, four groups of stony-irons (mesosiderites and three subgroups of pallasites), and 13 groups of irons are recognised, and together with ungrouped meteorites represent material from at least 130 parent bodies that had independent histories since the birth of the Solar System (Tables 1, 2).

## METEORITES IN AUSTRALIA

The first well-documented recoveries of meteorites in Australia were two large masses of iron weighing 3.5 and 1.5 t found in 1854 near Cranbourne in Victoria. An earlier discovery may have been the Barratta stony meteorite, reported to have been found in 1845 in Townsend County, New South Wales (Liversidge 1872), but Mason (1974) suggested the date of find cannot be confirmed. A description of the Cranbourne meteorites by Von Haidinger (1861) marked the beginning of research on Australian meteorites, although in this case not in Australia. Subsequently, during the period 1854–1928, eight additional masses of the Cranbourne meteorite shower were recovered from an area between Beaconsfield and Langwarrin bringing the total weight recovered to more than 10 t. Extensive literature on the Cranbourne irons has been summarised by Edwards & Baker (1944) and, more recently, by Grady (2000).

The most prominent scientist involved with the early description of meteorites from Western Australia was Edward Sydney Simpson (1875–1939). Simpson was appointed as Mineralogist and Assayer to the Geological Survey of Western Australia in 1897. 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 two years and became the first graduate of UWA.

Meteorites found in Australia have been reviewed, or listed, on numerous occasions in the past (Cooksey 1897; Anderson 1913; Prior 1923; Hodge-Smith 1939; Prior & Hey 1953; Hey 1966; Mason 1974; Gibbons 1977; Graham *et al*. 1985; Bevan 1992a; Grady 2000). Currently, data on 735 distinct meteorite recoveries from Australia are recorded in world-listings and many of these discoveries (91) were recovered from the Nullarbor Region, in Western Australia and South Australia. For climatic and geological reasons the Nullarbor Region has proved to be one of the most prolific areas of the world for meteorite recoveries outside of Antarctica (Bevan & Binns 1989a, b, c; Bevan 2006). Since 1985, systematic searching in the Western Australian Nullarbor has yielded several hundred stony meteorites many of which have yet to be described. Currently, described meteorite recoveries from Western Australia account for nearly half (350) of all meteorites known from Australia, including the largest known (Figure 2).

## THE SCIENCE AND THE SCIENTISTS

Undoubtedly the largest and most active meteorite research group in Australia in the 1950s and 1960s was at the Australian National University. The group at various times included John Francis Lovering, Stuart Ross Taylor, William Compston and Alfred Edward (Ted) Ringwood (1930–1993), all of whom made major contributions to the study of planetary materials.

### Moon

At various times, Lovering, Taylor, Ringwood and Compston separately worked on meteorites and, from 1969, were heavily involved in the study of samples returned from the Moon. In July 1969, Taylor, then at NASA in Houston, Texas, was the first scientist to analyse a sample of the Moon returned by Apollo 11. A New Zealand born petrologist and geochemist, Taylor's supervisor at NASA was Robin Brett, a South Australian. A byproduct of that first analysis of a lunar basalt was that it proved beyond doubt that tektites (distal terrestrial impact melt ejecta) could not have come from the Moon as had previously been proposed (see Taylor 1973 and references therein).

In the 1970s, Lovering, then Professor of Geology at the University of Melbourne, employed David A Wark (1939–2005) as his research assistant. Working on lunar basalt samples from the Apollo 11 mission, and using Lexan fission track maps, Wark (with Lovering) co-

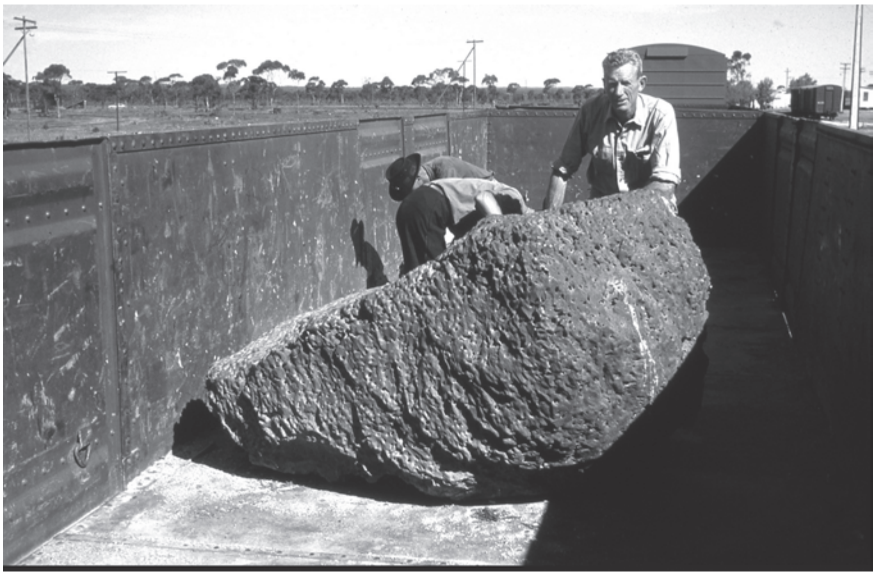

**Figure 2** The Mundrabilla iron meteorite (group IAB-complex) was found on the Nullarbor Plain in 1966. At 12.4 t it is the largest known from Australia.

discovered a hitherto unknown mineral, tranquillityite [$Fe^{2+}_8(ZrY)_2Ti_3Si_3O_{24}$] (Lovering *et al*. 1971). Later the same mineral was found in rocks from other Apollo missions and, more recently, in terrestrial rocks from Western Australia (Rasmussen *et al*. 2011). Using Lexan and additional techniques, other mineral phases in lunar rocks were characterised, such as zirconolite (Wark *et al*. 1973) and monazite (Lovering *et al*. 1974).

Compston, a geophysicist and a graduate of the University of Western Australia, moved to the Research School of Earth Sciences (ANU) following his PhD on carbon isotopes under the supervision of Peter Jeffery (1922–1990). After Compston, Jeffery supervised other students including John De Laeter (1933–2010) and Malcolm McCulloch both of whom later became prominent in the field of planetary science.

At ANU Compston continued his isotopic work on dating rocks. During the Apollo era he was a principal investigator of a group studying the ages of lunar rocks. Using the $^{87}Rb$–$^{87}Sr$ dating technique that he had previously applied to terrestrial rocks, Compston's group obtained an age of 3.8 Ga from the mesostasis (the last fraction of magma to crystallise) of a lunar basalt (Compston *et al*. 1970).

## Chemistry, mineralogy and petrology of the chondrites

The earliest attempts to classify the chondrites relied solely on texture. However, in 1916 G T Prior [British Museum (Natural History)] proposed a mineralogical classification and assigned the chondrites to three categories, enstatite, olivine–bronzite, and olivine–hypersthene on the basis of the Fe content of low-Ca pyroxene (Prior 1916, 1920). During the 1950s and 1960s, with improvements in the accuracy of analytical methods, a robust classification of the chondrites started to emerge. Chondrite groups not only differ in oxidation state, but significant differences also exist between the abundances of major, non-volatile elements they contain. This was demonstrated for Fe in chondrites by Urey & Craig (1953), who recognised two groups at around 22 wt% and 28 wt% Fe. These groups encompassed Prior's enstatite chondrites and olivine–bronzite chondrites, and an additional category (Mason 1962), carbonaceous chondrites (all high-Fe), and the olivine-hypersthene chondrites (low-Fe). Further detailed analysis showed that enstatite, ordinary and carbonaceous chondrites differ in the ratio of Mg/Si (Ahrens 1964, 1965). Further, Von Michaelis *et al*. (1969) showed that they also differ in Ca/Si, Ti/Si and Al/Si ratios. From the 1960s the accumulation of quality mineralogical analytical data, mainly using non-destructive methods such as the electron microprobe, led to the recognition of a small number of chondrites that were largely unaltered and contained unequilibrated minerals (Dodd & Van Schmus 1965; Schmitt *et al*. 1966; Binns 1967a). This led to classification of the chondrites by degree of crystallisation, culminating in a chemical–petrologic classification (Van Schmus & Wood 1967). The classification divides chondrites into groups E (enstatite chondrites), H (high-iron chondrites), L (low-iron chondrites), and LL (low total iron, low metallic iron chondrites) (Table 1). The H- L- and LL-chondrites are collectively known as 'ordinary chondrites'. Within each chemical group of chondrites, meteorites show varying degrees of crystallisation from least (type 3) to most (type 6) crystallised, with types 4 and 5 intermediate to these extremes. Types 1 and 2 refer to carbonaceous chondrites that have suffered hydrothermal alteration (Van Schmus & Wood 1967).

During the 1960s, R A (Ray) Binns then at the University of New England, and later at the University of Western Australia (1971–1977), conducted research into many aspects of the mineralogy and petrology of chondritic meteorites. Along with Van Schmus & Wood (1967), Binns recognised the importance of distinguishing between chondrites with similar chemical compositions but with different textures (Binns 1967a, b). The relationship between type 3 (unequilibrated chondrites) and types 4–6 chondrites was then a much disputed subject. Through detailed studies of the composition and crystallography of pyroxenes from non-carbonaceous chondrites, Binns (1967a, 1970), along with others, recognised the mineralogical distinction between

**Table 1** Meteorite classification: chondrites.

| Class | Group | Petrologic type | Subgroup | Mg/Si at* | Fe/Si at* |
|---|---|---|---|---|---|
| Carbonaceous (C) | CI | 1 | – | 1.066 | 8719 |
| | CM | 1-2 | – | 1.042 | 8177 |
| | CO | 3-4 | – | 1.053 | 7847 |
| | CV | 3-4 | CVa, CVb, CVred | 1.066 | 7578 |
| | CK | 3-6 | – | 1.127 | 7855 |
| | CR | 1-3 | – | 1.045 | 7875 |
| | CH | 3 | – | 1.063 | 15222 |
| | CB | 3 | CBa, CBb | – | – |
| Ordinary (OC) | H | 3-6 | – | 0.954 | 8177 |
| | L | 3-6 | – | 0.952 | 5838 |
| | LL | 3-6 | – | 0.928 | 4913 |
| Enstatite (E) | EH | 3-6 | – | 0.871 | 8730 |
| | EL | 3-6 | – | 0.731 | 5934 |
| | R (Rumuruti) | 3-6 | – | 0.934 | 7696 |
| | K (Kakangari) | 3 | – | – | – |

* Data from Hutchison 2004

unequilibrated and equilibrated chondrites correlated with textural variations, and that the range of properties found within each chemical–mineralogical group of chondrite could be interpreted as reflecting varying degrees of post-accumulation recrystallisation. The unequilibrated chondrites largely avoided recrystallisation, and represent the kind of material from which equilibrated chondrites were derived by prograde metamorphism on their parent bodies (Van Schmus & Wood 1967; Binns 1967a; Dodd 1969). These studies led to a greatly improved petrographic and genetic understanding of the chondrites.

The origin of the chondrules that make up the greater portion of the chondrites remains a matter of debate to the present day. However, early workers recognised that chondrules crystallised from molten droplets very early in the history of the Solar System (Hutchison 2004 and references therein). The heat sources to produce the chondrules, and to progressively metamorphose the chondrites also remain a matter of debate. However, there is wide consensus today that the heat source for metamorphism was the decay of short-lived radionuclides such as $Al^{26}$ (McKeegan & Davis 2005 and references therein).

In the late 1950s, early 1960s, Ringwood, then at ANU in Canberra, began documenting the mineralogy and chemistry of groups of chondrites. He postulated that several meteorite groups had formed by ‘auto-reduction’ of CI chondrite (formerly known as Type 1 carbonaceous chondrite), and concluded that the various suites of differentiated meteorites had formed by melting and differentiation of chondrite precursors (Ringwood 1961). Ringwood also formulated what became known as the ‘Chondritic Earth Model’ and discussed the composition and origin of the Solar System publishing extensively on the subject. Ringwood emphasised the importance of different oxidation states of primordial condensed matter of chondritic composition to account for different densities between Venus, Earth and Mars (Ringwood 1959, 1960, 1962). His study of meteorites also took Ringwood to Sweden where he worked with Kurt Fredriksson on chondritic meteorites, culminating in a paper on the origin of chondrules (Fredriksson & Ringwood 1963) and later, the origin of chondrites (Ringwood 1966).

In 1969, a new mineral was discovered in shock-induced melt veins in the Tenham ordinary chondrite from Queensland (Binns *et al*. 1969). The mineral, named ringwoodite in honour of the work of Ted Ringwood, is a high-pressure polymorph of olivine with a spinel structure. Ringwoodite is thought to be the most abundant mineral phase in the lower part of the Earth’s transition zone (525–600 km), and its structure and chemistry partly determine the properties of the Earth’s mantle at those depths, and had previously been synthesised by Ted Ringwood and Alan Major at ANU in 1966 (Ringwood & Major 1966). Later, in 1970, another high-pressure polymorph, this time of pyroxene with a garnet structure, was discovered in shock veins in the Coorara ordinary chondrite from the Western Australian Nullarbor (Smith & Mason 1970). The mineral was named majorite in honour of Alan Major and was later synthesised in the laboratory (Ringwood & Major 1971). A second high-pressure polymorph of olivine with an orthorhombic structure was found in the Peace River ordinary chondrite from Canada (Price *et al*. 1983). The mineral, wadsleyite, was named in honour of Arthur David Wadsley (1918–1969), and had previously been synthesised as a stable compound by Ringwood & Major (1966). Magnesian olivine $\alpha$-$Mg_2SiO_4$ under certain temperature and pressure conditions transforms to wadsleyite $\beta$-$Mg_2SiO_4$ and with increasing pressure transforms to ringwoodite $\gamma$-$Mg_2SiO_4$. In addition to an understanding of shock metamorphism in ordinary chondrites, an experimental understanding of these transformations has greatly improved our knowledge of the nature and properties of the Earth’s mantle.

**Table 2** Meteorite classification: non-chondritic meteorites

| | |
|---|---|
| **Primitive achondrites** | |
| Acapulcoites | Clan/same parent body? |
| Lodranites | |
| Silicates in IAB-complex irons | Clan/same parent body? |
| Winonaites | |
| **Differentiated achondrites**<br>**Achondrites (asteroidal)** | |
| Angrites | |
| Aubrites | |
| Brachinites | |
| Ureilites | |
| Howardites | HED clan, same parent body |
| Eucrites | |
| Diogenites | |
| **Achondrites (planetary)** | |
| Shergottites | Martian (SNC) |
| Nakhlites | |
| Chassignites | |
| Orthopyroxenites | |
| Lunar | Moon |
| **Stony irons** | |
| Mesosiderites | Possible related to HED clan |
| Pallasites | Main group Possible related to IIIAB irons |
| | Eagle Station |
| | Pyroxene |
| **Irons** | |
| IAB-complex* | |
| IC | |
| IIAB | |
| IIC | |
| IID | |
| IIE* | Possible differentiates from H-chondrite-like precursor |
| IIF | |
| IIG | |
| IIIAB | Possibly related to Main group pallasites |
| IIIE | |
| IIIF | |
| IVA* | |
| IVB | |
| Ungrouped | |

* Silicate-bearing irons

## Mineralogy, petrology and the characterisation of calcium–aluminium-rich inclusions in chondrites

While texturally most chondrites are dominated by chondrules and the matrix in which they are set, mineralogically they are complex aggregates of ferromagnesian silicates (olivine and pyroxene), Fe–Ni metal, Ca–Al-rich inclusions (often referred to as refractory inclusions, or CAIs), and rare aggregates of olivine grains (amoeboid olivine aggregates). Additionally, the mineralogy of chondrites may include magnetite, chromite (or chrome spinels), iron sulfides (troilite, pyrrhotite and pentlandite), carbonates, sulfates and 'serpentine' group minerals (for a detailed review of meteorite mineralogy see Rubin 1997a, b).

Ca–Al-rich inclusions contain refractory materials and range in size from sub-millimetre, to centimetre-sized, objects that occur in varying abundances in all groups of chondrites (Figure 3). The mineralogy and isotopic composition of Ca–Al-rich inclusions suggest that they are amongst the earliest solids to have formed in the Solar System, and this is confirmed by isotopic dating. Both Ca–Al-rich inclusions and chondrules are the products of very high temperature events during the early history of the Solar System, and the latter probably

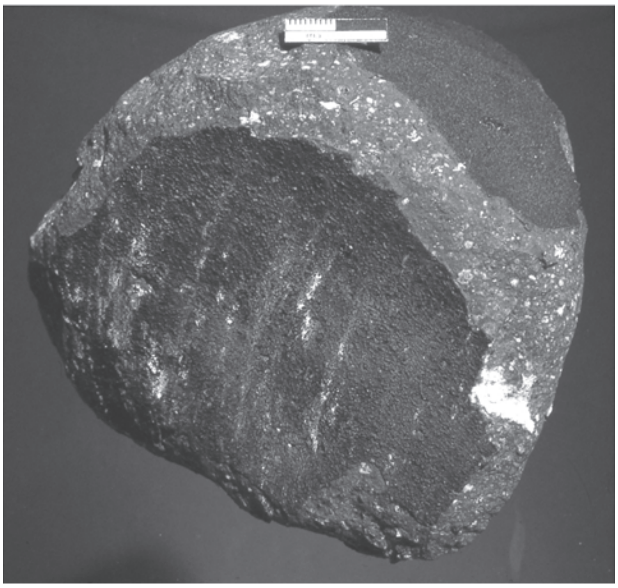

**Figure 3** Large white calcium-aluminium-rich inclusion (CAI) in the CV3 chondrite Allende (bottom right); centimetre scale.

originated from pre-existing solids in the nebula (MacPherson 2005; Rubin 2000; Shu *et al*. 2001).

Brian Harold Mason (1917–2009), a New Zealand born geochemist/mineralogist visited Ross Taylor's laboratory at ANU in the 1970s and made one of the most siginificant contributions to the study of CAIs. Analysing inclusions in Allende and based on their REE contents and mineral make up, Mason established a classification of CAIs into groups. Four distinct groups were recognised and designated I, II, III and IV, that indicated a complex history of formation from the ancestral nebula (Martin & Mason 1974; Mason & Martin 1977; Mason & Taylor 1982). This work was later superseded by MacPherson *et al*. (1988) who distinguished a number of 'types' of CAIs on the basis of their texture, primary mineralogy and composition.

In the 1970s and 80s, both Lovering and Wark also made major contributions to the understanding of the mineralogy of CAIs. In the Allende CV3 carbonaceous chondrite, thin layers each 5–10μm thick (rims) and total thickness 20–50μm of spinel plus perovskite, alteration products, and pyroxene are ubiquitous on coarse CAIs. This sequence of layers is identical to that making up the individual bodies in fine-grained aggregates (Wark & Lovering 1977). In honour of their work, these layers later became universally known as 'Wark–Lovering' rims (MacPherson *et al*. 1998). This detailed work on CAI rims fostered many other lines of inquiry into their origin, which remains uncertain to the present day. Wark & Lovering (1977) demonstrated that the second alteration layer, composed of nepheline, grossular and sodalite, had originally been melilite. In less-altered meteorites, rims show the primary melilite layer (Wark & Lovering 1980).

In later work, Wark (1985) classified CAIs according to both chemistry and petrology, and provided a review of rim formation (Wark & Boynton 2001). Wark's work on CAIs culminated in experimental methods to synthesise them in the laboratory, summarised by Wark (2005).

## An Australian role in the classification and understanding of iron meteorites

Until the 1950s iron meteorites were classified according to their structural characteristics and were assigned to eight classes. Octahedrites (5.6–18.1 wt% Ni), are those irons (6 classes) with discernable Widmanstätten patterns composed principally of a trellis work of the Fe–Ni minerals kamacite and taenite (Figure 4), hexahedrites (5.3–5.8 wt% Ni) lack the octahedrite structure and are essentially made of crystals of kamacite, while ataxites (15.8–60.8 wt% Ni) have microscopic octahedral structures. It was generally recognised that among iron meteorites there was an inverse relationship between the bulk content of Ni in irons and the bandwith of kamacite lamellae in the Widmanstätten pattern.

Michael J Frost, who gained a PhD from the University of Western Australia and later moved to the University of Cantebury in New Zealand, developed a rapid, easy method for the determination of kamacite bandwidths in iron meteorites, thereby determining their structural class (Frost 1965). On an etched section of an iron meteorite which is not normal to any one of the four sets of octahedral kamacite lamellae, the apparent width of kamacite bands will be greater than the true thickness. Depending on the orientation of the section plane there will be 4, 3, or 2 sets of kamacite lamellae. Using tracing paper, through a single point lines are drawn parallel to the sets of lamellae. In the case of 4 sets, the width of the narrowest bands are measured to give an average value. The largest angle between adjacent lines on the tracing paper is measured, and the average apparent bandwidth is multiplied by a correction factor (cf) appropriate to the maximum angle (60-62° cf 0.97; 64-66° cf 0.98; 68° cf 0.99; 70° cf 1.00; 90° cf 0.82). In the case of 3 sets, two angles will be the same or similar and the third angle will be unique. The apparent bandwidths of the two sets of lamellae that include the unique angle are measured. The weighted mean of the two averages is then multiplied by an appropriate correction factor (unique angle 10° cf 0.82; 20° cf 0.83; 30° cf 0.85; 40° cf 0.87; 45° cf 0.88; 50° cf 0.90; 55° cf 0.92; 60° cf 0.94; 63° cf 0.96; 66° cf 0.97; 68° cf 0.98; 70° cf 1.00). Finally, in the case of two sets, the apparent average width of the two sets is measured and the weighted mean of the two averages is multiplied by cf 0.82 (Frost 1965).

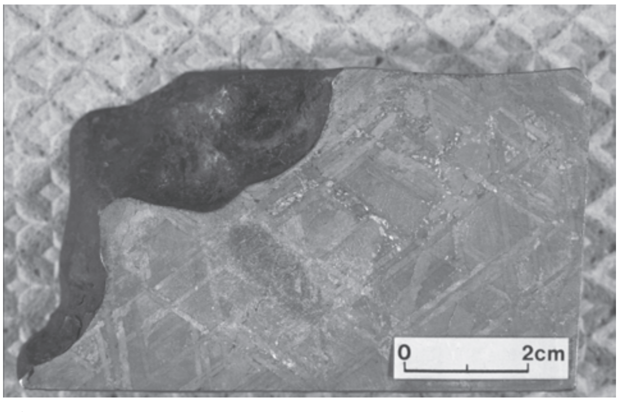

**Figure 4** Polished and etched slice showing the Widmanstätten pattern in the medium octahedrite (chemical group IIIAB iron) Duketon, found in Western Australia.

Through the 1950s, as analytical equipment improved, the amount and accuracy of major, minor, and trace-element data for iron meteorites increased and a chemical classification emerged by grouping apparently chemically related irons. The earliest work was done at the California Institute of Technology (Caltech) by Goldberg *et al*. (1951) who discovered that the Ga contents of 40 irons lie within three discrete ranges. On the basis of this they assigned Roman numerals to classes I, II and III. In 1953, Lovering joined the group at Caltech and continued the work (Lovering *et al*. 1957). Lovering *et al*. (1957) showed that the group with the highest range of Ga contents could be subdivided into two, and that Ga contents correlated with Ge. From trace-element data derived from the analysis of 88 irons, four groups were recognised in order of decreasing Ga and Ge and designated groups I to IV. Eleven irons fell outside the limits of any group and were considered anomalous. This notation forms the framework for the chemical classification of iron meteorites in use today.

From the mid-1960s, analysis of iron meteorites was taken up by J T Wasson and colleagues at the University of California in Los Angeles. Using more sensitive and precise analytical techniques, Wasson and co-workers have analysed >700 irons. Chemical comparisons between chondritic and iron meteorite metal show that, overall, irons have much wider compositional ranges for most elements. Notable are the trace-elements Ga, Ge and Ir. However, plots of Ga, Ge and Ir versus Ni distinguish 13 well-defined groups of irons and form the basis of a chemical classification (Goldberg *et al*. 1951; Lovering *et al*. 1957; Scott & Wasson 1975, 1976; Scott 1979; Kracher *et al*. 1980; Goldstein *et al*. 2009). Some 13% of irons (around 60) have compositions that do not fit into the groups. These were previously called anomalous, but are now called ungrouped. This work has provided a genetic classification that has led to major advances in the understanding of the interrelationships among iron meteorites (and other groups of meteorites) and their origin and evolution (see Goldstein *et al*. 2009 and references therein).

Chemical variations between groups of irons were probably established in chemically distinct environments (parent bodies) by processes similar to those which determined metal chemistries in chondritic meteorites (Scott 1979), whereas the regular chemical variation within groups of irons are attributed to the gravitational separation and subsequent crystallisation of molten metal during planetary differentiation (Scott 1972 & 1979; Kelly & Larimer 1977; Goldstein *et al*. 2009). Chemical trends (for Ni, Ga, Ge, Ir) in most iron meteorite groups are broadly consistent with fractional crystallisation of a single molten metallic core, and are called 'magmatic irons'. In contrast, irons of the group IAB complex (including those formerly labelled IIICD) lack extreme magmatic chemical fractionation trends and contain silicates, some with chondritic chemistries (Bunch *et al*. 1970; Benedix *et al*. 2000) indicating that they were never completely melted (Kracher *et al*. 1980). The group IAB complex of irons are undoubtedly the products of some melting, although compositional changes resulting from partial melting and incomplete separation of metal and silicate are poorly understood. Kelly & Larimer (1977) suggested that some groups of irons such as IAB may represent the products of fractional melting (the inverse of fractional crystallisation), but there is no consensus. The modern view is that non-magmatic irons such as the IAB-complex and group IIE that are silicate-bearing and with poorly defined chemical trends, are perhaps the result of impact mixing of molten metal and silicates, and that neither group formed from a single, isolated metallic melt (Goldstein *et al*. 2009).

Lovering (1957) suggested that mechanisms for the macrosegregation of elements in the cores of meteorite parent bodies imply that solidification may have been directional. Directional solidification is supported by elongated, parallel troilite nodules that occur in some irons. Both 'plane front' (Scott 1972) and 'dendritic' (Narayan & Goldstein 1982) solidification have been considered to account for elemental fractionations shown by the magmatic iron meteorite groups. However, computer modelling indicates that plane-front solidification is unstable in large molten metallic accumulations with moderate thermal gradients and solidification rates, and predicts dendritic solidification for irons.

'As cast' solidification structures are rarely seen on sections through average sized iron meteorites (<1 m) because the dendrite arm spacing on the scale of planetesimal cores may have been up to 0.5 km. The solubility of S in solid Fe–Ni is very low (<0.8 wt%) consequently, during solidification, S remains in the melt. In the pure Fe–Ni–S system troilite (FeS) begins to crystallise when the S content of the melt reaches 45 atom% and is concentrated where the last liquid solidifies. Solidifying Fe–Ni dendrites may randomly trap sulfur-rich interdendritic material, and this has been suggested as a mechanism to account for observed variations in the sulfide contents of magmatic irons. Meteorites that may represent interdendritic material include the sulfide-rich ungrouped iron Soroti, and the IAB complex irons Pitts, Mundrabilla, and the recently discovered iron from Western Australia, Prospector Pool (Figure 5).

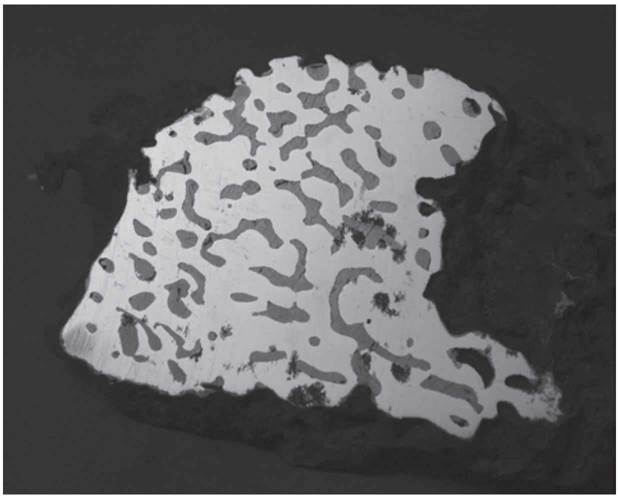

**Figure 5** Mixture of metal and troilite (dark) in a slice of the Prospector Pool iron meteorite (group IAB-complex) found in Western Australia (largest dimension 8 cm).

## Cohenite formation in iron meteorites

The iron–nickel carbide, cohenite $(FeNi)_3C$, is a common accessory precipitate in some groups of iron meteorites, notably the IAB complex and group IC. For example, in group IAB irons cohenite precipitates frequently occur associated with kamacite lamellae in the Widmanstätten pattern (Scott 1977). In some irons, cohenite has decomposed to granular ferrite and columnar graphite indicating mild reheating, or annealing during cooling. The morphological development and thermal history of cohenite is generally poorly understood. Cohenite is thermodynamically unstable. Buchwald (1975) noted that it is surprising that, given the slow, equilibrium cooling histories of many iron meteorites, cohenite survives at all. In iron meteorites generally, undecomposed carbides are more common than decomposed ones. Buchwald (1975) suggested that the apparent stability of cohenite is actually due to the difficulty of nucleating graphite. Robin Brett, then working at the US Geological Survey in Washington, noted that once nucleated in cohenite, however, graphite grows slowly at the expense of carbides with low-Ni ferrite as a byproduct and this seems dependent on the fractured nature of grains (Brett 1967). Annealing of shocked, strained and fractured cohenite causes it to decompose to ferrite and graphite. The temperature of heat treatment for this transformation is ~450–500°C.

From Fe–C phase equilibria and kinetic data, Brett (1967) showed that cohenite that formed in irons with <6 wt% Ni should decompose on cooling. Cohenite probably forms over a temperature range of 650–610°C during cooling, and P has a stabilising influence on its precipitation (Brett 1967). In meteorites containing up to 6 wt% Ni, regardless of the C content, all the cohenite would have precipitated from solid solution when the temperature had fallen to approximately 640°C (Brett 1967). The inability to form cohenite below approximately 610°C accounts for the lack of this phase in irons containing more than about 8 wt% Ni. Cohenite that formed at temperatures above 640°C should decompose on slow cooling. If cohenite does not form below 610°C then the only unaltered cohenite that persists in irons is in those containing 6–8 wt% Ni (Brett 1967).

In experimental heating of samples of the group IAB complex iron Canyon Diablo, Brentnall & Axon (1962) observed no apparent effect on cohenite in samples heated at 501°C for 24 hrs. Between 501 and 650°C, with heating periods varying from 15 mins to 6 hrs, a thin rim of ferrite developed around cohenite, and in a sample heated to 650°C for 3 hrs, incipient graphitisation occurred in cracks and veins. However, Brentnall & Axon (1962) noted that cohenite is generally unstable over the whole temperature range (300–1000°C) examined.

In order to establish the conditions of cohenite stability and the kinetics of its decomposition, Brett (1967) also performed heating experiments at three temperatures, 650, 750 and 800°C on samples of the cohenite-bearing IAB-complex iron Coolac that was found in New South Wales. In any given run, decomposition was more advanced in fractured cohenite grains, and decomposition first occurred along fractures, and then within crystals. Decomposition was complete in a sample of Coolac held at 650°C for 80 days. Brett (1967) noted the duration of runs in which total decomposition of cohenite had occurred and plotted the data along with those obtained previously by Ringwood & Seabrook (1962) thus contributing to our knowledge of the low temperature cooling history of irons.

## Opaque mineralogy of meteorites

The eminent German mineralogist Paul Ramdohr (1890–1985) visited the University of New South Wales in May 1962, and spent five months working with L J (Lawrie) Lawrence as a Visiting Professor of Geology. During this period, Ramdohr examined the opaque mineralogy in a suite of 17 meteorites provided by Oliver Chalmers, Curator at the Australian Museum in Sydney (Sutton 2012).

The meteorites included Adelie Land, the first meteorite found in Antarctica, and 12 chondrites, one achondrite, two pallasites, and a troilite nodule from an iron meteorite, all from localities in New South Wales (Ramdohr 1967).

As the result of Ramdohr's observations on meteorites, eight minerals which were known from terrestrial occurrences, though not previously from meteorites, were found to be fairly common constituents; others were recognised as accessory although had previously been considered rare. The latter included native copper and ilmenite. About 15 components were established that were previously not known as either terrestrial or meteoritic (Sutton 2012).

## Isotopic studies

Through the 1960s interest in meteoritics grew in Australia. In Western Australia a group of physicists at the University of Western Australia led by Peter Jeffery, obtained a mass spectrometer and began to search for isotopic anomalies of tin in meteorites (De Laeter & Jeffery 1965). In addition, this research group encouraged Gerald Joseph Home (Joe) McCall (1920–2013), a geologist at the University of Western Australia, to classify the stony meteorites in the collection of the Western Australian Museum, whilst De Laeter undertook a similar task for iron meteorites in the collection (De Laeter & Bevan 1992 and references therein). An X-ray fluorescence spectrometry facility was established at Curtin University (then the Western Australian Institute of Technology) to measure the nickel, cobalt, gallium and germanium contents of iron meteorites, and so determine their chemical classification (Thomas & De Laeter 1972).

The vintage year for planetary science was 1969. On 20 July NASAs Apollo 11 mission succeeded in placing a man on the Moon, but at either end of the same year and on opposite sides of the Earth two meteorite falls had a more profound effect on our understanding of the origin of the Solar System. On 8 February more than 2 t of fragments of a CV3 (Vigarano-type) carbonaceous chondrite fell near the Mexican town of Peublito de Allende. On 28 September ~0.5 t of fragments of a CM2 (Mighei-type) carbonaceous chondrite fell near the Australian town of Murchison in Victoria. Of groups previously known in only meagre amounts, the Murchison and Allende meteorites provided an abundance of material to work on.

More than a decade before the falls of Murchison and Allende, Burbidge *et al*. (1957) drew up a blueprint of nuclear reactions in stars that would produce all but a few of the elements and isotopes. Cameron (1957) came to similar conclusions independently. Shortly after the birth of the Universe, stars manufactured isotopes of the chemical elements. Massive stars with burnt-out iron cores become unstable, eventually exploding as supernovae and distributing newly formed isotopes into space. New generations of stars form and the process continues. In this view of the Universe, isotopic mixes of elements should vary in space and time. By the 1960s the search for corroborating isotopic anomalies in meteorites had begun in earnest.

The first indication that the proto-solar nebula had been seeded by debris from a nearby supernova came in 1960. Reynolds (1960) extracted a small amount of xenon gas from the Richardton ordinary chondrite that fell in the USA in 1918, that was found to contain more of the isotope $^{129}$Xe than predicted. The excess was attributed to the decay of the extinct radioactive isotope $^{129}$I with a half-life of only 16 Ma. $^{129}$I was made in a supernova shortly before it was incorporated into the meteoritic material. Because the daughter $^{129}$Xe had not been lost to space, the material must have cooled quickly. For the record to have survived, no more than around 170 Ma (around 10 half-lives) could have elapsed between the manufacture of $^{129}$I and the birth of the Solar System at 4.56 Ga. This was confirmation that young material had been added to the early Solar System.

Of the many isotopic anomalies discovered subsequently, one of the most significant is $^{26}$Mg as the decay product of the short-lived radioactive isotope $^{26}$Al with a half-life of 0.73 Ma. As early as 1952, Urey (1952) suggested that the decay of $^{26}$Al in the early Solar System could have been the source of heat for melting and differentiation of planetesimals. A concerted search for evidence of an excess of $^{26}$Mg in meteoritic materials started in the early 1970s. Schramm *et al*. (1970) found no anomalies in several meteorite samples. However, in 1974 two Australian scientists, Chris M Gray (Latrobe University) and William Compston (ANU) reported an excess of $^{26}$Mg in the Allende meteorite (Gray & Compston 1974), but their published results were regarded as inconclusive by American scientists working in the same field. This led Compston's colleague, Ringwood at the ANU to remark that this was 'uncharitable and reflects the chauvinism of U.S. scientists' (Brush 2006). Ringwood argued strongly that Gray and Compston's discovery of a $^{26}$Mg anomaly should receive the credit it deserved. Later, Lee *et al*. (1976) at Caltech discovered a large anomaly in $^{26}$Mg in a chondrule from the Allende meteorite, and suggested that the most plausible cause of the anomaly was the *in situ* decay of $^{26}$Al.

## Geochronology

Since the late 1970s, the development of ever more sensitive and accurate means of determining absolute ages of materials has led to a new generation of instruments. The most significant was the development of the Sensitive High-Resolution Ion Microprobe (SHRIMP). The SHRIMP originated in 1973 through a proposal by William Compston to build an ion microprobe at the Research School of Earth Sciences at the ANU in order to analyse individual mineral grains. The instrument was built during the period 1975–1977 and the first successful geological measurements were made in 1980 (Foster 2010 and references therein).

Shortly after, in 1983, the first major scientific discovery using the SHRIMP was the dating of zircon grains in rocks from Mt Narryer in Western Australia at >4000 Ma (Froude *et al*. 1983), then at nearby Jack Hills (Compston & Pidgeon 1986). Interest from commercial companies and other research groups, notably John De Laeter's group at Curtin University, led to a project to build commercial versions of the instrument. Today 15 instruments have been installed in laboratories around the world, including those at ANU and Geoscience Australia in Canberra, and two at Curtin University in Perth. The development of the SHRIMP has allowed advances in the accuracy of the chronology of meteorites and their components, and the instrument's high sensitivity and resolution can be used to measure REE and other trace elements in individual grains. The first SHRIMP at Curtin University was commissioned in 1993 and Allen K Kennedy returned to Australia from the US to run the instrument.

The development of the first SHRIMP, and the discovery of the oldest zircons, brought forth a new generation of scientists including Trevor R Ireland, Peter D Kinny (now at Curtin University) and D O Froude who were then students at ANU.

## Meteorite collecting and collections in Australia

In Australia, meteorite collections are held in all the State museums (including the Northern Territory). In addition, significant collections are held at some of Australia's universities, notably the Australian National University and the University of Melbourne. Other collections are held at Geoscience Australia in Canberra and CSIRO. One of the largest collections is held at the Western Australian Museum, a major component of which are meteorites recovered from the Nullarbor Region, and include several hundred meteorites that are yet to be classified and described (Bevan 2006).

In the 1960s, a major contribution to the collection of meteorites was made by an active group of scientists at the Western Australian School of Mines (now part of Curtin University) in Kalgoorlie. The principal researchers were William (Bill) Harold Cleverly (1917–1997) and M Keith Quartermaine, both of whom undertook meteorite collecting. During the decade of the 1960s almost a tonne of meteoritic material was amassed by the School of Mines, or via the school into other collections (Cleverly 1993). The material included 37 new meteorites representing an increase of ~2% to meteorites held in collections world-wide at that time. The 1960s also saw the recognition of the Nullarbor Region as an area of meteorite accumulation with time (see Bevan 2006 and references therein).

In 1963, an expedition funded by the National Geographic Society left Sydney to search for meteorites and tektites throughout Australia. The search party consisted of Brian Mason (then at the American Museum of Natural History), Edward Henderson (Smithsonian Institution), and Oliver Chalmers (Australian Museum, Sydney). In Western Australia they targeted the find-sites of two previously known meteorite finds; Dalgety Downs and Mount Egerton that had been discovered in 1941. The party relocated the find-site of Dalgety Downs and ~214 kg of material was recovered. A further visit to the site by Cleverly yielded another 40.9 kg of fragments (McCall 1966). The search for the find-site of the Mount Egerton meteorite by the National Geographic expedition was unsuccessful.

In 1986, a new meteorite recovery programme of the Western Australian Museum (WAMET) was initiated by the author. From 1992 to 1994, in collaboration with EUROMET, a pan-European group of research institutions devoted to meteorite research, systematic searches on four expeditions to the Nullarbor Region recovered more than 600 specimens of meteorites (totalling ~17 kg) during some 10 weeks of searching (Bevan 1992b; Bevan *et al*. 1998).

## Meteorites and paleoclimate

In the 1990s, with the recovery of large numbers of stony meteorites of varying terrestrial ages and states of preservation from the desert regions of the world, it was realised that paleoclimatic information might be obtained from them by a study of their weathering characteristics (Bland *et al*. 2000). Philip A Bland (then a Royal Society Travelling Fellow at the Western Australian Museum), the author, and A J T Jull of the University of Arizona undertook an innovative study of the terrestrial oxidation (weathering) and terrestrial age of ordinary chondritic meteorites from several arid areas of the world, notably the Nullarbor Region in Australia.

At the moment of entry into the Earth's atmosphere, a meteorite is exposed to contamination from, and alteration by, the terrestrial environment. Prolonged weathering transforms many of the minerals in meteorites, masks their original textures, redistributes elements, and eventually leads to their destruction. The processes of weathering leave a terrestrial 'fingerprint' in meteorite finds that can be used in climatic research. Meteorites that have survived prolonged weathering are 'recorders' of environmental conditions during their period of terrestrial residence.

Ordinary chondritic meteorites are particularly useful in understanding post-fall terrestrial processes for two main reasons. First, their terrestrial ages (the time they have spent on Earth since falling) can be measured (up to >40 ka) from the decay of the cosmogenically produced radionuclide $^{14}$C (half-life of 5.73 ka). The technique separates $^{14}$C produced by cosmic-ray bombardment in space from $^{14}$C contamination from terrestrial sources (see Jull 2006 and references therein). Second, the initial composition and normative mineralogy of ordinary chondrites prior to weathering is well constrained from the analysis of fresh falls (see Jarosewich 1990 and references therein). Virtually, all of the iron in equilibrated (types 5-6) ordinary chondrites is present as $Fe^0$ and $Fe^{2+}$. If an ordinary chondrite contains significant $Fe^{3+}$ then this is an indication of terrestrial weathering by the oxidation of Fe-bearing phases (rusting).

Bland *et al*. (2000) used an empirical approach to quantify the nature and degree of weathering suffered by an ordinary chondrite by the use of $^{57}$Fe Mössbauer Spectroscopy to measure %age ferric oxidation in ordinary chondrites. By correlation of oxidation state with terrestrial ages, the progression of weathering with time was determined.

Logically it would be expected that the degree of weathering of a meteorite would increase with greater terrestrial age. In the case of the meteorite accumulation in the Nullarbor Region, Bland *et al*. (2000) found that this was not the case (Figure 6). In the Nullarbor Region peaks in total oxidation for ordinary chondrites correspond with humid periods identified independently from speleothem growth in caves (Goede *et al*. 1990), palynology (Martin 1973) and lake-level studies (Street & Grove 1979; Bowler *et al*. 1976; Bowler 1978). A peak in %age oxidation for H-group chondrites is observed at ~1500–1000 a BP. Lake-level studies also indicate a period of more effective precipitation at ~2000–1000 a BP, and halite speleothem growth occurred at 2500±1200 a BP.

A possible mechanism that allows variation in oxidation that is not directly dependent on increasing terrestrial age is that the weathering of an ordinary chondrite (<1000 a after fall) appears initially to be rapid before oxidation is arrested and weathering reaches equilibrium (Bland *et al*. 2000). The reduction in weathering rate may correspond to a reduction in porosity of the stone caused by the oxidation and mobilisation of Fe–Ni metal and other primary minerals to oxyhydroxides of iron that fill the pore space thus preventing the percolation of fluids, and inhibiting further weathering (Bland *et al*. 2000).

Essentially, the humidity during the period a meteorite falls is the major factor determining the degree of initial weathering. A meteorite will undergo more initial weathering in a humid environment than in an arid one. The reduction of porosity early in a meteorites terrestrial history greatly reduces the weathering rate, and even a lightly weathered meteorite may be unaffected by subsequent humid periods (Bland *et al*.

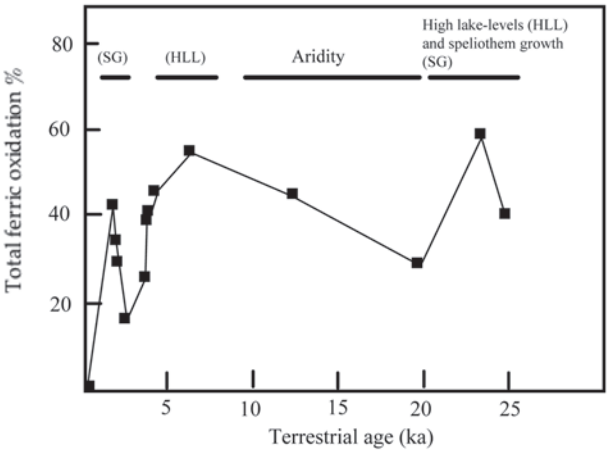

**Figure 6** Plot of total ferric oxidation (%) resulting from the alteration of metallic iron by the terrestrial oxidation of weathered H-group ordinary chondrites from the Nullarbor Region of Australia as determined by Mössbauer against their $^{14}$C terrestrial ages. Marked above are significant paleoclimatic events in southwest Australia for the same period (after Bland *et al*. 2000).

2000). The use of ordinary chondrite meteorites recovered from desert regions in paleoclimatic research has yet to be fully explored.

## AUSTRALIAN DESERT FIREBALL NETWORK

The newly established Australian Desert Fireball Network (ADFN) in the Western Australian Nullarbor is a world-leading facility designed to provide fundamentally important information to planetary scientists about the nature and origin of meteorites (Bland *et al*. 2012). Through an international collaboration led by Philip A Bland between Curtin University, Imperial College London, the Ondřejov Observatory in Prague, and the Western Australian Museum, construction of a trial all-sky camera network comprising four fireball observatories was completed in 2007 and enjoyed almost immediate success. A meteorite fall, Bunburra Rockhole, was photographed in July 2007 and was later recovered within 100 m of the landing site predicted by the network (Bland *et al*. 2009). A second recovered fall, Mason Gully, was photographed by the network on 13 April 2010 (Spurny *et al*. 2011).

Of the more than 50 000 meteorites in collections around the world, the vast majority are chance finds. Over the last 300 years or so, world-wide only about 1100 have actually been seen to fall and quickly recovered. Of these, the phenomena associated with the fall of only 16 have been photographed enabling the orbits of the objects that gave rise to the meteorites landing on Earth to be determined. Fragments of another meteorite fall were recovered by tracking a small asteroid that eventually collided with the Earth (Jenniskens *et al*. 2009).

Networks of all-sky cameras, designed to observe fireballs, calculate orbits and triangulate fall positions, have been established in several northern-hemisphere nations (USA and Canada) in the past, and one, the European Network, has been in operation for more than 40 years (Bowden 2006). Although hundreds of fireballs associated with large (>100 g) meteorites have been observed, remarkably only eight meteorites were recovered (the orbits of others were determined from chance photography). The poor success rate is explained simply by the location of the networks. Heavy vegetation, typical of central Europe, makes locating small meteorites difficult. Until now, no camera network has been established in an area, such as a desert, where meteorites can be recognised easily and quickly recovered. The climate of southwestern Australia is also conducive for observations with around 200 clear nights per year.

Four satellite-monitored cameras specifically designed to operate in extreme desert conditions have been deployed in the Nullarbor (Figure 7). Orbits are calculated from fireballs, and meteorite fall positions (over an area of ~200 000 km$^2$) are determined for later recovery. Data from the current network indicate that three to four meteorite falls are detected per year. In the sparsely vegetated Nullarbor, it is expected to recover a significant proportion of those photographically recorded meteorite falls, which will greatly increase the number of recovered meteorites with known orbits.

At present there is only an approximate knowledge of where most meteorites come from. Surveys of light reflected from asteroids reveal a diversity of bodies, each with a distinct inferred surface mineral make-up. An expanded collection of meteorites with known orbits will allow the relationship of some samples to specific regions, or bodies, providing a spatial context for interpreting meteorite composition.

The velocity of a meteoroid (a small natural body before landing on Earth) in the atmosphere is that of the object relative to the Earth (geocentric velocity). In order to calculate the orbit of the object in space the velocity of the object relative to the Sun (heliocentric velocity) at the Earth's distance from the Sun needs to be known. Taking into account the Earth's own orbital speed (29 km/s) and

**Figure 7** A fireball observatory of the Australian Desert Fireball Network on the Nullarbor in Western Australia, with solar power and satellite link (Courtesy of Geoff Deacon).

the rate of rotation of the Earth (~0.5 km/s) it is possible to work back to obtain the dimensions and shape of the orbit of the infalling body. In all cases measured previously, the orbits of bodies that have given rise to recovered meteorite falls are highly elliptical with their furthest point from the Sun in the asteroid belt between Mars and Jupiter. This is strong evidence, albeit circumstantial, that the majority of meteorites that fall to Earth are fragments broken from asteroids.

On 20 July 2007, two cameras of the ADFN detected the fall of a meteorite. At 19hrs 13mins 53.2 secs (±0.1 sec) Universal Time, a fireball was recorded low on the horizon east of the network area, and the atmospheric trajectory, luminosity of the fireball, orbit, and impact position were determined precisely. The record also indicated that the body broke in the atmosphere to give at least three surviving fragments.

The successful recovery of three fragments (174, 150 and 14.9 g) of the Bunburra Rockhole meteorite fall represented a number of scientific firsts. At the time it was only the fifth predicted meteorite fall in history, it was the first known meteorite from an Aten-type asteroid orbit, the first basaltic achondrite with a known orbit, and the first instrumentally observed meteorite fall in the southern hemisphere. Moreover, it was the first documented meteorite fall from a relatively small object that produced a short-lived fireball with a terminal height of 30 km.

The Bunburra Rockhole meteorite has proved very unusual, not least of which is its orbit. The Aten asteroids are a group of near-Earth asteroids, named after the first of the group to be discovered (2062 Aten). Half of their largest orbital dimension is less than the distance from the Earth to the Sun. However, because the orbits of asteroids can be highly elliptical, the orbit of an Aten asteroid need not be entirely contained within Earth's orbit. Nearly all known Aten asteroids have orbits with their greatest distance from the Sun beyond the Earth's orbit, as did Bunburra Rockhole.

Although many other basaltic achondrites similar to Bunburra Rockhole are known and have been linked, tentatively, to asteroid 4Vesta and related bodies called the V-type asteroids as their parent bodies, Bunburra Rockhole appears to have come from a different region of space. Although its chemical composition is not significantly different from other basaltic achondrites, the isotopic make-up of its oxygen distinguishes it.

When the ratios of heavier isotopes of oxygen ($^{17}$O, $^{18}$O) to light $^{16}$O in different samples from Earth are plotted against each other they lie on a line with a slope of exactly one-half. All Earth samples lie on this line, as do samples from the Moon. This is strong evidence that the Earth and the Moon are not chance associates, but formed from the same oxygen source in the same region of the Solar System. Any samples formed from another source of oxygen would lie on different lines. This is the case for Bunburra Rockhole. Not only did it form in a different region of the Solar System to the Earth and the Moon, it also appears to have formed in a different parent body from other similar basaltic igneous meteorites.

To date, the ADFN has recorded >550 fireballs. Of these, multi-station observations from which precise atmospheric trajectories and orbits have been calculated number 150. This is the first set of data for southern hemisphere fireballs, and it is possible that a new, active meteor shower has also been discovered. Of the events recorded on multiple stations, around 11 may have resulted in meteorites, not all of which are recoverable. Four of these are probable falls with masses within the range 10–100 g, five are certain falls with terminal masses greater than 100 g, and one had an initial mass of 20 t. Unfortunately, this latter fall, which may have had a cometary origin, fell into the Great Australian Bight. One certain fall, and two probable falls are, as yet, unrecovered and lie in easily searchable areas of the Nullarbor. Three additional recent events are almost certainly recoverable falls and calculations to locate them are in progress. In October 2010 a fragment of one of these falls, Mason Gully, weighing 24.54 g was recovered marking the second success of the ADFN (Spurny *et al*. 2011). An H5 ordinary chondrite, Mason Gully may also be compositionally anomalous.

With the successful operation of the network, a milestone in meteoritics has been achieved. Having demonstrated the undoubted viability of the project, the ADFN has already become a major contributor to Solar System research.

## IMPACT CRATERING

Meteorite impact is a significant geological process and the surviving impact record provides the only tangible evidence against which theoretical predictions of the effects of potentially catastrophic impact can be compared. Accumulating definitive evidence of impact is the most important aspect of crater studies. By establishing the impact origin of structures and determining their sizes and ages, the data can be used to calculate cratering rates with time, and predict the liklihood of another event occurring in future.

The first meteorite impact crater to be discovered in Australia was Dalgaranga in Western Australia in 1921. The structure was later confirmed as of impact origin by the discovery of meteorite fragments associated with the structure in 1923 (Simpson 1938). This discovery was followed by the discovery of meteorites at the Henbury craters (1931) and the Boxhole crater (1937) in the Northern Territory that confirmed their impact origin (Alderman 1932; Madigan 1937). At the time the only other craters known with associated surviving fragments of the projectile were Meteor Crater (1897) and Odessa (1922) both in the USA.

In 1947 the Wolfe Creek Crater (originally named Wolf Creek) was discovered from the air and later surveyed on the ground (Reeves & Chalmers 1949; Guppy & Matheson 1950). Wolfe Creek is the largest impact crater (~880 min diameter) associated with meteorites in Australia, and its discovery greatly heightened interest in impact studies.

Other, much larger, older and deeply eroded circular structures measuring tens of kilometres were recognised as of possible impact origin. Here no meteoritic material survived but evidence of intense shock-metamorphism and melting in the target rocks provided conclusive evidence of their impact origin.

**Figure 8** Satellite image of Gosses Bluff, Northern Territory. The Bluff (top centre) is an eroded remnant of the central uplift of a complex impact crater. The overall diameter of the crater (pale area surrounding the Bluff) is 24 km (Courtesy of the Australian Centre for Remote Sensing).

Perhaps the best example in Australia was the recognition of Gosses Bluff in the Northern Territory as an impact structure (Figure 8). In the late 1960s detailed geological mapping of Gosses Bluff by joint US Geological Survey and the then Bureau of Mineral Resources teams established the site as a classic example of the central uplift of a medium sized (24 km diameter) complex impact crater of late Jurassic age (Milton *et al.* 1972). The evidence for impact at Gosses Bluff includes impact melts, shatter cones, and shocked quartz. The study involved several Australians, notably Robin Brett (USGS) and Andrew Y Glikson (then at the BMR).

In the 1980s, Eugene Merle (Gene) Shoemaker (1928–1997) an American geologist, and his wife Carolyn Shoemaker, an astronomer, obtained funding to undertake a comprehensive study of impact structures in Australia. In collaboration with Australians, such as Andrew Glikson, the Shoemaker's discovered several new impact sites, and through meticulous mapping improved our knowledge of many of the structures that were already known (Shoemaker & Shoemaker 1996; Shoemaker *et al.* 2005).

From the early 1980s, an Australian geologist, Peter W Haines (now at the Geological Survey of Western Australia), has discovered and described several new impact structures and remains an active worker in the field. Haines is one of Australia's most prominent impact specialists and has reviewed the Australian crater record (Haines 2005 and references therein).

Today there are 37 structures in Australia that are recognised to varying degrees of certainty as impact structures. Five of these are small, young, simple bowl-shaped craters associated with meteorites (Bevan 1996; Bevan & McNamara 2009). Another 12 possible impact sites are currently under investigation, but to date lack conclusive evidence of an impact origin.

## SUMMARY

In Australia, since the late 1880s, contributions to meteoritics and planetary materials have been significant, diverse, and multidisciplinary, including the study of meteorites themselves, lunar rocks and impact cratering. These studies have involved the disciplines of petrology, mineralogy, metallurgy, isotopic studies, geochemistry and geochronology. Today there are active groups of scientists at the Australian National University, Curtin University, the University of Western Australia, Monash University, Sydney University, University of New South Wales, and Macquarie University. Research is also carried out on major collections of meteorites that are held at the Australian Museum in Sydney, and the State Museums of Victoria, South Australia and Western Australia.

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