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X-Ray Diffraction Analysis of Cohenite from Iron Meteorites

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Abstract

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It has recently been observed that cohenite grains from iron meteorites show evidence of shock-induced alterations in crystal character. This paper reports the results of an x-ray diffraction investigation of cohenite from 50 Canyon Diablo meteorites and 8 Odessa shock standards. The crystal character of cohenite appears rather sensitive to shock pressure over the range 0 - >1000kb. The alterations observed apparently represent successive stages in the solid state recrystallization of cohenite. This recrystallization probably occurs during the high-pressure portion of the shock wave since, because of cohenite's thermodynamic instability, the rate of its graphitization during low-pressure annealing appears to be much more rapid than its rate of recrystallization.

It has been found possible to establish a pressure scale based upon features observed in diffraction photographs of cohenite grains from shock standards. This pressure scale has verified the metallographic shock criteria proposed previously. The pressure gradient deduced by microscopy in a particular speciman has been verified and was found to be 20kb/cm. Estimates, from metallographic criteria, of the degree of shock suffered by Canyon Diablo meteorites is essentially paralleled by shock estimates.based on cohenite alteration. The sensitivity of the x-ray technique also serves to identify shocked meteorites which have not been at a pressure high enough to induce metallographic changes.

1. Introduction

In a previous communication (Lipschutz and Jaeger, 1966) we reported that the crystallographic character of several minerals from iron meteorites is significantly altered by shock. It is the purpose of this report to discuss, in some detail, the shock-induced alterations in cohenite (Fe_3C) over the pressure range 0 - >1000 kb. In addition, this report discusses several applications of the x-ray technique to the study of the pressure history of some iron meteorites.

Cohenite is the natural equivalent of the artificial orthorhombic iron carbide, cementite. It is found as an accessory mineral in a number of coarse and medium octahedrites, in three nickel-poor ataxites, and in the iron associated with the basaltic rocks of Disco Island, Greenland (Lovering, 1964). Chemically, cohenite differs from cementite only in that cohenite contains minor amounts of nickel and cobalt (Lovering, 1964; Brown and Lipschutz, 1965). It is thermodynamically unstable and the mere fact of its existence in meteorites has given rise to a rather warm debate regarding its applicability as a hydrostatic pressure indicator in iron meteorites (Ringwood, 1960, 1965; Ringwood and Seabrook, 1962; Lipschutz and Anders, 1961 a, b, 1964). The identification of cohenite in terrestrial metallic masses of shallow origin (Lovering, 1964), and recent work by Brett (unpublished data) would appear to support the contention that cohenite's survival is not due to its stabilization by high pre-terrestrial gravitational pressure in a lunar-sized object.

The cohenite grains themselves are present in two different associations in iron meteorites. Generally they are present as elongated anhedral crystals oriented in lines parallel to the kamacite (α Fe) bands forming the Widmanstätten structure. The individual grains range up to nearly one cm in length and may show some fractures. In addition cohenite may be present with schreibersite (Fe_3P) as a swathing band around troilite (FeS)-graphite inclusions. The grains making up the swathing band are also anhedral.

Cohenite has been studied rather extensively by microscopic techniques, most recently by El Goresy (1965). The only x-ray study which has been reported is that of Westgren and Phragmén (1924) who identified it by powder diffraction in the Magura coarse octahedrite.

2. Experimental

The iron meteorites chosen for this study (Table 1) consisted of a number of Canyon Diablo samples previously studied by metallography and mass spectrometry (Heymann, Lipschutz, Nielsen and Anders, 1966*; Heymann, 1965; Lipschutz, 1965). Pressure calibration standards were one-cm Odessa meteorite cubes which had been artificially shocked-loaded by P. S. DeCarli of the Stanford Research Institute (200, 400, 600, 800, 1000 kb samples) and by N. L. Coleburn of the U.S. Naval Ordnance Laboratory (190 and 600 kb samples). Because of possible shock attenuation, the pressures quoted for these standards are estimated to be accurate only to within ±100 kb. Also due to the small size of these standards rarefaction phenomena at the surfaces could conceivably have complicated the observable shock effects (Smith and Fowler, 1961) although there was no metallographic or crystallographic evidence that such reflection phenomena did, in fact, occur. Odessa samples were also used for annealing experiments, some of

*Hereafter referred to as HLNA.

which have been previously discussed by Lipschutz and Anders (1964). All Odessa specimens were taken from the same individual so as to minimize chemical compositional variation.

Single grains of cohenite were carefully pried out from exposed meteoritic surfaces so as not to disturb their crystallographic character. The specimens, which ranged up to about 0.1mm in length, were then individually x-rayed with Mn-filtered FeKα radiation in a 57.3 mm powder camera without rotation. Inasmuch as the cohenite grains contained no visually recognizable crystal faces it was not possible to orient the samples reproducibly with respect to the x-ray beam. However, specimen orientation was found not to be a critical factor in these experiments inasmuch as replicate exposures of a number of individual cohenite grains at 20° increments with respect to the x-ray beam yielded similar diffraction patterns.

Cohenite specimens were readily distinguished from optically similar schreibersite by taking rotation diffraction patterns of all samples. Powder diffraction standards of both schreibersite and cohenite were prepared of crystals from the Odessa meteorite and of grains chemically separated by Prof. G. Tschermak (obtained through the courtesy of Dr. N. Grogler).

3.1 Metallographic Observations

It has previously been shown (Lipschutz and Anders, 1961a; HLNA) that Canyon Diablo meteorite specimens differ considerably in shock history. Some specimens appear "normal" under the microscope (i.e. unaltered by shock) while others show evidence of having been exposed to shock pressures in excess of 750 kb. The physical appearance of the metallographically observable shock "barometers" have been described previously (HLNA) and need not be repeated in great detail here. However, it might be well to briefly discuss these barometers in order to relate them to the crystallographic alterations observed in cohenite.

Some of the most striking changes induced in iron meteorites during shock occur in kamacite. The kamacite, which initially consists of coarse single crystals, shows a fine-grained "matte" structure (Smith, 1958; Maringer and Manning, 1962) when shocked to pressures in the range 130 - 200 kb. This structure, which may have resulted from reversion of shock-formed ϵ iron (HLNA), is somewhat less fine-grained in kamacite shocked to pressures in the 400 - 600 kb range. Kamacite shocked to 800 kb or more is entirely recrystallized, either from recrystallization during the pressure pulse or as a result of the elevated after-shock residual temperature.

Shock-induced changes have also been observed in troilite (HLNA; El Goresy, 1965) which again might possibly have been due to elevated pressures and/or temperatures. Some changes, such as the formation of diffusion borders and eutectics, are due to diffusion-controlled processes and apparently occur only as a result of the high residual temperature (HLNA). The presence of pressure gradients and "inverse heating" have also been deduced by metallographic studies (Lipschutz and Anders, 1961a; HLNA).

With these observations in mind let us now consider the evidence presented by x-ray diffraction examination of cohenite.

3.2 Cohenite Pressure Scale

From the diffraction spacings of natural and artificially shocked samples, it appears that there is no significant variation in the lattice parameters of cohenite relative to those of cementite (Lipson and Petch, 1940). Thus it would seem that substitution of minor amounts of Ni and Co for Fe in the cementite structure has little or no effect on cohenite's thermodynamic metastability (Brown and Lipschutz, 1965).

Figure 1 illustrates diffraction patterns obtained from individual non-rotated cohenite grains of unshocked and artifically shock-loaded Odessa samples. The pattern of natural cohenite is shown as Figure 1a and consists of single-crystal spots with no unusual effects such as asterism or preferred orientation. The spots in the low angle region (to the left) arise as a result of the non-monochromatic character of the radiation. Figures 1b (200 kb), 1c (400 kb), 1d (600 kb) and 1e (800 kb) show a gradual alteration of the character of the cohenite. As the shock intensity is increased, the single-crystal spots gradually form long arc segments indicative of increasingly greater preferred orientation (see section 3.4). In the low angle region the spots gradually become elongated away from the outlet port and fainter. This reflects the preferred orientation of the former single-crystal spots and should not be confused with true asterism. Ultimately, the cohenite becomes polycrystalline and effectively randomly oriented (Figure 1f, 1000 kb) with a superposition of a preferred orientation.

Figure 2 illustrates typical x-ray photographs of individual nonrotated cohenite grains from various Canyon Diablo meteorites. The changes appear to be rather similar to those shown in Figure 1. Figure 2a (meteorite 26)* shows no

*The two-digit identification numbers listed in this paper refer to Canyon Diablo specimens described in HLNA.

shock-induced changes. Figure 2b (meteorite 9) shows some alteration indicative of a slight degree of shock. However, the preferred orientation of this pattern does not appear to be as pronounced as that of Odessa cohenite shocked to 200 kb (Figure 1b). The microstructures of both meteorites 26 and 9 appeared "normal" (unchanged by shock). It would seem therefore, that meteorite 9 has been shocked but to a somewhat lower pressure than is required to induce metallographically observable changes.

Regrettably none of the Canyon Diablo cohenite diffraction patterns exactly reproduced the appearance of photographs of Odessa cohenite shocked to 200 kb (Figure 1b) although several resembled Figure 1b more than they did Figure 2b. Figures 2c (meteorite 28) and 2d (meteorite 35) seem rather similar to Figures 1c and 1d and thus these grains probably were shocked to pressures of 400 and 600 kb, respectively. This conclusion is supported by metallographic study of meteorites 28 and 35 since both contained patches of the "matte" structure and recrystallized kamacite (HLNA). Meteorite 28 is apparently less strongly shocked than is meteorite 35 since, in the former, the recrystallized kamacite is localized along physical discontinuities (fault lines and phase boundaries) while in the latter there is no such localization. Figure 2e (meteorite 47) shows the diffraction pattern of a cohenite grain whose characteristics are similar to, but somewhat more strongly altered than, Figure 1e (Odessa cohenite at 800 kb). Meteorite 47, like meteorites 28 and 35, contains patches of both "matte" structure and recrystallized kamacite.

Figures 2f (meteorite 52) and 1f (1000 kb Odessa) seem very similar and thus probably represent equally shocked cohenite grains. Figure 2g (meteorite 34) shows an entirely polycrystalline pattern, although the orientation of the crystallites is not entirely random. Since the complete polycrystallinity of Figure 2g is not reproduced by photographs taken of cohenite grains shocked as high as 1000 kb, Figure 2g apparently represents a cohenite grain shocked to more than 1000 kb. It would seem, then, that meteorite 34 has been more strongly shocked than meteorite 52. This conclusion is supported by the metallographic observations of HLNA. Meteorite 52 contains ledeburite-like eutectic, shock-induced troilite changes (Types 2 and 3), and localized martensite (carbon diffusion) borders, in addition to the localized patches of "matte" structure and recrystallized kamacite observed in meteorites 28, 35, and 47. Meteorite 34 contains no observable troilite or "matte" structure but, instead, possesses a number of changes indicative of a high degree of shock (ledeburite-like and phosphide eutectics, abundant martensite, and recrystallized kamacite over the entire exposed polished surface).

It thus appears that the pressures estimated by the degree of cohenite's alteration agree in a qualitative manner with pressures which could be deduced from the presence of microstructural changes. In order to establish some sort of pressure scale based on shock-induced crystallographic alterations alone, it is necessary to adopt a set of objective criteria based on empirical evidence. The criteria chosen are listed in Table 2. Conservatively I would estimate the accuracy of the 200 kb value as $\left({+200 \atop -100}\right)$ and those of the 400, 600, and 800 kb values at somewhat less than ±200 kb. The 0 and 1000 kb values involve somewhat less subtle changes and thus probably are accurate to within ±100 kb.

3.3 Interpretation of X-Ray Photographs

The alterations shown in Figures 1 and 2 are most easily explained as representing successive steps in the shock-induced recrystallization of cohenite single crystals. If this interpretation is correct one could reasonably expect the recrystallization to be also visible microscopically. The metallographic observations of HLNA showed that, although the cohenite grains of some specimens were fractured, they did not seem polycrystalline. However, microscopic study of grains analogous to those illustrated in Figures 1f, 2f, and 2g showed that, using oil immersion, the cohenite appeared very finely recrystallized (El Goresy, 1965).

There are no doubt conceivable mechanical and thermal mechanisms which might be proposed to account for the diffraction features shown in Figure 2. Shock is always accompanied by elevation of temperature and thus a combination of direct shock-induced microfracturing and thermal recrystallization (accompanied by high pressure) might give rise to the features shown in Figures 1 and 2. The probability of simple thermal recrystallization by some hypothetical process (unaccompanied by the application of high pressure) or solely as a result of the high after-shock residual temperature seems rather low. As is well known, at atmospheric pressure, cohenite is thermodynamically unstable with respect to graphite (Ringwood, 1960, 1965; Ringwood and Seabrook, 1962; Lipschutz and Anders 1961a, b; 1964). Thus, prolonged heating of meteoritic cohenite at low pressures should result either in no change in the lightly shocked single-crystal pattern or, under the appropriate conditions of time and temperature, in the partial or complete graphitization of cohenite. For example, cohenite heated under conditions insufficient to extensively graphitize it (e.g. 640°C for 335 hours) yields a diffraction pattern similar to that of lightly shocked cohenite (Figure 3a). On the other hand, cohenite heated at 800°C for 335 hours (Figure 3b) is extensively graphitized (Lipschutz and Anders 1964). The predominant phase evident is α iron which shows a pronounced preferred orientation probably due to its formation and growth along graphite nucleation sites such as cracks. Graphite's diffraction lines are not apparent in Figure 3b because its concentration in the cohenite-kamacite-graphite assemblage is too low to be detectable. Even in the 800°C specimen, however, the ungraphitized cohenite has the same diffraction pattern characteristics as is shown by unaltered cohenite. Conceivably if the rate of low pressure thermally-induced recrystallization of cohenite were greater than the rate of its graphitization, appropriate conditions might be found such that the cohenite might be highly recrystallized and yet not extensively graphitized. This phenomenon was not observed in any of the annealed Odessa specimens studied. Since it is not feasible to perform all of the conceivable experiments which could absolutely eliminate this possibility, the mechanism of low-pressure thermally-induced recrystallization remains possible albeit not probable.

From the preceding discussion, it seems most likely that the cohenite alterations observed in Canyon Diablo meteorites are due to cohenite's shock-induced recrystallization. Probably this recrystallization occurred during passage of the pressure pulse itself and as a direct result of it. Thus, the cohenite alteration appears to be an inherently rapid process - a property which it should share with some of the other diffusionless shock indicators such as formation of the "matte" structure or of troilite type 2 (HLNA).

3.4 Unusual Diffraction Effects in Cohenite

A number of the cohenite grains from some of the Canyon Diablo specimens* examined showed asterism or broadened high-angle reflections. These meteorites showed no evidence for any metallographically observable shock-induced changes. Of the shock standards only the 190 kb Odessa specimen contained grains showing any trace of these features.

These features are similar to those induced in single crystals by mechanical deformation (for example, see Clark, 1955). Since shock waves are accompanied by a shear component which can cause mechanical deformation it may well be that these "unusual" features observed in Canyon Diablo cohenite grains arise as a result of relatively low-pressure shock-induced deformation (below about 200 kb). It is possible that they could arise at higher pressures except that they are overwhelmed by the predominant recrystallization effects.

One speculation should perhaps be mentioned in this connection. In cohenite shocked at 1000 kb (Figures 1f and 2f), the diffraction pattern observed is that of a preferred orientation superimposed on an anisotropic randomly oriented polycrystalline aggregate. Probably this pattern represents the recrystallization point of cohenite. A remote possibility exists, however, that there is some high pressure polymorph of cohenite which forms at about 1000 kb and subsequently reverts to the normal orthorhombic modification as the pressure is reduced.

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*These meteorites are indicated by asterisks in Table 1.

3.5 Pressure Gradients

It has been pointed out previously that most of the Canyon Diablo meteorites which show metallographic evidence for shock also indicate pronounced pressure and temperature gradients. Two such macroscopic samples are illustrated in Figure 6 of HLNA (meteorite 3) and Figure 4 of Anders and Lipschutz (1966a) (meteorite 52). The latter meteorite (Figure 4a) is a particularly striking example of such gradients. At the left end of the sample, the kamacite appears to unaffected by shock (N). Kamacite areas farther to the right exhibit the "matte" structure (ϵ), the "matte" structure converting to polycrystalline kamacite ($\epsilon \rightarrow R$), and finally completely recrystallized kamacite (R). The presence of an "inverse" temperature gradient is inferred from the observation of "hot spots" in the form of eutectics and small recrystallization areas in the interior of the specimen (Lipschutz and Anders 1961a; Anders and Lipschutz 1966a).

Because of the apparent dependence of the cohenite structure on pressure, it seemed of interest to examine various grains by x-ray diffraction at selected points within this specimen in order to verify the metallographically deduced pressure gradients. A location map of the cohenite samples is shown as Figure 4a. Diffraction patterns from the cohenite grains of locations a, b, c, and d in Figure 4a are illustrated in Figure 4b. An easily recognizable pressure gradient is present which qualitatively conforms to the metallographic map. Quantitatively, however, there are some differences. Cohenite from the kamacite region which is apparently unaffected by shock (N) shows the strongly preferred orientation characteristic of cohenite shocked to about 800 kb. Thus, the absence of the "matte" structure or other kamacite changes does not necessarily preclude the possibility of rather severe shock. Cohenite grains from regions farther to the right show evidence of increasingly higher shocks until, at the extreme right, only randomly oriented polycrystalline cohenite is present. From these patterns the 800-<1000, 1000, and >1000 kb regions could be rather clearly defined. It should be pointed out however that the degree of cohenite alteration in the 800-<1000 kb region apparently does not increase monotonically as one traverses from left to right. This arises perhaps from secondary rarefaction shocks occurring at the troilite-kamacite interfaces or from insensitivity of the x-ray technique. In any event, the cohenite grains present some evidence for a pressure gradient on the order of 20 kb/cm along this 11 cm. specimen.

3.6 Correlations Between Crystallographic Alterations and Metallographic Changes

It has been shown that the shock-induced alteration of cohenite provides a useful independent check on the metallographically observable shock-induced changes in Canyon Diablo meteorites. It seemed worthwhile then to re-examine the HLNA specimens by the x-ray method in order to verify our previous classifications and, incidentally, to allay the doubts raised by Carter and Kennedy (1966) as to the validity of our metallographic criteria for shock. In view of the strong pressure gradients discussed previously (Section 3.5) and in the absence of a detailed mapping of each meteorite in a manner similar to that discussed in Section 3.5, a perfect correlation between degree of cohenite alteration and the presence of appropriate metallographic changes could not be anticipated. However, a general correlation could be expected such that if, for example, a cohenite grain from a specimen showed a crystallographic alteration corresponding to a 600 kb Odessa cohenite, that specimen would also contain several other metallographic shock indicators (i.e. would fall into the moderately or heavily shocked groups of HLNA).

Table 1 lists the pressures deduced from the diffraction photographs of Canyon Diablo specimens examined in this study. For comparison, the shock-induced metallographic changes present in these specimens are also listed (HLNA; Lipschutz, 1965). The general agreement between the pressures estimated by x-ray diffraction and, by the criteria of HLNA seems to be reasonably satisfactory, thus lending some support to the validity of HLNA's shock criteria. There are some minor differences however, which deserve comment. Before discussing these it should be re-emphasized that in the absence of a detailed mapping of each meteorite (Section 3.5) one cannot know whether the pressures estimated by the crystallographic alterations are lower or upper limits or means of the shock suffered by each meteorite.

The first nine specimens listed in Table 1 (1-54A) show neither cohenite alteration nor metallographic changes. The next thirteen, however, (7-45) show some incipient cohenite recrystallization (which is not as pronounced as that of 200 kb Odessa cohenite), but no metallographic changes. This is not too surprising inasmuch as it would indicate that the alteration of cohenite's crystal character is induced by pressures lower than those required to change the meteorites' microstructure. It would therefore seem that these thirteen samples were shocked to below about 130 kb. Cohenite grains from the next three specimens (4, 23, and 37) appear similar to those from 200 kb Odessa specimens yet these, too, show no microstructural changes. It may be that their kamacite was not favorably oriented for formation of the "matte" structure (Smith, 1958; HLNA), or that the pressure magnitude may still have been below the threshold required for formation of the "matte" structure. The possibility cannot be excluded that the kamacite in these three specimens was shocked to about 200 kb. Certainly specimen 52 (Figure 4a) contains a region (N) in which the "matte" structure has apparently not formed although the pressure in that region was certainly high enough for its formation. The last nine specimens (19 - 34) would seem to present a coherent picture. Their cohenite has apparently been shocked to pressures of 1000 kb or more and they contain a number of microstructural changes indicative of rather severe reheating (i.e. shock). It would therefore seem that HLNA's metallographic criteria for this group are supported by the crystallographic alterations in cohenite.

The remaining sixteen meteorites (28 - 47) present a rather mixed aspect. Some would appear to have concordant crystallographic alterations and microstructural changes while others have shock indicators which appear discordant. For example, on metallographic grounds, meteorite 53 would appear to have been shocked higher than 600 kb while meteorite 47 would not appear to have been shocked to a pressure as high as 800 kb. Such apparent inconsistencies are only to be expected in view of the pronounced pressure gradients observed by microscopy and by x-ray diffraction analysis. Certainly the fact that most of these meteorites were not mapped by the x-ray method would tend to increase the number of such apparent inconsistencies.

Several additional conclusions can be drawn from the data listed in Table 1. First of all it had been noted previously (HLNA) that several Canyon Diablo specimens had cohenite grains which showed incipient graphitization but no metallographically observable shock effects (e.g. Figure 4, HLNA). It was therefore suggested that the cohenite graphitization observed in these meteorites was not due to shock but was instead due to their being heated by contact with hot ejecta. From the diffraction photographs it was observed that two of the meteorites (1 and 13) showed no cohenite alteration while the other two (9 and 24) showed evidence for shock pressures of more than 0 but less than 200 kb. Diffraction photographs of a number of cohenite grains from specimens 13 and 24 show α iron with a strong preferred orientation, in addition to the lightly and mildly shocked cohenite. Cohenite grains from the lightly and mildly shocked specimens 1 and 9 show neither α iron nor graphite-probably due to their low concentration and, hence, reduced temperature-time history. These observations would seem to support our previous suggestion (HLNA) of the low pressure-high temperature origin of cohenite graphitization in these four meteorites.

In view of the controversy surrounding the shock history of samples

54A and 54C (Carter and Kennedy, 1964, 1966; Anders and Lipschutz, 1966a, b) it seemed of particular interest to consider the cohenite alteration in grains from these two specimens. Carter and Kennedy claim that these two specimens are from the same 15 cm individual which shows no features attributable to shock but which contains diamonds. HLNA's data would, however, indicate that these two specimens differ in several important characteristics. One difference is that their He^3 contents differ by a factor of 180 (HLNA) whereas the maximum difference expected in a 15 cm individual would be a factor of 2. Thus, it would seem that 54A and 54C were separated by a distance of about 110 cm (Anders and Lipschutz, 1966a). Specimen 54A contains no diamonds although specimen 54C apparently does (HLNA; Anders and Lipschutz, 1966a; Carter and Kennedy, 1966; El Goresy, unpublished data).

Cohenite grains from sample 54A show diffraction patterns similar to those of unshocked samples. Cohenite grains from sample 54C, on the other hand, give diffraction patterns similar to those of cohenite shocked to 400 kb (Figure 5). These observations are in accord with the metallographic evidence (Table 1) presented previously by HLNA and Anders and Lipschutz (1966a). Quite apart from any doubts as to the origin of samples 54A and 54C in the same 15 cm Canyon Diablo specimen it thus seems evident that these two specimens differ considerably in their shock history and that the diamond-bearing sample (54C) has been shocked to pressures high enough to produce diamond from graphite.

4. Conclusions

From the evidence presented in this paper, it would seem that examination of cohenite's crystallographic alteration provides some useful information on the shock history of Canyon Diablo meteorites. The alterations appear to be due to cohenite's progressive solid-state recrystallization during the high-pressure portion of the shock pulse. These alterations apparently cannot be reproduced by heating unaccompanied by the application of high pressure. With particular reference to the use of this new "barometer" several conclusions can be drawn.

Comparison of cohenite's crystallographic alterations with microstructural changes has independently verified the shock criteria proposed by HLNA. The relative arrangement (by metallography) of Canyon Diablo specimens with respect to degree of shock is essentially paralleled by estimation of their shock history using x-ray diffraction. In addition to the specimens identified by HLNA as being shock-altered there appears to be an appreciable number of Canyon Diablo meteorites which have been shocked to pressures insufficient to induce microstructural changes. Furthermore, it has been found possible to estimate the shock pressures at a number of points across a specimen showing a pressure gradient. For meteorite 52 this gradient appears to be on the order of 20 kb/cm rather than the 10^6 - 10^7 kb/cm as interpreted by Carter and Kennedy (1966). With particular reference to the much-discussed specimens 54A and 54C (Carter and Kennedy, 1964, 1966; HLNA; Anders and Lipschutz, 1966a) the additional evidence presented here supported the conclusion that they differ considerably in shock history and that 54C (which contains diamonds) has been shocked to at least 400 kb.

In view of the progressive alteration of cohenite's crystal structure with increasing shock magnitude, it appears that cohenite is indeed a pressure indicator in iron meteorites, but not in the sense originally discussed by Ringwood and us.

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Table 1. Shock pressure estimation from cohenite, and shock indicators observed in Canyon Diablo meteorites.

Meteorite[a]	Pressure (kb)	Shock Indicators[b] "Matte" Structure	Recrystallized Kamacite	Eutectics	Carbon Diffusion Border	Troilite
1	0					
8	0					
13	0					
22	0					
26	0					
27	0					
29*	0					
42	0					
54A	0					
7*	<200					
9	<200					
11	<200					1
12*	<200					1
21*	<200					
24	<200					
25*	<200					
38*	<200					
39*	<200					
40*	<200					
41	<200					
44*	<200					
45*	<200					
4*	$\leq$200					
23*	$\leq$200					
37	$\leq$200					

Table 1 continued

Meteorite[a]	Pressure (kb)	"Matte" Structure	Recrystallized Kamacite	Eutectics	Carbon Diffusion Border	Troilite
		Shock Indicators[b]				
28	400	+	(+)			
54C	400	+	(+)			1,2
2	600	+	(+)			
3	600	+	+			
15	600		++		P	
20	600	+	(+)			
35	600	+	+			
53	600		++	L,Ph	m	3
586.1	600	+	+		m	2
32	600-800		++		P	
52	600->1000	+	+	L	m	2,3
5	800	+	+			2
10	800	+	+		m	
18	800		++		P	
30	800		++	L,Ph	P	2,3
47	800	+	+			
19	1000		++	Ph	P	
49	1000		++	L,Ph	m	2,3
50	1000		++	L,Ph	P	3
56	1000		++	L,Ph	m	2,3
371.3	1000		++	L	P	
16	>1000		++	L,Ph	m,P	
31	>1000		++	L,Ph	m	
33	>1000		++		m,P	
34	>1000		++	L,Ph	m	

Table 1 continued

(a). Two-digit identification numbers refer to meteorites whose metallography was described by HLNA; four-digit numbers, to meteorites described by Lipschutz, 1965. The asterisk refers to meteorites whose cohenite shows asterism or broadened, high-angle reflections.

(b). Metallographically observed shock indicators (HLNA; Lipschutz, 1965): +, localized feature; ++, general feature; (+) feature observed only along physical discontinuities; L, ledeburite-like eutectic; Ph, phosphide eutectics; m, martensite; P, pearlite; Troilite 1,2,3, unchanged, polycrystalline, or remelted troilite.

Table 2 Criteria for shock pressure estimation by cohenite's x-ray diffraction appearance.

Pressure (kb)	Criteria Adopted
0	Single-crystal diffraction spots. "White" radiation spots at outlet port.
200^{+200}_{-100}	Some diffraction "spots" now beginning to form are segments of preferred orientation, perhaps from two or more "spots". "White" radiation now results in streaks instead of spots.
400 ±200	All diffraction "spots" now distinct small arc-segments which may be forming from two or more "spots". Highest angle lines show definite blobbyness.
600 ±200	All diffraction "spots" now distinct arc-segments. Highest angle segments each subtend an angle of less than 30° with respect to x-ray source.
800 ±200	All diffraction "spots" are arc- segments. Highest angle reflection has at least one segment subtending an angle of 40° or more with respect to the x-ray source.
1000 ±100	Superposition of preferred orientation and polycrystalline orientation.
1000	No arcs of preferred orientation. Approximately random crystallite orientation although not completely isotropic distribution.

Figure Captions

Figure 1. X-ray diffraction photographs of individual non-rotated cohenite grains from Odessa iron meteorite samples: a) natural cohenite, b) through f) cohenite artificially shocked to 200, 400, 600, 800, and 1000 kb respectively. Note the gradual change, as a function of pressure, in the single-crystal spots (a) through a preferred orientation (b, c, d, e) into a randomly oriented aggregate showing a superimposed preferred orientation (f). The low angle reflections in these photographs are due to the non-monochromatic character of the radiation. Their "streaking" in the cases of the cohenite shocked to 200-800 kb (b-e) merely reflects the preferred orientation of the cohenite crystallites and does not represent mosaicism. The change suggested by these photographs is apparently that of the gradual shock-induced recrystallization of cohenite.

Figure 2. X-ray diffraction photographs of individual cohenite grains from different Canyon Diablo meteorites. Note that the changes in these specimens are similar to those shown in Figure 1. The specimens shown are from meteorites 26 (a), 9 (b), 28 (c), 35 (d), 47 (e), 52 (f), and 34 (g).

Figure 3. Diffraction photographs of individual cohenite grains from Odessa specimens heated for 335 hours at 640°C (a) and 800°C (b). Note that the cohenite shown in (a) appears unaltered (unshocked) while in (b), where it has graphitized extensively, the predominant phase is α iron which has a preferred orientation.

Figure 4a. Map of Canyon Diablo meteorite 52. The dashed lines bound regions of lightly shocked kamacite (N), "matte" (ϵ -iron transformation) structure (ϵ), recrystallizing matte structure ($\epsilon \rightarrow R$) and completely recrystallized kamacite (R). The digits 2 and 3 refer to recrystallized and remelted troilite and the circles indicate points from which cohenite grains were removed and x-rayed. The pressure limits indicated are estimated from the crystallographic character of the cohenite.

Figure 4b. Diffraction patterns of cohenite grains from region N (a); $\epsilon \rightarrow R$ (b); and R, (c) and (d). Note that a pressure gradient of about 20 kb/cm is indicated across the specimen, which is about 11 cm long.

Figure 5. Typical diffraction pattern of a cohenite grain from meteorite 54C. This grain has apparently been shocked to about 400 kb.

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