

MINERALOGY OF FIVE NEW ANTARCTIC UREILITES,
LEW86216, LEW85328, Y-791839, Y-75154, Y-8448, AND
THE ORIGIN OF THEIR CHEMICAL VARIATIONS
OF PYROXENE

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Abstract: Mineralogical studies of mafic silicates in heavily shocked ureilites, LEW86216, Y-75154, Y-791839, and moderately shocked ureilite LEW85328 were performed to reveal the chemical variations and textures produced by shock events on the ureilite parent body. Y-8448 is one of common ureilites, but such ureilites are found in relatively small numbers in Antarctica. Olivines in Y-75154 and LEW86216 show granoblastic textures and the carbonaceous veins are disrupted. Their pyroxenes show chemical variations toward enstatite. They are among the most heavily shocked ureilites. Grain rims of Y-791839 and LEW85328 show chemical variations due to shock. The chemical trends of all these heavily shocked ureilites cover the entire range of known individual ureilites. Shock effects of these ureilites are interpreted to have been produced during the break-up of their parent body. Their chemical variations may be applied to study of the chemical differentiation by the planetesimal-scale collision in the earliest stage of ureilite formation.

1. Introduction

Ureilites are a unique type of achondrite composed predominantly of coarse-grained olivine, pyroxene and carbonaceous matrix. High noble gas contents (GÖBEL *et al.*, 1978) and oxygen isotope anomaly (CLAYTON and MAYEDA, 1988) indicate association with carbonaceous chondrites. Discoveries of more than 22 ureilites from Antarctica had advanced the studies on ureilite genesis (GOODRICH *et al.*, 1987; TAKEDA *et al.*, 1988). Magnesian ureilites (TAKEDA, 1989) with the highest oxygen isotope anomaly have been found only in Antarctica (CLAYTON and MAYEDA, 1988). In this paper, we studied five new Antarctic ureilites, most of which show shock melting or heavily shocked features. Mineralogical studies of these ureilites will contribute to a better understanding of the chemical variations due to shock. The results are interpreted on the basis of a recently proposed ureilite genesis model (TAKEDA *et al.*, 1988; TAKEDA, 1987, 1989).

Yamato(Y)-75154 and LEW86216 are extraordinarily shocked ureilites, and their olivines are converted into granoblastic aggregates of fine-grained crystals. Y-791839 was reported to show chemical variations of pigeonites due to shock effect (YANAI and KOJIMA, 1987). Y-8448 is less heavily shocked, but a preliminary description (YANAI and KOJIMA, 1987) shows variations of chemical compositions of olivine and pyroxene.

Some areas of grain boundaries of LEW85328 show a macroscopically disturbed texture which is possibly related to a shock event. LEW85328 contains pigeonite with $Wo_{9.9}$ (TAKEDA *et al.*, 1988). This Wo content is the one of the highest values of pigeonites among known common ureilites (TAKEDA *et al.*, 1988).

Among the recently proposed ureilite formation models, impacts on the parent body (RUBIN, 1988; WARREN and KALLEMEYN, 1989) or planetesimal-scale collision (TAKEDA, 1989) are favored to preserve oxygen isotope anomaly. Chemical variations recorded in the above Antarctic ureilites will be attributed to the impacts at the last stage, but such examples can be used to gain information on the early melting by the planetesimal-scale collision.

Chemical constraints for the cumulate model have been explained by GOODRICH *et al.* (1987). This model proposed early planetary-scale differentiation to remove plagioclase components enriched in Eu. However, such large scale melting is not favored to preserve oxygen isotope anomaly reported by CLAYTON and MAYEDA (1988). Localized heat sources with short duration such as impact processes are preferable in order to preserve oxygen isotope anomaly. Some chemical aspects of the cumulate model may still be applicable to the collision model, since chemical processes during crystal growth of mafic silicates involved in the collision model are important to the genesis of ureilites. In this paper, we present a revised model of ureilite genesis to remove "plagiophile" elements by the planetesimal-scale collision (TAKEDA, 1989).

2. Samples and Experimental Procedures

The polished thin sections (PTS) of ureilites (LEW86216, 5, Y-75154, 51-1, Y-791839, 52-2, LEW85328, 25, Y-8448, 61-2) were provided by National Institute of Polar Research (NIPR) and Meteorite Working Group. They have been studied by an optical microscope, electron probe microanalyzer (JEOL 733 Superprobe at Ocean Research Institute, and JEOL 733 mkII electron probe at Geological Institute, University of Tokyo), and scanning electron microscope with EDS detectors (JEOL 840A and 820) and two-dimensional chemical map analysis (CMA) utilities of Kevex Super 8000 to correlate shock textures and variations of chemical compositions of olivines, pyroxenes and interstitial rim materials in these new ureilites.

A pigeonite crystal selected from LEW85328, 20 was mounted on a glass fiber and examined by the single crystal X-ray diffraction method by employing a precession camera, and the $h0l$ and $0kl$ nets were photographed by Zr-filtered Mo $K\alpha$ radiation to detect exsolved phases or inclusions.

Two samples stored at NIPR, Y-75154 and Y-791839 have not been allocated because they are less than 10 g. Their thin sections were investigated with JEOL 733 electron probe at NIPR by one of the authors (H.T.).

3. Results

3.1. LEW86216, 5

LEW86216, 5 is very small (about 2 mm²) and a polished thin section (PTS) may not be representative. It is heavily shocked and the olivines being converted into a

mosaic of tiny grains (aver. 0.05 mm, Fig. 1a). Pyroxene crystals in LEW86216, 5 are very small (typically about 0.1 mm in diameter), heavily shocked, and subangular in shape. Most of carbon and metal-sulfide veins are disrupted and we cannot recognize the original grain boundaries, but some amount of carbonaceous materials is seen to be concentrated in several parts of this PTS. The CMA observation shows that Ca is concentrated at grain boundaries of small polygonal olivine crystals forming a granoblastic olivine grain, which was originally a single crystal (Fig. 2).

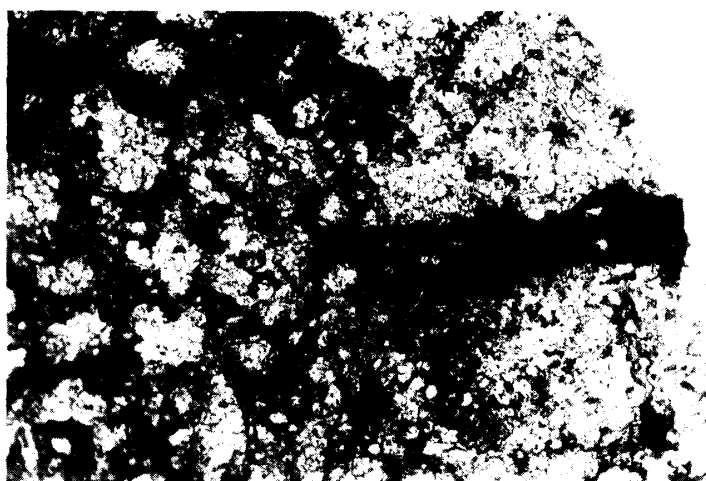


Fig. 1 (a) LEW86216, 5

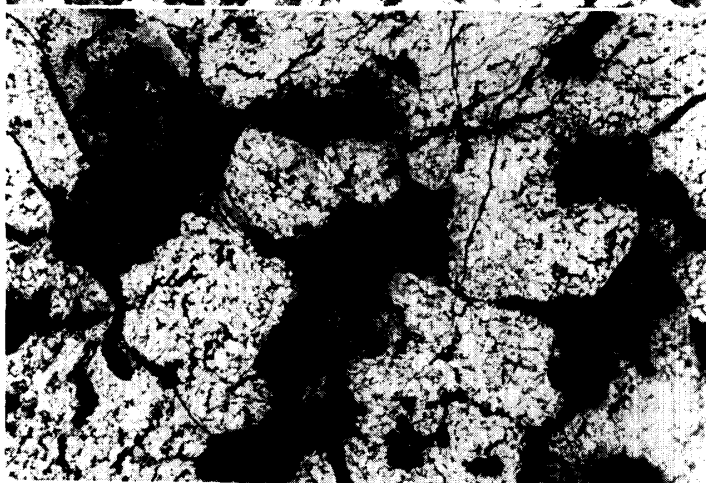


Fig. 1 (b) Y-75154, 51-1



Fig. 1 (c) Y-791839, 52-2



Fig. 1 (d) Y-791839, 52-2



Fig. 1 (e) LEW85328, 25



Fig. 1 (f) Y-8448, 61-2

Fig. 1. Photomicrograph of ureilites. Width is 1.2 mm except for (f). (a) LEW86216, 5: Heavily shocked olivines with a granoblastic texture. (b) Y-75154, 51-1: Heavily shocked olivine crystals were converted into aggregates of fine crystals, showing granoblastic texture. (c) Y-791839, 52-2: Elongated olivine crystals aligned parallel with each other. (d) Y-791839, 52-2: Olivine crystals are partly disturbed, and fine-grained dusty portions are present. Some parts of carbonaceous veins were lost. (e) LEW85328, 25: Heavily disturbed and reduced olivine crystals with relatively small size, and carbonaceous vein materials being modified in this area. (f) Y-8448, 61-2: Small, very fine dendritic barred olivines are also seen presumably in the "fusion crusts". Width is about 3.5 mm.

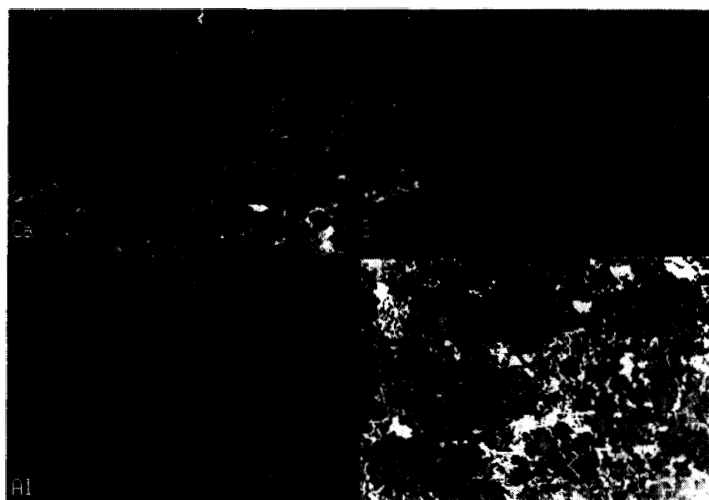


Fig. 2. Elemental maps of Ca, Al, S in LEW86216 obtained by CMA. Width is about 300 microns. Lower right portion is backscattered electron image (BEI) of this area. Note that Ca was concentrated at grain boundaries.

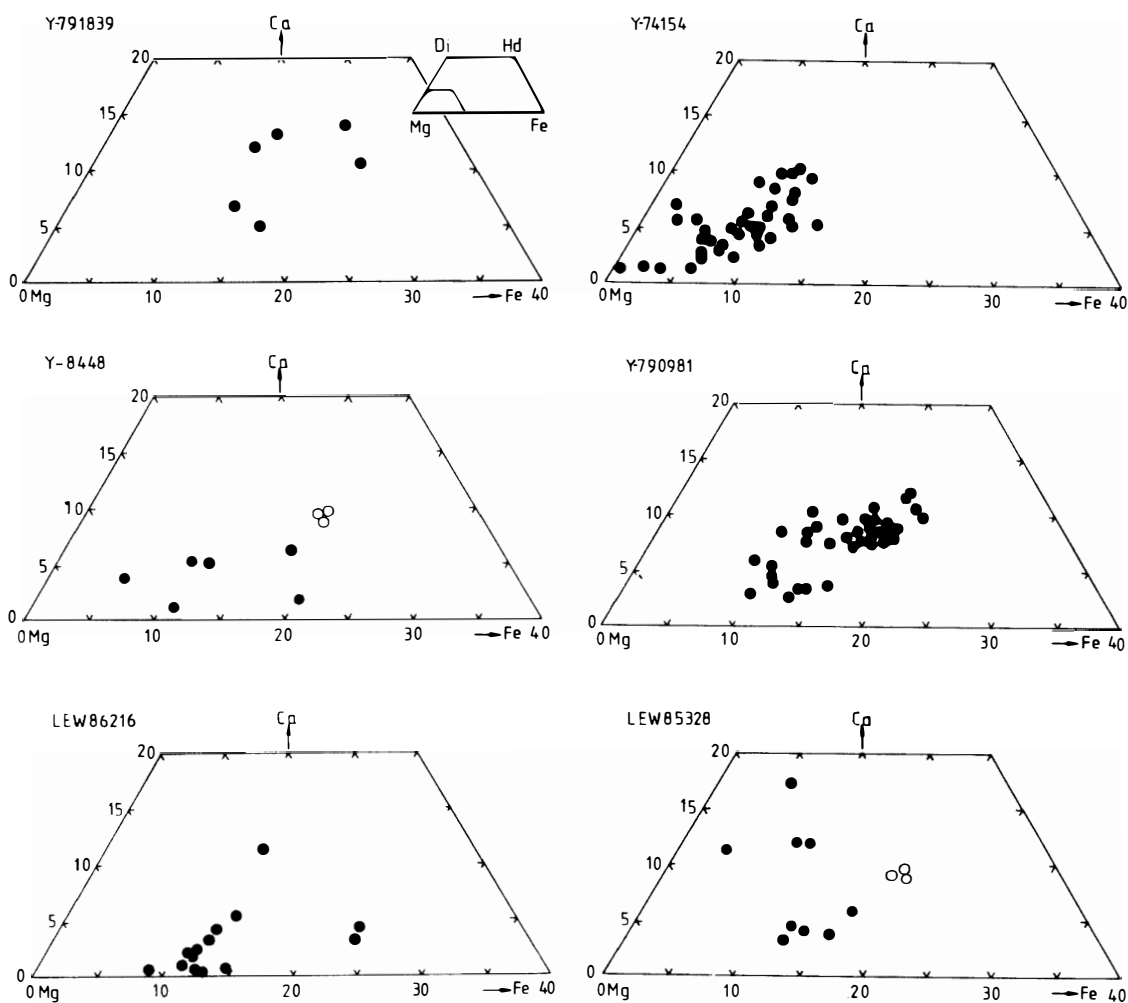


Fig. 3. Portions of enlarged pyroxene quadrilateral diagrams of LEW86216, 5, Y-75154, 51-1, Y-791839, 52-2, LEW85328, 25, and Y-8448, 61-2. The data of pyroxene compositions of Y-790981 are also included (OGATA et al., 1988). Open circles of LEW85328 and Y-8448 are core compositions.

The distribution of the chemical compositions of the LEW86216 pyroxenes are scattered in the pyroxene quadrilateral (Fig. 3) as shocked ureilites such as Y-790981 (OGATA *et al.*, 1988). Chemical compositions of olivine in LEW86216 are also scattered (Fa_{11} to Fa_{15}), and the predominant core composition is $Fa_{14.4}$. This trend may be one of characteristics of shock reduction, but because carbon veins are mixed with fine-grained mafic silicates, it is difficult to deduce its origin. The trend is not like those of polymict-brecciated ureilites (PRINZ *et al.*, 1986).

3.2. Y-75154, 51-1

This ureilite is also heavily shocked and the olivine crystals are converted into aggregates of fine crystals and show granoblastic textures (Fig. 1b). Parts of the carbonaceous veins and metal-sulfide veins have disappeared by shock vaporization, and the remainders are discontinuous, so that some parts of the original grain boundaries of olivine are not clear. Pigeonite crystals still keep their crystal morphology, and show a slight cloudy appearance, spotted by dust-like stains. Opaque materials, mostly troilites, are concentrated more at certain locations, where silicate grains show rounded shape indicating shock melting.

The chemical trends of pigeonites are scattered at the Mg-rich corner of the pyroxene quadrilateral towards the enstatite corner (Fig. 3). The pyroxene composition is one of the most magnesian among ureilites (Table 1). The typical olivine core composition is about Fa_{10} .

3.3. Y-791839, 52-2

Y-791839 has been described as a shock-melted ureilite (YANAI and KOJIMA, 1987). A part of the melted portion may be a thick fusion crust, but shock-altered portions are also present. Many olivine crystals are elongated along the growth direction and are aligned parallel with each other (Fig. 1c). Along rims and cracks of olivines fine dusty materials are deposited. Pyroxenes are rather rare. Along the grain boundaries at the rims, the olivine crystals are partly disturbed and fine-grained dusty portions are produced (Fig. 1d). Sometimes, carbon veins at such portions have disappeared and become voids. At one location, there is a glassy portion (possibly fusion crust) with fine-grained skeletal crystals.

The pyroxene crystals in Y-791839, 52-2 show cloudy appearances, and their chemical compositions by electron probe are also variable, scattered in a relatively more Fe-rich portion of the pyroxene quadrilateral (Table 1, Fig. 3) than Y-75154, 51-1. The higher Ca-values may represent mixed analyses between the pyroxene crystals and glassy inclusions in cloudy pyroxenes. The typical olivine core composition is about Fa_{25} .

3.4. LEW85328, 25

The general appearance of LEW85328, 25 PTS, is that of common ureilites such as Kenna but somewhat different in that shock-disturbed areas are scattered unevenly. In these areas are gathered heavily reduced olivines with small inclusions of reduced metal even in the interior of the grain. These olivines have irregular grain shape and relatively smaller size than those of other portions. Carbonaceous materials are seen

to be concentrated in several parts of this area. Pigeonites of slightly cloudy appearance are in contact with this portion (Fig. 1e).

The ropy glassy materials (about a few microns in width, Fig. 4) in pigeonites with partly cloudy appearance are classified into two groups: one is Ca, Al-rich (Al_2O_3 14.0 wt%, CaO 10.2, SiO_2 58.0) but some amounts of iron and magnesium are included

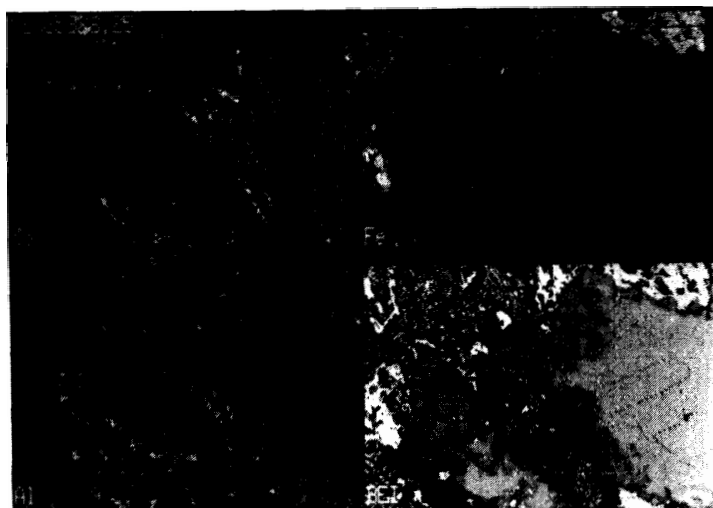


Fig. 4. BEI and elemental maps of Ca, Al, Fe of the LEW85328, 25 pigeonite with slightly cloudy appearance. Width is about 300 microns. Ca is partly concentrated at relatively dark-colored portions shown in BEI.



Fig. 5. BEI and Ca, Al, Fe elemental maps of LEW85328, 25 interstitial materials. Width is about 300 microns. Ca is concentrated in the interstitial materials.



Fig. 6. BEI and Ca, Al, Fe elemental maps of Y-8448, 61-2. Width is about 150 microns. Ca is concentrated in some portions of pyroxene rims.

(FeO 1.6 wt%, MgO 10.2 wt%); the other contains a higher amount of Si (SiO_2 69.4 wt%) with smaller content of magnesium (MgO 4.6 wt%). The core compositions of pyroxene ($\text{Ca}_{0.6}\text{Mg}_{72.1}\text{Fe}_{18.3}$; open circles in Fig. 3) and olivine ($\text{Fa}_{20.8}$) in this PTS are very uniform except for the above shock-disturbed areas.

There also exist interstitial rim materials in LEW85328, 25 PTS, which are also found in other ureilites (OGATA *et al.*, 1988; GOODRICH, 1986). The interstitial materials in LEW85328 consist of a Ca, Al-rich pyroxene and glass-like materials (Fig. 5).

The precession photograph of a pigeonite in LEW85328, 20 shows two slightly misoriented crystals with sharp diffraction spots, and no exsolution of augite. The sharp diffraction spots mean that this crystal had experienced weak shock effect, or was heavily shocked but the shock effects were annealed in a high temperature episode after the shock event. Absence of an exsolved augite implies that this crystal has experienced rapid cooling, as most ureilites did (MIYAMOTO *et al.*, 1985).

3.5. Y-8448, 61-2

The polished thin section of Y-8448, 61-2 revealed that olivine and pyroxene crystals are elongated. Carbonaceous materials are present at grain boundaries, which have reduced the rims of olivine crystals (Fig. 1f). Some vein metals are also present in carbonaceous veins. The crystals of mafic silicates are almost clear, except for reduced olivine rims. These features distinguish Y-8448 from other heavily shocked ureilites presented in this paper. The BEI (backscattered electron image) observations show that small (about 10–20 microns) Ca-rich portions and glassy materials are present in some pyroxene crystal rims (Fig. 6). The electron probe microanalyses of the pyroxene rims of Y-8448 show more Ca-rich or Mg-rich compositions than the pyroxene cores (Fig. 7) because these values are for the mixtures of pyroxene rims and small Ca-rich or Mg-rich inclusions. The electron probe microanalysis shows that the chemical compositions of mafic silicate cores of Y-8448 are uniform; about $\text{Fa}_{21.5}$ for olivine and $\text{Ca}_8\text{Mg}_{72.9}\text{Fe}_{19.1}$ for pyroxene (Tables 1 and 2). The pyroxene rims have

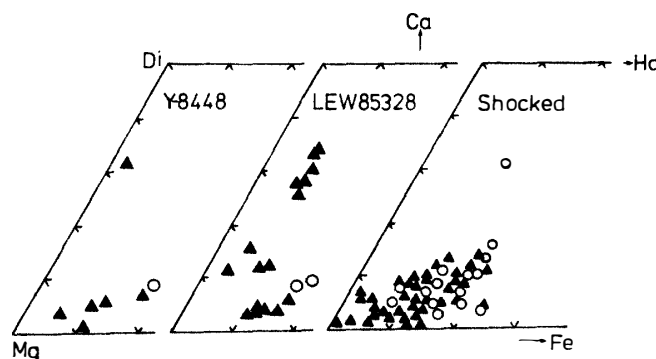


Fig. 7. Comparison of chemical variations of pyroxenes in the shocked ureilites, LEW85328 and Y-8448, with the entire range of chemical variations of individual ureilites. Open circles: core compositions of individual ureilites (BERKLEY *et al.*, 1980; TAKEDA, 1987, 1989). Solid triangles: measured values of various portions of pyroxenes in shocked ureilites and Y-8448.

Table 1. Chemical compositions (wt %, individual analysis of core) of pyroxenes in five ureilites.

	Y-75154			Y-791839	LEW86216	LEW85328	Y-8448
SiO ₂	56.1	56.1	55.3	55.4	57.2	55.2	54.5
TiO ₂	0.08	0.02	0.2	0.02	—	0.08	0.1
Al ₂ O ₃	0.1	0.09	0.6	0.1	0.06	1.48	0.1
Cr ₂ O ₃	0.9	1.0	1.0	1.2	1.0	1.3	1.2
FeO	5.5	5.3	6.2	7.8	7.3	11.6	11.6
MnO	0.3	0.6	0.5	0.5	0.4	0.4	0.4
MgO	32.2	32.8	27.0	28.5	33.6	25.8	26.3
CaO	3.8	3.3	8.4	6.4	0.5	4.8	4.5
Na ₂ O	—	—	0.06	0.03	—	0.2	0.2
K ₂ O	—	0.01	—	0.02	—	—	—
Total	98.9	99.12	99.26	99.95	100.06	100.86	99.8
Ca*	7.1	6.3	16.5	12.3	0.9	9.6	9.0
Mg	84.7	85.9	74.0	76.0	88.3	72.1	72.9
Fe	8.1	7.8	9.5	11.7	10.8	18.3	18.1

* Atomic percent.

— Stands for under detection limits.

Table 2. Chemical compositions (wt %, individual analysis) of olivines in five ureilites.

	Y-74154	Y-791839	LEW86216	LEW85328	Y-8448
SiO ₂	39.5	36.8	39.1	38.4	38.7
TiO ₂	0.05	0.01	—	—	—
Al ₂ O ₃	0.02	0.05	0.5	0.04	0.09
Cr ₂ O ₃	0.7	0.7	0.9	0.5	0.7
FeO	9.8	22.2	13.5	19.4	19.7
MnO	0.6	0.4	0.5	0.4	0.4
MgO	49.2	37.5	45.0	41.3	40.2
CaO	0.4	0.4	0.4	0.29	0.3
Na ₂ O	—	—	0.04	0.02	0.02
Total	100.3	98.1	99.9	100.4	100.1
Mg*	90	75.1	85.6	79.2	78.5
Fe	10	24.9	14.4	20.8	21.5

* Atomic percent.

— Stands for under detection limits.

lower Fe contents.

Along the margin of this section, there are dark-colored areas with many rounded holes, around which dendritic or barred crystals are grown (Fig. 1f). These areas are about 1 mm in width, and appeared to be fusion crusts. These dendritic materials consist of olivines and pyroxenes, which are set in a matrix of dark glassy materials, and show chemical zoning. Thus, the variations of chemical compositions of Y-8448 olivines and pyroxenes may be attributed to zoning of these dendritic crystals in fusion crusts and pyroxene rims.

4. Discussion

4.1. Shock textures and chemical variations of pyroxene

LEW86216, 5 shows the shock textures of large granoblastic olivines being converted to mosaic of small grains (Fig. 1a), and some parts of this ureilite show textures similar to the shock-recrystallized diogenites (TAKEDA *et al.*, 1981). The Ca concentration at grain boundaries in LEW86216 suggests that Ca was removed from the interior of olivine and concentrated at the rims where shock melts may have been produced by a shock event, and that such shock melts were quenched during rapid cooling by the parent body breakup. The olivine crystals of Y-75154, 51 are also converted into aggregates of fine crystals and show granoblastic textures (Fig. 1b). The granoblastic olivine textures and disruption of veins of LEW86216, 5 and Y-75154, 51 are also seen in the heavily shocked ureilites such as Goalpara and ALH81101 (BERKLEY *et al.*, 1980; TOYODA *et al.*, 1986).

Carbon and metal-sulfide veins in LEW86216, 5 are disrupted and the original grain boundaries cannot be recognized. Carbon veins also disappeared in some part of Y-75154, 51 PTS but grain boundaries are still preserved. These features suggest that some volatile components were vaporized and removed from grain boundaries when ureilites were heavily shocked.

From the iron-poor composition of pyroxenes in Y-75154, 51-1, we expect that this ureilite belongs to a high oxygen-anomaly group with very magnesian silicates on the basis of the study by CLAYTON and MAYEDA (1988). Y-791839 is the most Fe-rich ureilite we studied, with Fa content of olivine close to 25. The pyroxene crystals are small and are finely fractured. These findings of two Antarctic ureilites again expand the range of compositions of known ureilites.

The existence of interstitial rim materials in LEW85328, 25 suggests that it contains the remnants of shock melting prior to the parent body breakup. OGATA *et al.* (1988) showed that a shock event had occurred prior to the parent body breakup, and that the interstitial rim materials had already been solidified when the parent body was broken up. The interstitial rim materials in LEW85328, 25 are thought to have been formed by the same process.

As for the origin of the texture of irregularly shaped reduced olivines in LEW85328, 25 (Fig. 1e), we suggest two possibilities from the diffraction data which show slightly misoriented two crystals with sharp diffraction spots: (a) This meteorite had experienced the shock event which resulted in the parent body breakup, but this shock effect was so heterogeneous that crystals at the junctions, *etc.*, were preferentially disturbed, and portions of a pigeonite were partially melted. The pigeonite crystal examined by precession camera was affected weakly by this shock event. (b) This meteorite had been heavily shocked prior to the parent body breakup, but the shock texture of pigeonite and disturbed olivines was annealed by the residual heat to give sharp diffraction spots of pigeonite before the second shock event. The first shock event may have produced both the interstitial rim materials and irregularly shaped olivine texture. It is difficult to identify two cases on the basis of the results we have now, but the repeated collision cannot be ruled out.

Y-8448 has been found to be one of common ureilites, except for thick fusion

crusts including dendritic (or barred) olivines and pyroxenes. Y-8448 belongs to the type I subgroup of CLAYTON and MAYEDA (1988) and the intermediate group of TAKEDA (1989) according to the mafic silicate chemistry and oxygen isotope ratios. They demonstrated that Fa contents are correlated with the degree of oxygen isotope anomalies, and we expect that the oxygen isotope of Y-8448 may not be too anomalous. We propose that weakly shocked crystalline ureilites of this group can be called "ordinary ureilite" because they are the most common subgroup among ureilites.

We studied the chemical zonings and variations of pyroxene and olivine in Y-8448 in order to gain better understandings of the way how the Ca-Al-Fe-S melt was removed from the partially melted source material. However, these chemical variations and zonings turned out to be attributed to rims of mafic silicate and dendritic crystals in thick fusion crusts.

4.2. *Some constraints for the origin of ureilites*

General discussion of ureilite genesis is not the purpose of this paper. In this section, we show how the chemical variation of ureilitic pyroxenes described in this paper can be related to the chemical variations during their initial formation. TAKEDA (1989) and TAKEDA *et al.* (1989) outlined basic processes of the planetesimal-scale collision models, but the more detailed evidence of these processes have been left for the future studies. This paper deals with chemical variation due to shock.

LEW86216, 5 has a texture similar to shock-recrystallized diogenites (TAKEDA *et al.*, 1981). These diogenites have ureilite-like V-shaped chondrite-normalized REE (Rare Earth Elements) patterns with Eu depletion and considerable amounts of REE including Eu are enriched in recrystallized portions (MASUDA *et al.*, 1979). Discussion on the origin of REE distribution has been given in TAKEDA (1989).

Shock experiments by ARAKAWA *et al.* (1988) using mixtures of olivine, Ni and carbon show preferential melting of the olivine rims at grain boundaries and production of clean olivine crystals. The shock-altered ureilites (LEW86216, 5, Y-75154, Y-791839) described in the previous chapter also show disturbance at the grain boundaries. The experimental and natural evidence suggests that the initial chemical variation due to shock takes place at the grain boundaries or matrices.

The cloudy pigeonites in LEW85328, 25 contain the Ca, Al, Si-rich glass in a crystal. This glass is thought to have been produced by shock event (MORI and TAKEDA, 1983), but we are not sure whether this shock event was prior to the breakup of the parent body. On the other hand, the glassy materials containing higher amount of Si in LEW85328, 25 may have been produced by the reduction by carbon-bearing materials at the grain boundaries during the cooling subsequent to the parent body breakup.

Chemical variations of pyroxenes shown by the five shocked ureilites in the present study are similar to those of the entire trends shown by all ureilites (Fig. 7) taken together and Y-790981 studied previously (OGATA *et al.*, 1988). The chemical variations of pyroxenes in these ureilites are thought to be caused by shock events (OGATA *et al.*, 1988), because they are formed in a group of ureilites showing heavily shocked textures. The TEM studies by OGATA *et al.* (1988) detected a glass in pyroxenes and enstatite in the olivine rims reduced by carbonaceous materials in shock-modified portions. These shock melts (glasses) presumably produced by partial melting are too small to be an-

alyzed by an electron probe, and the values of such microanalysis show average compositions of mixtures of original crystals and glassy materials. This trend may suggest that the original chemical variation produced at the early stage of collision is not much different from the chemical range of individual ureilites within the same oxygen isotope subgroup as was pointed out by TAKEDA (1989).

The preferred orientation of olivine crystals of ureilites has been interpreted as the important evidence for the cumulate model of ureilite origin (BERKLEY *et al.*, 1980). Many olivine crystals of Y-8448 and Y-791839 also show such elongation, though we have only a small number of olivine grains in the PTS.

TSUKAHARA and YAMAZAKI (1976) showed that a texture similar to the texture of these ureilites can be produced without necessity of conventional "settling-type" cumulates. Hence, textures formed by crystal growth from partially melted olivine by TSUKAHARA and YAMAZAKI (1976), and those observed in the Y-791839 and Y-8448 ureilites may have common origin. Their study suggests that very elongated crystals of mafic silicates can be grown by a temperature-gradient zone refining process. In this case, we notice an importance of boundary (or wall) effects, in which elongated crystals grow perpendicular to the wall, induce competition of crystal growth, and leave boundaries parallel to the elongated crystals. In order to see wall effects we have to observe elongation direction of olivine crystals within a very large ureilite, which is very rare in the present meteorite collections.

The observations of heavily shocked ureilites discussed above indicate that the vaporization of volatile elements such as carbonaceous vein materials, partial melting of pigeonites and olivines and concentration of Ca-rich materials at grain boundaries of mosaic olivines had taken place by the latest stage of shock event during the breakup of the ureilite parent body.

If we extend this idea one step further, we expect that the information gained by the observation of the shock event of the latest stage of the ureilite history can be applied by analogy to the phenomena that took place in the beginning of the ureilite formation history by the planetesimal-scale collision (TAKEDA, 1989; TAKEDA *et al.*, 1988), because the heavy shock events had taken place in the same parent body with the related chemistries.

According to the planetesimal-scale collision model, preferential melting and crystal growth of carbonaceous chondrite-like source materials by collisions of two or more planetesimals are important processes in ureilite formation. Such processes are observed for shocked ureilites. This planetesimal-scale collision model requires a removal of Ca-Al, and Fe-Ni-S melts from the source material. It has not been fully understood, however, how the Ca-Al, and Fe-Ni-S melts were removed from the partially melted source material and residues of crystal growth.

WALKER and AGEE (1988) pointed out the difficulty of removing iron sulfide through the grain boundaries. TAKEDA *et al.* (1984) showed that Fe-Ni-S melts with siderophile elements have been lost from an LL chondrite by shock melting, recrystallization and annealing, and that a totally crystalline texture has been produced. The presence of volatiles in carbonaceous chondrite-like materials will help removal of melts. This process of removing melt (or melts) with certain elements depleted in ureilites from the source material within a relatively short time is most likely to be

retained during the process to form ureilites from carbonaceous chondrite-like material keeping its O-isotope ratio.

It has been observed that mixtures of sands and water will expel water by the passages of earthquake waves. This phenomenon has been called "liquefaction" (CASAGRANDE, 1971). One way of removing liquid from the mixtures of melts and solids during the planetesimal-scale collision process may be envisioned by processes like the liquefaction phenomenon occurring at the time of earthquakes. The reason why we refer to this phenomenon is that this is the process which can easily remove a liquid from a solid-liquid mixture when vibration was induced. Similar phenomenon is expected to take place by the planetesimal-scale collision on the ureilite parent body, since during the planetesimal-scale collision, shock waves may traverse the interior of the planetesimal, and a phenomenon similar to an earthquake will take place.

Applying this process to the preferential melting of ureilite source material, we interpreted that the Ca-Al, Fe-Ni-S melts play a role of water, and unmelted crystals play a role of sand, by analogy of the wet sand of the liquefaction. Liquefaction requires the high porosity, but the presence of shock melts may make the porosity high in a planetesimal.

We are not proposing that the liquefaction really took place on the ureilite parent body, but just want to mention that the liquefaction should be examined as a process of removing the melts. In real processes, presence of volatile elements in the ureilite source materials may play more important roles for the removal of shock partial melts, which will be much efficiently accompanied by the escape of gasses.

Among iron meteorites with silicate inclusions, Bocaiuva has the oxygen isotope ratios far from other iron meteorites with silicate inclusions, but similar to the ungrouped pallasites, so-called "Eagle Station Trio". Oxygen isotope ratio of Bocaiuva is near the mixing-line of CV and CO carbonaceous chondrites (MALVIN *et al.*, 1983).

According to one of the ureilite formation models involving impacts of RUBIN (1988), the Bocaiuva iron meteorite has been related to the ureilite parent body. SAITO and TAKEDA (1988) mentioned that the dense Fe-Ni-S melt and relatively light silicate melt formed by the planetesimal-scale collision were not fully separated in very low gravitational field of the small parent body, and that Bocaiuva was formed out of the mixed materials of Fe-Ni-S and silicate melt.

We agree with RUBIN (1988) in that this iron meteorite may be related to ureilite, and that the mechanism for ureilite formation may be applied to the formation of such a differentiated meteorite.

Further study including an experimental approach must be required in order to explain the mechanism of the removal of melt from the source material (or materials) of ureilite in more quantitative way.

In conclusion, chemical variations of five new Antarctic ureilites can be summarized as follows:

(1) The chemical variations of pyroxenes, and the partly disrupted carbonaceous vein materials in heavily shocked ureilites can be explained by partial melting and vaporization mainly at the grain-boundaries and rims. (2) The shock metamorphic processes on these heavily shocked ureilites are useful information to deduce the shock

events by the planetesimal-scale collision in the early formation stage of ureilites. (3) The mechanisms of liquefaction phenomenon may be applied to removal of shock partial melt and vapors with incompatible elements during the planetesimal-scale collision.

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