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Australian crater-forming meteorites

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Meteorites are associated with five impact structures in Australia. Three of them are group IIIAB irons (Wolf Creek, Henbury, and Boxhole), Veevers is a group IIAB iron, and material recovered from the crater at Dalgaranga is a mesosiderite stony-iron. The impacts range in age from a few thousand years (Dalgaranga, Henbury, Veevers, and Boxhole) to 300 000 years (Wolfe Creek Crater). Metallographic studies of the surviving fragments at some of the craters show that impact damage ranges from simple fracturing, through shock-hardening of metal, to plastic and shear deformation, reheating and attendant recrystallisation, and, ultimately, melting. Details of the microstructures of surviving fragments of iron meteorite from the craters suggest that shear deformation may have been an important mechanism in the disruption of the projectiles. Frictional heating from viscous drag between projectile and target, and from rapid shear deformation within the projectile, may be sufficient to melt and vaporise significant portions of the projectiles and account for the large deficit of meteoritic material from Australian impact craters.

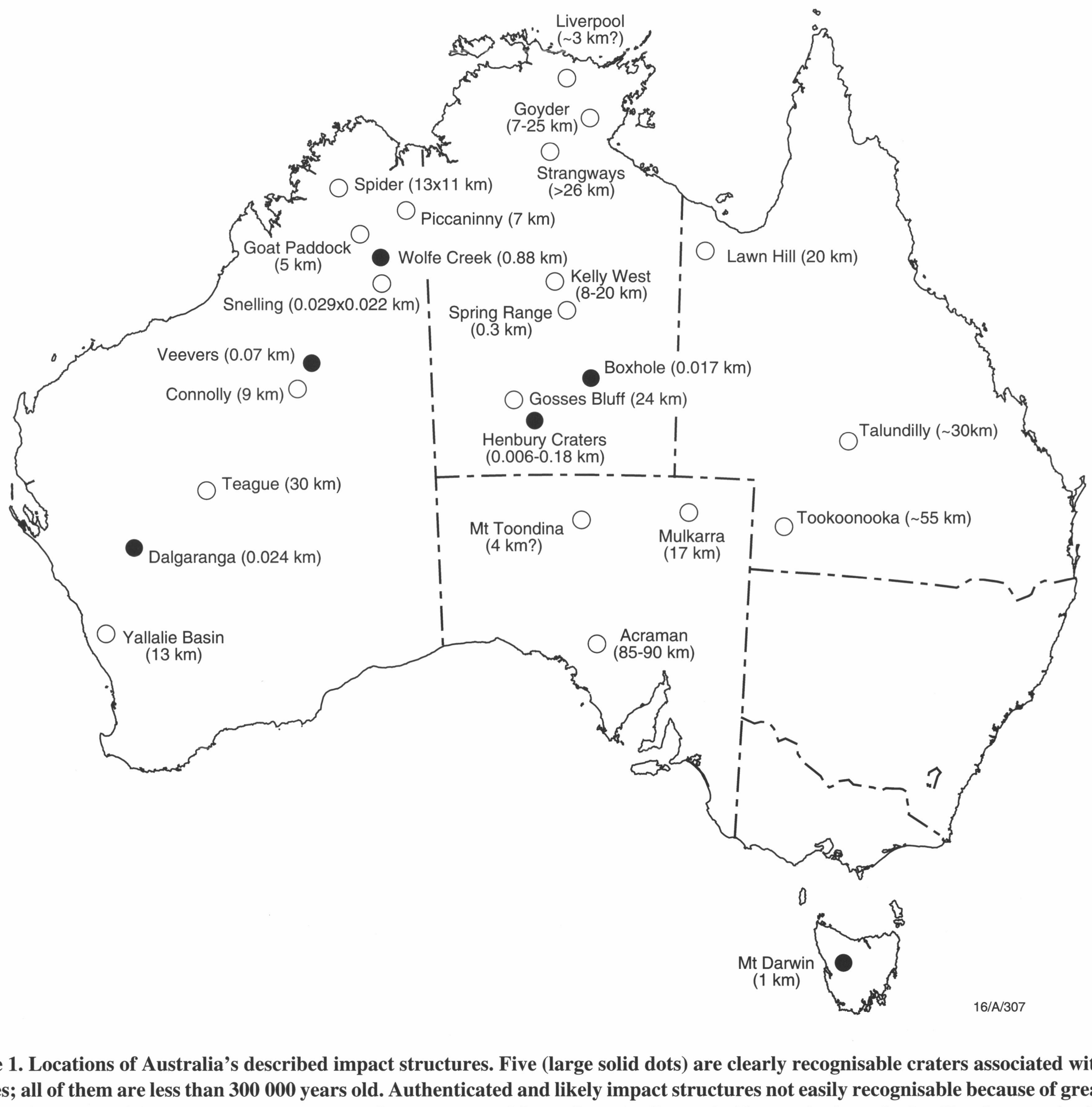

Figure 1. Locations of Australia's described impact structures. Five (large solid dots) are clearly recognisable craters associated with meteorites; all of them are less than 300 000 years old. Authenticated and likely impact structures not easily recognisable because of great age, deep erosion, or burial are shown as open dots. One structure, Mount Darwin Crater in Tasmania, is undoubtedly of meteorite impact origin (Fudali & Ford 1979), but no meteorites have been collected from the site. The indicated diameters of structures are based on conspicuous topographic expression or geophysical evidence, and may not reflect the original dimensions of very old, eroded complex structures (from Shoemaker & Shoemaker 1988; Buchanan et al. 1992).

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Table 1. Australian impact craters associated with meteorites

Name	*Coordinates*	*Diameter (km)*	*Age (Ma)*	*Meteorite type/class*
Dalgaranga	27°40'S, 117°17.5'E	0.024	<0.003?[1]	Stony-iron, mesosiderite
Veevers	22°58'06"S, 125°22'07"E	0.07	<0.004?[1]	Iron, group IIAB
Henbury (Craters)	24°35'S, 133°10'E	0.006-0.18	0.0042 ± 0.0019[2,3]	Iron, group IIIAB
Boxhole	22°37'S, 135°12'E	0.17	0.0054 ± 0.0015[2]	Iron, group IIIAB
Wolfe Creek Crater	19°18'S, 127°46'E	0.88	~0.30[4]	Iron, group IIIAB

[1] Shoemaker & Shoemaker (1988). [2] Kohman & Goel (1963). [3] Goel & Kohman (1963). [4] Shoemaker et al. (1990).

Introduction

Of the 23 structures identified as having originated from the impact of extraterrestrial objects in Australia, five (Wolfe Creek Crater, Henbury, Dalgaranga, Veevers, and Boxhole) are associated with meteorites (Fig. 1). All five are simple bowl-shaped structures ranging in diameter from 24 m (Dalgaranga) to 880 m (Wolfe Creek Crater) and in age from a few thousand years (Dalgaranga, Henbury, and Boxhole) to 300 000 years (Wolfe Creek Crater; Table 1). At each crater, the impacting meteorites have been identified as follows: Wolf Creek[1] (group IIIAB iron); Henbury (group IIIAB iron); Dalgaranga (mesosiderite stony-iron); Veevers (group IIAB iron); and Boxhole (group IIIAB iron). Detailed modern metallographic descriptions have been presented by Buchwald (1975, and references therein) for the residual fragments of the impacting irons at Wolfe Creek Crater, Boxhole, and Henbury, by Bevan et al. (1995) for the Veevers meteorite, and by Nininger & Huss (1960) and McCall (1965a) for the Dalgaranga mesosiderite and its occurrence.

Numerous studies have examined the thermomechanical alteration of the crater-forming meteorites wrought by shock-metamorphism resulting from impact with the Earth, and several authors have considered the mechanism of disruption of the original projectiles during the impact event (e.g., Heymann et al. 1966, and references therein; Vdovykin 1973). However, despite extensive theoretical and experimental work in the field of cratering mechanics, geological studies of craters (Shoemaker 1960, 1963; Grieve 1987, 1991; Melosh 1989, and references therein), and shock-metamorphism (e.g., Stöffler 1971, 1972, 1974; French & Short 1968, and references therein; Roddy et al. 1977, and references therein; Alexopoulos et al. 1988) there is still much to be learnt about the phase changes that occur in the impacting bodies (both target and projectile) and the resulting disposition of the material at the point of impact.

The surviving fragmental material from some of the Australian impactors unfortunately has been extensively corroded (e.g., Wolf Creek), and much of the original structure of the fragments that might have given an insight to the mechanism of disruption has been lost. Nevertheless, at other sites — notably Henbury, Veevers, and Dalgaranga — fresh material survives to the present day in meteorite collections. The purpose of this paper is to review the data on Australian crater-forming meteorites, and, by comparison with examples from other parts of the world, to examine possible mechanisms of disruption of the impacting projectiles.

[1] Historical research has revealed that the surname of the person after whom the crater was named was 'Wolfe' not 'Wolf'. Consequently, the locality 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.

Boxhole

The Boxhole crater, measuring about 170 m in diameter, is situated in the Northern Territory near the Plenty River at latitude 22°37'S, longitude 135°12'E. The crater, which was discovered in June 1937, is formed in schists and gneisses of Precambrian age, and has a rim raised about 3 m above the surrounding plain. Little fresh meteoritic material survives at the crater. During the first scientific examination of the crater, Madigan (1937) surveyed and described the structure. Two balls of 'iron-shale' (nodules of iron oxides representing the weathered remnants of fragments of the meteorite) and one fragment of meteoritic iron weighing about 100 g were found and analysed subsequently (Madigan 1940).

Since the discovery of the crater, much additional material, including one mass of 82 kg, has been recovered from the site. However, the total weight of fragments recovered from the crater that are documented in museum collections throughout the world is only around 280 kg (Graham et al. 1985). The largest single holding of material (178 kg) is at the South Australian Museum in Adelaide. Other collections have undoubtedly been made by private collectors; Buchwald (1975) estimated that perhaps as much as 500 kg of iron meteorites and around 50 kg of iron-shale have been recovered in total.

Soil in an area up to 1.5 km around the crater was sampled by Hodge & Wright (1970), who noted a spotty distribution of weathered meteorite particles similar to those discovered around the Henbury craters (Hodge 1971). Numerous shale-balls have been found buried in the soil around the crater, together with small fragments of less-weathered iron meteorite typically 50-200 g in weight (Buchwald 1975). Many of the small fragments are intensely deformed and twisted slugs of metal, or wedge-shaped fragments.

The metallography of the deformed fragments shows that the medium Widmanstätten pattern is bent and torn, that kamacite has been transformed by reheating and rapid cooling to unequilibrated α_2-kamacite, probably by the reaction α-γ-α_2, and that inclusions of schreibersite [$(Fe,Ni)_3P$] and troilite (FeS) are widely melted. Buchwald (1975) interpreted this alteration as the result of thermomechanical treatment resulting from compression and heating of the meteorite during the cratering event. The metallographic features indicate that the residual temperature of the deformed slugs must have been briefly above 1000°C.

Whereas many specimens of Boxhole are apparently disrupted fragments from a larger body that fragmented on impact, Buchwald (1975) has shown that some fragments became detached from the projectile during atmospheric passage and were not involved in the crater-forming event. One such specimen is a 3.7-kg mass preserved at the National Museum of Natural History in Washington. A metallographic examination of the undeformed portions of the meteorite (Buchwald 1975) shows a well-developed medium octahedrite (kamacite bandwidth 1.00 ± 0.15 mm) Widmanstätten pattern and shock-hardened ε-kamacite. The latter feature indicates that the meteorite was subjected to shock-loading in excess of 13 GPa before impact with the Earth.

Boxhole has been chemically classified as a group IIIAB iron containing 7.64% Ni, 18.1 ppm Ga, 37.2 ppm Ge, and 8.2 ppm Ir (Wasson & Kimberlin 1967).

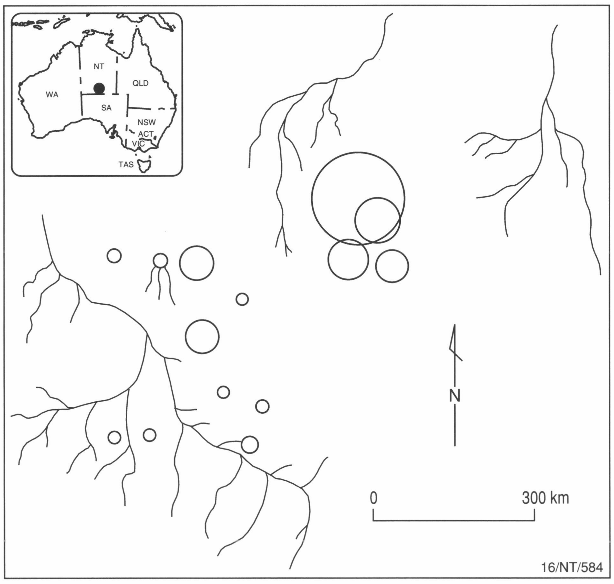

Figure 2. Schematic map of the crater strewn field at Henbury, Northern Territory (after Passey & Melosh 1980).

Wolf Creek

The Wolfe Creek Crater was discovered from the air in June 1947 by F. Reeves, N.B. Sauve, and D. Hart (Reeves & Chalmers 1949; Guppy & Matheson 1950). It is situated at latitude 19°10'S, longitude 127°46'E, on the margin of the Great Sandy Desert in Western Australia, and about 110 km south of Halls Creek. It measures 850–900 m (averaging 880 m) in diameter, and is the largest crater associated with meteorites known in Australia. Formed in Precambrian quartzites, it has a rim that rises up to 35 m above the surrounding sand plain, and about 50 m above the current flat crater floor. Depth/diameter relationships of simple impact craters (Melosh 1989), and a gravity survey by Fudali (1979), suggest that the crater is 140–150 m deep. It now contains an extensive aeolian sedimentary fill.

Fresh iron meteorite fragments are extremely rare at the crater (e.g., Cassidy 1954; McCall 1965b); only 1.3 kg of unoxidised material is known to have been collected. The most important specimens are a number of small masses discovered 4 km southwest of the crater and described by Taylor (1965). Several terrestrially produced secondary minerals have been described from the weathered material by White et al. (1967) and Faust et al. (1973). A substantial amount of iron-shale, including shale-balls weighing up to 300 kg (LaPaz 1954), has been recovered. Many of the shale-balls contain rare stringers and particles of fresh metal (Knox 1967), although Buchwald (1975) noted that corrosion has largely obscured the original structure of the meteorite. In all, several thousand kilograms of shale-balls have been recovered from the crater (McCall & de Laeter 1965).

An analysis of the fresh material (Scott et al. 1973) yielded 9.22% Ni, 18.4 ppm Ga, 37.3 ppm Ge, and 0.036 ppm Ir, showing that the meteorite belongs to chemical group IIIAB. Structurally, the Wolf Creek meteorite is a medium octahedrite with a kamacite bandwidth of 0.85 ± 0.15 mm (Buchwald 1975). Buchwald (1975) noted that the moderately fresh material consists of slugs of metal in which the Widmanstätten pattern is slightly distorted, particularly at the margins of the fragments, indicating plastic deformation associated with the break-up of the impacting body. Kamacite in Wolf Creek displays the shock-hardened ε-structure which Buchwald (1975) attributed to pre-terrestrial shock-loading of the meteorite. Although the classified fragments were found at a considerable distance from the crater, Buchwald (1975) concluded that the material was consistent with the more deeply weathered remnants found nearer the crater, and that they were undoubtedly the same meteorite.

More recently, E.M. and C.S. Shoemaker found additional fresh iron meteorite fragments weighing 10.4, 2, and 0.9 g near the crater. These are deposited (WAM 13659) at the Western Australian Museum in Perth, and remain to be described. The 10.4-g sample was used for a terrestrial age determination. From the ratios of $^{36}Cl/^{10}Be$ and $^{41}Ca/^{36}Cl$ for the meteorite, Shoemaker et al. (1990) reported an age for the crater of 300 000 years.

Henbury

The group of impact craters near the Finke River south of the Macdonnell Ranges at latitude 24°35'S, longitude 133°10'E in the Northern Territory are among the best studied in Australia. The crater field was recognised in 1931, and subsequently described by Alderman (1932a). Early search parties independently organised by Alderman (1932b) and R. Bedford of the then Kyancutta Museum are reported to have recovered 1447 individual fragments of meteorite — ranging in weight from less than a gram to 132 kg, and totalling 649 kg — including some shale-balls. Many specimens collected by R. Bedford were sent to the British Museum (Natural History) in London, where they were described by Spencer & Hey (1933) and reside to the present day.

Thirteen or fourteen craters ranging in diameter from 6–180 m have been identified in a strewn field trending roughly north-easterly. The largest craters are at the northeastern end of the field (Fig. 2). Extensive fieldwork has been carried out at the craters (e.g., Hodge 1965), and Milton (1972) has provided a detailed account of the geology. A magnetic survey of the area conducted by Rayner (1939) revealed no large magnetic anomalies, from which he concluded that large masses of meteoritic iron were not represented at the site. However, small anomalies

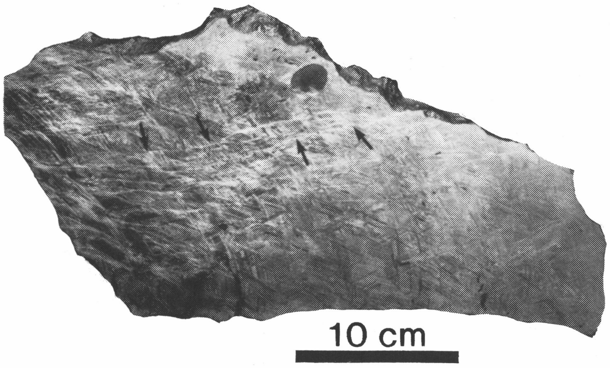

Figure 3. Polished and etched slice of a large mass of the Henbury meteorite showing flattening, distorted Widmanstätten pattern, and extensive zones of shear deformation (arrowed).

were associated with some iron fragments, and one weighing 18 kg was recovered from crater no. 5. Bedford had previously excavated three (nos. 10, 11, and 13) of the smallest craters. In the smallest crater (no. 13) he found four large masses of iron weighing 2.3, 10.9, 54.4, and 132.7 kg. Around and between the masses, 20 kg of iron-shale suggested that the four irons were corroded fragments of what was originally a single large mass (Spencer & Hey 1933; Buchwald 1975; Axon & Steele-Perkins 1975). Buchwald (1975) estimated that at least 1200 kg of meteorites have been recovered from the crater strewn field, most of which have been found in narrow zones of a few hundred metres around the craters.

Detailed metallographic examinations of numerous fragments of the Henbury meteorite (Buchwald 1975) have revealed an enormous range of internal structures that can be attributed to the impact. However, several of the large masses and some of the smaller fragments display unaltered Widmanstätten patterns, and do not appear to have been involved in the formation of the craters. These specimens retain regmaglypts, remnants of fusion crusts, and heat-affected zones as testimony to their independent flight through the atmosphere. The Henbury meteorite is a medium octahedrite with a bandwidth of 0.95 ± 0.1 mm, and belongs to chemical group IIIAB (Buchwald 1975; Wasson & Kimberlin 1967; Scott et al. 1973). Despite a chemical similarity between Henbury and Boxhole, and a suggestion that the two events were contemporaneous, Buchwald (1975) has shown that the metallurgy of the least damaged specimens of both meteorites have significant differences that seem to establish them as distinct. Moreover, Kohman & Goel (1963) and Goel & Kohman (1963) derived slightly different ages for the two cratering events.

Many masses of Henbury are intensely deformed and sheared (Fig. 3). These fragments are generally flattened, twisted, and torn with irregular sharp edges, and the surfaces of many display slickensides. The interior structures of deformed fragments show intensely bent and kneaded Widmanstätten patterns and varying degrees of annealing. Zones of shear deformation, some arranged en echelon, pervade the structures of the most intensely deformed fragments; they are accompanied by attendant recrystallisation of the metal. Kamacite in the smallest metallic slugs is generally transformed completely to α_2-kamacite, and the Widmanstätten structures of these specimens are indistinct and partly resorbed. Some fragments have been almost cleaved in half by shearing, and this has been accentuated by later terrestrial corrosion. Within the shear zones, accessory minerals such as troilite and schreibersite have been shock-melted and smeared out into veins. In the most severely shock-heated fragments, schreibersite has been largely resorbed.

Axon & Steele-Perkins (1975) studied a 5-kg slice from the 132.7-kg mass found in crater no. 13, and many of the shrapnel-like fragments from other craters generated by the impact. The large slice is traversed by a number of shear faults that parallel the outer surface of the section. Axon & Steele-Perkins (1975) suggested that the fracture surfaces of the mass could represent the extreme situation in which limited shear displacement gave way to physical separation along a faulted surface; this is supported by the observations of Buchwald (1975). From the morphology and metallography of the shrapnel-like fragments, Axon & Steele-Perkins (1975) concluded that fracturing of the impacting projectile probably occurred by separation along zones of intense shear deformation. Moreover, the thermal alteration of the surviving fragments was also generated by the rapid propagation of shear deformation.

The most severely deformed specimens have a high density of sheared surfaces. Shear zones vary from the microscopic (50–200 μm wide) to the macroscopic scale, in which shears with displacements of a few micrometres to several millimetres extend 40 cm across sections (Buchwald 1975; Axon & Steele-Perkins 1975). The impactor might have had larger zones of shear faulting, evidence of which would have been destroyed along with the bulk of the projectile.

Buchwald (1975) noted one heavily deformed Henbury fragment with a shear-ruptured slickensided surface covered by a thin fusion crust. He suggested that the crust formed when the fragment was hurled away from the impact site. However, it is more likely that the crust is a vestige of melted material that was generated by shearing during impact fragmentation.

Veevers

The Veevers meteorite impact crater (Fig. 4), measuring 70–80 m in diameter, was recognised in July 1975 (Yeates et al. 1976). The crater is situated between the Great Sandy and Gibson Deserts in Western Australia at latitude 22°58'06"S, longitude 125°22'07"E. At the time of discovery, the crater was surveyed, but no meteoritic material was recovered (Yeates et al. 1976). E.M. and C.S. Shoemaker visited the site twice, and recovered 36 metallic fragments and slugs (Fig. 5) weighing 298.1 g, mainly from near the rim to the north and east of the crater (Bevan et al. 1995).

Wasson et al. (1989) analysed the meteorite and showed that it is a normal member of chemical group IIAB containing 5.82% Ni, 57.7 ppm Ga, 160 ppm Ge, and 0.028 ppm Ir. Bevan et al. (1995) described the fragments as essentially single crystals of α-kamacite that have been partly or completely transformed by reheating to unequilibrated α_2-kamacite, particularly along zones of intense shear deformation. They concluded that the fragments represent individual kamacite lamellae which were separated from the original coarsest octahedral structure of the meteorite as the result of impact fragmentation; this conclusion confirmed earlier observations made by Wasson et al. (1989). Moreover, Bevan et al. (1995) suggested that the meteorite may have failed as the result of fracturing along zones of shear deformation. The pattern of shearing in some of the Veevers fragments locally indicates that the original octahedral structure of the meteorite may have influenced the selection of certain

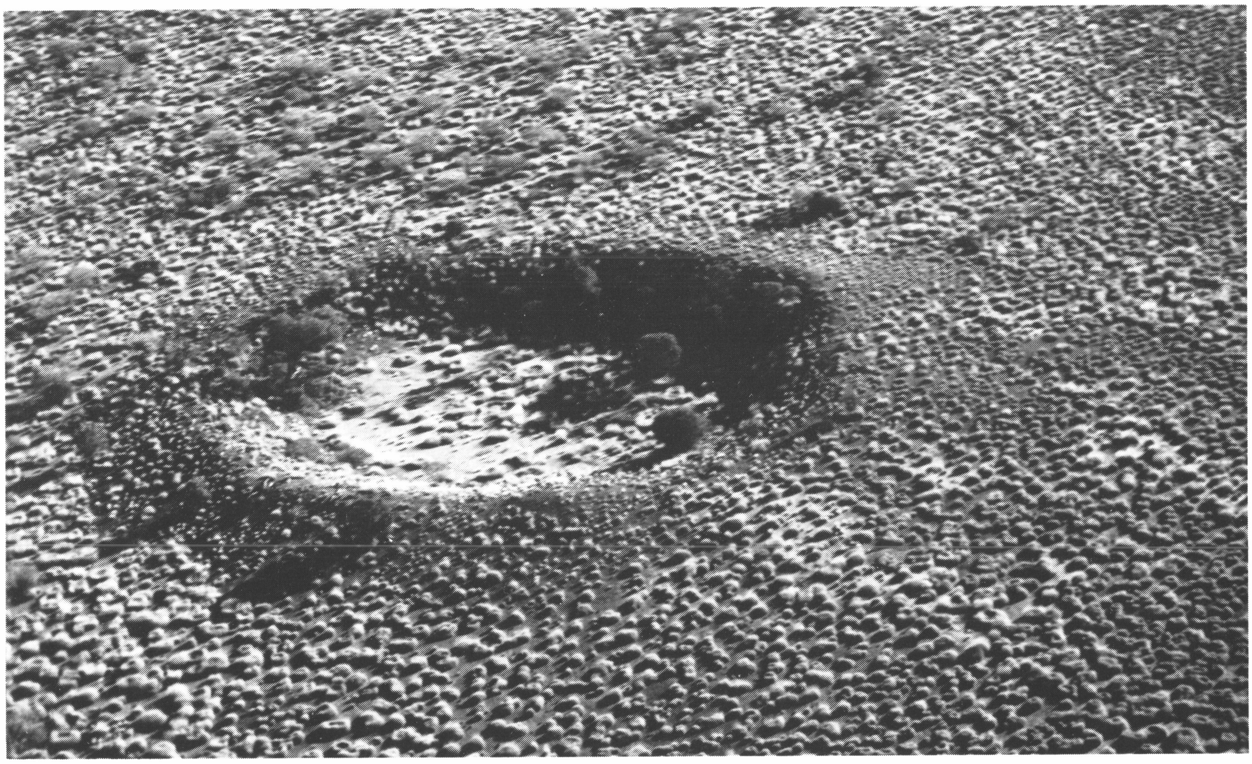

Figure 4. Oblique aerial view of the 70–80-m-diameter Veevers meteorite impact crater (named for geologist J.J. Veevers; photograph courtesy of A.N. Yeates, AGSO).

surfaces for shear faulting. From a metallographic study of the Veevers fragments, and comparisons with experimentally heat-treated samples of the Canyon Diablo meteorite, Bevan et al. (1995) suggested that terrestrial impact caused intense shock-loading which resulted in shearing and plastic deformation of the projectile and attendant localised shock-heating. The peak residual shock temperatures suggested by the surviving fragments is >800°C. As a result of the disruption of a portion of the meteorite along brittle-cracking paths, such as α–α crystal boundaries and schreibersite crystals, some of the energy of the impact might have been absorbed, allowing part of the original microstructure of the meteorite to be preserved.

Veevers is the only known crater-forming iron of group IIAB. The fall of another IIAB iron, Sikhote-Alin, which was observed in Siberia in 1947, resulted in 122 impact holes. However, Fesenkov & Krinov (1959) suggested that these are not true impact craters. Many of the recovered masses, totalling 23.2 t, display only the earliest stages of shock-metamorphism (Krinov 1963; Buchwald 1975).

Dalgaranga

The Dalgaranga crater, recognised in 1923 by G.E.P. Wellard, is the first such discovery known to have been caused by the impact of a meteorite in Australia (Fig. 6). Situated at latitude 27°40'S, longitude 117°17.5'E, the crater measures 24 m in diameter, and is around 3 m deep. Wellard is reported to have recovered numerous fragments of meteoritic material from the vicinity of the crater, but the whereabouts of the bulk of it is unknown. Additional collections made by H.H. Nininger and G.I. Huss of the American Meteorite Laboratory in 1959 and 1960 amounted to 207 specimens weighing 1098 g recovered from the area surrounding the crater, and 280 specimens weighing around 9.1 kg recovered from beneath the crater floor (Nininger & Huss 1960).

Simpson (1938) described the meteorite from a single fragment weighing 42 g, and concluded that it was an 'iron' with a medium octahedral structure. Later work by Nininger & Huss (1960) and McCall (1965a) showed that the impacting meteorite is a mesosiderite stony-iron. A modern analysis of the metallic portion of the meteorite — 8.8% Ni, 15.5 ppm Ga, 56 ppm Ge, and 4.2 ppm Ir (Wasson et al. 1974) — has confirmed a mesosiderite classification (Graham et al. 1985). A more recent analysis by Hassanzadeh et al. (1990) yielded 10.27% Ni, 12.7 ppm Ga, and 4.99 ppm Ir, showing that the metallic nodules in Dalgaranga vary in composition. This is reflected in structural variations of metallic nodules, which have Widmanstätten patterns ranging from finest to coarsest octahedrite.

Much of the material found at Dalgaranga, particularly the material from within the crater, is extensively altered by prolonged terrestrial weathering. Nevertheless, a substantial number of the fragments, including many metallic slugs, are well preserved. The metallic slugs display Widmanstätten patterns that are variably bent and deformed (Nininger & Huss 1960). The metallic portions of the meteorite locally show narrow zones of shear deformation along which metal has been finely recrystallised (Bevan & Griffin 1994). Other fragments show little effects of shock-metamorphism (Nininger & Huss 1960).

Discussion

Extensive studies of Meteor Crater in Arizona, USA (Shoemaker 1960, 1963), of the associated Canyon Diablo meteorite (Heymann et al. 1966; Vdovykin 1973), and of other simple impact structures throughout the world (e.g., Grieve 1991, and references therein), combined with experimental work on

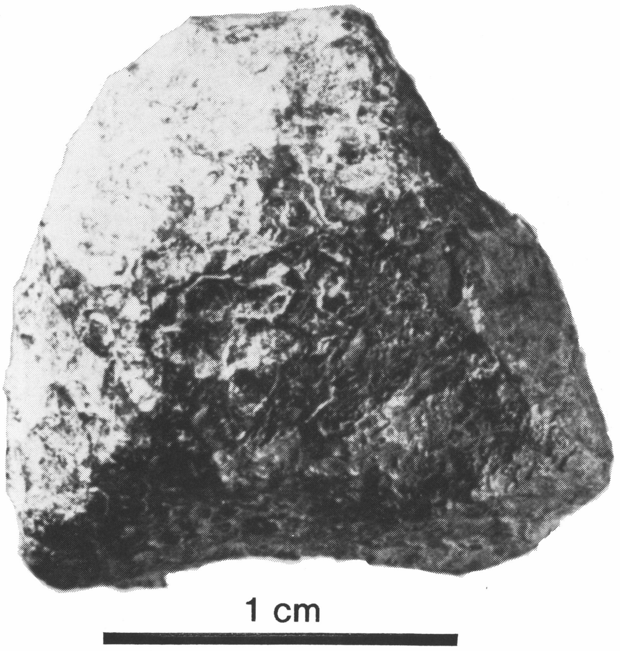

Figure 5. Fragment, weighing 8.9 g, of the Veevers crater-forming meteorite found by E.M. and C.S. Shoemaker in 1984.

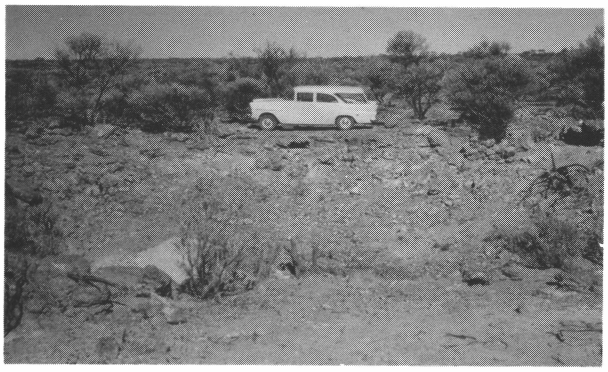

Figure 6. Dalgaranga meteorite impact crater (24 m in diameter), Western Australia, viewed from the north at ground level (courtesy of W.H. Cleverly and M.K. Quartermaine).

hypervelocity impact (Melosh 1989, and references therein), have provided much information on the mechanics of cratering.

Shoemaker et al. (1963) disputed the widely held concepts that a large part of a projectile travelling at a high velocity and causing a Meteor Crater-size structure would vaporise as it impacted into rock, and that the explosive expansion of the vapour produces the resultant crater. Nininger (1956) suggested that the metallic spherules that occur at Meteor Crater were formed by the condensation of iron–nickel vapour. However, Blau et al. (1973) and Kelly et al. (1974) have since shown that the metallic spheroids are more likely to have been generated by shock-melting.

From an experimental impact of a small (4.76-mm-diameter) steel sphere travelling at 4.27 km s^{-1} into a block of Coconino Sandstone collected from Meteor Crater, Shoemaker et al. (1963) showed that, for those conditions, the fusion of the projectile could not be due to compressive heating alone, or to the conduction of heat from the shocked target, but could be accounted for by the production of heat by viscous drag and friction along the projectile/target interface, and by frictional heating along shear planes within the projectile.

Shoemaker et al. (1963) showed convincingly that shear-generated frictional heating of the experimental steel projectile appeared adequate to account for the melted material recovered from the experiment, and was the best explanation for the occurrence of fused steel on the striated surfaces of the larger recovered fragments. They concluded from this experiment that abundant metallic spheres from the melting of an iron projectile could be produced without the generation of any significant amount of vapour, and that more definitive evidence was required to show that a significant fraction of the Meteor Crater projectile had been vaporised on impact. However, some scaling problems arise from the extrapolation of small-scale experiments to hypervelocity impacts of iron meteorites weighing tens of thousands of tons and measuring tens of metres in diameter.

Only general limits of the pressures required for phase changes in complex multiphase geological materials under conditions of compressive shock-loading are known (Ahrens & O'Keefe 1977). For melting and vaporisation of iron to occur by compression, estimates indicate that the onset of melting occurs at 220 GPa and is complete by 260 GPa, whereas vaporisation starts at 420 GPa and is complete at 1680 GPa (Ahrens & O'Keefe 1977). In an impact event, the greatest shock pressures occur during the initial contact and compression stage (Melosh 1989). During the initial compression stage of the vertical impact of a body weighing 50 000 t travelling at 15 km s^{-1} into a crystalline (anorthositic) target, the highest shock pressures attained are estimated to be of the order of hundreds of gigapascals. Although they are much greater than the yield strength of the impactor and target, the compressive pressures fall far short of those required to vaporise a significant portion of the projectile. Compressive pressures (1590 GPa) capable of extensive vaporisation are attained only for large impactors travelling at velocities of 30 km s^{-1} or more (Melosh 1989).

Most impacts are not vertical (Shoemaker 1962), and the morphology of many of the Australian craters (notably Henbury) supports this assertion. The physics of oblique impacts differs markedly from that of vertical or near-vertical impacts (Wichman & Schultz 1994, and references therein; Yang & Ahrens 1995, and references therein). Melosh (1989) noted that the principal difference between vertical and oblique impacts is apparent in the effects on the projectile. In a moderately oblique impact, the projectile is first compressed by shock generated at the target–projectile interface. The shock is then propagated into the projectile, and thus reduces the vertical component of its velocity. However, the horizontal component of the projectile's velocity remains large (Melosh 1989). Melosh (1989) pointed out that one of the consequences of oblique impacts is that 'jetting' may play a significant role.

Experimental work has shown that even at impact velocities of around 6 km s^{-1}, which are theoretically too low to melt large portions of either projectile or target, jets of incandescent debris shoot away rapidly at a low angle from the impact site (Melosh 1989). At low impact velocities, the jetting phenomenon, first observed by D.E. Gault, is evidently due to molten material. Melosh (1989) suggested that, at higher impact velocities, superheated vapour may be ejected; he propounded that the melt/vapour ratio, and the projectile mass, scale as the square of the impact velocity. He also noted that the effect of oblique impacts on the production of melt or vapour is not well known, although jetting may enhance the amount produced. However, recent work by Yang & Ahrens (1995, and references therein) has provided experimental data on impact-jetting during oblique impacts.

Differences in the dimensions and compositions of the known crater-forming meteorites, in the velocities and trajectories of the bodies, and in the nature of the target rocks have together led to large differences in the magnitudes of their impacting events and to a resultant enormous range of shock-induced features in the residual fragments. Observed damage of crater-forming irons ranges from simple fracturing, through shock-hardening of metal, to plastic and shear deformation, reheating, attendant recrystallisation, and, ultimately, melting. Nevertheless, Bevan et al. (1995) noted that there are some close similarities in the overall nature of the thermomechanical alteration and apparent mechanism of disruption suffered by many crater-forming irons.

Parting along zones of intense shear deformation and faulting appears to have been an important mechanism in the disruption of the Henbury and, to a lesser extent, Veevers projectiles (Axon & Steele-Perkins 1975; Bevan et al. 1995). Furthermore, heating and localised melting are demonstrably associated with shearing in residual fragments of both projectiles, and in the metallic portions of Dalgaranga. From their observations of Henbury, Axon & Steele-Perkins (1975) deduced that, once shearing is initiated on a selected surface, it is likely to be propagated by the local generation of heat and the superplastic lubrication of the small kamacite crystals in the zone of mylonitisation.

At all the crater sites in Australia, there is a large deficit of meteoritic material. Even at Meteor Crater in Arizona, the most comprehensively studied simple structure in the world, only around 30 t of fragmental material and an unknown weight of millimetre-size metallic iron–nickel spherules have been recovered from a projectile estimated to have weighed in the range 50 000–100 000 t (Shoemaker 1960, 1963; Vdovykin 1973; Melosh 1989). The question arises: where is the bulk of the impacting material? Substantial portions of the impacting projectiles must have been shock-melted; this assertion is supported by the occurrence of abundant metallic Fe–Ni spherules (or evidence of their pre-existence) at many of the sites. At Henbury, Fe–Ni globules have also been identified embedded in the impact-generated glasses (Taylor 1967; Gibbons et al. 1976), and the impactites generally contain significant concentrations of siderophile elements derived from the impactor (Attrep et al. 1991).

One possible reason for the paucity of meteoritic material at the impact sites is that much of the remnants of the projectiles are imbedded in impact breccias beneath the crater floors (E.M. Shoemaker, US Geological Survey, personal communication). However, the lack of sharp magnetic anomalies at the craters suggests that, if this is correct, the material must be very widely dispersed. Whether any significant portion of the material was vaporised in events of this scale has yet to be proved (e.g., Shoemaker et al. 1963).

Most frictional energy is dissipated as heat. Much of the heat is generated in the small areas of contact between the bodies, and the local temperatures may instantaneously be very high (Jaeger 1942). These transient high temperatures have been called 'flash temperatures'. Archard (1959) theorised that the maximum flash temperature which can be reached at a high-velocity steel–steel frictional contact, provided that the total load is borne by a single plastically deformed area, is of the order of 10 000°C (Arnell et al. 1991). Significantly, this temperature is well in excess of that required for vaporisation to occur.

Summary and conclusions

Metallographic evidence from the residual fragments of iron meteorites, and one stony-iron meteorite, from Australian simple impact craters provides strong support for the suggestion by Shoemaker et al. (1963), based on experimental work, that the bulk of the impact-generated thermal effects on high-velocity metallic projectiles are due to frictional heating. In surviving fragments of meteorites from Australian craters, thermal alteration appears to be largely associated with shear deformation. Whereas frictional heat is sufficient to melt parts of a small projectile, Shoemaker et al. (1963) have suggested that it is insufficient to vaporise a large part of it.

Despite the extensive terrestrial corrosion and disintegration of some of the meteorites, this process alone cannot account for the paucity of material at the sites of impact. Theoretical tribology (Arnell et al. 1991) suggests that high-velocity frictional contact can generate extreme temperatures locally, and may lead to jetting. The possibility that substantial portions of the projectiles were destroyed by vaporisation associated with the jetting phenomenon needs to be modelled mathematically, and the compounding effects of oblique impacts taken into account. Frictional contact between the projectile and target, and within shear zones in the projectile, are both sources of heat generation. Octahedral iron meteorites are composed of a trellis-work of interlocking plates of varying thicknesses, the Widmanstätten pattern. The interaction and collision of plates in the structure during the compressive stage of hypervelocity impact are, as yet, unknown.

The surviving fragments at the craters probably represent material scabbed from the outermost (perhaps rear) portions of the projectiles during the impact, and thrown with ejecta around the craters. However, some, particularly at the Henbury and Boxhole craters, represent fragments detached during atmospheric flight. Further studies, notably measurement of short-lived cosmogenic isotopes of both hand specimens and metallic spherules from Australian craters, may help to determine the spatial relationships between unmelted and melted material from the impacting projectiles.

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