Shock Histories of Hexahedrites and Ga - Ge Group III Octahedrites

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1. INTRODUCTION

From a preliminary study [1], by metallography and X-ray diffraction, of shock effects in 65 octahedrites we found that "unshocked" octahedrites (i.e. those exposed to shock pressures of less than 130 kb) were rather randomly distributed among the various Ga-Ge or chemical groups(1). However, of 57 octahedrites unaltered by heat, 34 had been "shocked" to pressures of 130-750 kb. While shocked meteorites occurred in all Ga-Ge groups, they appeared very heavily concentrated in group III. Of the 29 known or suspected members of this group studied, 25 had been shocked and 2 had been thermally altered at some time during their history. While the gallium and/or germanium contents of these 27 shocked or altered meteorites fell within the restricted limits of chemical groups III [4] the 2 unshocked samples fell outside of these limits. These results, in concert with other data, suggested that the shock effects present in these meteorites were acquired preterrestrially and that the members of these chemical groups III were simultaneously derived from the breakup of a single object about 650×10^6 years ago.

Several interesting possibilities were suggested by the apparent

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(1) We follow here our previously adopted procedure of referring to "Ga-Ge group" when using the limits established by Lovering et al. [2], to "chemical groups" when using the limits of Wasson and Kimberlin [3, 4] and to "group" when no ambiguity is possible.

ubiquity of shock effects in the group III meteorites. One of these was that the collision which produced these effects also played an important role in the ultimate capture by Earth of the group III fragments. If these effects were indeed ubiquitous, then two alternatives were available:

(1) Exposure to shock pressures above 130 kb was an essential prerequisite for eventual Earth-capture as, for example, if the group III parent were a Ring asteroid. An impulse of 1 km/sec (corresponding to a shock pressure of 130 kb) could then serve to alter the fragments' orbits into Mars-crossing ones, subsequently to be perturbed into Earth-crossing orbits by Mars' gravitational attraction.

(2) Exposure to shock pressures above 130 kb may have been essential or helpful for eventual Earth-capture but the 130 kb shock contour engulfed all of the group III parent.

If these effects were not ubiquitous (i.e. if one or more unshocked group III octahedrites could be found) then a third alternative was possible:

(3) Exposure to shock pressures above 130 kb was a helpful, albeit perhaps not essential, cause for eventual Earth-capture. This would arise if the group III parent were at least a partial Mars-crossing asteroid.

Following the completion of our original survey, Professor E. Anders informed us of an unpublished compendium of meteoritic photomicrographs [5]. Study of this compendium(2) uncovered a number of other shocked meteorites including 3 known and 6 suspected members of group III. However, there were also included photomicrographs of 2 known members and a suspected meteorite of group III which appeared to show unshocked meteorites. Similarly, photomicrographs of another group III meteorite, Thule, appeared to show yet another unshocked case [6]. Since we have already shown that meteorites can experience appreciable shock and yet appear microscopically to be unaffected [1, 7, 8], these four meteorites could conceivably be either shocked or unshocked.

In view of this uncertainty and in order to eliminate at least one of the alternatives available we decided to study a number of additional members of Ga-Ge group III. In particular our emphasis was to be placed on the 4 apparently unshocked cases, those members of chemical group IIIA having relatively rapid cooling rates [9], those meteorites having gallium and germanium contents in the chemical groups IIIA and IIIB overlap zone, and those Ga-Ge group III octahedrites lying outside of the limits of chemical groups III. In addition, we decided to include in this study a number of hexahedrites since it has been suggested [10, 11] that these may have a lunar origin. In view of the 2.4 km/sec lunar escape velocity, hexahedrites would be yet another group expected to show significant shock effects.

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(2) This is bound in nine volumes and is available in the American Museum of Natural History, the Chicago Natural History Museum, the University of Michigan and the U.S. National Museum.

2. EXPERIMENTAL

2.1 Sampling

The bases by which specimens were selected for study have already been outlined. Where a choice was available of gallium and germanium data for a particular meteorite, preference was given to those of Wasson and Kimberlin [4] for reasons listed previously [1]. The cooling rate data used were taken from Goldstein and Short [9]. The meteorites included are listed in Tables I - IV and the identification numbers of the specific specimens studied are listed in the Appendix.

2.2 Shock effects

As in our previous study [1], these were established by the use of metallographic and X-ray diffraction techniques. Any meteorite containing an unequivocal pressure indicator with a threshold of at least 130 kb was classified as "shocked" [12]. Meteorites not shocked to at least 130 kb were classified as "unshocked". As in our previous study several of the meteorites studied had been thermally altered at some time during their history. These meteorites are classified as "disordered" [8] and are considered individually in section 3.

Samples were first examined metallographically and any specimen whose kamacite (α-Fe) contained the ε-iron transformation structure was classified as shocked. By comparing these structures with those observed in our shock "standards" [12] we were able to estimate the shock pressure range to which these meteorites were exposed.(3) The X-ray diffraction technique was then used to study grains of kamacite or schreibersite (Fe_3P) from those meteorites apparently unaltered by shock or heat. Specimens in which preferred disorder [8] was found were classified as shocked and those free of preferred disorder, as unshocked. In this connection it is important to point out that the degree of crystal perfection (hence, the degree of shock) may differ among the "unshocked" meteorites. This will be discussed further in section 3.1.2.

Of the thermally altered meteorites, only Sams Valley contained schreibersite crystals large enough for X-ray diffraction study. Preferred disorder was found, indicating exposure to shock pressures of more than 130 kb (section 3.1.2). The bases by which the individual meteorites were classified are indicated in Tables I - IV.

3. RESULTS

3.1 Octahedrites of chemical groups III

Typically these meteorites are classified as shocked because their kamacite shows, uniformly, the "ordinary" ε-iron transformation structure

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(3) In meteorites shocked to pressures in the range 130-400 kb the transformation structure appears fine-grained and hard to resolve microscopically. This transformation structure is much coarser-grained and clearer in meteorites shocked in the 400-750 kb range.

illustrated in many previous papers [6, 12-17]. Occasionally, however, more "unusual" features emerge and it seems of interest, therefore, to discuss some of these here.

3.1.1 Apparently unaltered octahedrites

In addition to the four shocked, but apparently unaltered, octahedrites found previously [1], six more - Cape York (Savik), Casas Grandes, Cleveland, Drum Mts., Henbury and Thule - were discovered in this study. In these (e.g. Cleveland, Figure 1a), the kamacite contains many bands which resemble closely the Neumann bands (twins along the (112) planes) of meteorites naturally shocked to a maximum pressure well below 130 kb. As noted (section 1) X-ray diffraction patterns of kamacite from these meteorites show arcs indicating preferred disorder, hence exposure to shock pressures of at least 130 kb [8]. In this connection it seems noteworthy that while our sample of Drum Mts. microscopically appeared unaltered by shock, Perry's sample [5] contained the usual high-pressure transformation structure.

The microstructure of a more nearly "normal" shocked octahedrite (Breece) is illustrated in Figure 1b. Here, the kamacite grain to the left shows the low-pressure transformation structure. The grains to the upper and lower right however, appeared unaltered by shock, apparently because of their orientations with respect to the polished surface. Naturally, all such kamacite grains will yield diffraction patterns indicating preferred disorder.

3.1.2 Heat-altered octahedrites

Of the heat-altered meteorites included in our previous study [1], the kamacite of three (Carthage, Descubridora and Ruff's Mt.) had been randomly disordered into equiaxial, regular subgrains. This characteristic microstructure would seem to indicate that these meteorites had been shocked to 130-750 kb and, subsequently, altered by some long-term heat source [1, 18]. Possibly this source was kilometer-sized debris from the suggested collision partner of the group III octahedrites, the hypersthene chondrites [1].

In this study, no meteorite was found whose microstructure exactly duplicated those of Carthage, Descubridora and Ruff's Mt.. However a unique specimen, Sams Valley, was found to have a microstructure (Figure 1c) intermediate between these and that of an "ordinary" shocked group III octahedrite. Although most of the kamacite in Sams Valley has been thermally disordered into equiaxial subgrains, some still retain the ε-iron transformation structure. The fact that schreibersite grains from this meteorite yield X-ray diffraction photographs indicating preferred disorder (section 2.2) provides additional independent evidence that Sams Valley has been shocked to pressures above 130 kb. From the appearance of the taenite (γ-Fe) and plessite ($\alpha + \gamma$ mixtures) inclusions it would appear that this meteorite has been annealed at a maximum temperature well below 630°C. (4)

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(4) We have reproduced the microstructure of Sams Valley as well as those of Carthage, Descubridora and Ruff's Mt. by artificially annealing Odessa shock standards. A discussion of these experiments will be reported elsewhere [18].

Like Sams Valley, the heat-formed subgrains of Misteca also contain the residual ε-iron transformation structure. However these subgrains are neither equiaxial nor regular in their morphology suggesting some difference in reheating conditions. From the nature of the plessite and taenite inclusions, it would seem that Misteca was heated at temperatures between 700 and 750°C. Apparently then, subsequent to shock, Misteca had been heated to temperatures well above those experienced by Sams Valley, although perhaps for shorter effective times.

All three specimens of Boxhole studied were excavated by Dr. E. P. Henderson of the U.S. National Museum from the impact site [19]. Two of these had been heated, no doubt by shock, to above their α-γ transformation temperature and the third (U.S.N.M. 3227) contained the high-pressure ε-iron transformation structure. Since Boxhole was apparently a crater-forming meteorite the shock effects observed in these three samples might have been produced preterrestrially and/or on impact with the Earth. However, it is appropriate to point out that the Odessa and Boxhole craters have about the same dimensions and yet no naturally-shocked Odessa specimens are known. This suggests that impacts of this magnitude are not capable of producing detectable shock effects. Perhaps a study of the possible correlation of shock effects with geographic location of specimens around the Boxhole crater could establish the importance of terrestrial impact in producing shock effects.

The kamacite subgrains in Tambo Quemado, the last of the heat-altered group III meteorites, have a morphology similar to that of any iron meteorite which has been strongly heated by either shock [13] or man [14]. A major difference however is that the schreibersite inclusions have been entirely transformed into the Fe_3P-Fe eutectic (Figure 1d).(5) Evidentally this meteorite has been heated by some transient heat source to a residual temperature of at least 1050°C. Although the duration of this heating cannot be exactly determined, the lack of appreciable phosphorous diffusion conservatively suggests a time of much less than one minute, more likely a few seconds. This, in turn, implies that the most likely heat source was a shock wave and that the minimum shock pressure [13] experienced by Tambo Quemado was 1.4 megabars.

3.1.3 Willamette

One of the last octahedrites to be included in this study was to have been Willamette. The sample illustrated by Perry [5] showed a heat-altered microstructure consonant either with exposure to shock pressures above 750 kb or heating at temperatures above the α-γ transformation temperature. Neither of the specimens studied by us (Appendix) possessed this kind of

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(5) We thank Dr. M. A. Dayananda of Purdue's School of Metallurgy for verifying the composition of this eutectic by electron probe microanalysis.

microstructure. Instead, the kamacite grains of both appeared unaltered by shock, although adjacent kamacite grains of both showed differing degrees of twinning. This, in itself, was not surprising. However on X-ray diffraction study of the kamacite we were astonished to find evidence for significant deformation but no preferred disorder. This indicates then that at least these samples of Willamette had been exposed to a maximum shock pressure of less than 130 kb. As this paper was being written our astonishment was compounded by the receipt of a very recent review paper by Axon [15] including the results of a study of yet another Willamette sample. This last sample seems similar in appearance to that illustrated by Perry [5]. In fact, Axon concluded "...Willamette may be an example of material which has been shocked in the range between that which produces acicular kamacite and that required to remelt Nedagolla." Possible reasons for the discrepancies between our results and those of Perry and Axon are considered later (section 4.1).

3.2. Ga-Ge group III octahedrites which are not of chemical groups III.

Table III lists the results of our study of these six meteorites and little need be added to this summary. The two disordered specimens, La Caille and Victoria West, have apparently been heated to above the α-γ transformation temperature by some process, most likely artificially [20]. It would seem therefore that none of those six meteorites has been shocked either preterrestrially or on impact with the Earth.

3.3 Hexahedrites

Table IV lists the 15 specimens which we studied or of which photomicrographs have been published. While classification of Horse Creek as a hexahedrite may be questionable [19] it is included here for the sake of completeness. Of the six specimens we examined, the kamacite of two (Mt. Joy and Murphy) appeared deformed on X-ray diffraction study. In fact, the degree of deformation in the case of Mt. Joy (the more strongly affected), appears rather similar in extent to that evident in the case of Willamette. Metallographically, the kamacite of all fifteen appears unshocked, with no features of note evident. It would, of course, have been desirable to have studied the kamacite of the remaining nine specimens by the X-ray diffraction technique. At this stage, however, it seems safe to conclude that hexahedrites shocked to pressures in excess of 130 kb are rare.

4. DISCUSSION

4.1 Ga-Ge Group III octahedrites

In Figure 2 we have plotted the germanium versus gallium contents for the 54 known group III meteorites studied. With the possible exceptions of Narraburra and Thunda (for which the gallium and/or germanium measurements may be erroneously low [1]), all of the Ga-Ge group III octahedrites not of chemical groups III appear unshocked. This evidence, in concert with other independent arguments [4], suggests that these eight octahedrites

were derived from objects different from that which produced the chemical groups III octahedrites.

It may be seen from Figure 2 that, in chemical groups III, the "main-sequence" noted earlier [1] seems quite evident. The reasons for suspecting that such a sequence would exist have been covered previously [1, 4] and need not be repeated here. It seems sufficient to note merely that, with the possible exception of Willamette, all main-sequence octahedrites have been shocked, no matter what their structure, cooling rate, or chemical properties may be. Thus it seems likely that they have been derived from nearby regions of a single parent body with variable chemical and physical properties. Furthermore it would seem that preterrestrial impact shock and its associated heating effects (in the cases of Carthage, Descubridora, Ruff's Mt., Sams Valley, Tambo Quemado and, probably, Boxhole and Misteca) played a significant role in their history [1].

What of Willamette however? Of the 44 known, main-sequence octahedrites and the 12 suspected members of this group ([1], Table II) only this meteorite has apparently been shocked to pressures of less than 130 kb. At first glance this would seem to eliminate all but the third alternative listed in section 1. Unfortunately, however, on further scrutiny this may not be the case. The possibility of sample confusion prior to our investigation would seem very remote because both of our samples were obtained from different sources and had the distinctive microstructure characteristic of Willamette. This characteristic microstructure alone might suggest that Willamette was derived from an asteroid different from that which produced the main-sequence octahedrites and that its trace element contents and cooling rate fortuitously placed it in the main-sequence group. While this possibility cannot be eliminated we are reluctant to accept it in view of the structural variations already observed in objects with diameters on the order of hectometers [21].

A more palatable explanation is that the samples which we studied are not representative, in shock history, of the 13.6×10^6 g mass. If a 1 km/sec initial impulse was essential for eventual Earth-capture of the Willamette mass it is not necessary that all of the meteoroid be shocked to 130 kb but merely that the average pressure be at least this high. It may well be that the samples which we studied were shocked to a pressure in the neighborhood of 100 kb, in view of the kamacite deformation indicated by the X-ray diffraction patterns. In view of the 2 meter height and 1 x 2 meter dimensions of the base of this conical mass and the pressure gradient of $\sim$40 kb/cm deduced in one sample of Canyon Diablo [7] there may exist in Willamette evidence for an extremely large pressure gradient. If indeed the samples studied by Perry [5] and Axon [15] were randomly disordered by shock pressures above 750 kb, precisely the same explanation must be invoked. Thus the possibility that the average pressure experienced by Willamette exceeded 130 kb remains a very real one and will be tested in the very near future.

With regard to the hexahedrites, little need be added to the discussion in section 3.3. However, it should be noted that in these meteorites there

is no evidence for a shock-induced impulse of $\geq$ 1 km/sec, let alone for one of $\geq$ 2.4 km/sec (which, for nickel-iron, corresponds to 550 kb shock pressure [22]), lunar escape velocity. Since high ejection velocities for hexahedrites was not an essential prerequisite for eventual Earth-capture, their derivation in some manner from the Moon seems remote. More likely these meteorites, like many of the octahedrites, were derived from asteroids, perhaps from Apollo asteroids [10, 11].

5. CONCLUSIONS

Based on our results it seems that of the groups studied thus far, only in the main-sequence (chemical groups III) octahedrites is there evidence that shock played an important role in the eventual capture by Earth of iron meteorites. In the case of these octahedrites it would seem that most of the suggestions and conclusions reached in our preliminary survey [1] have been verified. Only with regard to whether shock was a helpful or necessary condition for eventual Earth-capture of these meteorites is there any question. Hopefully, this ambiguity can soon be resolved. In any event, if Willamette was indeed part of the object from which the main-sequence octahedrites were derived, it would appear that the 130 kb shock contour did not engulf all of the object and that only the first and third possibilities (section 1) remain.

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APPENDIX

This list includes source of sample studied - C.N.H.M. (Chicago Natural History Museum), U.S.N.M. (U.S. National Museum) and J.T.W. (J. T. Wasson) - and sample number (if known).

Aggie Creek (JTW - USNM 1448), Basedow Range (USNM - 1751), Braunau (CNHM - Me 55), Breece (CNHM - Me 2165), Boxhole (USNM - ___,____, 3227), Cape York (JTW), Casas Grandes (CNHM - Me 524), Chupaderos (CNHM - Me 1045), Cleveland (USNM - 1000), Coahuila (CNHM - Me 850), Costilla Peak (CNHM - Me 856), Drum Mts. (JTW - USNM 1417), Edmonton (JTW - USNM 1413), El Capitan (CNHM - Me 969), Franceville (CNHM - Me 863), Gun Creek (JTW), Henbury (CNHM - Me 2176), Hex River Mts. (CHNM - Me 986), Indian Valley (CNHM - Me 1950), La Caille (CNHM - Me 900), Madoc (CNHM - Me 1189), Misteca (CNHM - Me 956), Mt. Joy (CNHM - Me 482), Murphy (CNHM - Me 503), Providence (JTW), Sams Valley (CNHM - Me 1976), Scottsville (CNHM - Me 1403), Tambo Quemado (USNM - 1677), Thule (JTW), Verkhne Dnieprovsk (CNHM - Me 862), Victoria West (USNM - 3136), Willamette (CNHM - Me 1195; USNM - 3153).

TABLE I - METEORITES OF CHEMICAL GROUPS III STUDIED

Meteorite [20] (structural class)	Recovered mass (kg)	Ga[(a)] (ppm)	Ge[(a)] (ppm)	Chem. group	Shock history (kb) (Ref.)
Ruff's Mt. (Om)	53	21.5	46.5	IIIA	Disordered[§](b)
Misteca (Om)	4	22.2	42.6	IIIA	400-750[§](c)
Franceville (Om)	19	20.3	42.4	IIIA	400-750[†](c)
Drum Mts. (Om)	529	20.4	41.8	IIIA	400-750[†](d)
					130-400*(c)
Providence (Om)	7	20.2	41.5	IIIA	130-400[†](c)
Aggie Creek (Om)	43	20.5	39.9	IIIA	130-400[†](c)
Thule (Om)	49	19.3	39.8	IIIA	130-400*(e[↑],c)
Breece (Om)	50	19.4	37.9	IIIB	400-750[†](c)
Boxhole (Om)	>89	18.1	37.2	IIIA	Disordered[†](c)
					Disordered[†](c)
					400-750[†](c)
Willamette (Om)	13600	18.3	36.7	IIIA	Disordered[†](d)
					Disordered[†](g)
					<130* (c)
					<130* (c)
Canyon City (Om)	9	19.5	36.0	IIIA	130-750[†](d)
Cape York (Om)	>34000	19.2	36.0	IIIA	130-400*(d[↑],c)
Toluca (Om)	>250	18.2(f)	36(f)	III	130-750(g)
Apoala (Om)	85	18.3	35.2	IIIB	130-750[†](d)
Sams Valley (Om)	8	18.4	35.1	IIIB	130-750[§](c)
Henbury (Om)	>680	17.4	34.2	IIIA	Disordered[†](d)
					130-400* (c)
Costilla Peak (Om)	35	18.7	33.6	IIIA	400-750[†](c)
Verkhne Dnieprovsk (Off)	-	18.9	33.1	IIIB	130-400[†](c)
Chupaderos (Of)	20900	16.9	31.1	IIIB	400-750[†](c)
Tambo Quemado (Om)	141	17.6	31.0	IIIB	Disordered[§](d,c)
Casas Grandes (Om)	1550	17(h)	30(h)	III	130-400*(d[↑],c)

NOTES TO TABLE I

References

a. Data from Wasson and Kimberlin [4] unless otherwise noted
b. Buchwald [17]
c. This work
d. Perry [5]
e. Buchwald and Munck [6]
f. Smales et al.[23]
g. Axon [15]
h. Lovering et al.[2]

Shock criteria observed

† Sample studied only by metallography. If shocked, transformation structure evident. If disordered, kamacite sub-grain boundaries have random morphology.

§ Samples showing "unusual" structures (see text) on metallographic study.

* Samples studied by metallography and X-ray diffraction. If shocked, no transformation structure is apparent but diffraction patterns indicate preferred disorder. For discussion of Willamette, see text.

† Published photomicrographs appear to show lightly-shocked samples but our diffraction studies indicate shock effects.

TABLE II - POSSIBLE MEMBERS OF CHEMICAL GROUPS III [9]

Meteorite [20] (structural class)	Recovered mass (kg)	Shock history (kb)	Ref.
Bear Lodge (Om)	48	130 - 400†	a
Chilkoot (Om)	43	130 - 750†	a
Cleveland (Om)	115	130 - 400*	a†,c
El Capitan (Om)	28	400 - 750†	c
Harriman (Om)	13	130 - 750†	a
Kenton Co. (Om)	163	130 - 750†	a,b,d
Lenarto (Om)	108	130 - 750†	a
Madoc (Om)	168	400 - 750†	c
Staunton (Om)	110	130 - 750†	a

NOTES TO TABLE II

References

a. Perry [5]
b. Buchwald [17]
c. This work
d. Axon [15]

Shock criteria observed

The symbols have the same meaning as those in Table I.

TABLE III - METEORITES OF Ga-Ge GROUP III WHICH LIE OUTSIDE OF THE LIMITS OF CHEMICAL GROUPS III

Meteorite [20] (structural class)	Recovered mass (kg)	Ga (ppm)	Ge (ppm)	Ref.	Shock history (kb)	Ref.
Gun Creek (Om)	23	22.4	69.7	a	<130†	d
					<130*	c
Barranca Blanca (Ob)	12	22.1	63.9	a	<130†	d
Edmonton (Off)	10	25.4	34.6	a	<130†	d
					<130*	c
Victoria West (Of)	3	15.3	31.4	a	Disordered †	c
Basedow Range (Om)	-	15	30	b	<130*	c
La Caille (Om)	630	20	12.8	e	Disordered †	c

NOTES TO TABLE III

References

a. Wasson and Kimberlin [4]
b. Lovering et al. [2]
c. This work
d. Perry [5]
e. Smales et al. [23]

Shock criteria observed

† Samples studied only by metallography. If disordered, kamacite sub-grain boundaries have random morphology.

* Samples studied by metallography and X-ray diffraction. The diffraction patterns are similar to those of unshocked single crystals.

TABLE IV - HEXAHEDRITES

Meteorite	Recovered mass (kg)	Ga (ppm)	Ge (ppm)	Ref.	Shock history (kb)	Ref.
Braunau	39				<130*	a,b
Cedartown	11.3				<130	a
Coahuila	>1200	51	175	c	<130*	a,b
Hex River Mts.	60	45	143	d	<130	a,b
Horse Creek	0.6				<130	a
Indian Valley	14	56	160	d	<130*	a,b
Keen Mt.	6.7				<130	a
Mayodan	15				<130	a
Mt. Joy	385				<130*	a,b
Murphy	7.7	40	145	d	<130*	b
Rio Loa	4	47	228	d	<130	a
Sandia Mts.	45	53	143	d	<130	a
Scottsville	10	58	132	d	<130*	a,b
Sierra Gorda	22	57.4	170	e	<130	a
Walker Co.	75	59	170	c	<130	a

NOTES TO TABLE IV

a. Photomicrographs published by Perry [5] indicate the absence of a transformation structure in these samples.

b. This work. Pressure limits listed with an asterisk indicate samples studied both by metallography and X-ray diffraction.

c. Smales et al. [23]

d. Lovering et al. [2]

e. Wasson and Goldstein [24]

FIGURE CAPTIONS

Figure 1 - Atypical, shock-induced microstructural alterations in group III meteorites: (a) Cleveland; (b) Breece; (c) Sams Valley; (d) Tambo Quemado. In all cases the matrix is iron-nickel and the inclusions are (or were, in the case of Tambo Quemado) schreibersite, Fe_3P.

Figure 2 - Shock histories of 54 Ga-Ge group III octahedrites. Inverted triangles indicate cases of unusual, shock-induced microstructural alterations. With the possible exception of Willamette, all meteorites lying within the IIIA - IIIB boundaries are shocked; those outside are generally unshocked. The shocked meteorites seem to have been derived from a single object which was disrupted in a preterrestrial collision 650 m.y. ago. This impact produced the shock effects observed and probably played a dominant role in the eventual capture of the meteorites by Earth.

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