

Hardness of Kamacite and Shock Histories of 119 Meteorites

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We have used metallographic and X-ray diffraction techniques to study the shock histories of 119 iron and stony-iron meteorites and have measured the hardness of kamacite in these specimens and in artificially shocked unannealed and annealed meteorite specimens. Shock increases kamacite hardness, but complications introduced by other physical and chemical properties of meteorites limit its utility as a shock indicator. About 50% of the meteorites studied show evidence for preterrestrial shock loading to pressures of ≥ 130 kb, and 40% have not been shocked to such high pressures. The remaining meteorites have been heat altered in such a way that their shock histories cannot be determined explicitly. These results, together with those obtained previously, indicate that the plurality, if not the majority, of all iron and stony-iron meteorites sampled by the earth were shocked to pressures of ≥ 130 kb during preterrestrial collisions between asteroidal-sized objects.

In a preliminary survey of 65 octahedrites Jaeger and Lipschutz [1967a] found that a considerable number of iron meteorites contained evidence of involvement in violent preterrestrial collisions of considerable magnitude. They also found that shocked meteorites (i.e., those containing an unequivocal pressure indicator with a threshold of at least 130 kb) occur primarily in groups distinguishable by other physical and chemical properties, and they tentatively suggested that about half the known iron meteorites should fall within the 'shocked' category. Chemical groups III (i.e., IIIA, IIIB, and similar octahedrites but not IIIC or IIID) and IVA [Wasson and Kimberlin, 1967; Wasson, 1967; Wasson and Schaudy, 1971] seemed to contain unusually large proportions of such meteorites, as was verified by subsequent studies of more representatives of these groups. Jain and Lipschutz [1968, 1969, 1970] found that nearly all, if not all, of the 55 known or suspected members of group III studied and about 60% of the 26 known members of group IVA were

shocked in preterrestrial impact events. The coverage of other chemical groups of meteorites is not as complete, and this selectivity bias causes difficulties in realistically estimating the proportion of shocked iron meteorites on earth.

Shock effects in iron meteorites can be readily identified by using a combination of metallographic and X-ray diffraction studies [Lipschutz, 1968; Jain and Lipschutz, 1971]. Smith [1958] and Dieter [1961] found that the hardness of α iron is increased by shock loading, and subsequent studies show that other metals and alloys exhibit similar behavior. Maringer and Manning [1962] noted that the hardness of kamacite (α iron) in the shocked octahedrite Grant was higher than that in the unshocked Keen Mountain hexahedrite, and they and Zukas [1969], who studied a sample of Canyon Diablo shocked to >750 kb during terrestrial impact [Lipschutz and Anders, 1961; Lipschutz, 1965, 1967; Heymann et al., 1966], suggested that the hardness of kamacite in a thermally unaltered meteorite could be directly related to its degree of shock loading. We decided to investigate this possibility by comparing the hardness of a

number of meteorites with their degree of shock loading as deduced from metallographic and X-ray diffraction studies. Because we decided to minimize our selectivity bias primarily by examining all the polishable irons and stony irons in the Peabody Museum collection of Yale University, the results of this study could serve the additional purpose of providing a more realistic estimate of the proportions of unshocked and shocked meteorites on earth.

EXPERIMENT

In addition to studying meteorites of the Peabody Museum collection, we determined the hardnesses of Carbo, Narraburra, and Sam's Valley meteorites, whose shock histories and contents of gallium and germanium had already been determined. Each specimen was polished and etched at Yale to the extent necessary for determining the diamond pyramidal hardness (DPH) of its kamacite. The DPH values were measured by using a Leitz and/or a Zeiss-Hanemann microhardness testing machine with loads of 100 grams, and, where comparison was possible, both testing machines were found to yield similar results. The indentations were small (largest dimension $\sim 20\ \mu\text{m}$) in comparison with the grain size and were always distant from other phases. The DPH values found ranged from 100 to 350 kg/mm², the mean deviation in a typical meteorite being $\pm 5\ \text{kg/mm}^2$ for measurements on 10 different grains. In a few instances (Glorieta Mountain, Costilla Peak, and several heat-altered meteorites) we found somewhat larger deviations. We also measured the hardness of artificially shock-loaded Odessa meteorites, both unannealed and annealed, whose microstructural and X-ray diffraction characteristics have already been described [Heymann *et al.*, 1966; Jaeger and Lipschutz, 1968; Jain and Lipschutz, 1968]. To facilitate discussion, the meteorites studied are listed in Table 1 in order of increasing hardness and in the appendix alphabetically.

Sixty-two meteorites whose shock histories had not been previously established and seven that had been studied previously were forwarded to Purdue for investigation by metallographic and X-ray diffraction techniques. All specimens except Lexington, São Julião de Moreira, and Wichita, which were too large to be conveniently handled, were repolished and

studied first by metallography. Any specimen containing the ϵ iron transformation structure was considered shocked, and we estimated the peak pressure to which it had been exposed (Table 1) by comparing it with the Odessa meteorite shock 'standards.' The crystallographic character of kamacite grains in most of the shocked meteorites and in all other meteorites was then studied by the back reflection X-ray diffraction technique used previously [Jain and Lipschutz, 1970]. Unheated specimens yielding diffraction photographs indicating preferred disorder were classified as shocked, and the others as unshocked (i.e., shocked to pressures of $<130\ \text{kb}$). The semipolished surfaces of the three large specimens were etched deeply with dilute HNO₃, and their diffraction photographs exhibited only Laue spots typical of unshocked kamacite grains, those of Lexington and São Julião de Moreira indicating mild deformation. Three of the specimens (Ballinoo, Hammond Township, and Pittsburg) contained inclusions of accessory schreibersite (Fe₃P) large enough to be removed and studied by using the transmission X-ray diffraction technique. The diffraction photograph of Hammond Township indicated preferred disorder, and thus the specimen was shown to be shocked, whereas the others showed only Laue spots indicating the two meteorites to be unshocked [Lipschutz and Jaeger, 1966, 1969].

The specific bases by which we classified the 119 individual meteorites as to shock history are either indicated in Table 1 or discussed in the text. Specimens used for hardness measurements are identified in Table 1 by their number in the Peabody Museum meteorite catalog [Turekian, 1966], and in the 52 cases where a different specimen was studied by metallography and X-ray diffraction the results are listed on a separate line. Although all studies were made on the same sample in only 55% of the cases, our conclusions remain the same whether only these meteorites or all meteorites are considered.

RESULTS AND DISCUSSION

Because metallographic and X-ray diffraction studies provide the primary means for determining the shock history of meteorites, we will first summarize the results obtained by these methods. Eighty-nine of the 119 meteorites studied were thermally unaltered, and half (44)

TABLE 1. Shock Histories and Hardnesses of Iron and Stony-Iron Meteorites Studied

Meteorite	Structural Class*	Chemical Group†	Reference for Chemical Group	Hardness			Shock History	Reference for Shock History
				DPH ₅ ‡ kg/mm ²	Apparent Shock, kb	Identification No. §		
1. Tarapaca	Om	i	j	98		P402	Reheated <130 kb	a
2. Younegin	Og			132	0	P147		d
3. Mincy	M			139	0	P140	<130 kb	a
4. Mooranoppin	Ogg	Anomalous	k	143		P117	Reheated <130 kb	a
5. Netshaev	Ob	IIA	l	143	20	P69	<130 kb	b
6. Scottsville	H			155 (175)	85	P80b		
7. Mt. Joy	H	IIA	l	158	60	P120	<130 kb	b
8. Holland's Store	H			162 (182)		P148	Reheated <130 kb	a
9. Vaca Muerta	M	Anomalous	m	163	70	P72	Reheated	a
10. Hammond Twp.	Om			163		JTW		a, c
11. Seeläsgen	Ogg	I	j	163	70	P96e	<130 kb	a
12. Tombigbee River	Da	Anomalous	m	166 (186)	100	USNM 252	130 to 400 kb	a
13. Ehrenberg	Og	I	j	168	70	P43	<130 kb	a
14. Arlington	Om	Anomalous		171	80	P128	Reheated	e
15. Elbogen	Om			172		P7	<130 kb	a
16. Lexington Co.	Og	IIA	l	175	90	P68	<130 kb	b
17. Hex River Mt.	H			175 (195)	110	P108	<130 kb	d
18. Bohumilitz	Om	I	j	176	90	P14	<130 kb	b
19. Coahuila	H	IIA	l	176 (196)	110	P122	<130 kb	a
20. Morristown	M	I	j	176	90	P252	<130 kb	d
21. Bischtube	Og	III	n	180	90	P113	Reheated Reheated <130 kb	c
22. Roebourne	Om	I	j	180		P126	Reheated Reheated <130 kb	a
23. Cranbourne	Og	IID	l	181	90	P134	Reheated <130 kb	a
24. Rodeo	Of	IIIC	l	182	90	JTW	Reheated Reheated 130 to 400 kb	a
25. Ballinoo	Off	IIIA	l	182		P26	Reheated	a
26. Pittsburg	Ogg	IIIA		182	90	P203	Reheated Reheated <130 kb	a
27. Billings	Om			184		P119	Reheated	a
28. Verkhne Udinsk	Om	Anomalous	k	185 (205)		P112	Reheated Reheated <130 kb	d
29. Kendall Co.	H							
30. Nocoleche	Om							

TABLE 1. (continued)

Meteorite	Structural Class*	Chemical Group†	Reference for Chemical Group	Identification No.s	Hardness		Shock History	Reference for Shock History
					DPH, ‡ kg/mm ²	Apparent Shock, kb		
31. Braunau	H	IIIA	z	P76	186	90	<130 kb	b
32. Odessa	Og	I	j	P90	189 (210)	110	<130 kb	d, f
33. Shrewsbury	Om	I	j	P294	189	90	<130 kb	a
34. Rosario	Og	I	j	P189	189	90	<130 kb	a
35. Luis Lopez	Om	I	j	P125	190	90	<130 kb	a
36. Walker Co.	H	IIA	o	P153	190	90	<130 kb	a
37. Grand Rapids	Of	Anomalous	p	P23a	190 (210)	110	<130 kb	d
38. Smithville	Og	I	j	P82a	191	90	<130 kb	a
39. Denton Co.	Om	I	j	P21	193	90	Reheated	a
40. Seneca Falls	Om	I	j	P42	194	90	Reheated	a
41. Gibeon	Of	IVA	q	P31	197	100	<130 kb	a, i
42. Sandia Mts.	H	IIB	z	P45	198	100	<130 kb	a, b
43. Dalton	Om	IIB	z	USNM 855	198 (218)	120	Reheated	a
44. Sao Juliao de Moreira	Ogg	II	n	P423	199	120	<130 kb	a
45. Murphy	H	II	n	P132	199	120	<130 kb	a
46. Schwetzn	Om	IIIA	m	P13	201 (221)	130	Reheated	a
47. Ruff's Mt.	Om	IIIA	m	P289	201	130	Reheated	b
48. Chesterville	H, Da	IIIA	m	P30	202	110	Reheated	a
49. Descubridora	Om	IIIA	m	P27	203 (213)	130	Reheated	a
50. Tazewell	Off	IIID	p	P58	205	110	Reheated	a, d
51. Hressk	H	IIA	z	P34	206	110	130 to 750 kb	a
52. Toubil River	Om	I	j	P509	207 (227)	130	<130 kb	a
53. Toluca	Om	I	j	P156	207	110	Reheated	a
54. Silver Crown	Og	IIB	z	P4	208	110	130 to 750 kb	b
55. Ainsworth	Ogg	IIB	z	P109	209	110	<130 kb	a
56. Huizopa	Of	IWA	q	P162	209	110	130 to 400 kb	d
57. Bendego	Og	I-An-3	j	P293	210	110	Reheated	d
58. Carlton	Of	IIIC	p	P86	210	110	<130 kb	d
59. Steinbach	S			P100	210	110	<130 kb	a
				P71	212	120	<130 kb	a

TABLE 1. (continued)

Meteorite	Structural Class*	Chemical Group†	Reference for Chemical Group	Hardness		Shock History	Reference for Shock History
				DPH, ¶ kg/mm ²	Apparent Shock, kb		
60. St. Genevieve	Of	Anomalous	q	213	120	<130 kb	a
61. Ponca Creek	Ogg	IIB	l	213	120, 800	400 to 750 kb	a, d
62. Bear Creek	Of	IIIB	m			130 to 750 kb	d
63. Butler	Off	Anomalous	j	214	120, 800	Reheated	a
64. Brenham	P	Anomalous	m	214	120	<130 kb	a
65. Wichita Co.	Og	I	j	215	120	<130 kb	a
66. Nejed	Of	IWA		216	120	<130 kb	a
67. Joe Wright Mt.	Om	IIIB		217	120, 800	400 to 750 kb	a
68. Hraschina	Om	I	j	217		Reheated	a
69. Canyon Diablo	Og	I	j			<130 to >1000 kb	d, f, g, h
70. Misteca	Og	I	j	217		Reheated	b
71. Fort Pierre	Om	IIIC	p	218		Reheated	a
72. Mungindi	Off	IIIC	p	218		<130 kb	d
73. Salt River	Off	IIC	l	220	120	Reheated	a
74. Plymouth	Om	III	l	222	130	130 to 400 kb	a
75. Carbo	Om	IID	l	223		<130 kb	d
76. Union Co.	Ogg	I-An-3	j	224	130	400 to 750 kb	a
77. Mt. Stirling	Og	Anomalous	l	224	730	<130 kb	a
78. Sacramento Mts.	Om	IIIA	m	225	130	130 to 400 kb	d
79. Neumtannsdorf	H			225	130		
80. Burlington	Om			226 (246)	150	130 to 400 kb	a
81. Cranberry Plains	Of			227		Reheated	a
82. Carthage	Om	IIIA	m	230		Reheated	a, d
83. Glorieta Mt.	Om-P	Pallasite	p	230	140	Reheated	a, d
84. Lenarto	Om	III		233		<130 kb	a, b
85. Imilac	P			238	140, 610	130 to 750 kb	
86. Glorieta Mt.	Om-P	Pallasite	p	238	140	<130 kb	a
87. Obernkirchen	Of	IVA	o	244		400 kb	i
88. Bridgewater	Of	IIIA	m	249	150, 520	130 to 400 kb	a
89. San Angelo	Om	III	n	250	150	130 to 400 kb	a, d
90. Thunda	Om	IIID	l	258		400 to 750 kb	d
91. Puquios	Of	IIID	l	261	470	130 to 400 kb	a

TABLE 1. (continued)

Meteorite	Structural Class*	Chemical Group†	Reference for Chemical Group	Identification No.‡	Hardness		Shock History	Reference for Shock History
					DPH, ¶ kg/mm ²	Apparent Shock, kb		
92. Canton	Om	III	<i>o</i>	P111	261	160, 470	130 to 750 kb	<i>d</i>
93. Sam's Valley	Om	IIIB	<i>m</i>	JTW	263		Reheated	<i>b</i>
94. La Grange	Of	IVA	<i>q</i>	P411	268	160, 440	130 to 750 kb	<i>b</i>
95. Coopertown	Om	III	<i>n</i>	P231a	269	440	400 to 750 kb	<i>d, e</i>
96. Orange River	Om	III		P39	270		Reheated	<i>a</i>
97. Santa Rosa	Da	I-An-3	<i>j</i>	P78	270	160, 440	130 to 400 kb	<i>a</i>
98. Costilla Peak	Om	IIIA	<i>m</i>	P150	270	160, 440	400 to 750 kb	<i>b</i>
99. Tonganoxie	Om	IIIA		P131	271	160	130 to 400 kb	<i>a</i>
100. Merceditas	Om	IIIA	<i>m</i>	P115	272	160, 440	130 to 400 kb	<i>d</i>
101. Bacubirito	Off	Anomalous		P155	277		Reheated	<i>a</i>
102. Henbury	Om	IIIA	<i>m</i>				Reheated	<i>b</i>
103. Guilford Co.	Om			P408g	280		130 to 400 kb	<i>b</i>
104. Frankfort	Om			P22	286	390	400 to 750 kb	<i>a</i>
105. Russel Gulch	Of			P54	289	170, 380	130 to 400 kb	<i>d</i>
106. Bella Roca	Of	IIIB	<i>m</i>	P55	292	180, 360	130 to 400 kb	<i>a</i>
107. El Capitan	Om	III		P99	296	180, 360	130 to 750 kb	<i>d</i>
108. Nelson Co.	Ogg	Anomalous	<i>m</i>	P113	296	180, 360	400 to 750 kb	<i>b</i>
109. Putnam Co.	Of	IVA	<i>q</i>	JTW	297	180, 350	130 to 400 kb	<i>a</i>
110. Williamstown	Om	IIIA	<i>m</i>	P40	297	180, 350	400 to 750 kb	<i>b</i>
111. Magura	Og	I	<i>j</i>	P16a	297	180, 350	400 to 750 kb	<i>d</i>
112. Madoc	Om			P161	299	180, 350	400 to 750 kb	<i>d</i>
113. Staunton	Om	III		P186	300	190, 350	130 to 400 kb	<i>d</i>
114. Narraburra	Off	III	<i>n</i>	P35	302	190, 350	400 to 750 kb	<i>b</i>
115. Kenton Co.	Om	IIIA		P61a	309	190, 330	130 to 750 kb	<i>b</i>
				JTW	313	190, 330	400 to 750 kb	<i>d</i>
							130 to 750 kb	<i>b</i>

TABLE 1. (continued)

Meteorite	Structural Class*	Chemical Group†	Reference for Chemical Group	Identification No.‡	Hardness		Shock History	Reference for Shock History
					DPH, ¶ kg/mm ²	Apparent Shock, kb		
116. Wellend	Om			P264	320	200, 310		
117. Augustinovka	Of			P104	328	210, 300	130 to 400 kb	a
118. Trenton	Om	IIIA	m	P135	330	210, 290	130 to 400 kb	a
							130 to 750 kb	d
119. Mt. Edith	Om	IIIB	m	P63a	346	250		
				P137	347	250	400 to 750 kb	d

Results listed on separate lines indicate that different specimens were studied for hardness measurements and for shock histories.

References: a, this study; b, *Jain and Lipschultz* [1969]; c, *Axon* [1965]; d, *Jaeger and Lipschultz* [1967b]; e, *Jaeger and Lipschultz* [1967a]; f, *Lipschultz* [1967]; g, *Heymann et al.* [1966]; h, *Jaeger and Lipschultz* [1968]; i, *Jain and Lipschultz* [1970]; j, *Wasson* [1970a]; k, *Wasson* [1970b]; l, *Wasson* [1969]; m, *Wasson and Kimberlin* [1967]; n, *Lovering et al.* [1957]; o, *Smales et al.* [1967]; p, *Wasson and Schaudy* [1971]; q, *Wasson* [1967].

*Structural classifications from *Hey* [1966], except where subsequent bandwidth measurements [*Goldstein and Short*, 1967] cause them to be superseded.

†Assignments in italics estimated from cooling rate data [*Goldstein and Short*, 1967].

‡Catalog numbers of meteorites from the Peabody Museum of Yale University [*Turekian*, 1966]. Samples indicated by JTW loaned by J. T. Wasson (UCLA); those indicated by USNM numbers loaned by R. S. Clarke, Jr. (U. S. National Museum).

¶Numbers in parentheses are modified values.

|| Shocked meteorites classified as such by the presence of ϵ iron transformation structure (shock pressure estimates in roman type); shock-induced preferred disorder only (>130), the microstructure of *Izewel* not having been studied; or shock-induced preferred disorder in the absence of the transformation structure (130 to 140). Unshocked meteorites listed as <130; those whose kamacite indicates low-pressure deformation on X-ray diffraction study listed as <130. Meteorites altered by exposure to temperature above α - γ transformation temperature under conditions such that their shock histories cannot be explicitly determined listed as reheated; those containing evidence of shock loading prior to thermal alteration at temperatures below α - γ transformation structure listed as reheated; those containing evidence of being unshocked prior to thermal alteration listed as reheated.

proved unshocked. Diffraction photographs showed that the kamacite of 18 unshocked meteorites (Table 1) possessed features suggestive of deformation by high-stress processes, perhaps shock loading at pressures near but below 130 kb. The remaining 45 thermally unaltered meteorites were shocked by pressures of 130–750 kb; 40 exhibit the ϵ iron transformation structure, similar to those illustrated in many previous papers [Heymann *et al.*, 1966; Jain and Lipschutz, 1971]. It has already been demonstrated [Jain and Lipschutz, 1971] that iron meteorites can be shock loaded to pressures of ≥ 130 kb and yet apparently contain no metallographically detectable shock effects. Diffraction photographs of kamacite from such meteorites exhibit preferred disorder, however, and San Angelo, Tonganoxie, and Tombigbee River, like Henbury and Tazewell (discussed previously, Table 1), are of this sort.

It is noteworthy that two samples of Costilla Peak differ somewhat in shock history, both, however, having been shocked to pressures of ≥ 130 kb (Table 1). A reviewer pointed out that, because of the possibility of strong pressure gradients, classification of a meteorite as shocked or unshocked really applies only to that part of the meteorite actually studied. Although such a pressure gradient certainly exists in Canyon Diablo [Heymann *et al.*, 1966; Lipschutz, 1967], we should point out that two or more samples of 25 thermally unaltered small meteorites have been examined in this study and in previous studies, and in no case has the classification of the replicates unquestionably differed.

Twelve of the 30 heat altered meteorites (Table 1) exhibit structures that could arise from either exposure to very-high-pressure shock waves or short-term heating at atmospheric pressure and temperatures above the α - γ transformation temperature [Jain and Lipschutz, 1971]. One of these 12 is a Canyon Diablo specimen that could well have been shocked to pressures of >750 kb during terrestrial impact [Lipschutz and Anders, 1961; Heymann *et al.*, 1966]. The textures of Elbogen [Jaeger and Lipschutz, 1967b] and Pittsburg resemble the microstructures of these 12 meteorites, but diffraction patterns of Fe_3P inclusions indicate both to be unshocked. Dalton and Kendall County exhibit a rather different tex-

ture, similar to that produced by heating an unshocked Odessa specimen for 3.3 hours at 700°C [Jain and Lipschutz, 1968]; both probably experienced heating conditions similar to these. Interestingly, Marvin [1962] found euhedral tridymite crystals in another sample of Kendall County, and it is thus indicated that after the formation of this mineral this meteorite had not been exposed to pressures of >3 kb. Tridymite has also been reported in Steinbach and Vaca Muerta [Mason, 1962], and Marvin [1962] discovered its higher-pressure polymorph, cristobalite, in Carbo. We have found these meteorites to be unshocked (Table 1).

The remaining 14 heat-altered meteorites present evidence for prior shock loading. The textures of Burlington, Toubil River, and Verkhne Udinsk resemble the texture of Misteca [Jain and Lipschutz, 1969, 1971]; i.e., the kamacite exhibits an acicular morphology with many subgrains containing residual ϵ iron transformation structure. Diffraction patterns of kamacite from these meteorites are consistent with the textural appearance, since the X-ray photographs indicate preferred disorder superimposed on a more or less complete Debye ring. The nature of the taenite and plessite inclusions in these meteorites suggest short-term heating at temperatures of 700° – 750°C . The textures of the 10 remaining meteorites are similar in that the subgrains of the disordered kamacite are more regular (i.e., mosaiclike). In Sam's Valley the residual ϵ iron transformation structure is apparent in some subgrains [Jain and Lipschutz, 1969] as it also is when Odessa samples artificially shocked to 200 kb are heated at 480°C for 11–12 days [Jain and Lipschutz, 1968]. The subgrains in kamacite of Chesterville, Hammond Township, Holland's Store, Orange River, and Seneca Falls, like those of Carthage, Descubridora, and Ruff's Mountain [Jain and Lipschutz, 1968], are clear, and this texture resembles that of Odessa samples artificially shocked at 400 kb and subsequently heated at temperatures of 465° – 500°C for 3–12 days. Preferred disorder of schreibersite from Hammond Township provides further independent evidence for substantial shock loading. The microstructure of the Descubridora sample is virtually identical to that of another sample studied by Jaeger and Lipschutz [1967a]. The kamacite in Roebourne sample P126 (Table 1),

on the other hand, is acicular and resembles that in the ablation zone of the sample studied by Axon [1965]. The kamacite in the interior of the second Roebourne sample exhibited a mosaic texture similar to that of Descubridora. The presence of Fe_3P eutectic in sample P126 indicates heating, probably by aerodynamic ablation, to $\geq 1050^\circ\text{C}$ for only a few seconds. In summary, these 14 samples seem to have been shocked preterrestrially and subsequently heated for extended periods in most, if not all, cases by contact with massive shock-heated ejecta from their parent bodies or their collision partners [Jaeger and Lipschutz, 1967a; Jain and Lipschutz, 1968, 1969, 1970]. Interestingly, six of these samples are members of group III, and four others, whose Ga and Ge contents have not yet been determined, are medium octahedrites and could well belong to this extraordinary group.

Most of the meteorites studied here can be assigned to specific chemical groups on the basis of their Ga and Ge contents, structural properties, and/or cooling rates (Table 1). The proportion of shocked meteorites in each group is not modified markedly by the addition of these new data, and so our previous conclusions remain unaltered. Thus shock may have provided an essential (for group III) or helpful (for group IVA) vehicle by which these meteorites were ultimately captured by earth, whereas the parent bodies of the other chemical groups apparently had precollision orbits such that the shock-induced impulse played a minor role at best in the subsequent histories of the meteorites [Jain and Lipschutz, 1971].

Dieter [1961] related the hardness of iron to the degree of shock loading up to 550 kb, and we have extended this relationship for kamacite up to 1000 kb. In the natural environment other variables (e.g., compositional variations and thermal events) could cloud this relationship and limit the use of hardness as a measure of the shock history of meteorites.

In principle the chemical compositional variability of kamacite suggests that it is necessary to determine the effect of each solute on hardness and their concentrations in the grain whose hardness is being measured. In practice this requirement would negate the advantages of ease of sample preparation and ease and rapidity of hardness measurements. Many elements have

such low concentrations in kamacite that their effects can be ignored. However, the effect of P on the hardness of α iron and its over-all compositional variation in kamacite [Reed, 1969] suggests a maximum effect on DPH of ~ 20 kg/mm². The data of Speich and Swann [1965] indicate a DPH increase of $\sim 5\%$ for each 1% increase of Ni in the kamacite compositional range 5–7% Ni [Goldstein and Short, 1967], which can be compensated for (Table 1) in hexahedrites and other low-nickel meteorites from bulk Ni measurements [Hey, 1966]. Different grains in the same octahedrite may vary by as much as 0.5% Ni [Goldstein, 1965], and, in the absence of detailed compositional information on the grain being measured, these variations and those of P imply extreme hardness uncertainties of ~ 30 kg/mm².

The influence of annealing is evident in the DPH values of kamacite in samples of Bella Roca (a typical shocked group III octahedrite), Gibeon (an unshocked octahedrite whose kamacite shows evidence for unusual deformation), and Coahuila (a typical unshocked hexahedrite whose kamacite is strain free) heated for 1 hour at temperatures up to 800°C (Figure 1). The minimums in all curves near 600°C – 650°C probably correspond to the disappearance of all shock-induced structural damage, and the differences between these minimums may well reflect chemical compositional differences. The hardness increase beyond 650°C no doubt reflects the α - γ transformation of iron. Annealed, unshocked, and artificially shocked Odessa specimens exhibit similar trends. It appears that kamacite hardness is reduced by 20–30 kg/mm² by annealing under conditions such that thermal alteration is not detectable visually; annealing under more extreme conditions yields substantially lower DPH values as well as easily discernible microstructural alterations.

The relationship between shock loading and kamacite hardness (Figure 2) was derived from the DPH values for an unshocked Odessa meteorite (195 ± 5 kg/mm²), Odessa samples shocked artificially to 200 (298 ± 10), 400 (280 ± 10), 600 (230 ± 5), 800 (220 ± 15), and 1000 kb (205 ± 15), and an alloy of Fe and 8% Ni [Zukas, 1969] compositionally similar to Odessa [Hey, 1966]. We also used 140 kg/mm², the mean hardness of fully annealed kamacite in Coahuila and Gibeon (Figure 1), as the origin

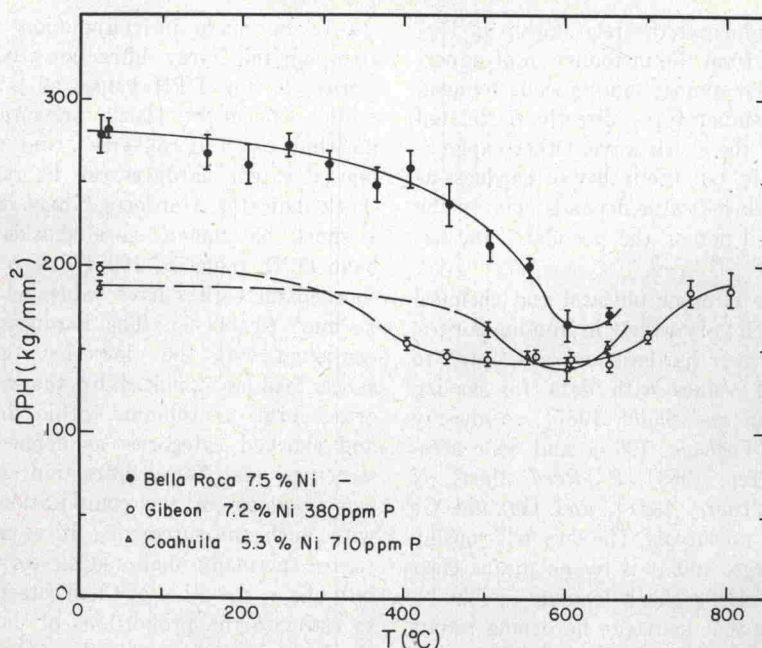


Fig. 1. Diamond pyramidal hardness of kamacite (α iron) in different samples of shocked (Bella Roca), unshocked naturally deformed (Gibeon), and undeformed (Coahuila) meteorites. All samples were annealed for 1 hour and quenched. The uncertainties indicated are mean deviations.

of the curve and the greatest hardness of the meteorites we studied (Table 1) as its maximum. The monotonic increase of hardness with shock

pressure to ~ 250 kb is similar to that observed by Dieter [1961], who tentatively suggested the hardness decrease at higher pressures shown by

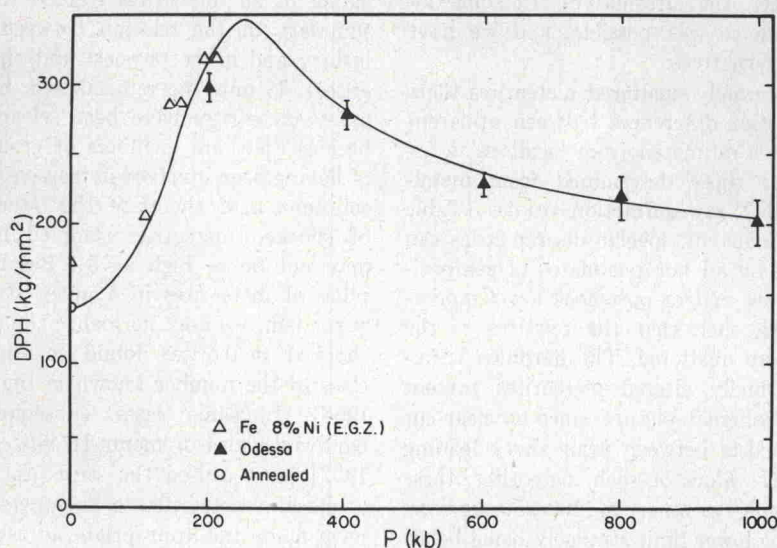


Fig. 2. Diamond pyramidal hardness versus degree of shock loading in meteorites and an artificial alloy. The curve is constrained to pass through the DPH value for fully annealed kamacite (α iron) and the maximum hardness measured in the meteorites investigated. The uncertainties indicated are mean deviations.

our data. We interpret the relationship in Figure 2 as arising from the introduction of imperfections and their almost simultaneous removal by the high temperatures directly associated with passage of the shock wave. Other explanations are possible, but the utility of hardness as a potential shock indicator depends only on the phenomenon and not on the postulated mechanism.

To determine if other physical and chemical properties, which vary widely in iron meteorites, are related to their hardness, we attempted to correlate DPH values with data for cooling rates [Goldstein and Short, 1967], cosmic-ray exposure age [Voshage, 1967], and concentrations of Ni [Hey, 1966], P [Reed, 1969], N [Gibson and Moore, 1971], and Ga and Ge (Table 1) with no success. The only relationship that does emerge, and it is by no means clear cut, is one involving shock loading (Table 1), which indicates that kamacite hardening results primarily from shock. We have used DPH measurements and the relationship in Figure 2 to derive apparent shock pressures for thermally unaltered meteorites only (Table 1). Because meteorites having DPH values of >210 kg/mm² could fall on either the low (<250 kb) or the high-pressure (>250 kb) part of the curve (Figure 2), we used microstructural data to choose between the alternatives. In some instances no choice was possible, and we have listed both alternatives.

Even in thermally unaltered meteorites there are a number of differences between apparent shock pressures estimated from hardness measurements and those determined from metallographic and X-ray diffraction studies (Table 1). Most, but not all, specific discrepancies can be reconciled by ad hoc postulates of compositional variations and/or postshock low-temperature annealing such that the textures of the meteorites were unaltered. The hardness variations in thermally altered meteorites present an even less coherent picture, since no clear-cut relationship exists between prior shock loading and the DPH values of such meteorites, these values spanning a range of 100–280 kg/mm² (Table 1), the lower limit strangely being below that of fully annealed kamacite.

Clearly, hardness measurements alone are of limited utility in deducing the shock history of iron and stony-iron meteorites and should

always be made in conjunction with metallographic and X-ray diffraction studies. All meteorites having DPH values of >250 kg/mm² exhibit effects of shock pressures of ≥ 130 kb (but not the converse), and to this very limited extent hardness can be regarded as a shock indicator. Hardness cannot be considered a shock barometer, since shocked meteorites have DPH values of 160–170 kg/mm² and unshocked meteorites have values as high as 244 kg/mm² (Table 1). The hardness results are consistent with the view that the degree of shock loading exhibited by the various meteorites forms continuums within the unshocked and shocked categories as defined by microstructural and X-ray diffraction criteria. However, because of the complications associated with such measurements, it seems safest to regard thermally unaltered meteorites as falling into one or the other of these categories in order to estimate the proportions of unshocked and shocked meteorites on earth.

We have already studied nearly 36% (213) of the 592 known iron (excluding nickel-rich ataxites, which contain little or no recognizable kamacite) and stony-iron meteorites cataloged by Hey [1966], and nearly $\frac{2}{3}$ of these contain evidence for shock loading to pressures of ≥ 130 kb (see Jain and Lipschutz [1971] for a listing of all meteorites studied to date and a summary of the relation between their shock history and other physical and chemical properties). It must be remembered, however, that many meteorites have been selected for study because they are members of groups suspected of having been involved in massive preterrestrial collisions, and therefore the 'true' proportion of shocked meteorites sampled by the earth may not be as high as $\frac{2}{3}$. Because our sampling of meteorites in a given structural class is random, we may normalize the proportion of shocked meteorites found in each structural class to the number known in that class [Hey, 1966]. In some cases, subsequent kamacite bandwidth measurements [Goldstein and Short, 1967] have caused the structural classification of specific meteorites to be superseded, and we have made the appropriate adjustments within the framework of the classification scheme used by Hey [1966].

The relevant data are listed in Table 2. An ideal sampling to estimate the proportions of

TABLE 2. Distribution of Shocked, Unshocked, and Reheated Meteorites Among Various Structural Classes

Structural Class	Number of Meteorites Known	Number of Meteorites Studied	Known Meteorites Studied, %	Reheated*	Reheated†	Reheated‡	Unshocked	Shocked
Ogg	24	11	46		1		5	5
Og	98	23	23	1		1	15	6
Ob	7	1	14				1	
Om	215	93	43	6	2	13	10	62
Of	69	43	62	8		2	12	21
Off	22	10	45	4			4	2
H	55	17	31		1	2	12	2
Met.	3	2	67			2		
P	45	3	7				3	
S	1	1	100				1	
M	25	3	12				3	
Da	28	6	21				1	
Total	592	263	~36			1	3	5

*Meteorites altered by exposure to temperatures above α - γ transformation temperature under conditions such that their shock histories cannot be explicitly determined.

†Meteorites containing evidence of being unshocked prior to thermal alteration.

‡Meteorites containing evidence of shock loading prior to thermal alteration at temperatures below α - γ transformation structure.

shocked and unshocked meteorites would be one in which each structural class is represented equally. Clearly (Table 2), our sampling is less than ideal, since medium, fine, and finest octahedrites (the first two groups containing very large percentages of shocked meteorites) are overrepresented, whereas coarse octahedrites (which contain a high percentage of unshocked meteorites), nickel-poor ataxites, pallasites, and mesosiderites are underrepresented. Because of the normalization, however, this problem is not serious. If reheated meteorites containing evidence for shock loading and no shock loading prior to thermal alteration are grouped with the other shocked and unshocked meteorites (Table 2), the proportions of each type recovered on earth are 49% and 43%, respectively. Nothing can be deduced about the preterrestrial shock history of the remaining 8%. If consideration is confined to the thermally unaltered meteorites only, the proportions become 53% and 47%, respectively. Thus the plurality, if not the majority, of all iron and stony-iron meteorites sampled by the earth have been appreciably shock loaded during massive preterrestrial collisions. The existence of a significant proportion of unshocked meteorites (i.e., those shocked to pressures of <130 kb) implies, of course, that the breakup of some parent bodies was accomplished in such a manner that specific regions received little or no measurable amount of shock loading.

CONCLUSIONS

The results obtained in this study indicate that shock loading is primarily responsible for the hardening of kamacite in iron and stony-iron meteorites. Although hardness measurements are easy to make, they are difficult to interpret because of the influence of other physical and chemical properties of kamacite. Thus hardness is of limited utility as a shock indicator, and in any event these measurements should be made in conjunction with metallographic and X-ray diffraction studies, which in themselves are more useful in deducing the shock history of meteorites.

Of the 119 meteorites included in this study, 59 (including 14 that were subsequently heat altered) were found to have been shock loaded in massive preterrestrial collisions, and only 48 (including 4 heat altered ones) contained no

effects arising from the exposure to shock pressures of ≥ 130 kb. An additional 12 meteorites had been heat altered in such a way that their prior shock history was obscured. These results, together with those obtained previously, indicate that the plurality, if not the majority, of all iron and stony-iron meteorites sampled by earth have been shocked in massive preterrestrial collisions. As is noted elsewhere [Jain and Lipschutz, 1971], these shock effects can be correlated with other physical and chemical properties of meteorites, and it is thus indicated that shock played an important role in the postcollision histories of the meteorites and that indeed, in some cases, it may have been responsible for their ultimate capture by earth.

APPENDIX

The meteorites studied are listed alphabetically. The number in parentheses refers to the meteorite's position in Table 1.

Ainsworth (55); Arlington (14); Augustin-ovka (117); Bacubirito (101); Ballinoo (25); Bear Creek (62); Bella Roca (106); Bendego (57); Billings (27); Bischtübe (21); Bohumilitz (18); Braunau (31); Brenham (64); Bridgewater (88); Burlington (80); Butler (63); Canton (92); Canyon Diablo (69); Carbo (75); Carlton (58); Carthage (82); Chesterville (48); Coahuila (19); Coopertown (95); Costilla Peak (98); Cranberry Plains (81); Cranbourne (23); Dalton (43); Denton County (39); Descubridora (49); Ehrenberg (13); Elbogen (15); El Capitan (107); Ft. Pierre (71); Frankfort (104); Gibeon (41); Glorieta Mountain (83, 86); Grand Rapids (37); Guilford County (103); Hammond Township (10); Henbury (102); Hex River Mountain (17); Holland's Store (8); Hraschina (68); Hressk (51); Huizopa (56); Imilac (85); Joe Wright Mountain (67); Kendall County (29); Kenton County (115); La Grange (94); Lenarto (84); Lexington County (16); Luis Lopez (35); Madoc (112); Magura (111); Merceditas (100); Mincy (3); Misteca (70); Mooranoppin (4); Morristown (20); Mt. Edith (119); Mt. Joy (7); Mt. Stirling (77); Mungindi (72); Murphy (45); Narraburra (114); Nejed (66); Nelson County (108); Nenntmannsdorf (79); Netshaevo (5); Nocoleche (30); Obernkirchen (87); Odessa (32); Orange River (96); Pittsburg (26); Plymouth (74); Ponca

Creek (61); Puquios (91); Putnam County (109); Rodeo (24); Roebourne (22); Rosario (34); Ruff's Mountain (47); Russel Gulch (105); Sacramento Mountains (78); St. Genevieve (60); Salt River (73); Sams Valley (93); San Angelo (89); Sandia Mountains (42); Santa Rosa (97); São Julião de Moreira (44); Schwetz (46); Scottsville (6); Seeläsgen (11); Seneca Falls (40); Shrewsbury (33); Silver Crown (54); Smithville (38); Staunton (113); Steinbach (59); Tarapaca (1); Tazewell (50); Thunda (90); Toluca (53); Tombigbee River (12); Tonganoxie (99); Toubil River (52); Trenton (118); Union County (76); Vaca Muerta (9); Verkhné Udinsk (28); Walker County (36); Welland (116); Wichita County (65); Williamstown (110); Younegin (2).

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REFERENCES

- Axon, H. J., Metallurgy of meteorites, *Progr. Mater. Sci.*, **13**, 183, 1965.
- Dieter, G. E., Metallurgical effects of high-intensity shock waves in metals, in *Response of Metals to High-Velocity Deformation*, edited by P. G. Shewmon and V. F. Zackay, p. 409, Interscience, New York, 1961.
- Gibson, E. K., Jr., and C. B. Moore, The distribution of total nitrogen in iron meteorites, *Geochim. Cosmochim. Acta*, **35**, 877, 1971.
- Goldstein, J. I., The formation of the kamacite phase in metallic meteorites, *J. Geophys. Res.*, **70**, 6223, 1965.
- Goldstein, J. I., and J. M. Short, The iron meteorites, their thermal history and parent bodies, *Geochim. Cosmochim. Acta*, **31**, 1733, 1967.
- Hey, M. H., *Catalogue of Meteorites* (3rd ed.), 637 pp., British Museum of Natural History, London, 1966.
- Heymann, D., M. E. Lipschutz, B. M. Nielsen, and E. Anders, Canyon Diablo meteorite: Metallographic and mass spectrometric study of 56 fragments, *J. Geophys. Res.*, **71**, 619, 1966.
- Jaeger, R. R., and M. E. Lipschutz, Implications of shock effects in iron meteorites, *Geochim. Cosmochim. Acta*, **31**, 1811, 1967a.
- Jaeger, R. R., and M. E. Lipschutz, The pressure history of some iron meteorites, *Nature*, **213**, 975, 1967b.
- Jaeger, R. R., and M. E. Lipschutz, X-ray diffraction study of kamacite from iron meteorites, *Geochim. Cosmochim. Acta*, **32**, 773, 1968.
- Jain, A. V., and M. E. Lipschutz, Response of previously shocked iron meteorites to heat treatment, *Nature*, **220**, 139, 1968.
- Jain, A. V., and M. E. Lipschutz, Shock histories of hexahedrites and Ga-Ge group III octahedrites, in *Meteorite Research*, edited by P. M. Millman, p. 826, D. Reidel, Dordrecht, Netherlands, 1969.
- Jain, A. V., and M. E. Lipschutz, On preferred disorder and the shock history of chemical group IVA meteorites, *Geochim. Cosmochim. Acta*, **34**, 833, 1970.
- Jain, A. V., and M. E. Lipschutz, Shock history of iron meteorites and their parent bodies: A review 1967-1971, *Chem. Erde*, **30**, 199, 1971.
- Lipschutz, M. E., Origin of atypical meteorites from the Arizona meteorite crater, *Nature*, **208**, 636, 1965.
- Lipschutz, M. E., X-ray diffraction analysis of cohenite from iron meteorites, *Geochim. Cosmochim. Acta*, **31**, 621, 1967.
- Lipschutz, M. E., Shock effects in iron meteorites: A review, in *Shock Metamorphism of Natural Materials*, edited by B. M. French and N. M. Short, p. 571, Mono, Baltimore, Md., 1968.
- Lipschutz, M. E., and E. Anders, The record in the meteorites, 4, Origin of diamonds in iron meteorites, *Geochim. Cosmochim. Acta*, **24**, 83, 1961.
- Lipschutz, M. E., and R. R. Jaeger, X-ray diffraction study of minerals from shocked iron meteorites, *Science*, **152**, 1055, 1966.
- Lipschutz, M. E., and R. R. Jaeger, Shock-induced preferred disorder in solids, *Nature*, **222**, 766, 1969.
- Lovering, J. F., W. Nichiporuk, A. Chodos, and H. Brown, The distribution of gallium, germanium, cobalt, chromium, and copper in iron and stony-iron meteorites in relation to nickel content and structure, *Geochim. Cosmochim. Acta*, **11**, 262, 1957.
- Maringer, R. E., and G. K. Manning, Some observations on deformation and thermal alterations in meteoritic iron, in *Researches on Meteorites*, edited by C. B. Moore, p. 123, John Wiley, New York, 1962.
- Marvin, U., Cristobalite in the Carbo iron meteorite, *Nature*, **196**, 634, 1962.
- Mason, B., *Meteorites*, p. 68, John Wiley, New York, 1962.
- Reed, S. J. B., Phosphorous in meteoritic nickel-

- iron, in *Meteorite Research*, edited by P. M. Millman, p. 749, D. Reidel, Dordrecht, Netherlands, 1969.
- Smales, A. A., D. Mapper, and K. F. Fouché, The distribution of some trace elements in iron meteorites, as determined by neutron activation, *Geochim. Cosmochim. Acta*, **31**, 673, 1967.
- Smith, C. S., Metallographic study of metals after explosive shock, *Trans. AIME*, **212**, 574, 1958.
- Speich, G. R., and P. R. Swann, Yield strength and transformation substructure of quenched iron-nickel alloys, *J. Iron Steel Inst. London*, **203**, 480, 1965.
- Turekian, K. K., The meteorite and tektite collections of Yale University, *Yale University Postilla*, no. 101, Yale University, New Haven, Conn., 1966.
- Voshage, H., Bestrahlungsalter and Herkunft der Eisenmeteorite, *Z. Naturforsch. A*, **22**, 477, 1967.
- Wasson, J. T., The chemical classification of iron meteorites, 1, A study of iron meteorites with low concentrations of gallium and germanium, *Geochim. Cosmochim. Acta*, **31**, 161, 1967.
- Wasson, J. T., The chemical classification of iron meteorites, 3, Hexahedrites and other irons with germanium concentrations between 80 and 200 ppm, *Geochim. Cosmochim. Acta*, **33**, 859, 1969.
- Wasson, J. T., The chemical classification of iron meteorites, 4, Irons with Ge concentrations greater than 190 ppm and other meteorites associated with group I, *Icarus*, **12**, 407, 1970a.
- Wasson, J. T., Ni, Ga, Ge and Ir in the metal of iron meteorites with silicate inclusions, *Geochim. Cosmochim. Acta*, **34**, 957, 1970b.
- Wasson, J. T., and J. Kimberlin, The chemical classification of iron meteorites, 2, Irons and pallasites with germanium concentrations between 8 and 100 ppm, *Geochim. Cosmochim. Acta*, **31**, 2065, 1967.
- Wasson, J. T., and R. Schaudy, The chemical classification of iron meteorites, 5, Groups IIIc and IIId and other irons with germanium concentrations between 1 and 25 ppm, *Icarus*, **14**, 59, 1971.
- Zukas, E. G., Metallurgical results from shock-loaded iron alloys applied to a meteorite, *J. Geophys. Res.*, **74**, 1993, 1969.

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