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MINERALOGICAL STUDY OF THE ALH-77283 IRON METEORITE

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Abstract: Of the many meteorites recovered so far from the Yamato Mountains and Victoria Land, Antarctica, only twenty-four have been irons. One of these, Allan Hills-77283, type IA coarse octahedrite, contains diamond-lonsdaleite nodules, for which extraterrestrial shock origin has been proposed. The shock textures of ALH-77283,52 have been studied by metallographic, X-ray and electron diffraction, and analytical SEM techniques. The shock pressure and temperature were estimated to be about 600–750 kb and 400–500°C from the shock-hatched and recrystallized kamacites in comparison with the standard scale produced by the shock-loaded experiments on the Odessa iron meteorite (HEYMANN *et al.*: J. Geophys. Res., **71**, 619, 1966; M. E. LIPSCHUTZ: Geochim. Cosmochim. Acta, **31**, 621, 1967).

1. Introduction

Among many meteorites recovered so far from the Yamato Mountains and Victoria Land, only twenty-five irons have been discovered (NAGATA and TAGUCHI, 1987). Allan Hills (ALH)-77283 is one of IAOg irons found in the Allan Hills and weights 10.5 kg. It is material from the internationally known individual meteorite specimen Allan Hills A77283 (GRAHAM *et al.*, 1985) that both CLARKE *et al.* and we worked with. The preliminary description by CLARKE *et al.* (1981) reported that ALH-77283 contains troilite-graphite-schreibersite-cohenite inclusions rich in the carbonado-type diamond and lonsdaleite nodules previously described from the Canyon Diablo meteorite. The Canyon Diablo iron meteorite has been known as the excavator of Meteor Crater, Arizona. Canyon Diablo is the only other iron meteorite that contains authenticated diamonds. Canyon Diablo diamonds were believed to have been produced by a high-pressure shock event possibly by terrestrial impact.

The shock transformation of Canyon Diablo is well studied by HEYMANN *et al.* (1966) and LIPSCHUTZ (1967). They used samples of the Odessa iron meteorite (coarse octahedrite IA) which had been artificially shock-loaded by P. S. DECARLI of the Stanford Research Institute (200, 400, 500, 800, and 1000 kb samples), and by N. L. COLEBURN of the U. S. Naval Ordnance Laboratory (190 and 600 kb samples) as the pressure comparison scale for meteoritic iron. HEYMANN *et al.* (1966) well described the shock textures of Canyon Diablo. The estimation of its shock pressure using X-ray diffraction photographs of cohenite has been carried out by LIPSCHUTZ (1967). BUCHWALD (1975) investigated many polished and etched sections of the Canyon

Diablo and divided the meteorite into seven shock transformation stages (Table 2). Because ALH-77283 passed through the atmosphere as a small individual, the shock event which produced the structural deformation has been proposed as preterrestrial (CLARKE *et al.*, 1981). The presence of extraterrestrial diamonds in ALHA77283 makes the argument that Canyon Diablo diamonds must have been produced by terrestrial impact a little less convincing that it was earlier (CLARKE, private communication, 1986). The range of shock pressure estimated by them is well above 200 less than 750 kb. In order to gain better understanding of the preterrestrial shock histories, we have studied in detail its metal and cohenite by scanning electron microscopy (SEM), optical metallographic microscopy and single crystal X-ray and electron diffraction. The results without electron diffraction were compared with the previous studies of the Canyon Diablo meteorite and the shock-loaded samples to estimate the shock pressure more accurately. The range of shock pressure thus estimated is in agreement with formation of diamond.

2. Sample and Experiment

Sample of ALH-77283,52 (Type IA coarse octahedrite), $0.5\times1\times1$ cm in size, was supplied from National Institute of Polar Research (NIPR), Tokyo. The sample does not include inclusions of diamond, which we requested for our study. Three slices of ALH-77283,52 were mounted and polished using normal metallographic polishing techniques. After polishing, the polished sections were etched with 2% nital for about 45 s.

Light optical examinations of these samples were performed using a reflected microscope. Scanning electron microscope (SEM) examination was performed using a JEOL JSM-840 scanning electron microscope and a HITACHI H-600 transmission electron microscope (TEM) with the SEM mode. The chemical compositions of metals were analized by the SEM mode of the analytical TEM equipped with an Energy Dispersive Detector. The standardless ZAF method of the Kevex system has been used to reduce the data. The transmission electron microscope (TEM) examination was performed using JEOL 100 CX transmission electron microscope at 100 kV. The samples of TEM study were performed in two ways: one sample was ion-thinned by the GATAN model 600 ion-milling machine, and the other was pulverized to produce a powdered sample of ♯ 200 meshes.

Cohenite samples of ALH-77283,52 was removed carefully from a thin slice and mounted on a glass fiber for the X-ray examination. A Laue X-ray diffraction photograph was taken with no rotation of crystals and no movement of the film casette because LIPSCHUTZ (1967) used this method to estimate shock pressure. We used the precession camera instead of the powder camera used by him.

3. Results

3.1. Optical and SEM examination

Typical reflected photos of the texture of ALH-77283,52 are shown in Figs. 1a and 1b. The sample of ALH-77283,52 varies in texture within the same polished and

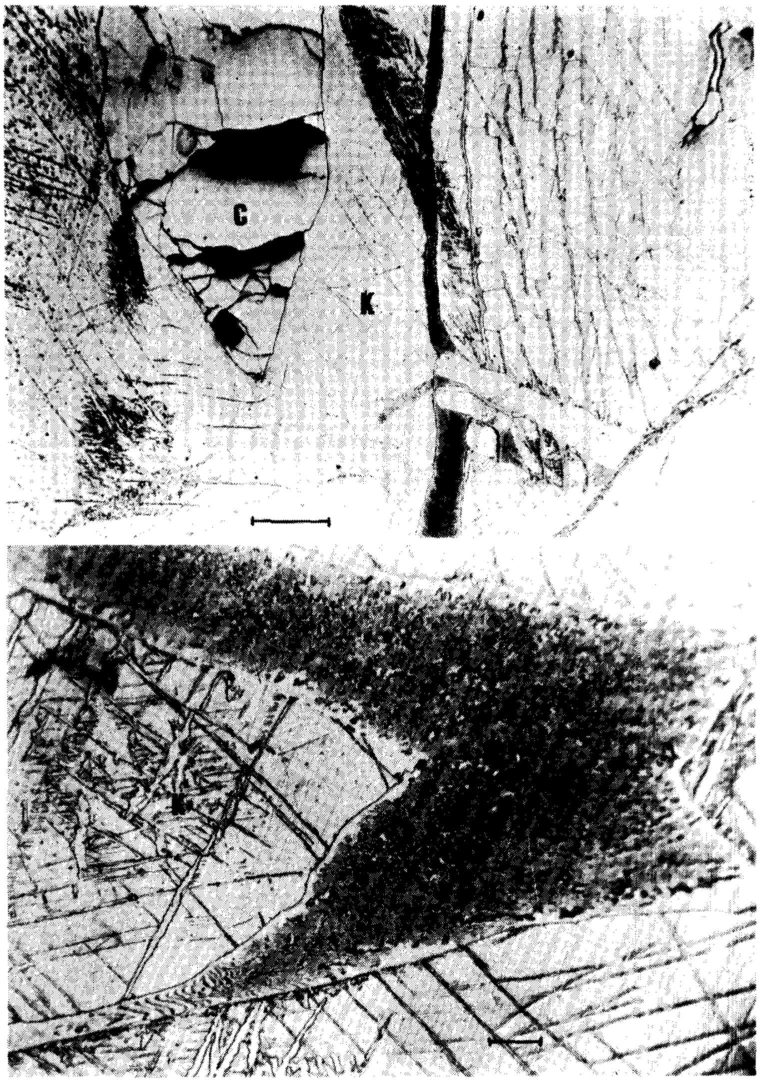

Fig. 1. The photomicrograph of polished and etched surface of ALH-77283, 52. K: kamacite, C: cohenite.

a. Kamacite showing Neumann bands (k: center), which are paralell or cross each other, and a few isolated patches of shock-hatched kamacite (upper). Cohenite (C) inclusion has many cracks, and no carbon diffusion zone. Scale bar: 100 μ.

b. Taenite (T: center), kamacite with Neumann bands and shock-hatched kamacites (left). This photograph shows that the Neumann bands become a well developped transverse hatching, which is called the shock-hatched kamacite. Scale bar: 20 μ.

Table 1. Shock textures of kamacite of ALH-77283,52.

	Shock-atched kamacite	Recrystallized kamacite
Texture	Aggregates of cross-hatched bristles; about 1.5–5 μ in width	Aggregates of small grains; about 5–15 μ in diameter
Occurrence	Isolated patches in localized areas. They are similar to Fig. 2b of HEYMANN *et al.* (1966)	Mainly exist beside cohenites as a zone
Estimated T or P	About 600–750 kb	About 500°C
Figures	Figs. 1a, 1b, 2a, 2b and 3	Fig. 4

etched section. They are summarized in Table 1. The kamacite displays Neumann bands, which are substituted by hatched structures. The sample consists of taenite, cohenite and the kamacite which has Neumann bands and shock-hatched texture (Fig. 1a). The cohenite has many cracks, and no decomposition to graphite is seen. This means that ALH-77283 did not experience higher temperatures above 675°C (as estimated by the HEYMANN's procedure, 1966). These microphotographs indicate that, on the basis of shock textures, ALH-77283 is in general similar to the Canyon Diablo meteorite. As the shock textures of iron-nickel minerals were described in detail by

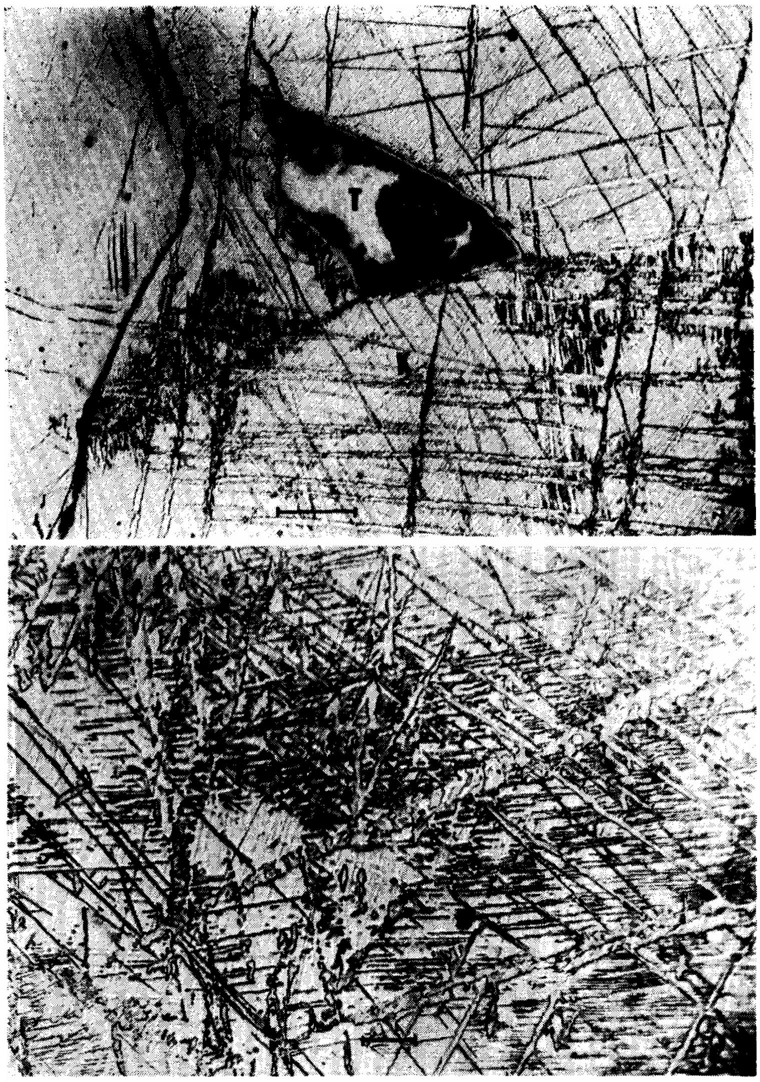

Fig. 2. Photomicrograph of polished and etched surface of ALH-77283, 52, containing shock-hatched kamacites.

a. Kamacites with a few isolated patches of shock-hatched kamacite (K: center). T: taenite. This is similar to Fig. 2b in Heymann*'s paper. Scale bar 100 μ.*

b. The magnified photograph of shock-hatched kamacites. Scale bar 20 μ.

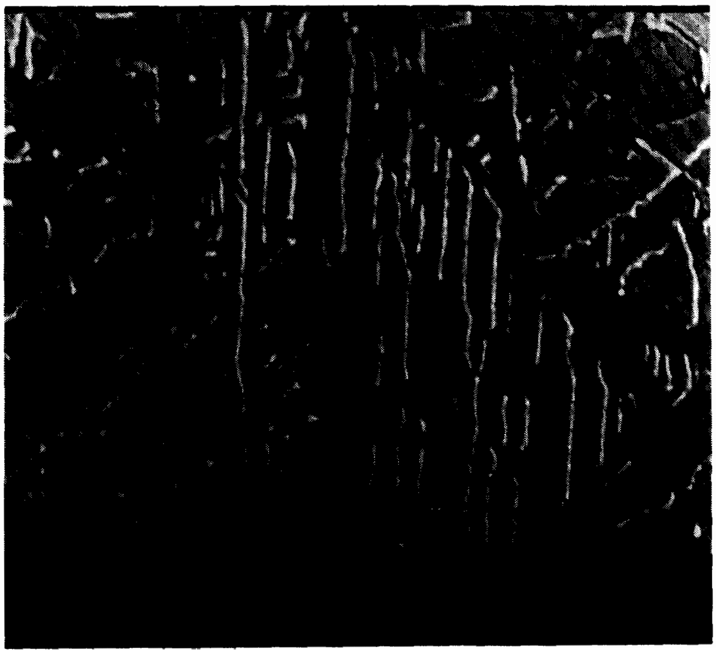

Fig. 3. SEM photograph of shock-hatched kamacites. Small fine bristles and wide "bristles" which consist of several fine bristles are seen. Scale bar: 10μ.

Fig. 4. Partially recrystallized kamacites (lower) within the kamacite. They appear beside cohenites and taenites. K: kamacite, T: taenite, C: cohenite. Scale bar: 100 μ.

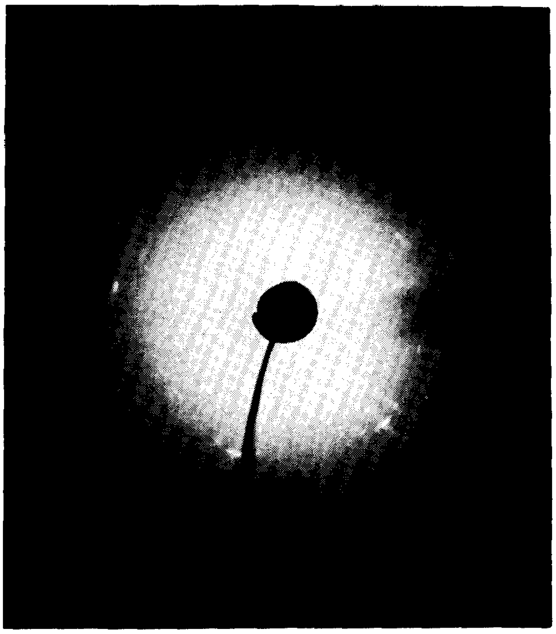

Fig. 5. X-ray diffraction photograph of cohenite of ALH-77283,52. Taken with no-rotation of crystal and with Mokα radiation.

HEYMANN *et al.* (1966) and BUCHWALD (1975), this study has been carried out by comparing our results with those of the previous descriptions of the shock textures.

3.1.1. Neumann bands

Neumann bands of ALH-77283,52 (Figs. 1a, 1b and 2a) appear in most of the kamacites that are neither shock hatched kamacite nor recrystallized kamacite. The width of Neumann bands is about 0.5 μ. Some of them are parallel, and others cross each other. SMITH (1958) studied this structure and estimated that it would be made by the pressure higher than 80 kb.

3.1.2. Shock-hatched kamacites

On the surface of ALH-77283,52, some kamacites have bristles. They are called shock-hatched kamacites, or ε-Fe. The bristles of shock-hatched kamacite are very fine (about 1.5–5 μ in width) and sharp (Figs. 2a and 2b). The shock-hatched kamacites appear in localized areas, not throughout the entire specimen. The sample contains a few isolated patches of shock-hatched kamacite. In appearance, these isolated patches of shock-hatched kamacite are similar to those of the Canyon Diablo meteorite, reported by HEYMANN *et al.* (1966).

Because HEYMANN *et al.* (1966) studied the relationships between the textures of shock-hatched kamacites and the shock pressure, we can estimate the shock pressure from the texture of shock-hatched kamacites by HEYMANN's procedure. According to his procedure, the shock-hatched kamacites are seen between the shock pressure 130 and 750 kb. Thus, ALH-77283,52 is shown to be at least in this range of this shock pressure. More accurate pressure will be discussed in the next chapter. A SEM photograph of this shock-hatched kamacite is shown in Fig. 3. In the magnification of Fig. 3, there are seen fine bristles and wide "bristles" which may be bundle of fine bristles.

Ni contents of the bristles and the matrix kamacites were analized by the SEM mode of the analytical TEM on 25 points but no difference of Ni contents was detected.

3.1.3. Recrystallized kamacite

We found partially recrystallized kamacites on the microscopic scale (Fig. 4). They appear in localized areas, mainly beside the cohenites. The recrystallized kamacites are seen as the aggregate of small grains of 5 to 15 μ in diameter. They are distinctly different from shock-hatched kamacites. They do not show bristles. They are very useful when we estimate the shock pressure and temperature. According to the study of HEYMANN *et al.* (1966) on the relationships of recrystallized kamacite and temperature, the residual temperature of the shock event of ALH-77283 can be estimated to be about 500°C from these recrystallized kamacites which show the aggregate of small grains, 5–15 μ in diameter without bristles.

3.2. *X-ray and electron diffraction study of cohenites and kamacites*

Cohenite is an accessory mineral in a number of coarse and medium octahedrites. The cohenites of ALH-77283 are seen here and there in polished and etched sections (Figs. 1a and 2a). They are large (about 0.5–1 mm in width) cracked inclusions. This is their common appearance of cohenite in type IA coarse octahedrites. Because our berylium window EDS cannot detect carbon, we use the electron diffraction (Fig. 6) to confirm that this mineral is cohenite. The cohenite part was carefully picked up from the sample and then it was powdered. Therefore, there may exist only very small amounts of kamacite, taenite, and schreibersite except cohenite in the sample. All the reflections of electron diffraction pattern could be indexed within the experimental errors using the cohenite cell parameters. The X-ray diffraction photograph of the ALH-77283 cohenite (Fig. 5) shows that single diffraction spot forms small arc segments, which may be formed by two or more spots. This feature is different from the powder pattern because the edge of the arc segments is very sharp. Higher angle lines of this cohenite were not observed. This photograph is similar to that of cohenite shock loaded at the shock pressure at least over 200 kb (LIPSCHUTZ, 1967) as discussed below. Further study is required to estimate the shock pressure more accurately.

The electron diffraction patterns of the powdered cohenites of ALH-77283,52 (Figs. 6a and 6b), showed the sharp single diffraction spots indicating that the areas are not destroyed (Fig. 6a), while other regions show the Debye-Scherrer rings (Fig. 6b).

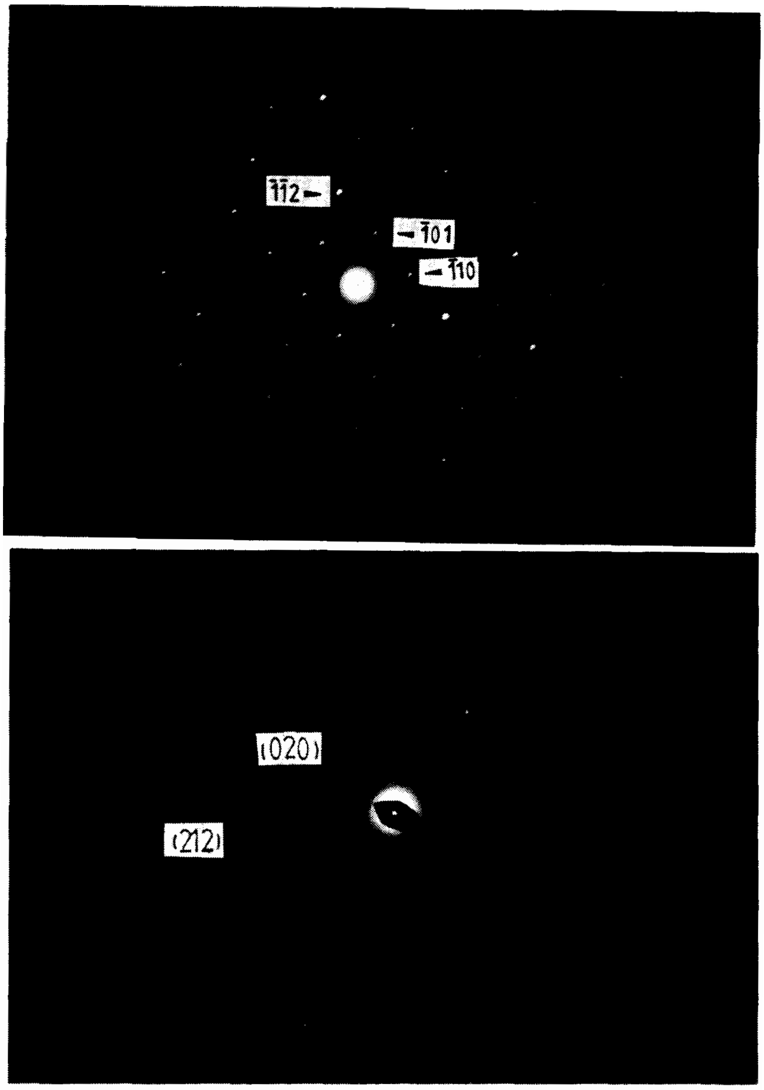

Fig. 6. Electron diffraction photograph of cohenite of ALH-77283,52. Accelerate voltage is 100 kV.

a. "Normal" (not destroyed) spots which seem not shocked.

b. Debye-Scherrer ring. This seems to be shocked, and became to be polycrystalline (powder).

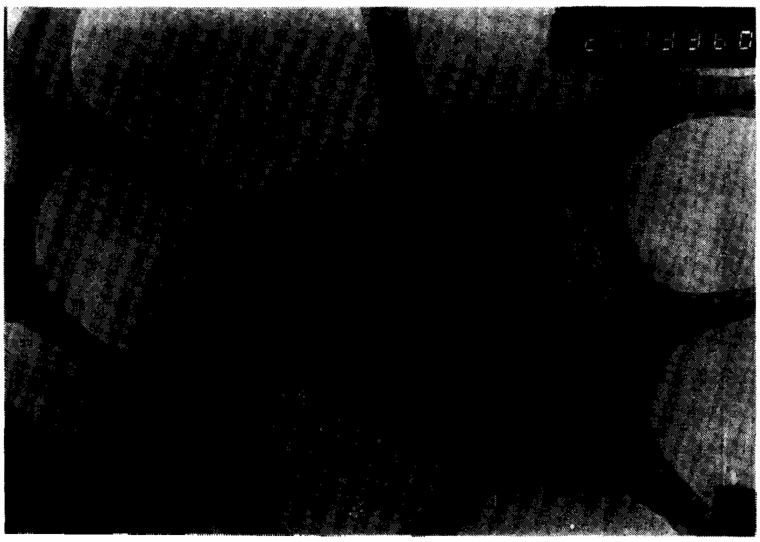

Fig. 7. The TEM photograph of cohenite of Fig. 6. Scale bar is 1.5 μ.

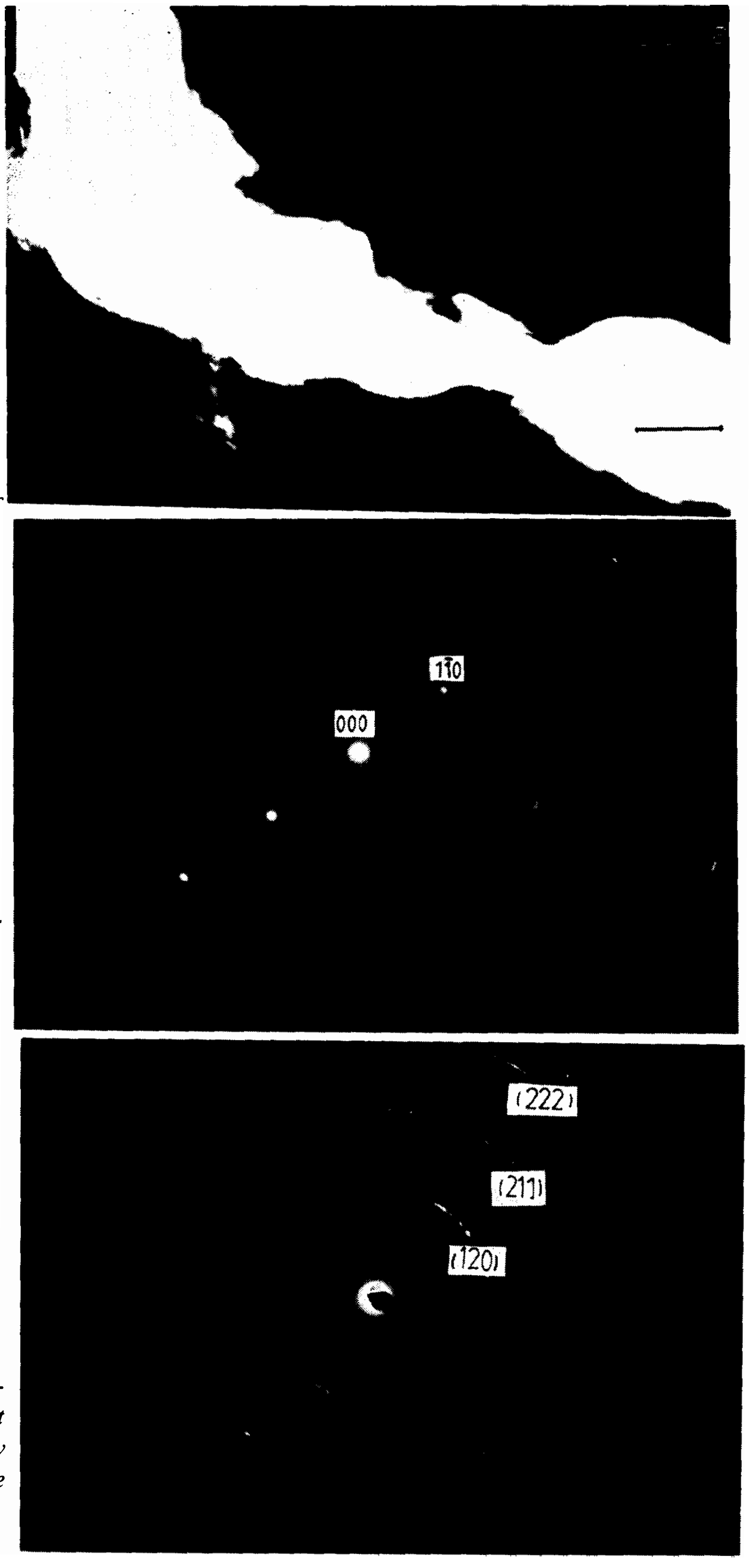

Fig. 8. The TEM photograph and electron diffraction photograph of kamacite near the shock-hatched kamacites.

a. Thin foil of kamacite. Foil plane is parallel to (110) of kamacite. Scale bar is 1.5 μ.

b. Electron diffraction photograph of kamacite of (a). There are "normal" spots seemingly not shocked.

c. Electron diffraction photograph of kamacite distant from (a) in about 10μ; they are perfectly polycrystalline because of the shock event.

Powder grains are about 1–5 μ in diameter.

In the thin foil of kamacites near the shock-hatched kamacite of ALH-77283,52 (Fig. 7), the electron diffraction pattern shows the "normal" (undestroyed) spots or Debye-Scherrer rings (Figs. 8b and 8c).

4. Discussion

As is represented by the presence of diamond of the preterrestrial origin, this meteorite experienced an intense shock event. Before combining these results to estimate the temperature and pressure of the shock event, we discuss separately pressure indicators observed in this meteorite.

First, we applied the pressure scale of the Canyon Diablo meteorite to the textures of Neumann bands and shock-hatched kamacite of ALH-77283.

From HEYMANN *et al.* (1966), Neumann bands require shock of at least above 80 kb at room temperature, but they can be produced by weaker shocks at lower temperatures. They seem to be present in most iron meteorites, having been produced during impact on the earth. Thus Neumann bands are of little use to estimate the shock pressure. At pressure greater than 130 kb, a transformation structure appears on kamacites, resulted from temporary conversion of α- to ε-Fe, shock-hatched kamacite of SMITH (1958). The shock-hatched kamacite begins to appear at 130 kb. Its appearance changes with pressures from 130 to 600 kb showing a progression of metallographic structures and this survives up to 750 kb (HEYMANN *et al.*, 1966).

Varieties of texture were found in meteoritic iron artificially shocked to 190–600 kb by HEYMANN *et al.* (1966), who stated that at the lower pressure the Neumann bands begin to show a slight amount of feathering. The background is dense, fine-grained, and hard to resolve. At higher pressure, the Neumann bands show a well-developped transverse hatching, and the background has thinned out to a pattern of fine but sharp, clearly resolvable lines. The samples of the Canyon Diablo meteorite that seemed to have been shocked to higher pressure tend to contain a few isolated patches of shock-hatched kamacites.

CLARKE *et al.* (1981) estimated the shock pressure of ALH-77283 to be well above 200 less than 750 kb by employing HEYMANN's procedure. However, we think that the shock pressure has been estimated more accurately by our detailed study of shock-hatched kamacites.

HEYMANN *et al.* (1966) reported that the fine but sharp shock-hatched kamacites indicate higher pressure in the range of 130–750 kb. Because similar fine but sharp shock-hatched kamacite is also seen in ALH-77283, we think that the shock-hatched kamacite in ALH-77283 indicates higher pressure in the range, of 130–750 kb. Furthermore, the appearance of shock-hatched kamacites of ALH-77283 resembles that of the Canyon Diablo meteorite shocked to about 600 kb, which is in Fig. 2b of HEYMANN's paper (HEYMANN *et al.*, 1966). Thus the maximum shock pressure of ALH-77283,52 may be within the range of about 600–750 kb.

Second, we discuss the partially recrystallized kamacite. HEYMANN *et al.* (1966) suggested that kamacites begin to recrystallize at the temperature around 500°C (Fig. 6). The partially recrystallized kamacites observed in ALH-77283 may indicate temperature about 500°C.

Third, we discuss the X-ray and electron diffraction photographs of cohenite separated from ALH-77283. LIPSCHUTZ and ANDERS (1964) and LIPSCHUTZ (1967) suggested that it is possible to establish a pressure scale based upon features observed in the diffraction photograph of cohenite grains from the pressure standards of shock loading experiments. According to LIPSCHUTZ (1967), at 0 kb, single crystal diffraction spots are seen, and "white" radiation spots are in the outlet part. At 200 kb, some diffraction spots begin to form arc segments due to preferred orientation, perhaps from two or more spots. "White" radiation now results in streaks instead of spots. At 400 kb, all diffraction spots now form distinct small arc segments. Highest angle lines show a definite blebby feature. The arc segments are clearly different from the powder line because the edges of arc segments are sharp. Because this character is seen in the diffraction photograph of the cohenite of ALH-77283, we can apply the diffraction pattern to LIPSCHUTZ's scale. By comparing the characteristics of the diffraction spots of ALH-77283 (Fig. 5) with the LIPSCHUTZ's scale, we estimate that this cohenite crystal experienced at least a pressure over 200 kb.

The electron diffraction pattern of cohenites of ALH-77283,52, however, varies from one area to another, and one shows the "normal" spots indicating that the small area is not destroyed. The other area that shows the Debye-Scherrer rings is within the order of a few microns. From this observation of cohenites of ALH-77283,52, we think that the shock effect of cohenites is not homogeneous within this range, 1–5 μ.

The electron diffraction pattern of kamacites near the shock-hatched kamacites of ALH-77283,52 also varies from the "normal" diffraction spots to Debye-Scherrer rings within the range of 10–15 μ. This result is similar to that of cohenites.

The X-ray diffraction of cohenite covers an area of about 300–600 μ in diameter, while the electron diffraction covers an area of about 1–5 μ in diameter. The difference in the sizes of diffracting areas implies that the X-ray diffraction pattern represents an average shock feature between the shocked and unshocked areas.

By combining all the results except for the electron diffraction pattern, we can estimate more accurate shock temperature and pressure of the shock event. According to HEYMANN's procedure, the relationships between shock pressure and residual temperature is well known for pure iron, and these data can be applied to kamacite with little error. These relationships are shown in Fig. 9. In this figure, they have assumed an initial temperature of +90°C, which is considered to be the radiation temperature of iron meteorites at 1 A.U. We can plot our data on this figure. By plotting the shock pressure (600–750 kb) estimated from shock-hatched kamacites, it shows the corresponding residual temperature 400–500°C in Fig. 9. By plotting the temperature from the partially recrystallized kamacite, it shows the corresponding shock pressure around 750 kb. By combining these data, we estimate the shock pressure and residual temperature as 600–750 kb and 400–500°C respectively. The estimation of shock pressure from the X-ray diffraction study of cohenite of ALH-77283 (over 200 kb) is within the range of the shock pressure estimated above.

By comparing our data with those of the Canyon Diablo meteorite of BUCHWALD (1975), who divided the Canyon Diablo into seven stages of shock-transformation, we found that the texture of kamacite of ALH-77283 is similar to BUCHWALD's stages II

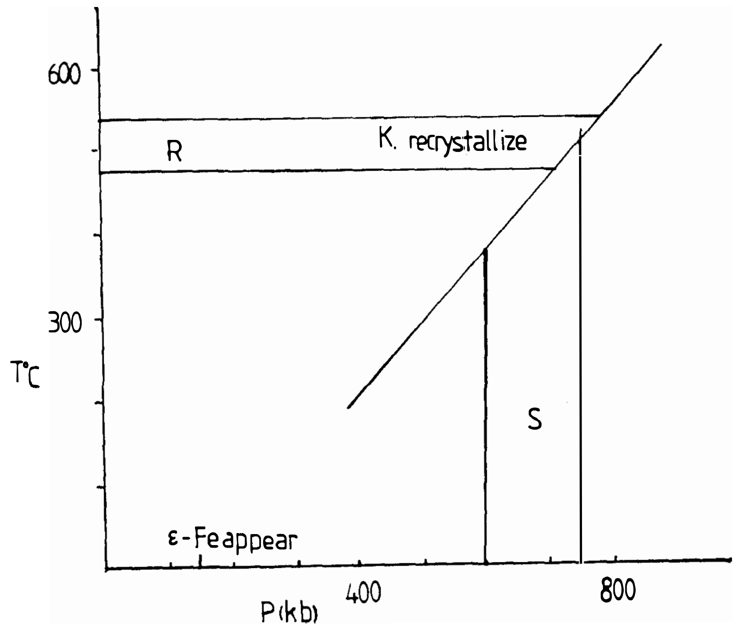

Fig. 9. Residual temperature in shocked iron vs. shock pressures, for an initial temperature of +90°C. Metallographic observable changes in iron meteorites of about 7% Ni are also indicated (after HEYMANN et al., 1966). S: Estimated pressure by shock-hatched kamacites. R: Estimated temperature by recrystallized kamacites.

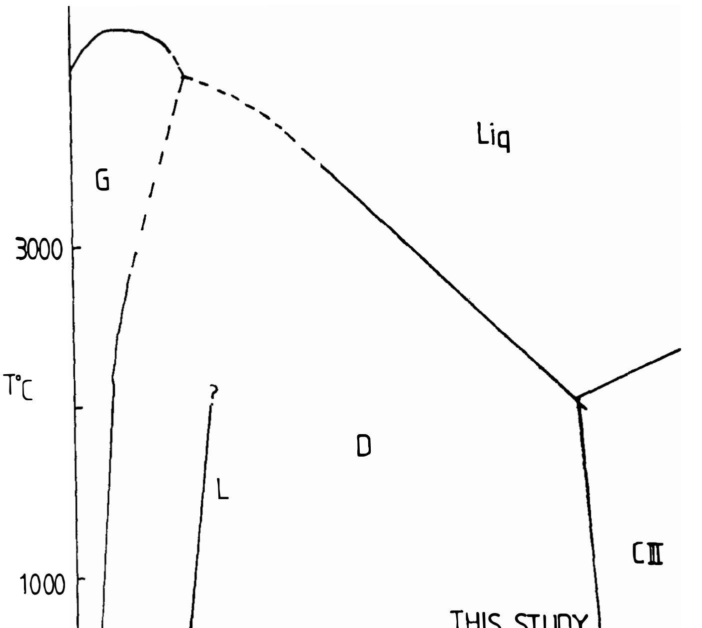

Fig. 10. Phase diagram of carbon (after HURLBUT and KLEIN, 1977). G: graphite, L: lonsdaleite, D: diamond, CIII: carbon III. Estimated pressure and temperature zone is plotted.

Table 2. Seven stages of shock-transformation of Canyon Diablo meteorite (after BUCHWALD, *1975).*

Classification	Kamacite structure*	Estimated residual bulk temperature
"Unshocked" I	Np	$< 400°C$
Shock-hardened II	ε, Nb	$< 400°C$
	N	
	r	
Shock-annealed III	Np, r	$\sim 500°C$
Shock-annealed IV	R, Np	$> 600°C$
Shock-annealed V	α_2	$> 750°C$
Shock-annealed VI	α_2	$> 900°C$
Shock-melted VII	α_2	$>1050°C$

* Np: Neumann bands with $<1\ \mu$ precipitates.
ε: Hatched shock-hardened kamacite.
Nb: Neumann bands with bristles.
N: Normal Neumann bands.
r: Recrystallized along shear zones.
R: Wholly recrystallized.
α_2: Diffusionless transformation from γ to α_2.

and III (Table 2), because the shock textures of ALH-77283 satisfy the description listed for both stages II and III. According to his study, the temperature of shock events of these stages is about 400–500°C.

Thus, this estimation is consistent with the condition of diamond formation (Fig. 10), previously proposed for this meteorite. The argument by CLARKE (private communication, 1986) about the Canyon Diablo diamond is the following. ALHA77283 did pass through our atmosphere as a small body. The presence of a well developped heat-altered zone demonstrates this. In this case, then the heat-altered zone (atmospheric passage) must have come after the event that produced the shock features in the metal and the diamond associations. The important point is that the meteorite brought its shock features with it as it approached our atmosphere. Small size and soft landing allow us to recognize this distinction in the sequence of events. All of this strongly suggests to him that there was a major shock event on the parent body of ALHA77283. Canyon Diablo and ALHA77283 have the same structures and indistinguishable chemistry. There is a good chance that they are from the same parent body. If so, the Canyon Diablo material was probably severely shocked preterrestrially. The arguments presented to date do not preclude Canyon Diablo having brought many or even all of its diamonds in it.

5. Summary

(1) From shock-hatched kamacites and partially recrystallized kamacite, the shock pressure and temperature are estimated to be about 600–750 kb and 400–500°C.

(2) The textures of ALHA77283 indicates that the shock stage of ALH-77283 is between BUCHWALD's stages II and III, which correspond to the temperature 400–500°C.

(3) The X-ray diffraction photograph of ALH-77283 cohenite crystal suggests that the shock pressure is over 200 kb according to LIPSCHUTZ's scale.

(4) The electron diffraction pattern of cohenite of ALH-77283,52 revealed that the shock effect is not homogeneous within the order of a few microns.

(5) The shock pressure and temperature thus estimated is consistent with the diamond stability.

Acknowledgments

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