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SHOCK EFFECTS EXPERIMENTS ON SERPENTINE AND THERMAL METAMORPHIC CONDITIONS IN ANTARCTIC CARBONACEOUS CHONDRITE

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Abstract: The unique Antarctic carbonaceous chondrites, Belgica (B)-7904, Yamato (Y)-86720, Y-82162, Y-793321 are thermally metamorphosed. However, the heat source of the thermal metamorphism is not known. Two strong possibilities are shock-induced heating and heating on the parent body. The explosive impact method was used to check the possibility of heating of phyllosilicates by shock compression. Examining the shocked specimens from the Murchison meteorite and terrestrial lizardite, the following were found: (1) Phyllosilicates in the shocked (>32.1 GPa) specimens changed to nearly amorphous substances; (2) the phyllosilicates in specimens shocked at lower pressures were still crystalline and undamaged; (3) some void-like (bubble) textures were widely observed in the amorphous substances; (4) the other minerals such as pyroxenes and olivines which did not change to glass phases seem to be little affected by shock. These facts do not suggest that the unique Antarctic chondrites experienced significant shock.

1. Introduction

Antarctic carbonaceous chondrites, Belgica (B)-7904, Yamato (Y)-86720 and Yamato (Y)-82162 are unique in their petrographic features (TOMEOKA *et al.*, 1989a, b; ZOLENSKY *et al.*, 1989; MAYEDA and CLAYTON, 1990; IKEDA, 1991, 1992). These three have characteristics of both CI and CM groups or intermediate features between the two: their oxygen isotopic nature is similar to that of CI, but Y-86720 and B-7904 are similar to CM in mineralogy and chemistry. Y-82162 is similar to CI but has many characteristic clasts. Furthermore, these three and Yamato (Y)-793321 carbonaceous chondrites experienced characteristic thermal metamorphism (AKAI, 1984, 1988, 1990) which has not been found from non-Antarctic carbonaceous chondrites except for equilibrated carbonaceous chondrites.

The following characteristics of the thermal metamorphism can be summarized: (1) dehydration and subsequent transformation of serpentine type phyllosilicates to olivine through an intermediate structure; (2) formation of void structures (AKAI, 1992b). The origin of the void structure is not fully clear but will be discussed in another paper.

T-T-T (Time-Temperature-Transformation) diagrams were obtained by heating experiments for estimation of the thermal metamorphism observed in meteorites (AKAI, 1992a). Comparing these experimental results to the observed data on the unusual carbonaceous chondrites, the degree of thermal metamorphism experienced by them was estimated to be in the following order: B-7904 $\geqq$ Y-86720 > Y-82162 > Y-793321. However, the causes of metamorphism (heating) or its equivalent events are not yet clear.

MIYAMOTO (1991) pointed out that the suggested metamorphic temperature for the unique carbonaceous chondrites is theoretically obtainable through internal heating by decay of extinct radionuclides.

On the other hand, heating by radiation from a fixed star (for example, the T-Tauri stage of the sun) may also be possible.

KIMURA and IKEDA (1992) suggested that a shock event (< 45 GPa) may be the most plausible mechanism for the heating of constituent minerals in B-7904. Shock-recovery experiments on phyllosilicates have been carried out (BOSLOUGH *et al.*, 1980; LANGE *et al.*, 1985; TYBURCZY *et al.*, 1986; TYBURCZY, 1991). Other shock experiments have been carried out on quartz by TATTEVIN *et al.* (1990). KIMURA and IKEDA (1992) referred to the results of LANGE *et al.* (1985) in which antigorite shocked up to 45 GPa lacks petrographically observable shock indicators, although a significant amount of H_2O was driven out of the antigorite. These results seem to be consistent with the results of observation of thermally metamorphosed Antarctic carbonaceous chondrite. However, there are no direct observations confirming such changes for shock metamorphosed phyllosilicates by HRTEM yet.

Shock events are believed to have occurred widely in the early solar system and to be closely related to carbonaceous chondritic materials. So, shock recovery experiments could establish systematic changes in various minerals by increasing shock pressures.

Thus, the purposes of this study are: (1) to test the effect of shock-induced heating, (2) to summarize the shock effects in phyllosilicates over the pressure range 12.7 to 57.6 GPa, and (3) to evaluate shock effects in the constituent mineral grains and also in the textures.

2. Shock Experiments

The impact method accelerated by a propellant gun which is reviewed by GOTO and SYONO (1984) has been used for the shock recovery experiments reported here. In this study, specimens from the Murchison meteorite (run No. #304, #316, #320, #321) and lizardite (#302, #303, #314, #315) from Lizard, Cornwall, England were used although the composition of the latter material is not always similar to those in meteorites. Lizardite contains much Mg, on the other hand, serpentine in carbonaceous chondrite is Fe rich in general (BARBER, 1981; Akai, 1988).

The experiments were carried out at the National Institute for Research in Inorganic Materials by one of the authors (T. S.).

The shock wave reflects within specimen of which shock impedance is lower than that of the metal container if the specimen is thin enough relative to the flyer

Table 1. Shock experiment conditions.

Run No.	Impact velocity (km/s)	First pressure* (GPa)	The last equilibrium pressure (GPa)
#302	1.22	13.2	26.3
#303	1.71	19.5	39.6
#304	1.44		32.1
#314	0.86	5.2	10.0
#315	1.31	8.3	16.1
#316	1.06		12.7
#320	1.78		57.6
#321	1.08		23.0

* First pressures can be calculated only when Hugoniot of the specimen is known.

plate. The first shock state is established by the impact velocity and the Hugoniot of the specimen. During multiple shock reflections the pressure increases up to the final equilibrium pressure which is established by the impact velocity and the Hugoniot of the metal container (Table 1).

Specimens were prepared as follows: specimen disks were mounted in stainless steel rings of 6 mm in inner diameter. Both sides of the ring were sandwiched by stainless steel disks. Planar shock waves were transmitted to the specimen through this design. The Hugoniot of serpentine by TYBURCZY (1991) was used to calculate the first shock state of lizardite. Flyers were an Al-alloy stainless steel and tungsten. Pressures were estimated by the impedance match method using the measured impact velocity of the flyer plates.

Table 1 shows the shock conditions.

3. Results and Discussions

Examination of the shocked specimens revealed the following:

The phyllosilicates in shocked specimens #316, and #314 & #315 were still crystalline and not damaged by the shock pressures below 16 GPa (peak pressure), although some heterogeneous pressure effects are present. In TEM images of #316, crystalline serpentine with minor damage was found (Fig. 1). Such results may be due to heterogeneities of pressure transmission into the specimens. The other minerals such as pyroxenes, olivines and so on seem to have been little affected by the relatively weak shock pressures investigated here. The phyllosilicates in shocked specimens of #321 were also crystalline (Fig. 2).

Phyllosilicates in the specimens of #304, #302 and #303 shocked above 26 GPa (peak pressure) were changed to an almost amorphous state, although these changes were inhomogeneous probably because of heterogeniety in shock effects on the serpentine. Figure 3 shows the results for run product #304. Figure 3b is a TEM image of run #304, showing a shocked serpentine grain exhibiting only a few remnant lattice fringes. The phyllosilicates in #320 subjected to the highest shock pressure in the present experiments were changed to an amorphous state with

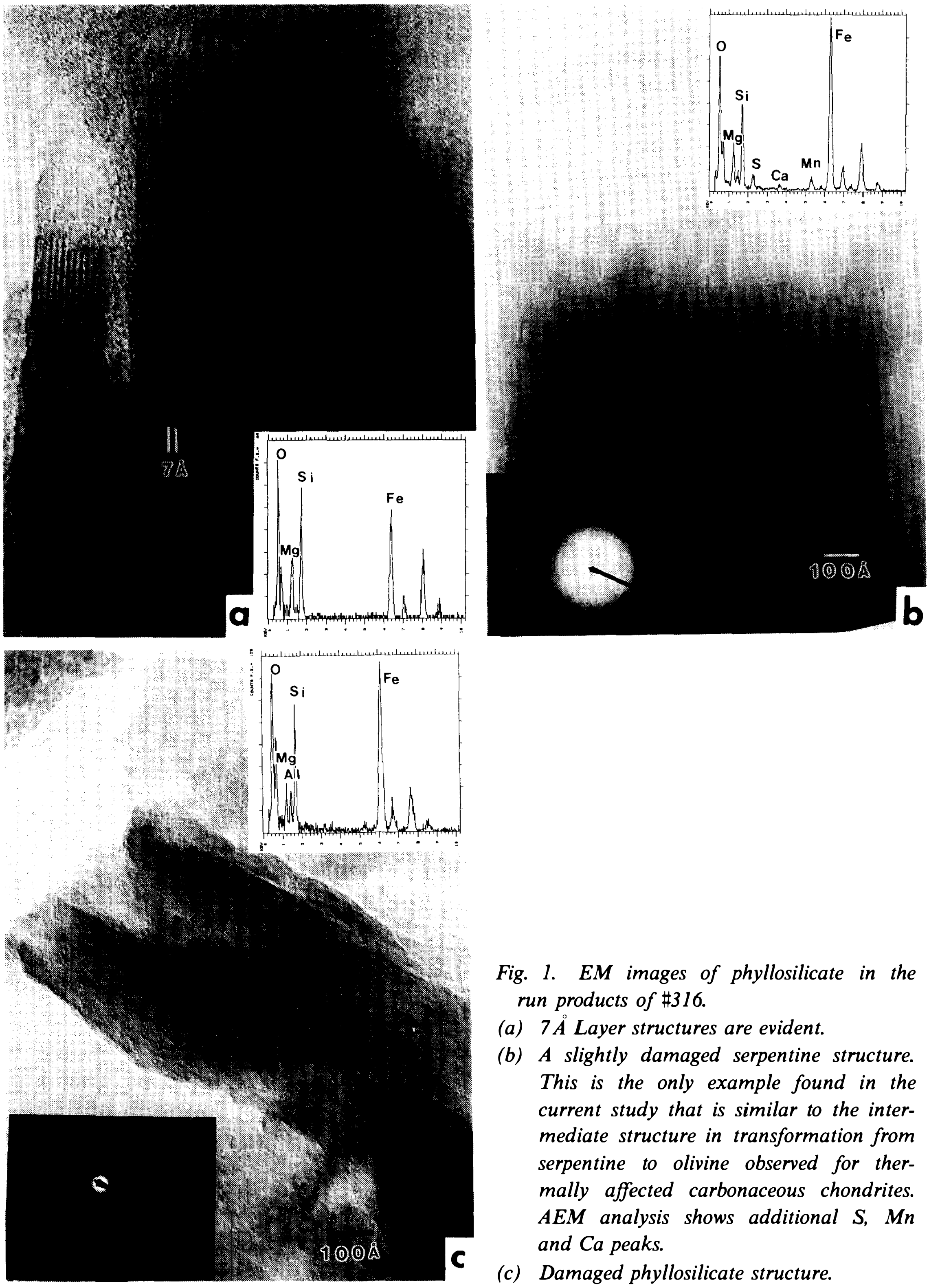


Fig. 1. EM images of phyllosilicate in the run products of #316.

- *(a) 7 Å Layer structures are evident.*
- *(b) A slightly damaged serpentine structure. This is the only example found in the current study that is similar to the intermediate structure in transformation from serpentine to olivine observed for thermally affected carbonaceous chondrites. AEM analysis shows additional S, Mn and Ca peaks.*
- *(c) Damaged phyllosilicate structure.*

occasional presence of void-like (bubble) textures (Fig. 4). No surviving phyllosilicates were found in this run product. However, the other typical textural features resulting from shock, for example, shock lamelae, planar features, fragmentation

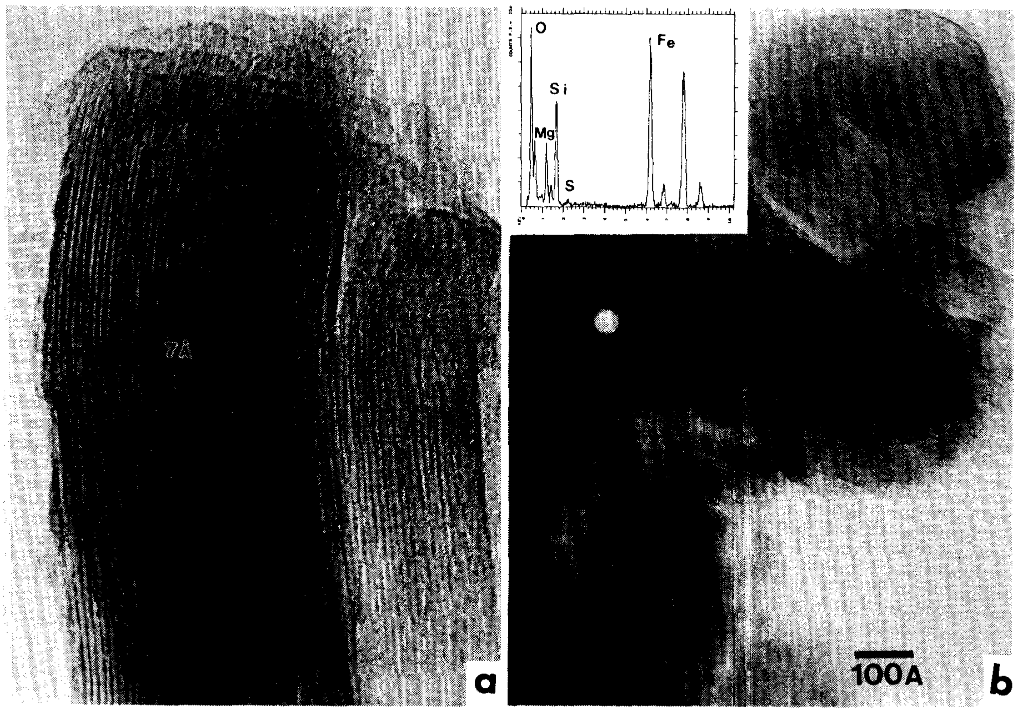


Fig. 2. EM images of the run product of #321.

(a) Layer structure of 7Å phyllosilicates (serpentines).

(b) Nearly amorphous state formed by shock, with only faintly recognizable layer structure.

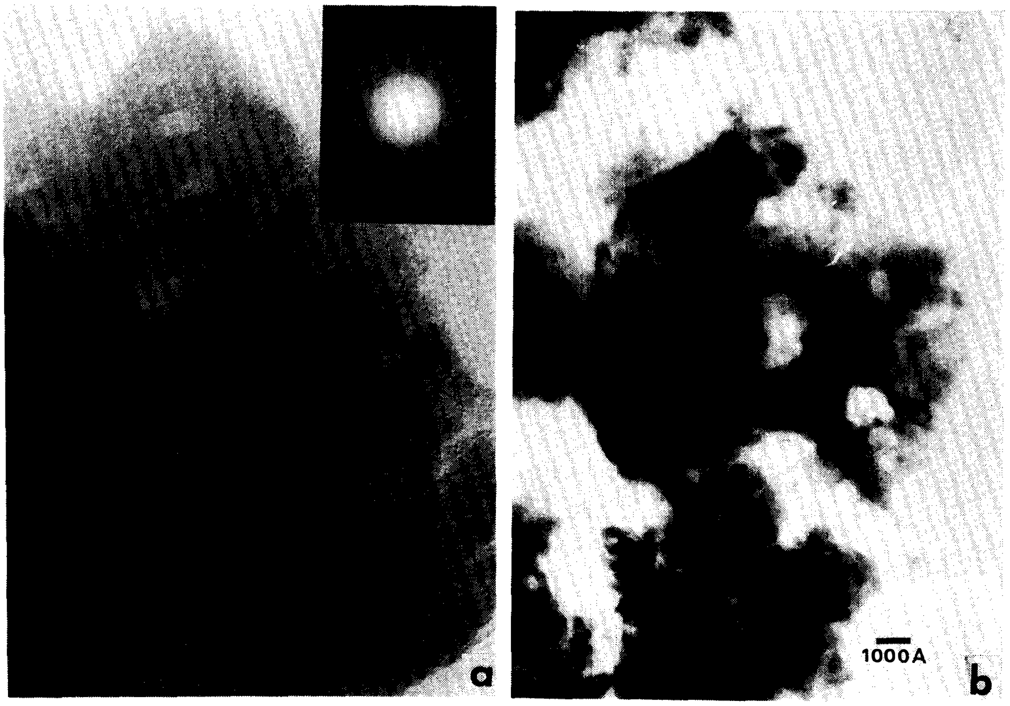


Fig. 3. EM images of nearly amorphous materials transformed from phyllosilicate in the Murchison meteorite (product of run #304).

a, b: Nearly amorphous substances and irregular voids (bubbles) are found.

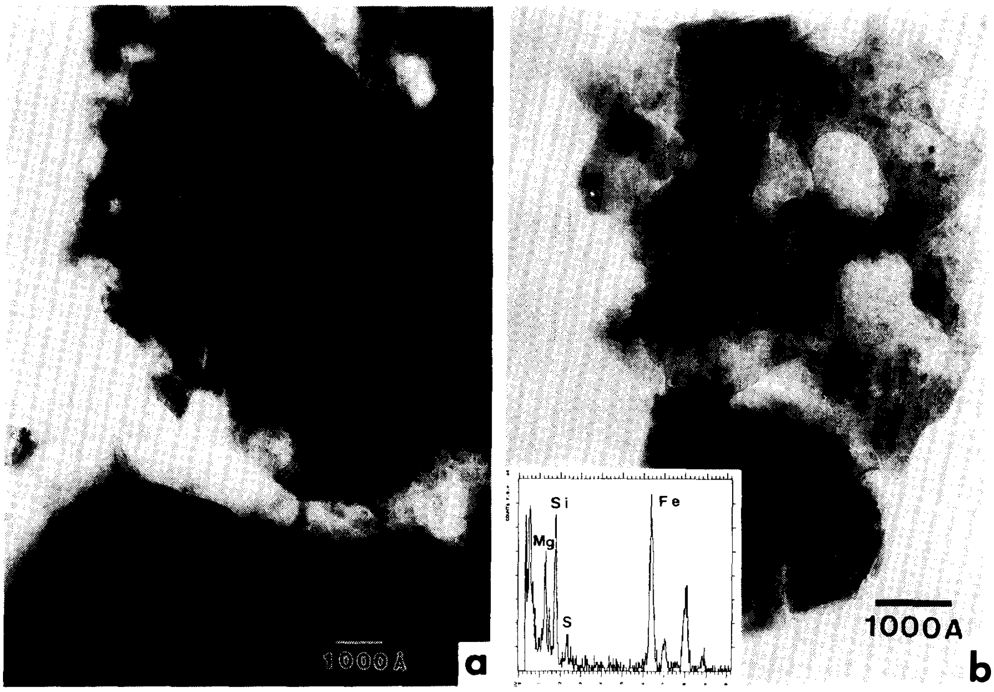
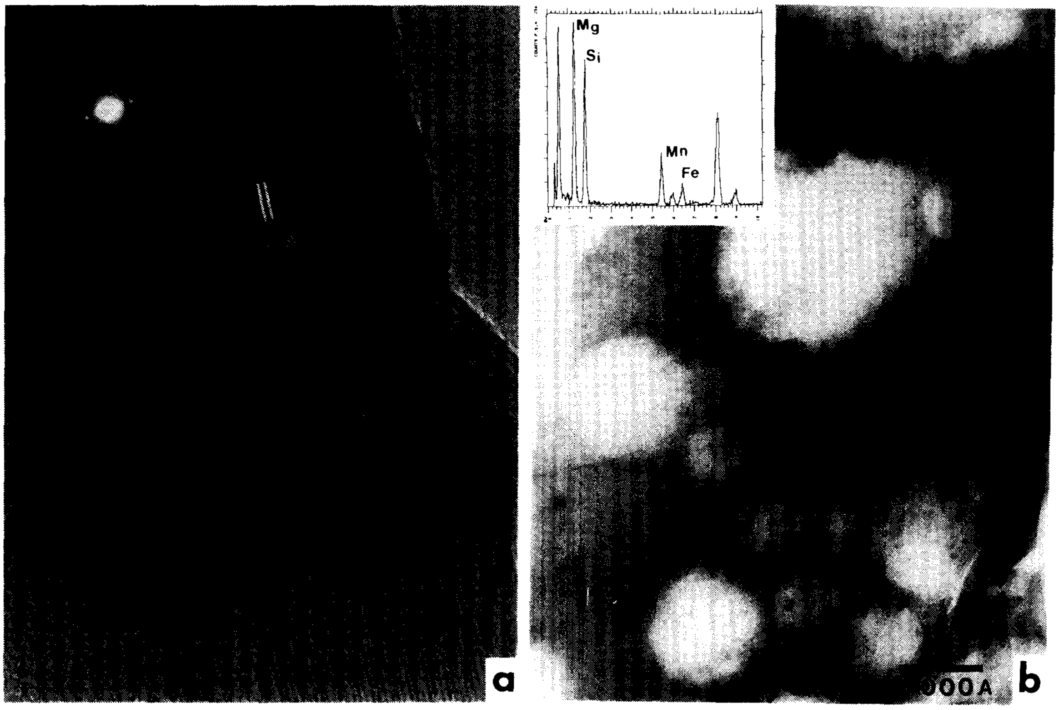


*Fig. 4. EM images of amorphous substances found in the products of run No. #320.
a, b: Glass phases produced by shock. Bubble or void structures are predominant.*



Figs. 5a, b. EM images of shocked terrestrial lizardite (a: #315; b: #303).

and so on, were not evident.

AEM analyses were carried out on phyllosilicates and amorphous substances derived probably from the phyllosilicates. AEM spectra are shown in Figs. 1, 2, 4

Table 2. Results observed in shock experiments.

Run No.	Impact velocity (km/s)	The last equilibrium pressure (GPa)	Observed results	
			Phyllosilicate	Glass
Phyllosilicates in Murchison meteorite				
#316	1.06	12.7	○△	×△
#321	1.08	23.0	○△	△
#304	1.44	32.1	×△	○
#320	1.78	57.6	×	○
Terrestrial lizardite				
#314	0.86	10.0	○	×
#315	1.31	16.1	○	○△
#302	1.22	26.3	○△	○△
#303	1.71	39.6	×	○

○: present, ×: absent, △: identification is not certain.
Glass: amorphous materials.

and 5. Compositions of phyllosilicates in the Murchison meteorite vary to a considerable degree (BARBER, 1981; AKAI, 1988). In general, amorphous substances formed have compositions which are fundamentally similar to those of unshocked serpentine but sometimes with additional small amounts of S, Ca and/or Mn. Tochilinite and other sulfides may be damaged and offer S to amorphous materials although direct evidence for this is not yet confirmed.

The results of this study are summarized in Table 2. Transitional structures in the transformation from serpentine to an olivine structure were not clearly found but the amorphous state was widely observed (Fig. 5) in serpentines shocked in excess of 32 GPa.

It has been revealed by LANGE *et al.* (1985) that shock-recovered antigorite serpentine showed changes in its infrared spectra and in textures, such as partial melting with gas bubbles, and also showed shock-induced water loss. TYBURCZY *et al.* (1986) also studied shock-induced volatile loss from a carbonaceous chondrite in order to interpret the distribution of volatiles within an accreting planet. They examined the Murchison meteorite and showed that devolatilization started at about 11 GPa and was almost completed at about 30 GPa.

However, detailed observations of such changes by TEM have not been carried out. The present study revealed fine structures and fine textures in changes of phyllosilicate by shock effects. The present result that serpentine shocked at above 30 GPa is in a nearly amorphous state is consistent with that of TYBURCZY *et al.* (1986). The formation of the amorphous state from serpentine was suggested in this study although the process is not clear.

4. Summary

In examining the shocked specimens the following results were obtained:

(1) Phyllosilicates shocked at ≧32 GPa were changed to a nearly amorphous

state.

(2) On the other hand, phyllosilicates shocked to pressures <23 GPa were still crystalline and not apparently damaged.

(3) Some void-like (bubble) textures were widely observed in the amorphous, shocked phyllosilicates.

(4) However, the other textural features of shock were not observed. Other minerals, for example pyroxenes and olivines seem to be little affected by shock.

(5) Furthermore, transitional structures intermediate between serpentine and olivine structure were not clearly observed.

(6) Phyllosilicates are very susceptible to pressure, becoming amorphous at pressures $\geqq 32$ GPa in our experiments.

(7) These facts suggest that the unique Antarctic carbonaceous chondrites did not experience significant impact pressures. In particular, amorphous (glass) substances are not observed in the Antarctic carbonaceous chondrites.

Void-like (bubble) structures are observed exclusively in olivine grains in the latter meteorites.

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