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Metallography and thermo-mechanical treatment of the Veevers (IIAB) crater-forming iron meteorite

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Abstract — Thirty six fragments of iron meteorite (group IIAB – Wasson *et al.* 1989) totalling 298.1 g found at Veevers crater in Western Australia (22°58'06"S, 125°22'07"E) represent the disrupted remnants of the crater-forming projectile, and confirm an origin for the *ca.* 75 m crater by meteorite impact. The morphology and metallography of the residual material show that the impacting meteorite was a coarsest octahedrite with a kamacite bandwidth of > 8.6 mm. Disruption of the meteorite during impact probably occurred along the grain boundaries of α-kamacite crystals in the original octahedral structure, but may also have resulted from failure related to intense shear deformation. Further disintegration of the surviving fragments may have occurred as the result of prolonged terrestrial weathering. Thermo-mechanical alteration of the micro-structure of the meteorite as a result of impact includes transient, localised re-heating to >800°C, shearing and plastic deformation. Failure of parts of the meteorite along brittle-cracking paths, such as crystal boundaries, may have absorbed some of the energy of terrestrial impact and allowed portions of the original micro-structure of the meteorite to be preserved. Veevers is the only known group IIAB iron associated with an impact crater.

INTRODUCTION

In Australia there are five meteorite impact craters (Wolfe Creek, Dalgaranga, Henbury, Boxhole and Veevers) with associated meteoritic fragments representing the remnants of the impacting projectiles. Of these, Veevers crater is the most recently recognised and the least well described. Veevers meteorite impact crater is situated between the Great Sandy and Gibson Deserts in Western Australia at co-ordinates 22°58'06"S, 125°22'07"E. The bowl-shaped, circular structure, measuring 70–80 m in diameter and 7 m deep, was recognised as a possible impact crater in July 1975 (Yeates *et al.* 1976). Yeates *et al.* (1976) surveyed the crater but did not find any meteoritic material that would have provided conclusive evidence of an origin by meteorite impact. Subsequently, in August 1984, two of us (EMS and CSS) visited the locality and recovered several small fragments of iron meteorite from two localities immediately to the north of the crater (Figure 1). The material (Table 1– WAM 13645–46) comprises several irregular, weathered fragments, the largest weighing 8.9 g. In July 1986, during a further visit to carry out a detailed survey of the crater (Shoemaker and Shoemaker 1988), an additional 32 metallic slugs and fragments of meteoritic iron were recovered, the largest weighing 36.3 g (Graham 1989) (see Table 1). Most of this material was found just to the east of the crater, on the flanks of the crater rim and adjacent plain (Figure 1). A precise age for the crater has not yet been published, although Shoemaker and Shoemaker (1988) estimated that it was formed around 4000 years ago.

More recently, Wasson *et al.* (1989) analysed the meteorite and have shown it to be a normal member of chemical group IIAB containing 5.82 wt% Ni, 57.7 μg/g Ga, 160 μg/g Ge and 0.028 μg/g Ir. Wasson *et al.* (1989) also suggested that the size of the recovered fragments reflects separation of cm-thick kamacite lamellae as the result of weathering or impact fragmentation. In this paper, a detailed metallographic description of the meteorite is provided, and the disruptive thermo-mechanical history of the meteorite during crater-forming impact is interpreted.

PHYSICAL DESCRIPTION AND SAMPLE PREPARATION

The weights and dimensions of the meteorite fragments recovered from the vicinity of Veevers crater are listed in Table 1 and shown (WAM

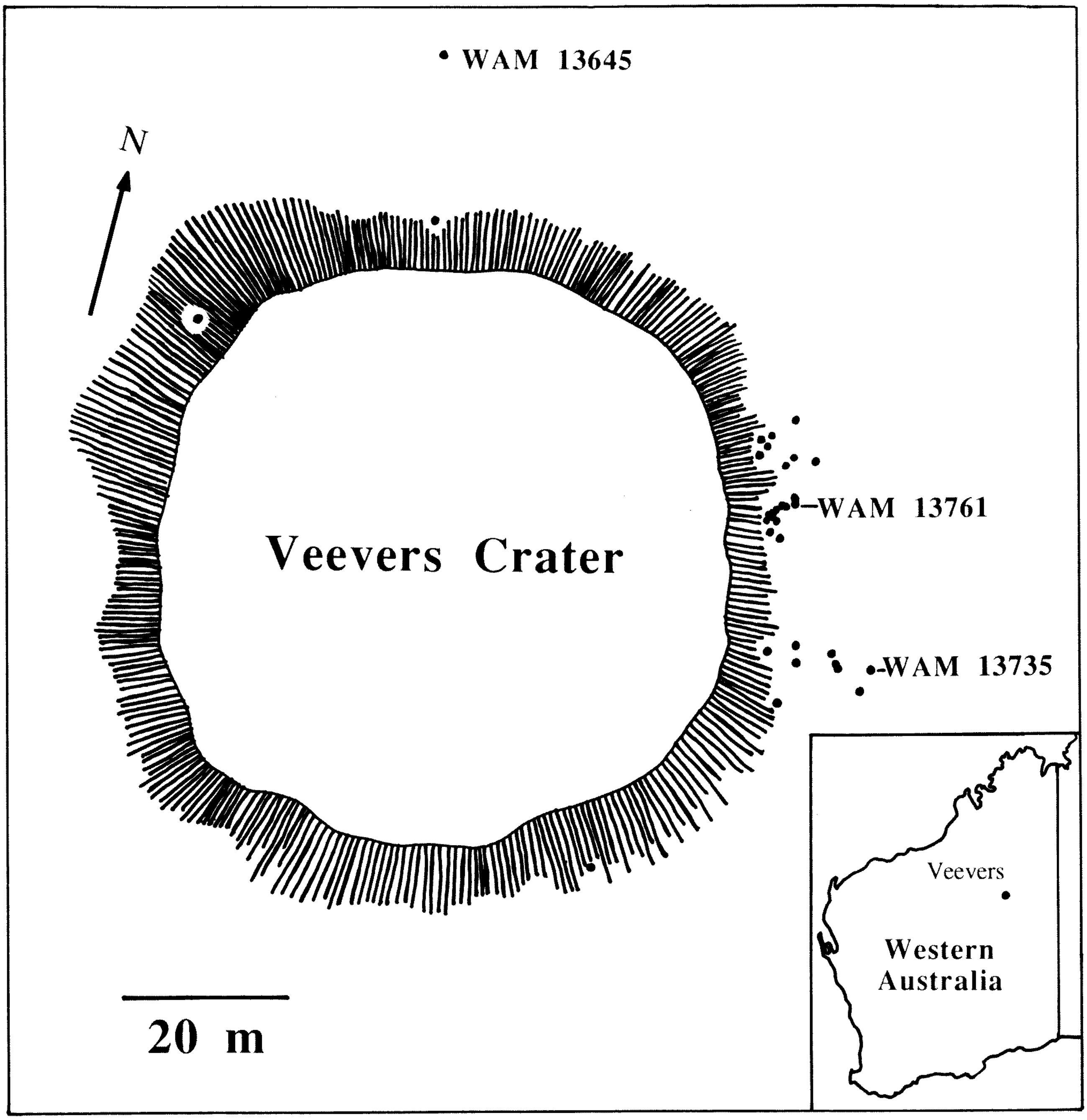

Figure 1 Location of Veevers crater and schematic map showing the distribution of meteorite fragments found by E.M. and C.S. Shoemaker.

13731–13762) in Figure 2. Fragments are weathered and possess variably thick (up to 1mm) rinds of terrestrial corrosion products around fresh metal. The total weight of the fragments is 298.1 g; individual fragments range in weight from < 0.1–36.3 g with a mass distribution skewed towards fragments in the range 2 – 8 g (Figure 3b). Fragments weighing more than 3 g are generally elongate and flattened in shape; the ratios (L/T) of their lengths (L) to maximum thicknesses (T) average 3 and range from 1.6 – 6.5. Fragments weighing more than 3 g have a mean thickness of 8.6 mm (Figure 3a).

Two fragments, one found to the north (WAM 13645) and one found to the east (WAM 13761) of the crater, were cut along their long axes, then polished and micro-etched with 2% nital for metallographic examination. An additional, irregularly shaped fragment (WAM 13735), also found to the east of the crater, was cut perpendicular to a suspected grain boundary.

METALLOGRAPHY AND STRUCTURAL CLASSIFICATION

Microscopically, the fragments examined are composed essentially of single crystals of α-FeNi (kamacite) that have been partially or completely

Table 1 Numbers, weights and dimensions of iron meteorite fragments found at Veevers impact crater

Field No.	WAM No.	weight (g)	length L (mm)	max.thickness T (mm)
VC–1–84	13645	8.9	17.9	11.4
VC–4–84	13646.1	4	32.9	5.05
VC–4–84	13646.2	2.2	23.9	4.6
VC–4–84	13646.3	<0.1	(fragments)	
VC–1–86	13731	6.9	26.75	8.05
VC–2–86	13732	2.5	20.4	5.75
VC–3–86	13733	1.8	15.7	4.9
VC–4–86	13734	12.4	20.3	9.2
VC–5–86	13735	13.9	33.1	9.3
VC–6–86	13736	4.5	27.3	6.5
VC–7–86	13737	9.3	25.5	8.9
VC–8–86	13738	3.9	16.05	8.25
VC–9–86	13739	6	20.6	8.55
VC–10–86	13740	1.3	21.15	4.6
VC–11–86	13741	8.5	24.8	8.9
VC–12–86	13742	4.7	20.35	8.45
VC–13–86	13743	13.8	30.35	11.1
VC–14–86	13744	18	26.95	12.95
VC–15–86	13745	12.2	34.7	7.3
VC–16–86	13746	1.9	15.85	4.4
VC–17–86	13747	17.8	24.35	12.95
VC–18–86	13748	2.8	17.75	5.2
VC–19–86	13749	7.7	19.45	7.8
VC–20–86	13750	2.3	15.85	5.6
VC–21–86	13751	1.3	(small fragments)	
VC–22–86	13752	26.6	(specimen used for terrestrial age determination)	
VC–23–86	13753	4.7	15.65	7.0
VC–24–86	13754	4.9	17.5	8.75
VC–25–86	13755	6.2	21.75	7.8
VC–26–86	13756	5	19.5	7.2
VC–27–86	13757	4.8	19.0	6.75
VC–28–86	13758	4.6	17.1	8.1
VC–29–86	13759	6.6	22.0	6.05
VC–30–86	13760	19.1	36.0	11.3
VC–31–86	13761	36.3	31.35	15.4
VC–32–86	13762	10.6	26.8	8.3

transformed to unequilibrated, ragged α_2-kamacite similar to that found in the heat affected zones of freshly fallen irons. Metal in the fragments WAM 13761 (36.3 g) and WAM 13735 (13.9 g) found to the east of the crater shows complete transformation to coarse (10-200 µm units), ragged α_2, whereas the largest fragment (WAM 13645 – 8.9 g) found to the north of the crater is only partially transformed to finer grained (5–50 µm) α_2 units, mainly along zones of intense shear deformation.

One fragment (WAM 13761) displays several mm-sized inclusions of schreibersite [$(FeNi)_3P$], and both fragments examined contain abundant rhabdites (prismatic crystals of schreibersite). In all fragments examined, schreibersite crystals and rhabdites are kinked, kneaded and deformed, and their grain boundaries show incipient reaction haloes with the surrounding metal (Figure 4a). Evidence of shock-melting in Veevers is sparse. However, where shear-zones intersect large crystals of schreibersite, small (< 20 µm) cloudy, wedge-shaped pools of shock-melted phosphide have been generated that penetrate the phosphide from the phosphide-metal interface. Additionally, some rhabdites have been smeared out and melted along zones of shear deformation.

Portions of fragment WAM 13645 that have not been transformed to α_2 show deep-seated Neumann bands (mechanical shock-twins) that are degenerated (Figure 4b), and sub-grain boundaries that are decorated with rhabdites. The fragments have been plastically deformed and the metal is traversed by a few intense zones (<1 mm wide) of shear deformation characterized by sub-microscopic recrystallization. Locally, terrestrial corrosion has penetrated along cracks developed in the shear-zones making them visible to the naked eye. Several shear-zones run parallel with, and close to, the outer surfaces of the fragments. In the fragment from north of the crater, three sets of

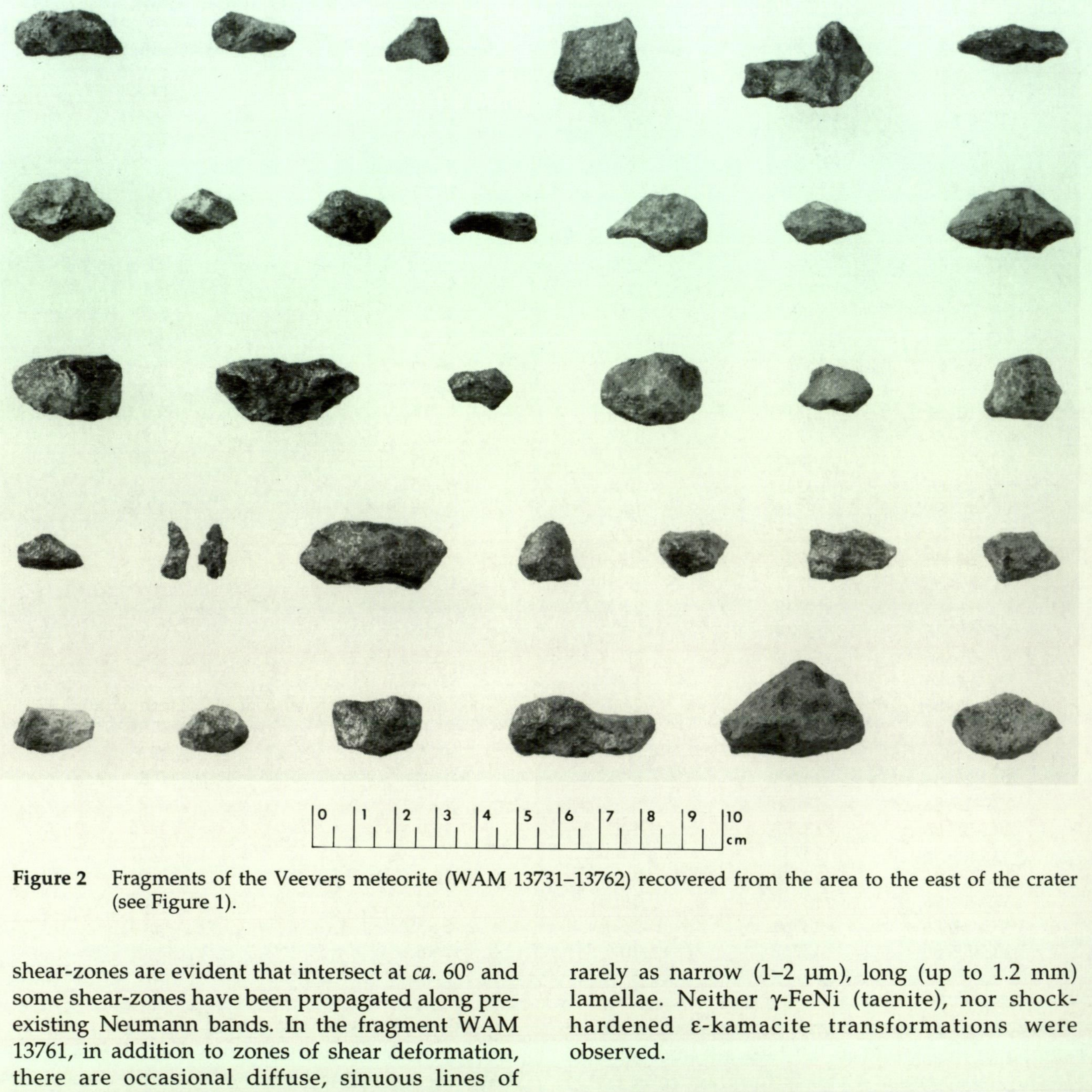

Figure 2 Fragments of the Veevers meteorite (WAM 13731–13762) recovered from the area to the east of the crater (see Figure 1).

shear-zones are evident that intersect at *ca.* 60° and some shear-zones have been propagated along pre-existing Neumann bands. In the fragment WAM 13761, in addition to zones of shear deformation, there are occasional diffuse, sinuous lines of stained metal that do not appear to be associated with plastic deformation. One such sinuous line is cut and displaced by a shear-zone indicating that the structure from which it was formed pre-dates plastic deformation of the metal (Figure 4c). The displacement of the structure indicates that the throw of the shear zone is *ca.* 400 µm.

The suspected grain boundary in fragment WAM 13735 is heavily invaded with terrestrial corrosion products that have masked the original structure. Vestiges of troilite occur and, locally, terrestrial oxides pseudomorph a pre-existing eutectic-like structure. Other minerals observed in the unaltered portions of Veevers fragments include carlsbergite (CrN) and an unidentified, partially resorped mineral (Figure 4b), probably roaldite ($[Fe,Ni]_4N$) (Nielsen and Buchwald 1981), the latter occurring rarely as narrow (1–2 µm), long (up to 1.2 mm) lamellae. Neither γ-FeNi (taenite), nor shock-hardened ε-kamacite transformations were observed.

Structural classification

All previously described irons belonging to chemical sub-group IIB with Ni contents in the range 5.5–6.9 wt % are structurally coarsest octahedrites (Ogg) with α-kamacite bandwidths >3.3 mm (Buchwald 1975). Disruption of the Veevers projectile during impact has destroyed the original macro-structure of the meteorite. However, the nature of the surviving fragments gives some indication of the original structure of the meteorite. The shape and mineralogy of the fragments show that, predominantly, the structure of the meteorite comprised irregular, stubby lamellae of kamacite (L/T *c.*1.6–6.5). From their plate-like morphology, it follows that the maximum thicknesses of the surviving fragments are likely to approximate to the kamacite

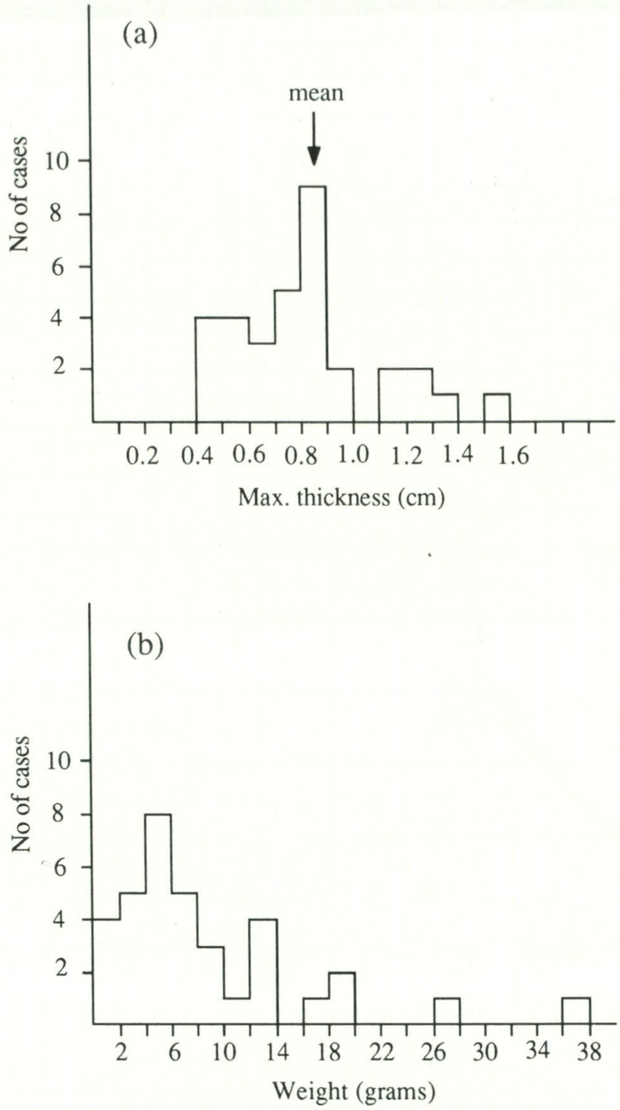

Figure 3 Dimensional and mass analysis of meteorite fragments found at Veevers crater; **(a)** fragment thickness frequency, **(b)** mass frequency.

bandwidth of the original octahedral structure. The average thickness of fragments > 3 g is 8.6 mm (Figure 3a), whereas the average thickness of fragments > 5 g is 9.6 mm. These dimensions indicate a coarsest octahedral (Ogg) structure, and correspond well with the bandwidths (9 – 10 mm) of other group IIAB irons with similar Ni contents (*ca.* 5.8 wt%) that have been described (Buchwald 1975).

Group IIAB irons with bulk Ni contents greater than 5.5 wt% frequently contain some residual γ-taenite or plessite (α+γ) (Buchwald, 1975). The frequency of taenite or plessite fields in these meteorites rarely exceeds one in sectional areas ranging from 10 – 25 cm^2. The bulk Ni content (5.82 wt%) of Veevers (Wasson *et al.* 1989) suggests that some residual γ-taenite should be present in the meteorite. In the small sectional area of the residual fragments of Veevers examined (< 4 cm^2) no taenite or plessite was encountered. However, it is likely that the undisrupted Veevers meteorite contained residual taenite.

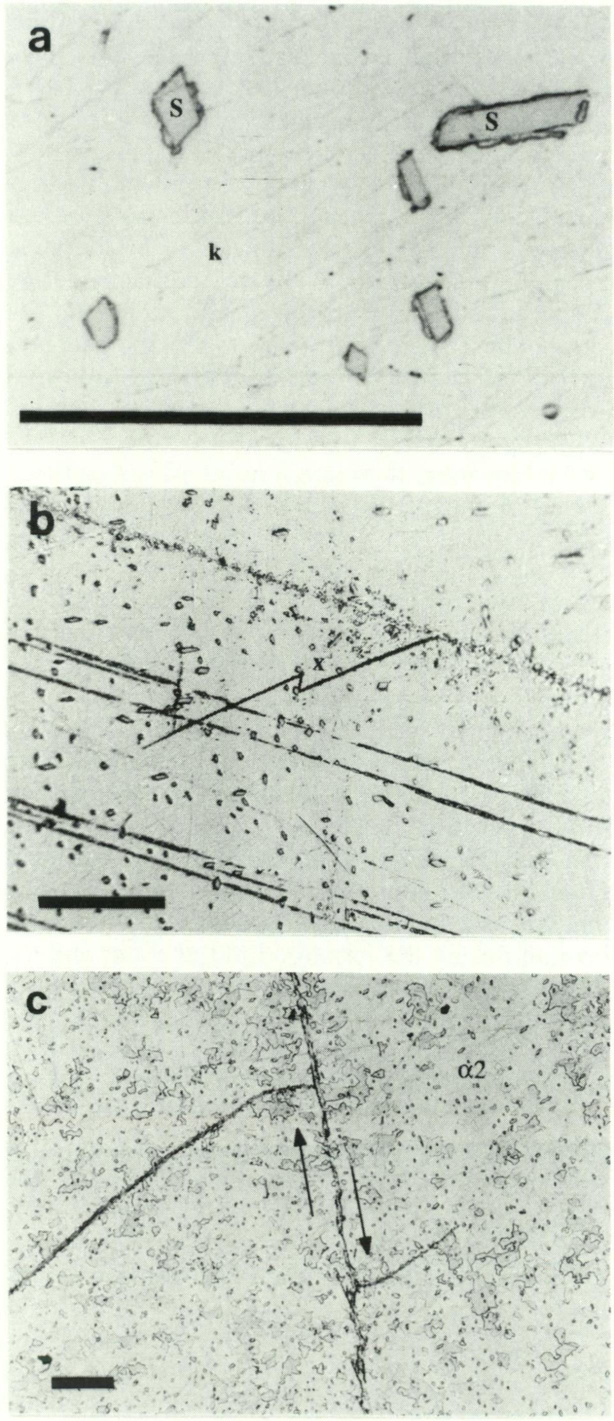

Figure 4 Details of the microstructure of Veevers meteorite fragments. **(a)** Schreibersite [s] showing incipient reaction haloes with surrounding kamacite [k]. **(b)** Kamacite containing abundant rhabdites, degenerated Neumann bands and lamellae of an unidentified mineral [x], probably roaldite. **(c)** Sinuous line of stained metal (probably decomposed roaldite) cut and translated by a zone of shear deformation (arrowed). Surrounding metal transformed to ragged α_2-kamacite. Scale bars 100 µm (2% nital etch).

DISCUSSION

In Veevers fragments, transformation of kamacite to ragged α_2 indicates a transient, but severe re-heating to temperatures above the α to γ transformation temperature, followed by rapid cooling (Brentnall and Axon 1962; Axon *et al.* 1968; Lipschutz 1968). Reaction haloes between schreibersite and metal indicate incipient resorption of the phosphide and are also consistent with a brief, but severe re-heating event. This re-heating event is superimposed on earlier formed structures in Veevers and appears to be the most recent thermal event in the history of the meteorite. There are several possible explanations for the cause of the re-heating in Veevers that include; pre-terrestrial cosmic shock reheating, frictional heating during atmospheric passage, shock reheating on impact, and contact with hot impact ejecta. However, there are a number of significant features of the microstructure of Veevers indicating that the observed effects of transient re-heating were associated with the impact event.

As shown for Canyon Diablo by Heymann *et al.* (1966), the localised occurrence of severe thermal effects observed in the interiors of some of the Veevers fragments indicates steep temperature gradients that exclude conductive heating (e.g., atmospheric passage and contact with hot ejecta) as a mechanism for re-heating. In Veevers, the superimposition of thermal alteration on earlier structures, and its clear association in at least one fragment with intense shear deformation, suggests that heating in that case was caused by shock-loading during the formation of the crater and the disruption of the impacting projectile. However, in the largest fragment recovered (WAM 13761) the general transformation of metal to α_2-kamacite that is not obviously associated with mechanical deformation does not exclude the possibility of conductive re-heating. Notwithstanding, the similarity of the condition of the schreibersite and rhabdites in all three fragments examined is consistent with re-heating for short (seconds) duration rather than prolonged (minutes/hours) heat-treatment in a hot ejecta blanket.

Comparison with experimentally heated and shock re-heated samples of iron meteorite allows the magnitude and duration of thermo-mechanical treatment of Veevers to be determined more accurately. The thermal effects observed in kamacite and schreibersite in lightly shocked samples of Canyon Diablo experimentally heat-treated in air for 10 and 100 seconds at 800 – 850 °C (Figure 5a and b) and allowed to cool by radiation are very similar to the range of structures observed in Veevers fragments. In these samples, metal is partially or wholly transformed to α_2-kamacite comprising 10 – 200 μm units, and

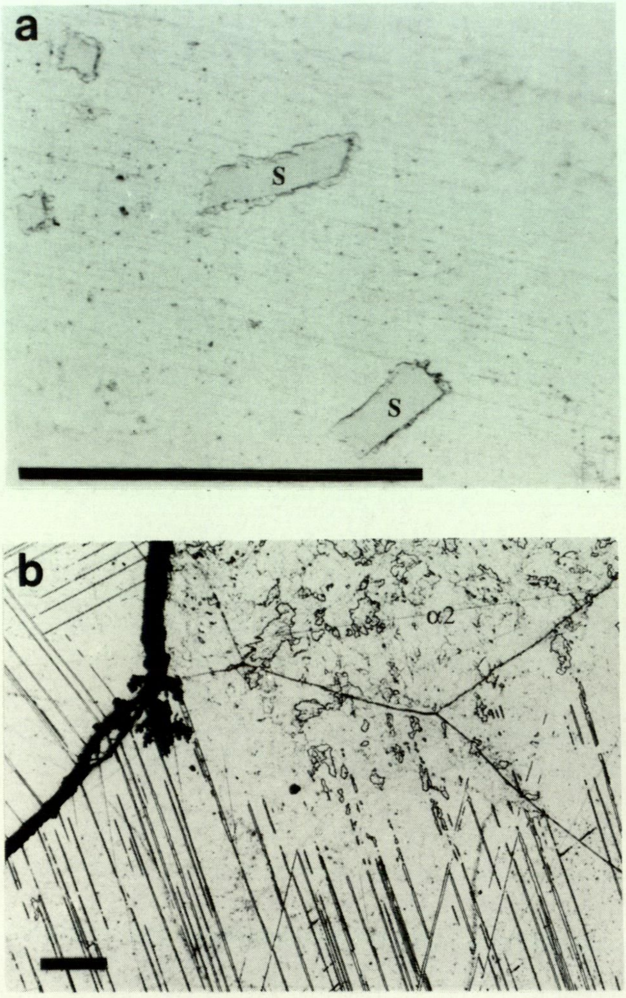

Figure 5 Samples of the IAB iron, Canyon Diablo, experimentally heated in air for **(a)** 100 secs at 800°C and **(b)** 10 secs at 850°C. Note incipient reaction schreibersite [s] with surrounding metal, degenerated Neumann bands and α_2 transformations. Scale bars 100 μm (2% nital etch).

phosphides show incipient, ragged reaction haloes with surrounding metal. In samples heated to the same temperatures but for longer (100 – 1000 secs) periods, the reaction haloes around phosphides become more prominent, and thorn-like protuberances penetrate the metal from the phosphide metal interface. These features were not observed in the Veevers fragments examined.

The peak temperature to which Veevers fragments were subjected during terrestrial impact is more difficult to determine. Samples of Canyon Diablo experimentally heated to 1000°C for short duration (300 secs) by Brentnall and Axon (1962) showed extensive eutectic melting and resorption of schreibersite. Widespread melting of schreibersite was not observed in the Veevers fragments examined, suggesting that overall re-heating of the surviving fragments was considerably less than 1000°C. However, to account for the isolated areas of incipiently melted schreibersite, attenuation of shock waves at grain boundaries and shearing could have generated localised 'hot spots' where temperatures may have approached 1000°C. Incipient melting of schreibersite at grain boundaries as the result of intense shear deformation observed in Veevers is identical to that described by Axon *et al.* (1977) from similarly deformed phosphide inclusions in the crater-forming iron Canyon Diablo. Evidence from fragment WAM 13735 indicates that extensive shock-melting in Veevers may have occurred along those grain boundaries containing abundant troilite. Troilite has a low shock impedence relative to Fe and is known to induce high shock-temperatures even under conditions of moderate shock-loading.

The shock pressures required to produce the structural changes in Veevers fragments can be inferred from the estimated residual temperatures indicated by the thermal alteration of minerals in the meteorite. The relationship between shock pressure and residual temperature for pure iron has been determined experimentally by McQueen *et al.* (1962) and for iron meteorite material by Heymann *et al.* (1966). In shocked iron meteorites, extensive or complete transformation to α_2-kamacite occurs at applied pressures in the range 0.8 – 1Mb (Heymann *et al.* 1966). In specimens of the Odessa meteorite shocked to pressures in this range, Heymann *et al.* (1966) also noted that small patches of shock-hardened ε-kamacite may occur once in sectional areas up to 20 cm^2. The apparent absence of ε-kamacite in Veevers may simply be a function of the small sectional area of the meteorite examined.

As suggested by Wasson *et al.* (1989), the plate-like morphology of the surviving fragments of Veevers indicates that the meteorite broke up during impact predominantly along α-α crystal boundaries in the original octahedral structure. Large crystals of schreibersite, such as that observed in Veevers fragment WAM 13761, also provide brittle-cracking paths that could have facilitated break-up. From a study of shrapnel-like fragments of the Henbury crater-forming iron, Axon and Steele-Perkins (1975) have suggested that fracturing of that meteorite took place along surfaces of shear-faulting generated during impact. Parting along zones of shear displacement may have provided an additional mechanism of failure in the Veevers meteorite, and this is supported by the occurrence of shear-zones that parallel the outer surfaces of the fragments. The angles of intersection (*ca.* 60°) of some of the shear-zones in Veevers coincides with the angles between the (111) directions of kamacite in the octahedral structure of iron meteorites. It is possible that the habit planes of the octahedral structure and other cubic planes in Veevers influenced the shearing forces generated by impact. Subsequently, the penetration of terrestrial oxidation along grain boundaries and shear-zones may have led to further disintegration of the surviving fragments, as suggested by Wasson *et al.* (1989).

Much of the pre-terrestrial micro-structure of Veevers has been destroyed or modified as the result of thermo-mechanical alteration during crater-forming impact. Nevertheless, portions of the original micro-structure of the meteorite have been preserved. The observed Neumann bands that have been plastically deformed and partially degenerated by re-heating appear to pre-date terrestrial impact. The sinuous lines of stained metal observed in fragment WAM 13761 are interpreted as the resorped lamellae of an as yet unidentified mineral, probably roaldite.

Comparison with other crater-forming irons

Out of the twelve other crater-forming irons known (Grieve 1991), the most extensively studied are Canyon Diablo (IAB), Odessa (IAB) and Henbury (IIIAB) (Buchwald 1975). Canyon Diablo and Odessa are both coarse octahedrites, whereas Henbury is a medium octahedrite. All three meteorites are associated with craters that are very much larger than Veevers. In the case of Henbury, the impact resulted in some thirteen craters including several that are of similar size to Veevers. Structural variations between the crater-forming irons and differences in the magnitude of their impacting events have resulted in an enormous range of shock-induced features in the surviving fragments. Notwithstanding, there are strong similarities in the overall nature of thermo-mechanical alteration and mechanism of disruption suffered by many crater-forming irons.

In terms of crater size, the closest analogue to Veevers is the largest of a group of nine craters at Kaalijärv, located on Saaremaa Island, Estonia (Buchwald 1975). The largest crater measures 110 m in diameter and eight smaller craters vary from 12 – 40 m in diameter (Tiirmaa 1992). Kaalijärv is a coarse octahedrite (IAB) and the material recovered from the craters comprises small slugs of metal generally less than 20 g in weight (Buchwald 1975). Metallographically, the Kaalijärv meteorite shows shock hardening, shear deformation and localised recrystallization of metal. Overall, the thermal alteration of Kaalijärv fragments is less than those observed in Veevers fragments and is generally confined to zones of shear deformation.

The IIAB iron Sikhote-Alin, that fell in eastern Siberia in 1947, is the largest known shower in historical times and is structurally and chemically similar to Veevers. Some 23.2 tons of fragmental material were recovered from a large strewnfield covering 1.6 sq. km and including 122 impact holes (Krinov 1963; Buchwald 1975 – and references therein). Many of the masses of Sikhote-Alin broke up during impact and some of the recovered fragments display the earliest stages of shock-metamorphism. Buchwald (1975) noted that many of the disrupted fragments showed octahedral parting, and that fissures are well developed along kamacite grain boundaries that are loaded with schreibersite. However, more intensely deformed fragments also show shear deformation and visibly distorted zones near their surfaces. In addition, Buchwald (1975) noted that fissures had also developed along the cubic cleavage planes of kamacite lamellae in Sikhote-Alin, although these appeared to have played a minor rôle during the fragmentation of the impacting masses.

Although of much less intensity, the style of thermo-mechanical impact alteration displayed by both the Sikhote-Alin and Kaalijärv meteorites is very similar to that observed in Veevers fragments.

SUMMARY AND CONCLUSIONS

Veevers is the only known crater-forming iron of chemical group IIAB. Sub-group IIB irons are rare, accounting for only 4% of all iron meteorites, and less than 0.5% of all meteorites. The association of an unusual meteorite type with an impact crater is especially significant. Dry conditions and extremely low erosion rates in the arid zone of Australia over at least the last 4000 years account for the excellent state of preservation of both the crater and the surviving fragments of meteorite.

The metallography of the surviving fragments of Veevers shows that the meteorite was subjected to a pre-terrestrial history of mild shock-loading of a thoroughly annealed structure that resulted in at least one generation of Neumann band deformation. Subsequently, terrestrial impact caused intense shock-loading of the meteorite that resulted in shearing and plastic deformation with attendant localised heating to >800°C. In accommodating the complex pattern of shock waves generated by high-velocity impact with the Earth, a portion of the meteorite was disrupted mainly along kamacite crystal boundaries in the original coarsest (> 8.6 mm) octahedral structure. Failure may also have occurred as the result of fracturing along zones of intense shear-deformation that may, in turn, have been influenced by the octahedral structure of the meteorite. As a result of the disruption of a portion of the projectile along brittle-cracking paths some of the energy of the impact event may have been absorbed, allowing portions of the original microstructure of the meteorite to be preserved.

Most of the remains of the meteorite may be mixed widely with the breccia under the crater floor. A subordinate fraction of the meteorite was broadly sprayed out of the crater and is now buried beneath the surrounding sand sheet. Subsequently, terrestrial weathering has corroded the fragments and may also have contributed to further disintegration. However, because of prolonged aridity in the desert region where the crater occurs, rusting is not extensive and the fragments retain large cores of fresh metal. The close approximation of the average thickness of fragments (8.6 mm) to the bandwidths (9 – 10 mm) of other IIAB irons of similar Ni content suggests that corrosional losses due to weathering were unlikely to have been greater than 1–2 mm. A thorough search of a wide area around the crater may yield larger fragments of Veevers that became detached from the projectile during atmospheric flight, and that were not involved in the cratering event.

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