MINERALOGICAL STUDY OF MATRIX- AND GROUNDMASS-PHYLLOSILICATES, AND ISOLATED OLIVINES IN YAMATO-791198 AND -793321: WITH SPECIAL REFERENCE TO NEW FINDING OF 14Å CHLORITE IN GROUNDMASS

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Abstract: Zoning pattern of the isolated olivine grains in Antarctic C2 (CM2) chondrite Yamato-791198 (Y-791198) and Y-793321 analyzed by EPMA suggests that similar bimodal zoning pattern modes are present in isolated olivine grains in both CM2 and CO3 chondrites (NAGAHARA and KUSHIRO, Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 66, 1982), which may be due to close relations of isolated olivine grains in both CM2 and CO3 chondrites. However, modal ratios of magnesium-rich olivine to iron-rich olivine are different between CM2's and CO3 (Allan Hills-77307).

Microtextures of matrix minerals in Y-791198 were observed by means of the Electron Microscope (EM) and the High Resolution Electron Microscope (HREM). The same type of phyllosilicates often accumulates in narrow regions (~μm). Some olivine grains show corosion-like irregular outlines suggesting that some fluid phase may be responsible for alteration. Under a petrographic microscope, the groundmass phyllosilicates seem to have been derived by alteration. These textural evidences suggest the alteration range from μm- to mm-scales.

Four types of phyllosilicates (7Å platy, 7Å poorly organized tubular, 7Å poorly crystallized and 17Å mixed layer types) were observed in Y-791198. A 11Å layer mineral (tochilinite; MACKINNON and ZOLENSKY, Nature, **309**, 240, 1984) was also observed. These characteristics are the same as those in Murchison and Y-74662. Therefore, these matrix minerals may be common in most of C2 (CM2) chondrites not showing a thermal effect.

14Å chlorite was observed in the groundmass of chondrules in Y-791198. There are very distinct differences in the phyllosilicate constituent types between the groundmass and the matrix. This difference may be an important clue to understanding the origin of the two types of phyllosilicates in the matrix and the groundmass. Some possible formation processes were considered. It is evident that alteration did happen in the earlier stage of the solar system.

1. Introduction

Carbonaceous chondrites are generally considered to be among the most primitive rock samples in the solar system, and their origin is variously inferred (NAGY *et al.*, 1963; LARIMER, 1967; CAMERON, 1973; BUNCH and CHANG, 1978, 1980; IKEDA, 1983; KOJIMA *et al.*, 1984; WILKENING, 1978). Many problems concerning carbonaceous chondrites remain unsolved; for example, the formation condition of the matrix phyllosilicates and the genetic relationships among C1, C2, C3 and C4 types. Carbonaceous chondrites contain significant quantities of dark, fine-grained matrices. The matrices in C1(CI1) and C2(CM2) are composed of significant amounts of phyllosilicates, lesser amounts of magnetites, carbonates, sulfides and organic polymers. These minerals are extremely fine-grained and are difficult to identify and characterize. Recent High Resolution Electron Microscope (HREM) investigation has facilitated the characterization of these minerals and provided much information concerning the origin of these meteorites. Previous studies of the matrix phyllosilicates by HREM have shown that there are two distinct types of C2 chondrites; one is Murchison type (including Yamato-74662 (Y-74662) and probably Mighei), and the other is Yamato-793321 (Y-793321) type (including Belgica-7904 (B-7904): AKAI, 1984; the details will be given in another paper). The former type contains 7Å platy phyllosilicate, 17Å mixed layer phyllosilicate-sulfides (serpentine+tochilinite structure; MACKINNON and ZOLENSKY, 1984), poorly crystallized 7Å type phyllosilicate (a very thin phyllosilicate with only a few layers), 7Å phyllosilicate with tubular morphology, and characteristic 11Å layer minerals which were speculated to be tochilinites by MACKINNON and ZOLENSKY (1984). The latter type (Y-793321 and B-7904) contains platy 9–13Å minerals with many characteristic defects which were identified to be intermediate phases in transformation from serpentine to olivine (AKAI, 1984; the details will be given in another paper). The first objective of this study is to examine the phyllosilicate types in the Y-791198 matrix and compare them with the previous results. The results of the HREM study on the matrix phases in Y-793321 have been reported at the 9th symposium on Antarctic meteorites (AKAI, 1984; and one in preparation). We report all the results on Y-791198 together with the analyses of zoning patterns of isolated olivine grains in Y-793321. We consider that the analyses of zoning patterns in isolated olivine grains may become one of the potential methods to clarify the genetic interrelation between C2 and C3 types. This examination of zoning pattern analyses is the second objective. The third objective is to characterize the phyllosilicates that occur in the groundmass of chondrules ("spinach phase": FUCHS *et al.*, 1973). No observation of groundmass phyllosilicates was made by HREM and Analytical Electron Microscope (AEM), although matrix phyllosilicates have been studied in detail by EM, HREM and/or AEM (MACKINNON and BUSECK, 1979; MACKINNON, 1982; AKAI, 1980a, 1982, 1984; BARBER, 1981; TOMEOKA and BUSECK, 1983). The characterization and comparison of the groundmass phyllosilicates and the matrix phyllosilicates may provide a potential clue to understanding the genesis of phyllosilicates in the C2 chondrite itself.

2. Experimental

2.1. Analysis by EPMA

A JXA-5A electron probe microanalyzer, operated at 15 kV and *ca.* 0.02 μA specimen current, was used to examine the chemical composition of matrix, groundmass and isolated olivine grains. The diameter of an electron beam used for the analyses of the matrix and groundmass was $\sim$10 μm, and that used for the analyses of olivine was $\sim$3 μm. Three to five different points were analyzed in each isolated olivine grain.

2.2. Analysis by Analytical Electron Microscope (AEM)

A JEM 200CX TEM, operated at 200 kV and combined with energy dispersive X-ray detector TN-2000 was used for both high-resolution imaging and quantitative chemical analyses. The quantitative analyses were carried out using experimentally determined K-values.

2.3. High Resolution Electron Microscopy (HREM)

Matrix specimens for EM were prepared either by cutting and ion-thinning an epoxy-impregnated petrographic polished thin section, or by crushing a small piece of the specimen and placing it on carbon-coated microgrids. The groundmass phyllosilicates were extracted by ultra thin glass fiber tubes, then were dispersed in distilled water and then were placed on a carbon-coated microgrid. A JEM 200 CX was used, operating at 200 kV.

3. Results

3.1. General description (textural relations) of Y-791198

A general description of Y-791198 is briefly given by KOJIMA *et al.* (1984). This meteorite consists of matrix, chondrules, CAI's, isolated olivines and pyroxenes, opaque minerals, calcites, devitrified glass fragments, etc. (Fig. 1). The volume ratio of non-matrix to matrix in this meteorite is similar to those in other C2 chondrites (FUCHS *et al.*, 1973). Chondrules are classified into two types; one is composed of small porphyritic olivine-pyroxene grains, and the other consists of porphyritic euhedral olivines. Green groundmass phyllosilicates ('spinach' phase: FUCHS *et al.*, 1973) are present in or at the rims of the chondrules or mineral grains. Isolated olivine

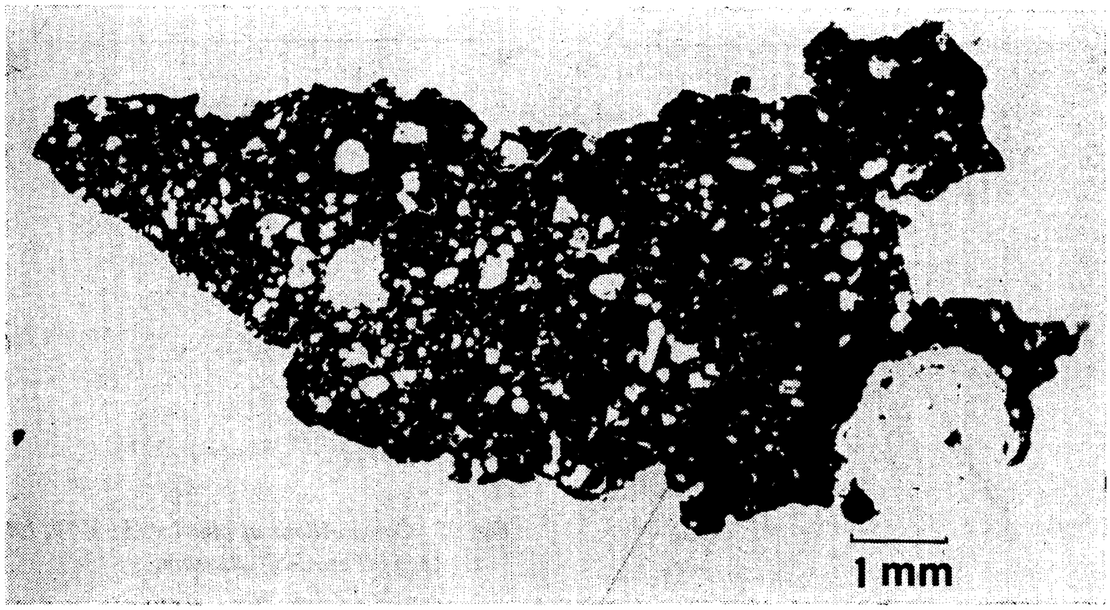
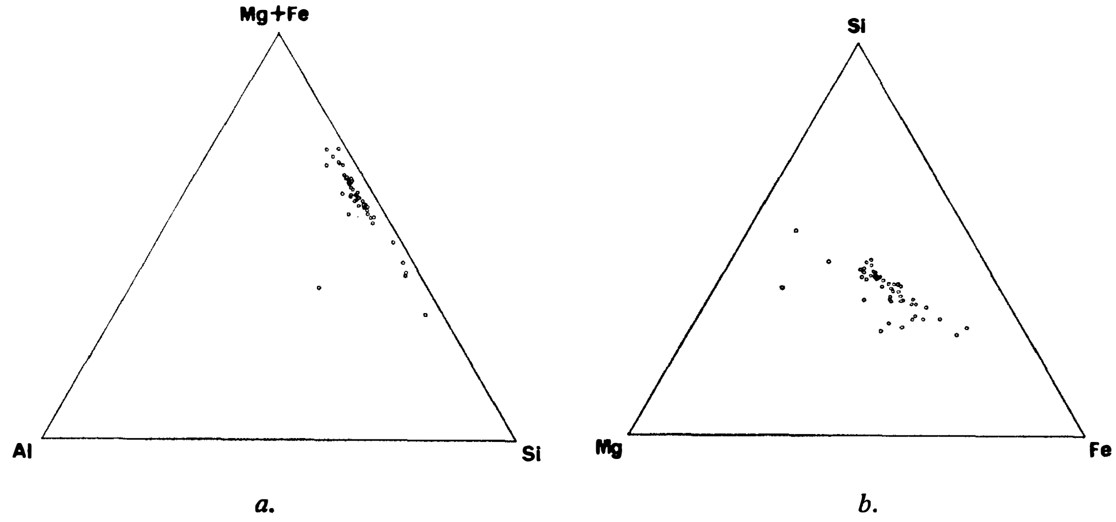


Fig. 1. Photomicrograph of Y-791198 (opened polars). Largest chondrule is about 0.5 mm in size. Isolated olivine grains are homogeneously distributed.

grains have angular shapes ranging from 3 μm to 0.8 mm in diameter and are homogeneously distributed in the matrix. Isolated pyroxene grains were rare. X-ray powder diffraction pattern showed a relatively strong 7Å peak that corresponds to serpentine. Spherical or irregular-shaped opaque grains occur in chondrules, inclusions and the matrix. They are Fe-Ni metal, troilite and/or oxides. Fe-Mg pyroxene occurs in a minor amount and commonly shows polysynthetic twinning. Most Fe-Mg pyroxenes were probably consumed to form phyllosilicate (Kojima *et al.*, 1984). On the contrary, olivine is abundant. This order of susceptibility to alteration is not consistent with the usual order of the weathering on the earth's surface. Contrary to the fact that B-7904 shows slightly preferred orientation in arrangements of isolated mineral grains, no such preferred orientation was found in the polished thin section of Y-791198 (sp. no. Y-791198,74-1) examined in this study.

3.2. Compositions of matrix and groundmass in Y-791198

EPMA analysis of the matrix and groundmass of Y-791198 (Y-791198,19 and ,40)



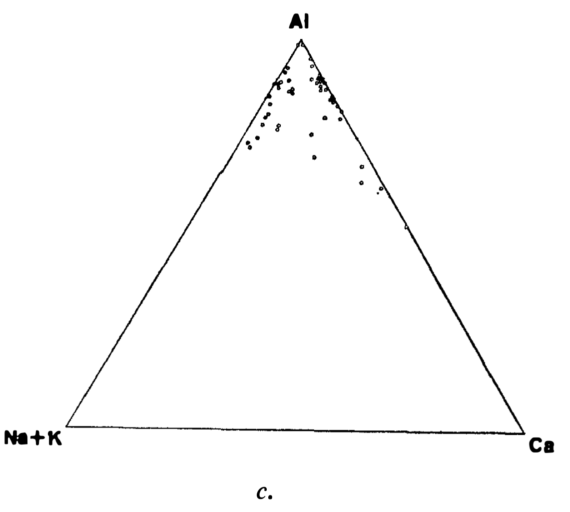


Fig. 2. Compositions of matrices in Y-791198.
a. (Mg+Fe)-Al-Si diagram.
b. Si-Mg-Fe diagram.
c. Al-(Na+K)-Ca diagram.

has been reported by KOJIMA *et al.* (1984). The results from a new thin section (Y-791198,74-1) in this study are essentially similar to their results.

3.2.1. Matrix

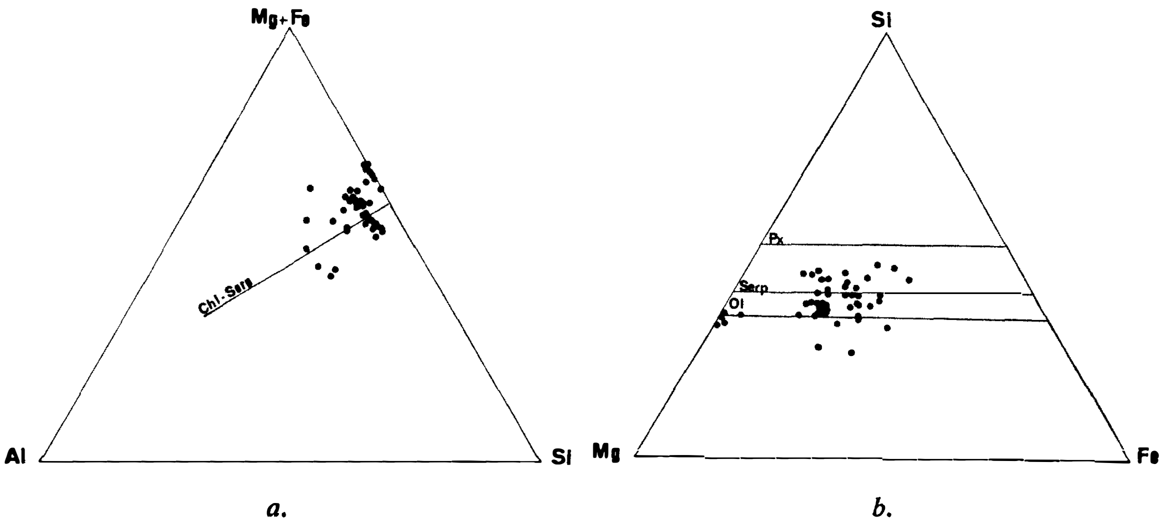
Figure 2 shows the chemical composition of the matrix in Y-791198 (Y-791198,74-1). In the figure, the characteristic features are essentially similar to those by KOJIMA *et al.* (1984).

3.2.2. Groundmass

Chemical compositions of chondrule groundmass are plotted in Al-(Na+K)-Ca diagram, Si-Mg-Fe diagram and (Mg+Fe)-Al-Si diagram (Figs. 3 and 4). In the diagrams, the compositions obtained by EPMA plot in a considerably wide range near the chlorite-serpentine tie line, which is similar to the result by KOJIMA *et al.* (1984). The compositions obtained by AEM (Fig. 4) plot in a relatively narrow region near the chlorite-serpentine tie line. However, the deviation from the tie line may be due to the presence of finely intergrown other minerals.

3.2.3. Isolated olivines in Y-791198 and Y-793321

Isolated olivine grains in Y-791198 and Y-793321 were classified into two types of



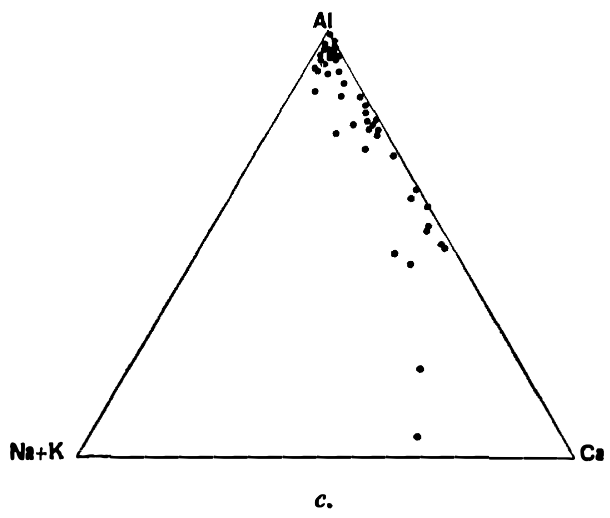
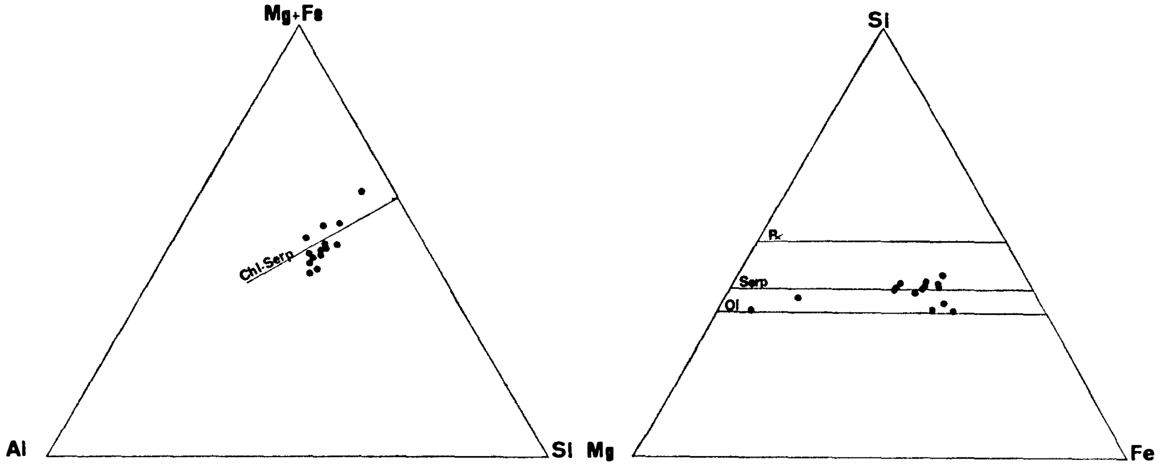
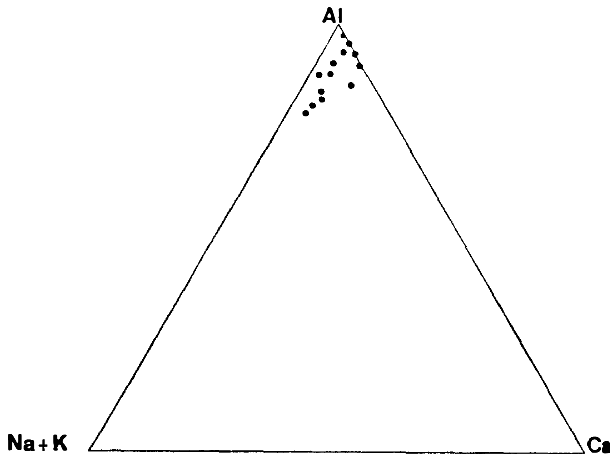


Fig. 3. Compositions of groundmass phyllosilicates in Y-791198 obtained by EPMA.
a. (Mg+Fe)-Al-Si diagram.
b. Si-Mg-Fe diagram.
c. Al-(Na+K)-Ca diagram.



a. b.



c.

Fig. 4. Compositions of groundmass phyllosilicates in Y-791198 obtained by AEM analysis. Compare these results with Fig. 3.
a. (Mg+Fe)-Al-Si diagram.
b. Si-Mg-Fe diagram.
c. Al-(Na+K)-Ca diagram.

C2 chondrite, as suggested previously (KERRIDGE and MACDOUGALL, 1976; MCSWEEN 1977; RICHARDSON and MCSWEEN, 1978; OLSEN and GROSSMANN, 1978; DESNOYERS, 1980; NAGAHARA and KUSHIRO, 1982): one type is magnesium-rich and the other is iron-rich. Chemical modes and zoning patterns of the isolated olivine grains in Y-793321 and Y-791198 were analyzed by the method used by NAGAHARA and KUSHIRO (1982) for a C3(CO3) chondrite. The results are shown in Figs. 5a and 5b respectively. Essential features of these diagrams are the same as those of the Allan Hills-77307 C3(CO3) chondrite. The magnesium-rich olivines have a very narrow compositional range and are homogeneous. The iron-rich olivine shows a wide compositional range of zoning as in Figs. 5a and 5b. The modal ratios of the two types of olivines are slightly different; in Y-791198, magnesium-rich olivines are about two times more abundant than iron-rich olivines. In Y-793321, magnesium-rich olivines are slightly richer than iron-rich olivines.

3.3. EM, HREM and AEM observation

Both chemical and structural data on the same mineral grains have been collected

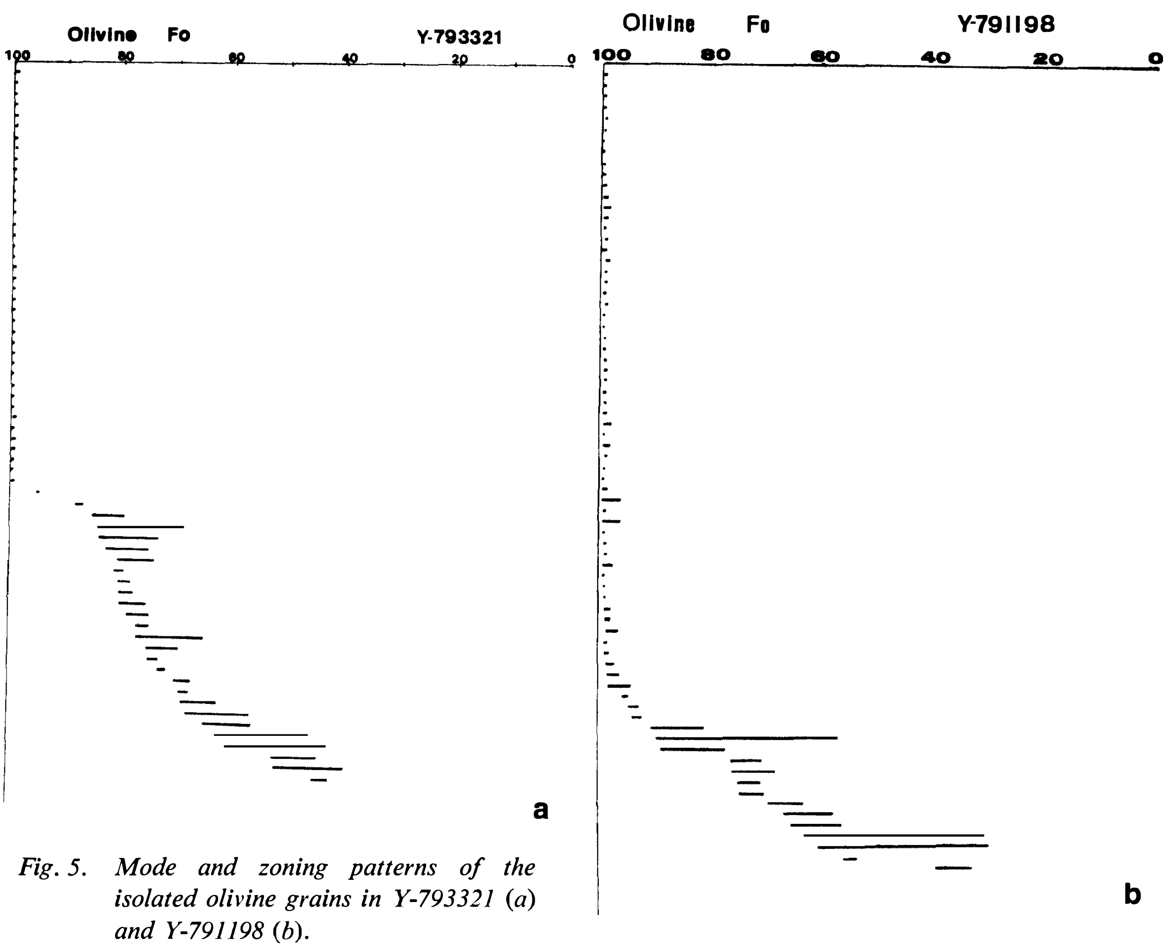


Fig. 5. Mode and zoning patterns of the isolated olivine grains in Y-793321 (a) and Y-791198 (b).

as much as possible. However, it was difficult to obtain chemical information when the small minerals were embeded in or are very closely associated with other materials (especially some amorphous substances).

3.3.1. Matrix texture

Figures 6a and 6b show electron micrograph of matrix of Y-791198. In general, the matrix is heterogeneous and is composed of various phyllosilicates and lessor amounts of Fe-Mg pyroxene, Fe-Ni metals, calcite, troilite, pentlandite, etc. A tendency of accumulation of the same type of grains in small regions was observed (as a kind of domain); for example, platy phyllosilicates, tubular phyllosilicates or Fe-sulfides are often respectively aggregated in small regions in compact aggregates (Figs. 6a and 6b). These features of the heterogeneities may become one of the clues in consideration of the genesis of the phyllosilicates and of the carbonaceous chondrite itself; for example, one of the possible interpretations is that the phyllosilicates were altered from parent materials with such 'domain' size. Irregular outlines and cracks of olivine grains which are very similar to those in minerals found in terrestrial hydrothermal alteration were found to be a characteristic feature of these chondrites (Fig. 7). This indicates alteration by some fluid phase. The texture suggests that phyllosilicates might have been formed by alteration of pre-existing silicate grains as suggested by numerous earlier studies (*e.g.*, BUNCH and CHANG, 1978, 1980).

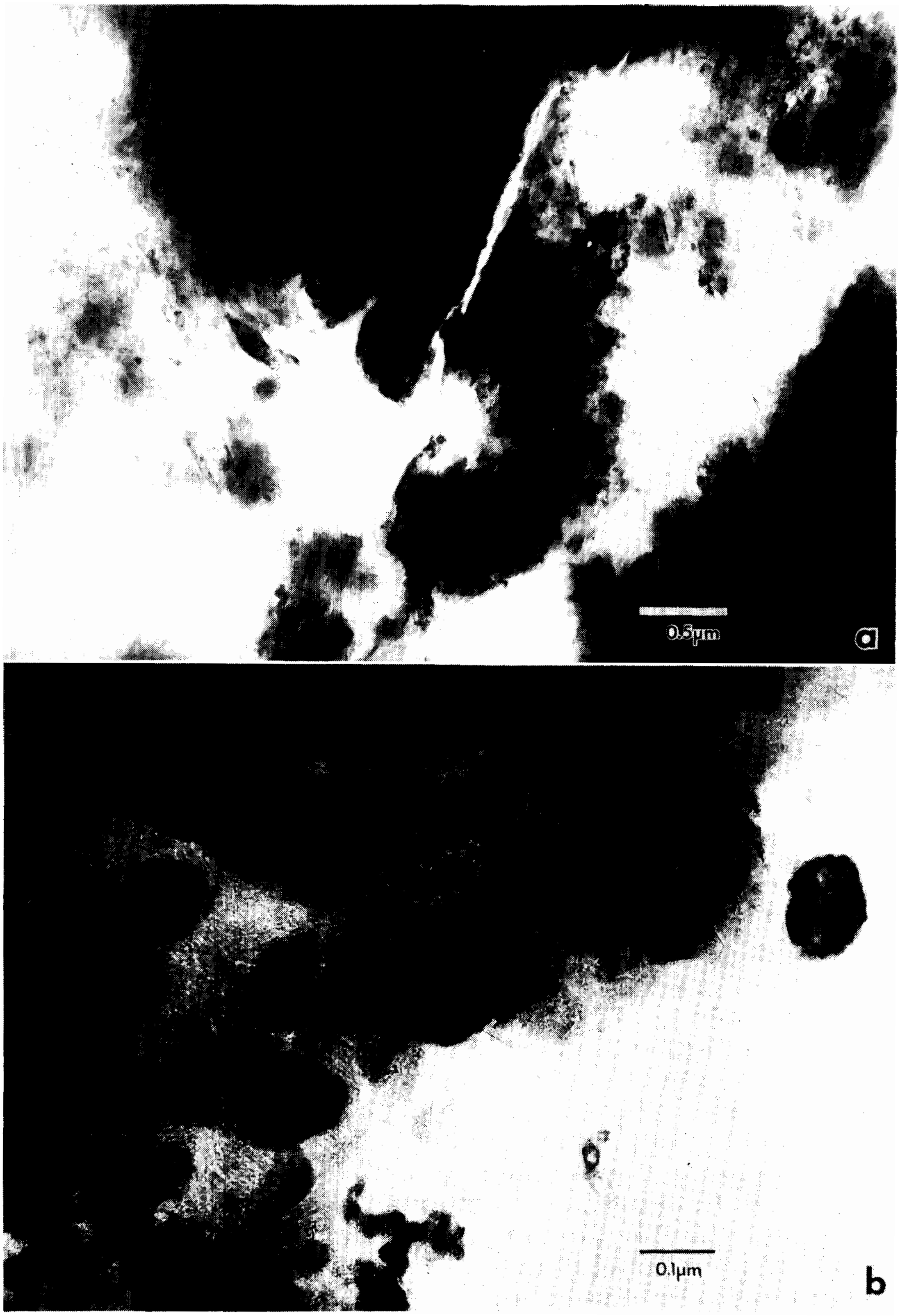


Fig. 6. Electron micrograph indicating matrix textures in Y-791198.
a. In this region, phyllosilicates are aggregated.
b. In the figure, FeS grains are aggregated.

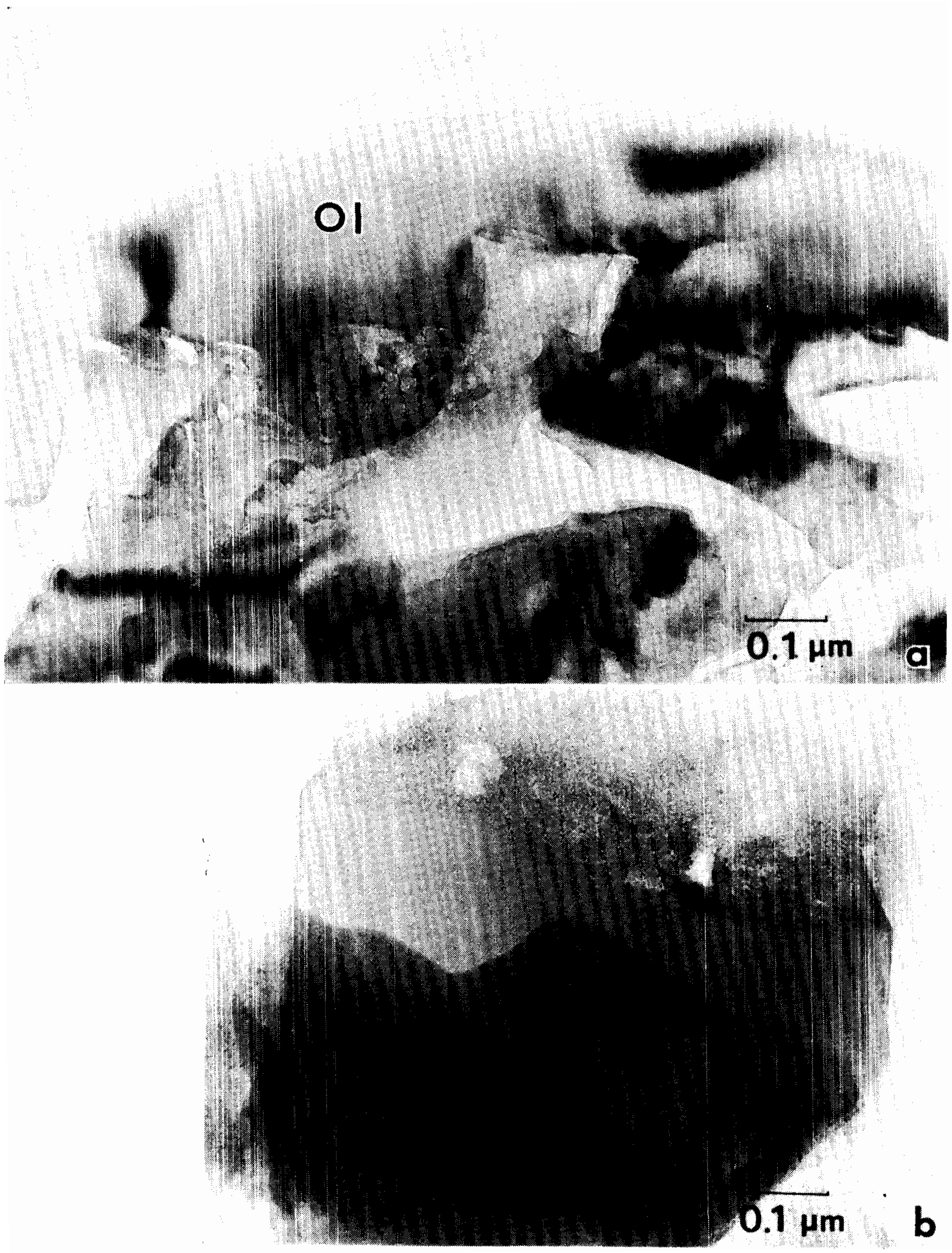


Fig. 7. Electron micrograph indicating matrix mineral grains (a: forsterites) whose shapes appear as if they were corroded by some fluid phase (Y-791198).

3.3.2. Phyllosilicate types

Phyllosilicate types in the matrix were closely examined by HREM. Phyllosilicates in the Y-791198 matrix can be divided into the following four types based on

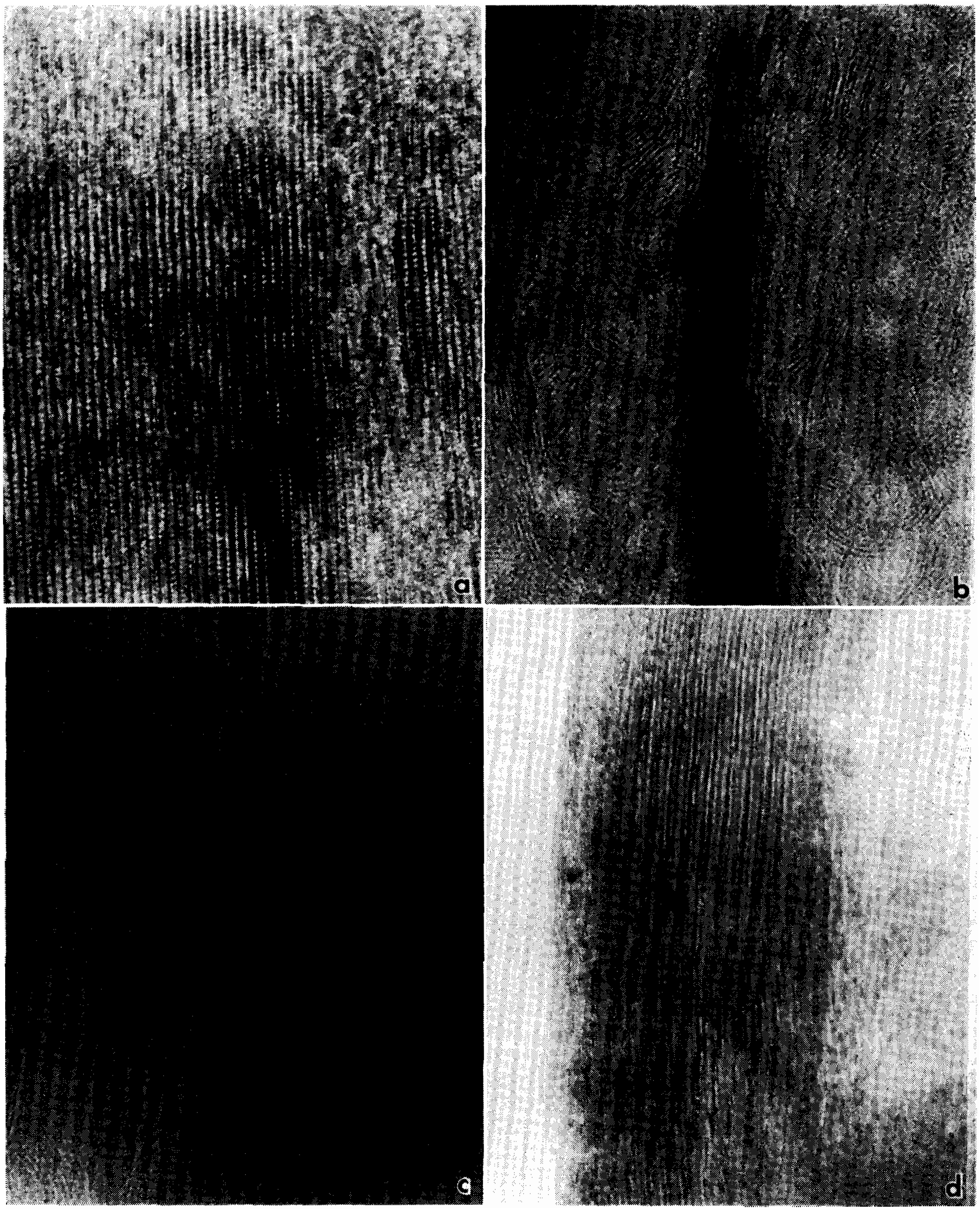


Fig. 8. Electron micrographs of matrix phyllosilicate types in Y-791198.

a. 7Å thick platy phyllosilicate.

b. A section of poorly crystallized tubular 7Å phyllosilicate.

c. Poorly crystallized 7Å phyllosilicates which are composed of only a few lattice fringes of silicate layers.

d. 17Å mixed layer minerals composed of 7Å serpentine layer and other 10Å layer (tochilinite; MACKINNON and ZOLENSKY, 1984).

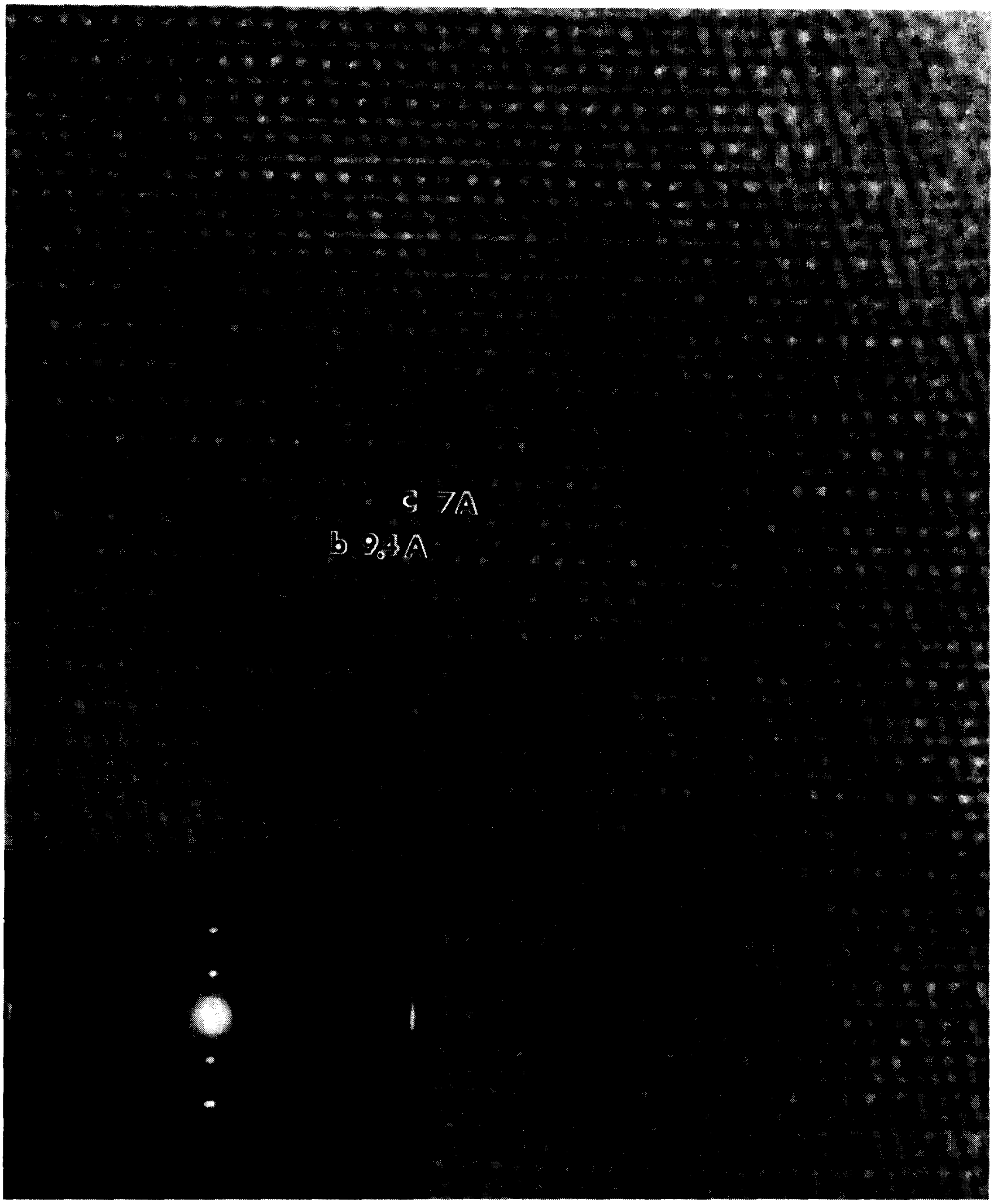


Fig. 9. High resolution electron micrograph of stacking disorder in 7Å thick platy phyllosilicate (Y-791198).

structure and morphology observed by HREM. 1) A 7Å platy phyllosilicate (Fig. 8a). It shows a characteristic stacking disorder (Fig. 9). Such stacking disorder has also been observed in Murchison and Y-74662 (AKAI, 1980a, 1982). The platy phyllosilicates are usually angular. The Fe/(Mg+Fe) ratio of the 7Å platy phyllosilicate varies in a range between 0.5 and 0.8. The high Fe/(Mg+Fe) ratio of this 7Å type phyllosilicate and a small content of Al make it resemble lizardite serpentine.

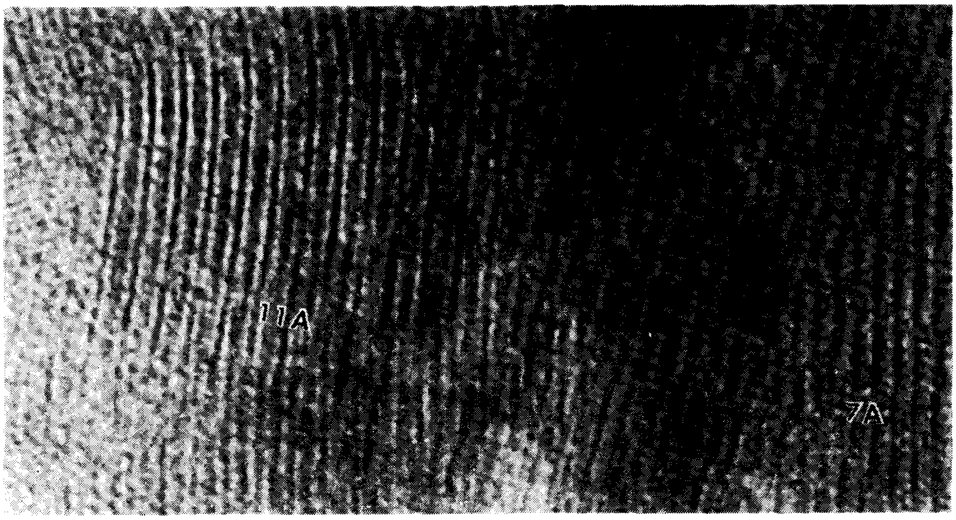


Fig. 10. Electron micrograph of 11Å layer mineral in Y-791198 which were recently supposed to be tochilinite (MACKINNON and ZOLENSKY, 1984). It is grown in parallel intergrowth with 7Å platy phyllosilicate.

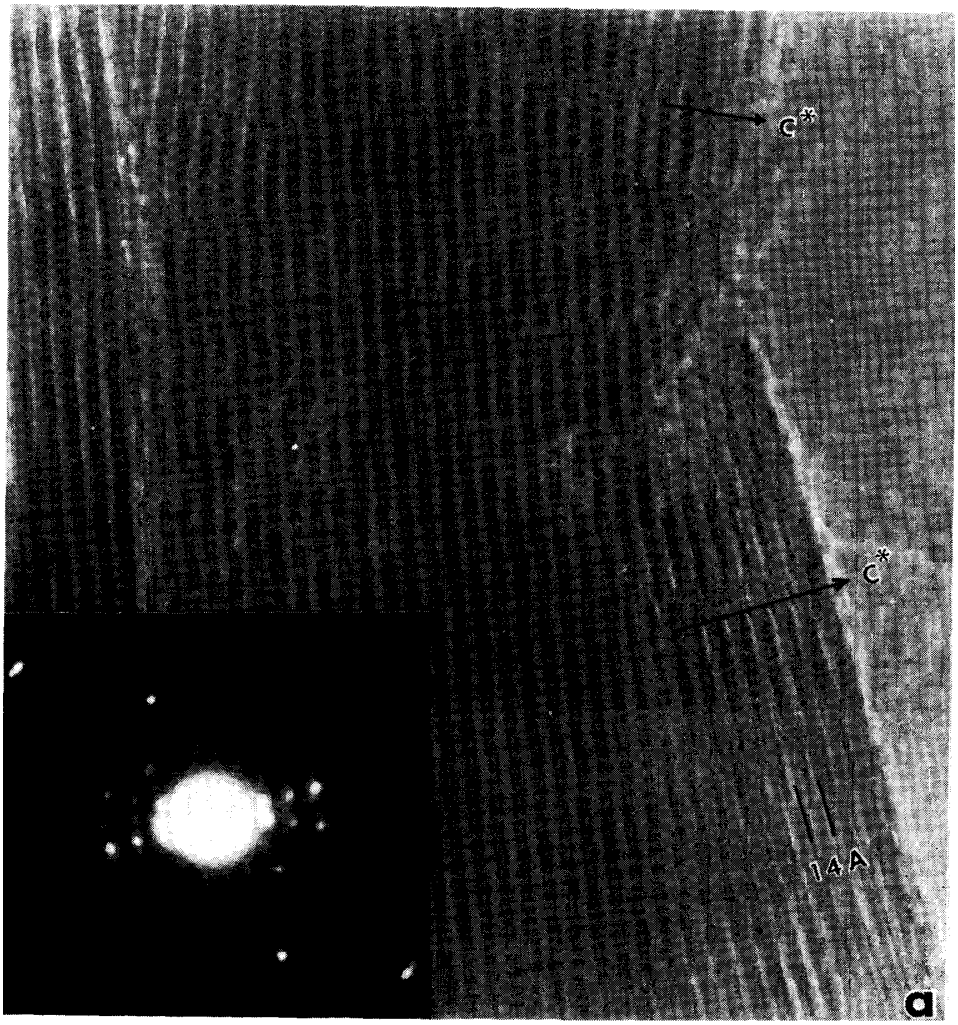
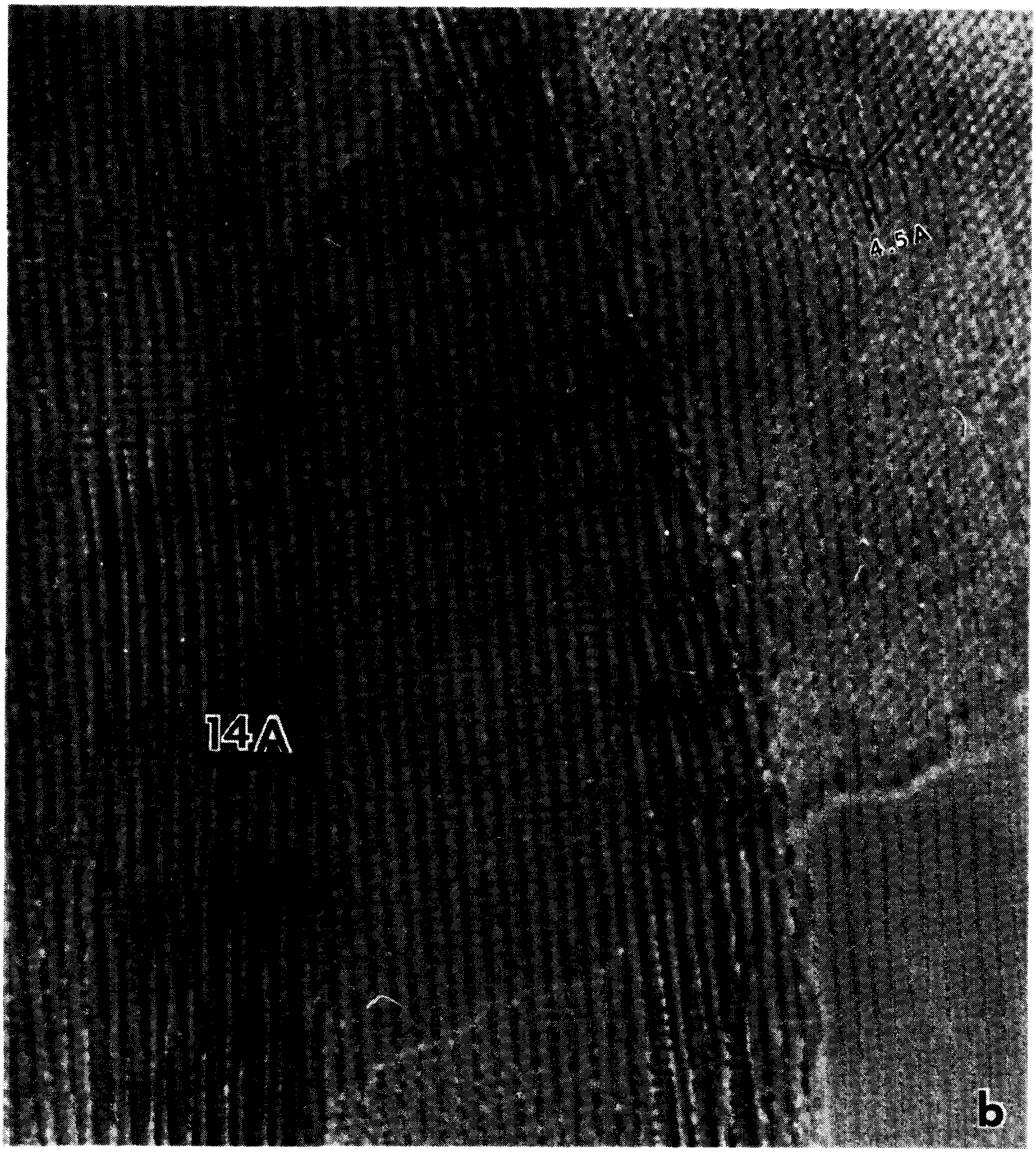


Fig. 11a.



Figs. 11a, b. High resolution electron micrographs of groundmass phyllosilicates (Y-791198). 14Å chlorite was observed for the first time in carbonaceous chondrite.

2) 7Å poorly crystallized tubular phyllosilicates. These may correspond to poorly crystalline chrysotile (Fig. 8b). These phyllosilicates are usually aggregated in small μm-scale domain-like regions. 3) Poorly crystallized 7Å layer structures (Fig. 8c). They are composed of only a few lattice layers and are commonly associated with the type 2) phyllosilicates. 4) 17Å platy mixed layer mineral which was recently proposed to be coherently interstratified serpentine and tochilinite by MACKINNON and ZOLENSKY (1984) (Fig. 8d). 5) 11Å platy minerals (tochilinite). This mineral has been suggested to be tochilinite (MACKINNON and ZOLENSKY, 1984). It often occurs in parallel intergrowth with the 7Å platy phyllosilicate and is therefore contained in this section

*Table 1. Results of AEM analysis of 14Å chlorites in groundmass represented by atomic ratio.**

	Phyllosilicate in Fig. 11a		Phyllosilicate in Fig. 11b	
Si	6.135	8	5.985	8
Al	1.865		2.015	
Al	2.475	11.69	2.122	11.80
Ti	0		0.232	
Fe**	5.093		6.076	
Mn	0		0.285	
Mg	3.846		2.680	
Ca	0.277		0.220	
Na	0		0	
K	0		0.189	
Fe/(Mg+Fe)	0.569		0.693	

* On the basis of $O_{20}(OH)_8$. ** Fe^{2+}.

(Fig. 10). These features (1 ~ 5) are similar to those found in Murchison and Y-74662 (AKAI, 1980a, 1982).

3.3.3. Groundmass phyllosilicates

We observed phyllosilicates in the groundmass of chondrules and in large isolated olivines. The results of the HREM works are given in Figs. 11a and 11b which show the HREM images of a phyllosilicate having 14Å interlayer spacing. These underfocussed images (especially Fig. 11b) indicate that the 14Å period is composed of a narrow dark lattice fringe and a relatively wide dark lattice fringe which may correspond to an interlayer sheet and a talc layer, respectively (*cf.* AKAI, 1980b; SPINNLER *et al.*, 1984). The AEM results are shown in Table 1. These phyllosilicates are thought to be a 14Å chlorite mostly with Fe/(Mg+Fe) ratio ≒0.4–0.7 and ^{IV}Al ≒ 1.8–3.0 on the basis of $O_{20}(OH)_8$. Although the previous EPMA analysis showed that these phyllosilicates may be (7Å septe- or 14Å?) chlorite (KOJIMA *et al.*, 1984, etc.), this has not been confirmed for a single crystal by HREM. In the present examination, the presence of the 14Å phyllosillicate, chlorite was directly confirmed. Paragenetic existence of 7Å platy phyllosillicates (probably serpentine) was sometimes found.

4. Discussions and Summary

Characteristic features in the textural relations (heterogeneities in the matrix texture) have been described. Heterogeneities and homogeneities at several size levels (cm ~ mm level, μm level) can be distinguished. That is, chondrules and isolated olivines are homogeneously distributed throughout these meteorites. Furthermore, the matrix seems to be homogeneous in both texture and chemistry under a petrographic microscope. However, at the μm size level, the tendency of accumulation of phyllosilicates of the same type in narrow regions was often recognized. Such heterogeneities at the μm size level may correspond either to parent materials of the similar size for alteration or to some accretion unit of such size. More examinations are necessary to clarify these problems.

Irregular outlines of olivine grains were sometimes found, which suggest alteration by some fluid phase. Textural evidence suggests alteration range from μm- to mm-scales. The composition of the material (phyllosilicates and/or amorphous substances) just adjacent to olivine grains is very iron-rich in general and is not dependent on the olivine composition. That is, even adjacent to iron-free forsterite, iron-rich phyllosilicates or almost amorphous materials are found.

Zoning pattern analysis of the isolated olivine grains suggests that similar bimodal zoning pattern modes in isolated olivine grains, both in CM2 and CO3, may be due to genetic relationships between isolated olivine grains in both CM2 and CO3 chondrites. This may also suggest the closeness of CM2 and CO3 chondrites themselves. That is, both CM2 and CO3 chondrites may have been formed from two different original materials; magnesium-rich high temperature precursor materials and relatively low temperature iron-rich precursor materials according to the scenario of NAGAHARA and KUSHIRO (1982). However, the modal ratio of the magnesium-rich type olivine grains to iron-rich type ones is different between those of CM2's (especially on Y-791198) and CO3 (ALH-77307). The precise meaning of this is not yet known but it may be correlated to the degree of alteration, or some other causes; for example, iron-rich type olivine being more easily altered. Such event may have occurred, but further examinations are necessary.

Examining the phyllosilicates in Y-791198 matrix, four types of them (7Å platy phyllosilicate, 7Å poorly crystallized tubular phyllosilicate, 7Å poorly crystallized phyllosilicate, 17Å mixed layer type) were observed. A 11Å layer mineral (tochilinite?) was also observed. All features of phyllosilicate types lead us to conclude that characteristics of Y-791198 are the same as those in Murchison, Y-74662, probably Mighei and so on, and they are different from Y-793321 and B-7904. This means that these constituents of the matrix phases may be a very common feature for most C2(CM2) chondrites not showing thermal effects. The AEM analysis of the 7Å phyllosilicate showed a relatively wide range of composition (especially in Fe/(Mg+Fe) ratio). More examinations may be necessary for other C2 chondrites, and then C1 chondrite to elucidate the genetic relationships of carbonaceous chondrites.

Groundmass phyllosilicates were confirmed for the first time by HREM and AEM to be mostly 14Å chlorite with $Fe/(Mg+Fe) \fallingdotseq 0.4$–$0.7$ and $^{IV}Al \fallingdotseq 1.8$–$3.0$ (on the basis of $O_{20}(OH)_8$), although the number of analysis is not large. The 14Å phyllosilicates have not been found as matrix phyllosilicates. In the groundmass phyllosilicates, sometimes 7Å serpentine structure is also associated, especially in phyllosilicates derived from isolated olivines. However, there are very distinct differences in the type of phyllosilicate constituents. These differences may be a very important clue for estimating the origin of the two types of phyllosilicates in matrix and groundmass. One probable interpretation is that these different structure types of phyllosilicate may be due to differences of the parent materials and/or alteration stages as suggested by KOJIMA *et al.* (1984). Another interpretation may be that they were formed in entirely different places, times and/or conditions, and accreted later. Was the place where the alteration occurred either on a parent body, in the early solar nebula or in other places such as satellites of Mars, asteroids, interplanetary dust, comets or rings of Uranus (WILKENING, 1978)? Many speculations are still contained in these interpretations and it may be the very necessary challenge to bring back and examine the materials in question from asteroids, interplanetary dusts, comets and so on, for the next decades. However, the only evident point is that alteration did happen in the earliest age of the history of the solar system, in contrast to the 'recent' alteration on our aqua-planet, the earth.

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