MINERALOGY OF THE YAMATO DIOGENITES AS POSSIBLE PIECES OF A SINGLE FALL

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***Abstract*:** Among 30 diogenites recovered from the Yamato meteorite field by the JARE parties, 29 meteorites totaling 6775.8 g have a granoblastic texture distinct from known diogenites. We have proposed on the basis of their mineralogy that we are dealing with pieces of a single fall. In order to clarify their identity, we have reexamined thin sections of Yamato-74013, -74097, -74136 with optical, electron optical (TEM) and microprobe techniques. The meteorites are composed of fine-grained orthopyroxenes surrounded by coarse-grained areas and of chromites up to 5 mm in diameter. Finer-grained portions with a haze of tiny inclusions of troilite and metallic iron show a subtle parallel structure that transects the granularity. The structure can be interpreted to be decorated with linear features produced by a shock event. The TEM observation of clear orthopyroxenes in coarser-grained areas (0.4–3.0 mm) shows stacking faults parallel to (100), which are thought to have been produced by weak shock effects when the meteorite mass was formed. Neither exsolution nor dislocation indicating low strain-rate deformation has been observed. The rims of the large clear orthopyroxenes are richer in Ca and Fe than the other portions. In interstices of the coarsest portion, there are found graphic intergrowth of plagioclase and a silica mineral, and coarse-grained troilite. The characteristic texture of the Yamato diogenites may have been formed by recrystallization of a few very large crystals by heavy shock processes, and subsequent thermal annealing. Coarse-grained areas may indicate intergranular melting and recrystallization. Because the coarsest portions with rare-earth-element-rich plagioclase are distributed over intervals of a few cm, the differences found in separate masses may be attributed to the heterogeneity of sampling.

1. Introduction

Among 30 diogenites (Table 1) recovered from the Yamato meteorite field by the JARE parties, 29 meteorites totaling 6775.8 g have granoblastic texture distinct from known diogenites. Petrographic description is represented by that of Yamato-74013 given by DUKE in our previous paper (TAKEDA *et al.*, 1979b). The importance of this

Table 1. List of the Yamato diogenites.*

Specimen No.	Weight (g)	Dimension (cm)
Y-692	138	7
Y-74005	3.8	1.6 × 1.0
Y-74010	298.5	9.0 × 6.5
Y-74011	206.0	6.5 × 5.0
Y-74013	2059.5	15.0 × 10.0
Y-74031	6.1	1.7 × 1.6
Y-74037	591.9	8.6 × 8.2
Y-74096	16.1	2.6 × 2.4
Y-74097	2193.9	16.0 × 11.0
Y-74109	43.5	4.5 × 4.0
Y-74125	107.0	5.2 × 3.7
Y-74126	14.5	3.1 × 2.0
Y-74136	725.0	9.0 × 7.0
Y-74150	33.4	3.2 × 3.0
Y-74151	49.1	3.5 × 2.7
Y-74162	3 9	1.7 × 1.4
Y-74344	1.4	1.3 × 1.1
Y-74347	7.8	2.2 × 1.6
Y-74368	4.1	1.5 × 1.3
Y-74448	17.7	2.7 × 2.5
Y-74546	7.3	2.2 × 1.2
Y-74606	2.9	2.0 × 1.2
Y-74648	185.5	4.0 × 3.5
Y-75001	4.1	1.7 × 0.7
Y-75004	37.0	3.5 × 2.8
Y-75007	2.6	1.5 × 0.9
Y-75014	3.0	1.4 × 1.4
Y-75032**	189.1	5.5 × 6.0
Y-75285	3.1	1.4 × 1.3
Y-75299	9.1	2.2 × 2.2

* After YANAI (1979).
** Unrecrystallized.

characteristic texture was first noted by us in Yamato-692 (TAKEDA *et al.*, 1975, 1978). The texture is totally unlike that of Tatahouine which appears to be the only other unbrecciated diogenite. We have proposed on the basis of their mineralogy and bulk compositions that we are dealing with pieces of a single fall. Actually, four of the larger pieces recovered from distant locations were found to match with each other (Figs. 1, 2) (YANAI, private communication, 1981). Some differences in the rare-earth element abundances and isotopic compositions found among these meteorites (MASUDA *et al.*, 1979; NAKAMURA, 1979) appear to cast doubt on the above hypothesis but these may be attributed to heterogeneity in mineral distribution within a single meteorite. In order to clarify their identity, we have reexamined thin sections of Yamato-74013, 74097, 74136, 74648, 74037, 74010 and 74011 with optical, electron optical and microprobe techniques. Yamato-75032 is another unique diogenite with the most Ca- and Fe-rich pyroxenes (TAKEDA *et al.*, 1979a).

The evidence of recrystallization found for the Yamato diogenites suggested that some diogenites may have a quite complex thermal history involving reheating and, in some cases, almost complete recrystallization. The young ^{40}Ar-^{39}Ar age obtained for Yamato-74097 (KANEOKA *et al.*, 1979) is in agreement with the reheating events. The Rb-Sr and Sm-Nd systems of the Yamato diogenites were proposed to have been partially reset by young multiple metamorphic events (possibly at $1.1 \sim 1.8$ b.y. ago) by NAKAMURA (1979). We have suggested that the disturbed Rb-Sr and Sm-Nd isotopic systems of the Yamato diogenites may be the result of heterogeneous distribution of minor phases that might have formed during young metamorphic events. However, no real picture of the reheating event has been proposed.

Because the controversy about their identity as a single fall largely rests on the heterogeneous distribution of minerals produced by the reheating events, we reinvestigated the three-dimensional distribution of coarsely crystallized minerals, especially orthopyroxenes and plagioclases in Yamato-74013. The chemical zoning in the orthopyroxenes in various portions of the meteorite, which show different textures and mineral assemblages, were reinvestigated by an electron microprobe. The presence of minute inclusions and dislocations has been studied with the transmission electron microscope (by H. MORI). The results have been interpreted in the light of new observations on the thermal and deformational histories of diogenite (MORI and TAKEDA, 1981) and on shock-produced textures in pyroxenes in the Yamato-74659 ureilite (TAKEDA and YANAI, 1978) and in lunar analogues of meteoritic pyroxenes (TAKEDA *et al.*, 1981).

2. Samples and Experimental Methods

Macroscopic observation of Yamato-74013, -74097 and -74136 was performed in hand specimen. A parallelepiped-like chip of Yamato-74013,31 (42.0 g) was processed at NASA Johnson Space Center through the courtesy of Dr. M. B. DUKE. Three polished thin sections perpendicular to each other were cut from the chip to observe the directional differences in texture. Fourteen thick sections about 0.2 mm in thickness were sliced in succession from the remaining chip parallel to one of the above three sections. Three-dimensional distribution of the coarsely crystallized bands and chromites was investigated on these sequential sections. Sample Yamato-74097,91 (0.01 g) was chipped from a bright grass-green patch, which is irregularly

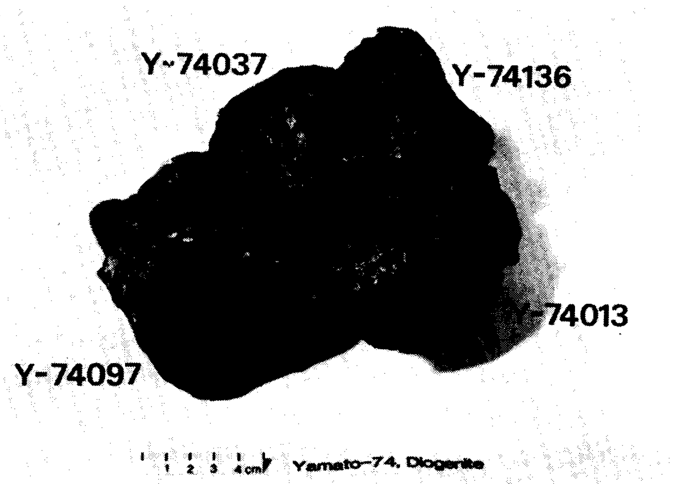

Fig. 1a. Photographs of Yamato-74097, 74013, 74037 and 74136, all joined together.

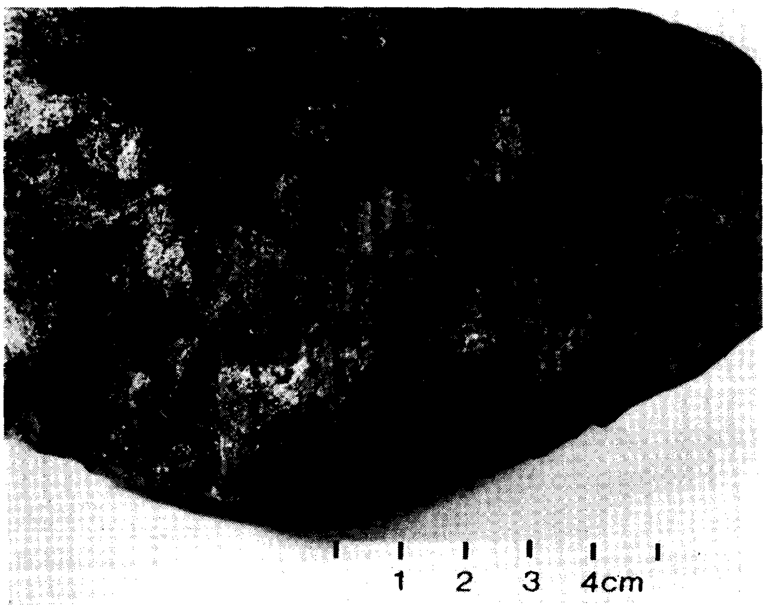

Fig. 1b. A close-up view of Yamato-74097 showing planar bands. Note the vertical lines.

distributed in this sample. A thin section was made from this chip. The bulk composition of Yamato-74013 was obtained by a standard wet-chemical method by Mr. H. HARAMURA of the University of Tokyo through the courtesy of Professor I. KUSHIRO of the Geological Institute.

The partial chemical analyses were made with a JEOL JXA-5 electron probe X-ray microanalyzer with a 40° take-off angle, to obtain Ca-Mg-Fe proportions of orthopyroxenes which show various textures. About 440 points were analyzed to deduce

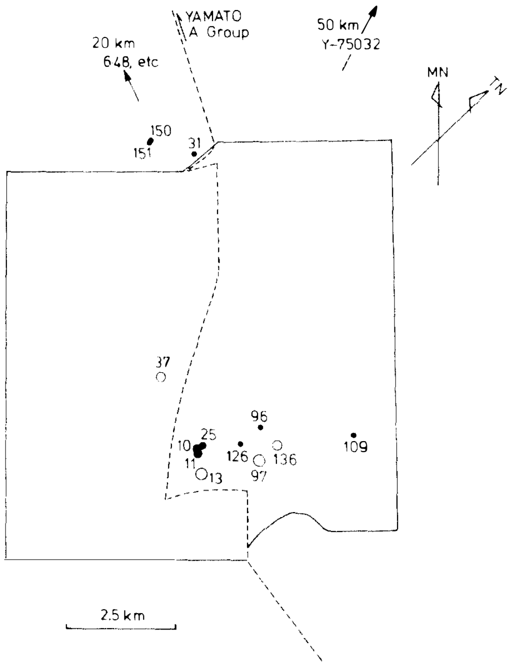

Fig. 2. Sampling sites (solid circle) of the Yamato diogenites within the systematic search area (square) in the Meteorite Ice Field. White circle: diogenites in Fig. 1a. Size of circle indicates relative weight. TN: true north, MN: magnetic north. Specimen numbers are shown without Y-74.

chemical differences due to textural variations and chemical zoning within a single crystal. The quantitative chemical analyses of minerals were made with a JEOL 733 electron probe X-ray microanalyzer with a 40° take-off angle. The method is the same as that of KUSHIRO and NAKAMURA (1970). A few single crystals of large clear orthopyroxenes in Yamato-74013 were separated from a chipped surface of the specimen. The pyroxene crystals were mounted approximately along the *c*-axis, and were aligned with the spindle axis parallel to the c^* direction. Precession photographs of *h0l* nets were taken by using Zr-filtered Mo $K\alpha$ radiation. Subsequently the crystals were mounted in araldite with a particular crystallographic axis perpendicular to a slide glass, and were polished to prepare thin oriented single crystals for the microprobe and optical study. After the X-ray and optical examinations, the orthopyroxenes of the Yamato-74013 diogenite were ion-thinned for a transmission electron microscopic (TEM) observation at 100 kV.

3. Results

3.1. Macroscopic observation

Yamato-74097 (2193.9 g), -74013 (2059.5 g), -74136 (725.0 g) and -74037 (591.9 g) are the four largest samples of the Yamato diogenites, which are interpreted to be pieces of a single fall. These four meteorites recovered at different locations were found to join together as is shown in Fig. 1a. Their locations are indicated in Fig. 2 (white circle) together with those of other Yamato diogenites found within an area where meteorites were extensively surveyed in 1974. The most distant pair (3.1 km)

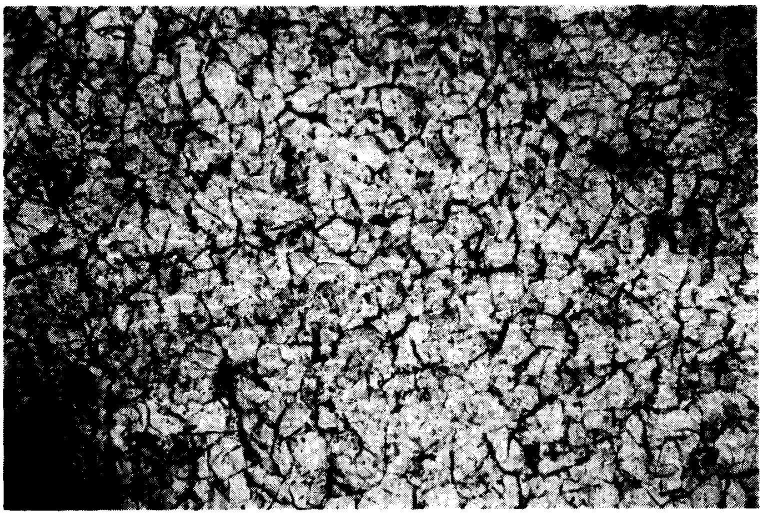

Fig. 3. Photomicrograph of the fine-grained area in Yamato-74013. Width is 2.4 mm. Note a straight band of clear crystals from upper left to middle right, and fine parallel structures nearly horizontal.

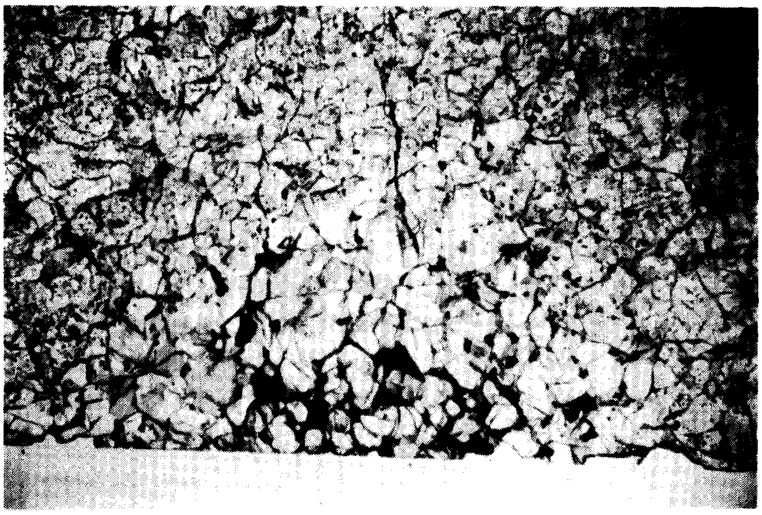

Fig. 4. Photomicrograph of the coarse-grained area at the edge of Yamato-74013. Width is 2.4 mm.

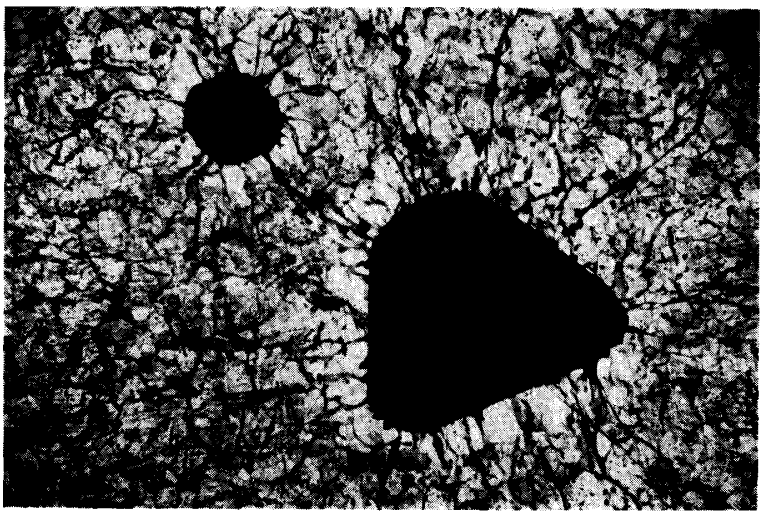

Fig. 5. Photomicrograph of the coarse-grained areas around euhedral chromites in Yamato-74013. Width is 2.4 mm.

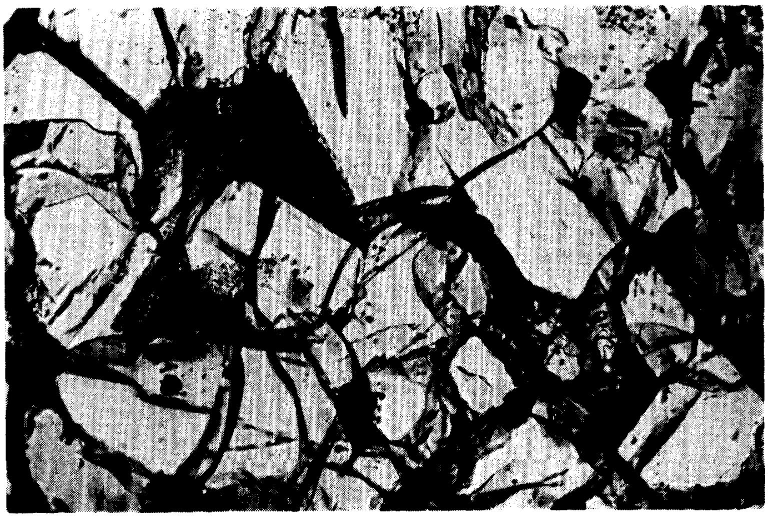

Fig. 6a. Photomicrograph of plagioclase and a silica mineral in the coarse-grained area in Yamato-74013. Black angular grains: troilites; gray interstitial materials with a graphic texture: plagioclase and silica. White: orthopyroxenes. Width is 0.80 mm.

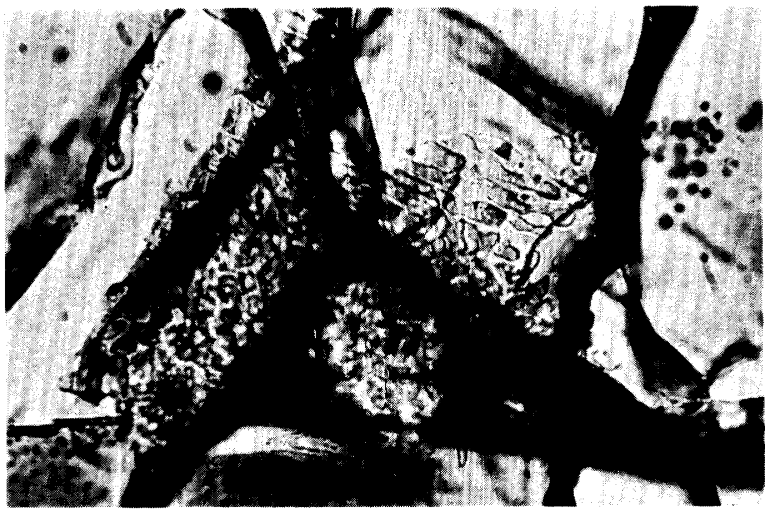

Fig. 6b. Enlarged view of the graphic textures exhibited by plagioclase and silica mineral assemblages at the middle left edge in Fig. 6a. Width is 0.20 mm.

among four pieces is Y-74037 and Y-74136, and the closest pair (0.6 km) is Y-74097 and Y-74136. All recrystallized Yamato diogenites were found within a 4×20 km area along the flow direction of ice. However, Y-75032, another kind of unique diogenite, was found at 50 km north (TN) of the area where major masses of the recrystallized Yamato diogenites were recovered.

Yamato-74097 is the largest broken mass slightly elongated, with almost no fusion crust. The color is dark olive yellow with irregular patches of bright grass-green color. Planar features of dark color alternate with green-colored portions perpendicular to

Fig. 7a. Photomicrograph of Yamato-74013. Width is 0.8 mm. Parallel structures marked by relative abundance of opaques and short fractures are observed in finer-grained areas. This structure transects the granularity. Tiny inclusions are mostly troilites.

Fig. 7b. Enlarged view of the parallel structures. Width is 2.0 mm.

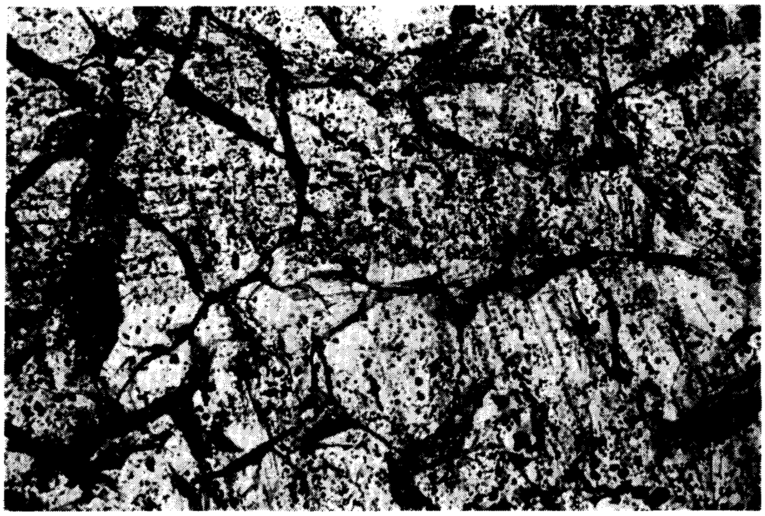

Fig. 8. Photomicrograph of the parallel structures in two different orientations of Yamato-74013. Width is 0.8 mm.

Fig. 9. Photomicrograph of the parallel structures partly erased. A coarse-grained band of clear, dust-free orthopyroxenes with coarse opaque minerals runs diagonally. Yamato-74013. Width is 0.80 mm.

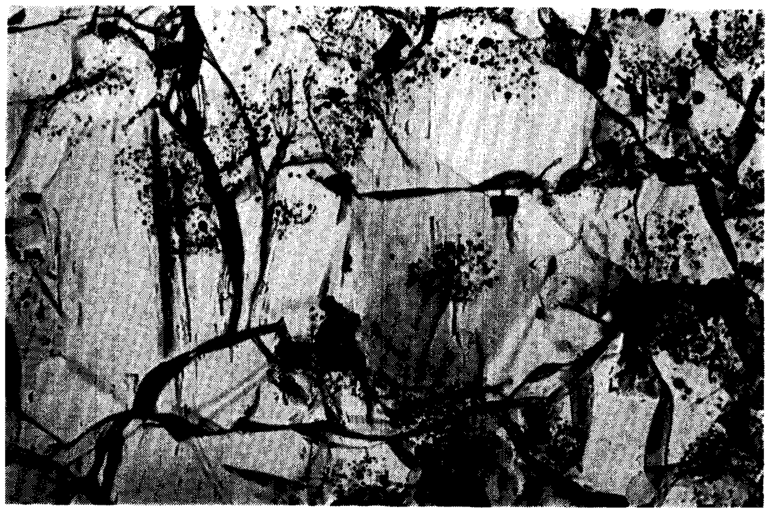

Fig. 10a. Coarse-grained area with clear large crystals of orthopyroxene. A haze of tiny inclusions of opaque minerals is left in the core of a recrystallized grain. The size of troilite is also larger than that in the finer-grained areas. Width is 0.8 mm.

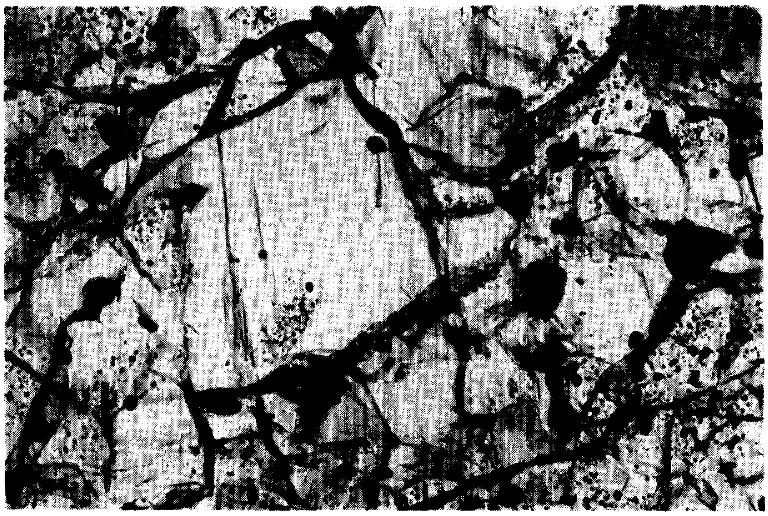

Fig. 10b. Very large clear orthopyroxene in a narrow coarse-grained vein in Yamato-74013. Width is 0.80 mm.

the longest direction (Fig. 1b). Irregular bands of dark yellow color consisting of large clear orthopyroxene crystals are distributed on the surface. Yamato-74013 is round and second largest in mass with a very scanty fusion crust (silky shiny black color). Yamato-74037 has no fusion crust. Yamato-74136 preserves approximately one-third of the shiny fusion crust, the remainder being removed by abrasion. Only one very small Yamato diogenite (Yamato-74031, 6.1 g) preserves considerable fusion crust covering the entire surface. The surface features of these diogenites are the same as that of Yamato-74097, except that the bright green-colored area in Yamato-74097 was not observed in other diogenites. Yamato-74136 contains more coarse-grained portions than the other Yamato diogenites.

3.2. Microscopic observations

A unique feature of the Yamato recrystallized diogenites among known diogenites (MASON, 1962) is a granoblastic texture of orthopyroxene, which was first pointed out by REID (TAKEDA *et al.*, 1975). More detailed petrographic description was given by DUKE in our previous paper (TAKEDA *et al.*, 1979b).

Yamato-74013 has a granoblastic texture, primarily in orthopyroxene, with grain size 0.1–0.2 mm in finer-grained areas, 0.4–3.0 mm in coarser-grained areas. Finer-grained portions have a haze of tiny inclusions of troilite, with yet smaller blebs of metallic iron in some troilite grains (Fig. 3). In coarser-grained areas, the troilite also is coarser and the pyroxene clear (Figs. 4 and 5). In a very coarse-grained area, plagioclases and silica minerals coexist with a coarse opaque mineral (Fig. 6).

The fine-grained areas are more abundant than the coarse-grained, and cover areas up to 3 cm or more in diameter and seem to be surrounded by coarse-grained

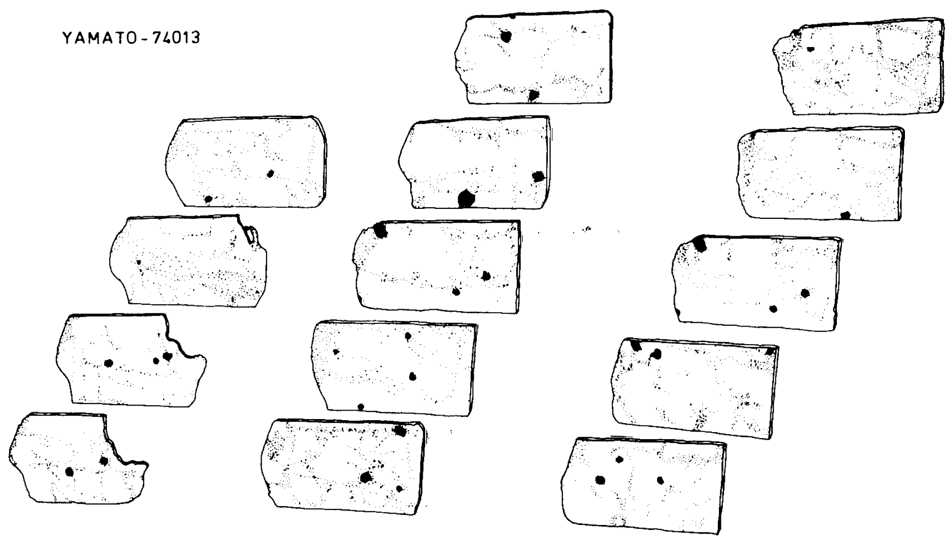

Fig. 11. Three-dimensional distribution of the coarse-grained areas (dotted) and chromites (black) in Yamato-74013. Successively cut slices are shown in sequence from lower left to upper right.

areas, giving the fine-grained areas the appearance of clots in a network of veins. The fine-grained areas show a subtle parallel structure that transects the granularity (Figs. 7 and 8). This structure is marked by relative abundance of opaque (troilite) grains, and short fractures. They are most prominent in areas of dense opaque inclusions. The orientation of this structure is largely uniform over dimensions of the samples studied (2–3 cm). In three dimensions, the structure is relatively coarse on two faces, and fine on the orthogonal face of the sample.

Chromite occurs as isolated clots up to 5 mm in diameter and in veinlets. Chromite in both occurrences contains inclusions of troilite, rare silicate (composition to be determined) and metal. The isolated chromites are rounded; they are surrounded by a 0.2–0.3 mm zone of clear, coarser pyroxene and are foci for radiating fracture patterns (Fig. 5).

We believe that we are dealing with a single or very small number of coarse pyroxene crystals that have been recrystallized by shock processes to a fine-grained granoblastic texture.

The parallel structures observed in the fine-grained areas look like planar features often observed in shocked minerals. Such planar features were observed in pigeonite single crystals in the Yamato-74659 ureilite (Fig. 1 in TAKEDA and YANAI, 1978). The X-ray diffraction study indicates that the orientation of the plane is nearly equal to (001). No large opaque minerals were detected along the plane. In the Yamato diogenite, the traces of the planes are not preserved, but the linear distribution of the minute opaque minerals defines the planes (Fig. 7) with certain intervals. In a rare

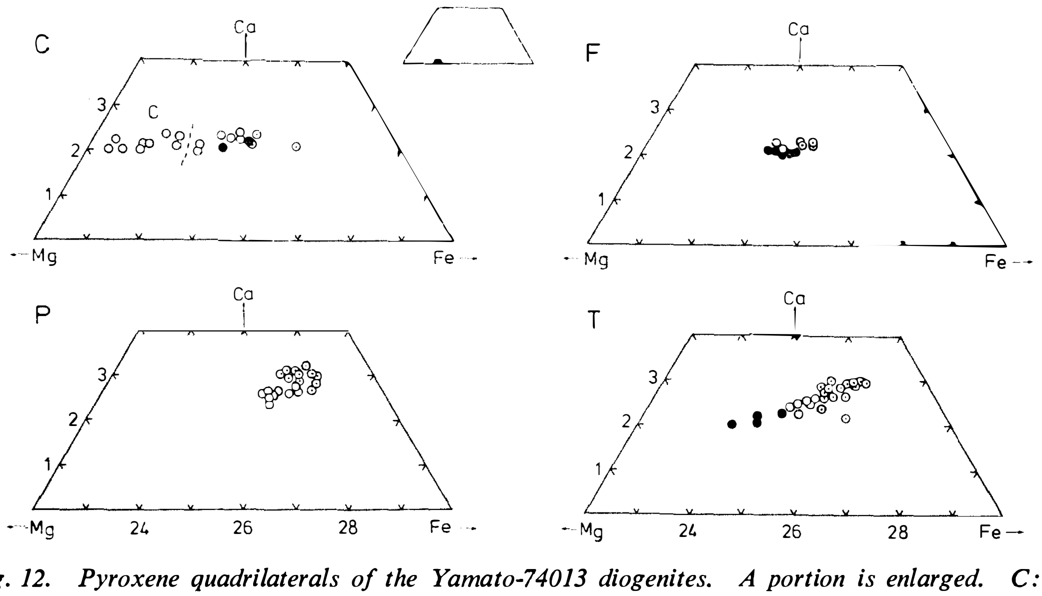

Fig. 12. Pyroxene quadrilaterals of the Yamato-74013 diogenites. A portion is enlarged. C: around chromite; P: around plagioclase; T: transitional portion between the coarse-grained and dusty fine-grained areas; and F: fine-grained area. Open circles: core; circles with a dot: rims of the clear crystals; and solid circles: fine-grained area.

case, the weak planar features were observed nearly perpendicular to the major parallel structure (Fig. 8).

In the coarse-grained area, the parallel structures are completely erased. In a transitional area, where dusty materials are partly removed or where the width of the coarse-grained band is narrow (Figs. 3 and 9), a part of the parallel structures is still left in the middle of a partly cleared crystal (Fig. 9). In the transitional area where the parallel structures were not preserved, only dense aggregates of dust inclusions are left in the central portion of a crystal (Fig. 10).

Three-dimensional textures reconstructed from the successively cut thin sections (Fig. 11) revealed that the coarse-grained areas form networks of irregularly curved veins or straight bands parallel to a certain direction or radial from a chromite. At the intersection of a few veins, there is a very coarse-grained area, where a plagioclase-silica assemblage occurs (Fig. 6).

The two-dimensional distribution of the bands in some of these diogenites suggests that this portion was the original matrix of the brecciated diogenite filling the interstices between the unbrecciated pyroxene clasts. Concentration of the Ca-rich materials in the matrix was taken as an evidence to support this idea. However, our observation on the presence of the straight bands and melted pocket-like distribution of the very coarse-grained areas more likely indicate that they were produced by shock effects. Whether the original materials were brecciated or not can not be disclosed unequivocally by the present study.

3.3. Chemical variation of the orthopyroxenes

A preliminary examination of the Yamato diogenites reported the following

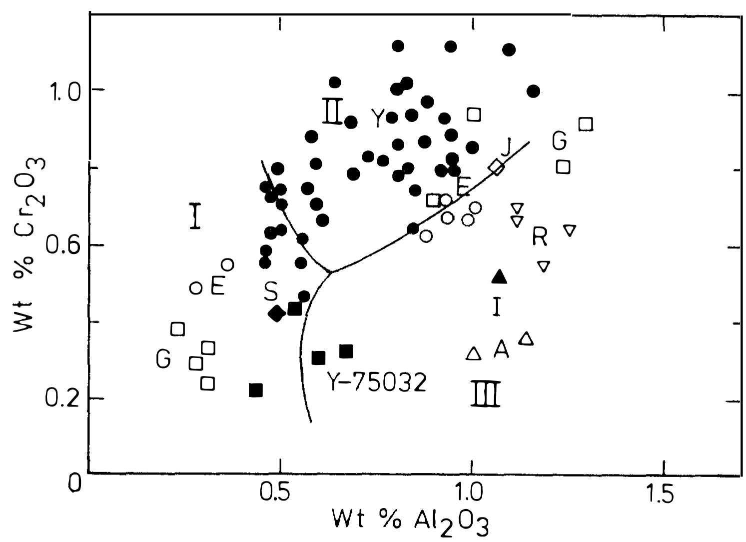

Fig. 13. Diogenite composition classes based on Al and Cr in orthopyroxene. After HEWINS (1981) with new data of Yamato-74013 (Y: solid circles) and -75032. A: Allan Hills-77256, E: Ellemeet, G: Garland, I: Ibbenbühren, J: Johnstown, R: Roda, S: Shalka.

chemical characteristics of the recrystalized diogenites. The chemical compositions of the orthopyroxenes in these Yamato diogenites fall in the range between $Ca_{1.9}Mg_{75.1}Fe_{23.0}$ and $Ca_3Mg_{71}Fe_{26}$. This compositional range (Fig. 12) is within that of the known diogenites (FREDRIKSSON *et al.*, 1976). The lower limit of the iron-calcium content of the orthopyroxenes in the Yamato recrystallized diogenites is close to that of Tatahouine, and the upper limit is beyond the Ibbenbühren pyroxene (Fig. 12). The chemical compositions of orthopyroxenes in the individual Yamato-74

Table 2. Selected chemical compositions of orthopyroxenes (1–6), plagioclase (7), and silica (8) from Yamato-74013.

Element	1 Fine dusty	2 Coarse clear	3 Core chrom.*	4 Edge chrom.	5 Core plag.*	6 Rim plag.	7 Plag.	8 Silica
SiO_2	53.8	53.6	53.0	53.4	53.6	52.9	44.9	98.8
TiO_2	0.03	0.07	0.04	0.06	0.12	0.14	0.06	0.09
Al_2O_3	0.50	0.88	0.58	0.51	0.62	1.27	34.2	0.69
Cr_2O_3	0.81	0.87	0.90	1.12	0.67	1.24	0.05	0.05
FeO	16.52	16.36	16.21	14.86	16.36	16.10	0.23	0.21
MnO	0.57	0.55	0.60	0.57	0.67	0.67	0.05	0.02
MgO	26.8	26.4	26.4	27.6	26.5	25.3	0.06	0.01
CaO	1.17	1.15	1.15	1.26	1.12	1.53	18.24	0.16
Na_2O	0.00	0.00	0.01	0.00	0.00	0.02	1.09	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.10
Total	100.20	99.88	98.89	99.38	99.66	99.17	98.92	100.13
	Cations per 6 oxygens						8 oxygens	
Si	1.955	1.954	1.954	1.948	1.958	1.947	2.096	3.963
Ti	0.001	0.002	0.001	0.002	0.003	0.004	0.002	0.003
Al	0.021	0.038	0.025	0.022	0.027	0.055	1.881	0.033
Cr	0.023	0.025	0.026	0.032	0.019	0.036	0.002	0.002
Fe	0.502	0.499	0.499	0.453	0.500	0.495	0.009	0.007
Mn	0.017	0.017	0.019	0.018	0.021	0.021	0.002	0.001
Mg	1.455	1.432	1.449	1.499	1.442	1.385	0.004	0.001
Ca	0.046	0.045	0.045	0.049	0.044	0.060	0.913	0.007
Na	0.000	0.000	0.001	0.000	0.000	0.001	0.099	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.005
Total	4.020	4.012	4.019	4.023	4.014	4.004	5.010	4.022
Ca**	2.3	2.3	2.3	2.5	2.2	3.1	—	—
Mg	72.6	72.5	72.7	74.9	72.6	71.4	—	—
Fe	25.1	25.2	25.0	22.6	25.2	25.5	—	—

* Adjacent minerals, chrom.: chromite, plag.: plagioclase.

** Atomic %.

diogenites are given in Fig. 3 and Tables 1 and 2 of TAKEDA *et al.* (1978). The compositional variation of all seven Yamato-74 diogenites is considered to be identical. The composition within one crystal is uniform, but the calcium and iron contents in the large clear orthopyroxenes appear to be slightly higher than those of inclusion-rich small ones.

More detailed microprobe work on over 400 points on orthopyroxenes in areas exhibiting different textures shows subtle but distinct chemical zonings in clear large orthopyroxenes in the very coarse-grained area (Fig. 12, P and T).

The Ca and Fe contents of large, clear orthopyroxenes (nearly 1 mm in diameter) with almost no opaque inclusions (Fig. 10) are as low as those of the dusty orthopyroxenes in the fine-grained areas. The rims of the large, clear pyroxene crystal show higher Ca and Fe concentrations than those of the cores. This trend is notable towards the plagioclase boundaries. This chemical variation is not so evident when the grain-size of the clear dust-free orthopyroxene is small. The marginal portion of a clear pyroxene adjacent to a large chromite is very depleted in the Fe content (Fig. 12, C).

The Ca and Fe contents of the fine-grained area full of opaque inclusions are low in general (Fig. 12, F) but higher that those at the chromite boundaries. Both the inter- and intragranular variations in the chemical composition of pyroxenes in the fine-grained area are not as extensive as those of the other areas. This trend is maintained for the small dust-free portion of the crystals in the narrow coarse-grained bands within the dusty area of the thin sections. The evidence of the small chemical variation within the fine-grained area suggests that this area represents the original unaltered state.

The evidence of chemical zoning in the very coarse-grained areas accompanying plagioclase and a silica mineral and around chromite crystals may indicate that migration of cations took place during or subsequent to the high temperature stage by the shock events. Large grain-sizes of both pyroxenes and troilites and the concentration of Ca- and Al-rich minerals in the coarse-grained areas suggest that this portion might have been partially melted. However, preservation of the chemical zonings and a lack of exsolution lamellae in pyroxene reveal that the subsequent cooling rate after the high temperature stage was relatively fast.

The chemical variations in other elements in pyroxene are given in Fig. 13, and are compared with those by HEWINS (1981). The Cr_2O_3/Al_2O_3 values are distributed from Type I of HEWINS to Type II, where most of the Ca-rich rims are plotted. The chemical compositions of representative minerals are given in Table 2.

3.4. Microtextures of the coarse-grained orthopyroxenes

The microtextures of the diogenitic pyroxenes studied with the TEM techniques (MORI and TAKEDA, 1981) are represented by subboundaries in a single crystal, formed by assemblages of dislocations and decorated by exsolved augites, chromites, troilites and tridymites with certain crystallographic directions in common with the host orthopyroxene. The TEM study showed that the orthopyroxenes in an ordinary diogenite from Antarctica (Allan Hills-77256) had fairly high density of stacking faults and dislocations (TAKEDA *et al.*, 1980). Many of the dislocations were arrayed into low-angle subboundaries.

Unlike these ordinary diogenitic pyroxenes, the Yamato-74013 pyroxenes did not have any of the microstructures previously described for diogenites. The TEM observation of the coarse-grained orthopyroxenes in Yamato-74013 shows stacking faults parallel to (100), which are thought to have been produced by weak shock effects when the meteorite mass was formed. Neither exsolution nor dislocation indicating low strain-rate deformation has been observed. The results are in agreement with a deformational history that the Yamato diogenites were originally heavily shocked, producing intergranular melting and then a short period of thermal annealing was followed by relatively rapid cooling and no other subsequent thermal nor deformational event took place until the meteorite mass was formed.

4. Discussion

Among thirty diogenites found in the Yamato meteorite field, twenty-nine have been proposed to be pieces of a single fall, because of their unique granoblastic textures. The only other Yamato diogenite, Yamato-75032 has a chemical composition and texture distinctly different from other known diogenites (MASON, 1962; TAKEDA *et al.*, 1979a). For most diogenites the original crystallization was followed by mechanical brecciation without substantial recrystallization. The evidence of recrystallization found for the Yamato diogenites indicates their unique nature as was pointed out by us for Yamato-692 (TAKEDA *et al.*, 1975). The texture is totally unlike that of Tatahouine, which appears to be the only other unbrecciated diogenite (A. M. REID, private communication, 1975). In order to explain the event which caused this recrystallization, more detailed studies on shock effects in pyroxene are required. Whether the unique Yamato diogenites are pieces of a single fall or not may rest on the interpretation of the origin of heterogeneous distribution of recrystallized materials within the single meteorite.

Since we reported the results of our preliminary examination of the Yamato-74 diogenites (TAKEDA *et al.*, 1978), some new evidences on the textures of shocked meteorite have been accumulated. Planar features nearly parallel to (001) of pigeonite have been found in a shocked pyroxene-rich ureilite, Yamato-74659 (TAKEDA and YANAI, 1978). The linear structures found in Y-74013 resemble those of the shock-produced features in the ureilite. Inhomogeneous distribution of olivine vitrophyres and quench products of shock-melt pockets in cm-order scale found in a unique achondrite, Allan Hills-77005 (ISHII *et al.*, 1979), give some clues to interpret the distribution of coarse-grained areas in Y-74013. Our finding of subboundaries decorated with troilites, chromites and tridymites in many diogenites (MORI and TAKEDA, 1981) can be used to understand the presence of a haze of tiny inclusions of troilite in the Yamato diogenites.

In the light of the above new developments in diogenite mineralogy, the thermal and deformational histories of the unique Yamato diogenites, consistent with our new observation on Y-74013, can be constrained as (1) crystallization in the deep crust on the parent body, (2) one or more impact events during the subsolidus cooling under slight reducing and sulfurizing conditions, (3) the final strong impact event, which produced recrystallization and partial melting, followed by relatively rapid cooling, (4) ejection of a parental mass of the Yamato diogenite from the parent body, which was eventually brought into the orbit near the Earth, and (5) breakup of the original meteorite mass during the flight through the Earth's dense atmosphere.

The uniform chemical composition of pyroxenes in the fine-grained area in different masses of the Yamato diogenites and the large euhedral chromite crystals may support an idea of near-equilibrium crystallization in the deep crust (MASON, 1967; TAKEDA, 1979). This initial crystallization must have taken place very early in the history of the solar system, but the radiogenic clock was reset by a later impact event.

During the subsolidus cooling, a portion of the deep crust experienced a shock event, which produced planar features in pyroxenes and deformation of the chromite crystals. The temperature at this stage was low enough not to cause creep of dislocations to form subboundaries, which are observed in many diogenites. However, a slight reducing condition and a sulfurization process, which decorated subboundaries in many diogenites with troilites, chromites and tridymites (MORI and TAKEDA, 1981), produced troilites and other dusty inclusions in planar structures and dislocations in the shocked pyroxenes. Evidence of subsolidus reduction has been reported for lunar mare basalts (BRETT *et al.*, 1971) and diogenites (GOOLEY and MOORE, 1976). The reduction of pyroxene with supply of sulfur may produce troilites and oxide minerals.

The time of this dust formation can not be deduced because of the disturbances by the subsequent shock event. The polycrystallization (or recrystallization) of large original pyroxene crystals may have taken place after the above events, because the parallel structures transect the granularity of the recrystallized pyroxenes. The euhedral chromite crystals are interpreted as inherited from coarse crystalline rocks because of their unusually large crystal size in comparison with those of pyroxenes.

The final impact event that produced the characteristic granoblastic texture must have brought many parts of the rock above the melting point. Because the effects of the shock waves on crystalline rocks are expected to be very complex, partially melted portions may be distributed quite unevenly. Uneven distribution of melt pokets in a few cm intervals found in a heavily shocked meteorite (ALH-77005) gives a strong support for the shock-melted origin of the coarse-grained areas of the Yamato diogenites which are also distributed over a few cm intervals. Since the original grain sizes of the diogenitic pyroxenes are assumed to be larger than those of ALH-77005, detailed shock features could be different. A preferential melting could occur at the grain boundaries of pyroxenes or between pyroxene and chromite. This interpretation is in agreement with the observed distribution of the coarse-grained areas.

A possibility that the heat source which produced the coarse-grained area is radiogenic, such as ^{26}Al, is unlikely, although the coarse-grained areas are distributed around Al-rich minerals such as chromite and plagioclase. The presence of a straight band of partly clear coarse crystals at a place where no Al is concentrated rules out such radiogenic heating.

The degree of partial heating may differ from one place to another. At a place where the temperature was high enough to expel dusty sulfide inclusions, but not high enough to melt the minerals, only clear crystals of relatively small grain sizes will be produced. At a place where large-scale partial melting took place, the Al and Ca atoms and possibly rare-earth atoms will be concentrated and plagioclases will crystallize in the interstices of pyroxenes. The sulfide component removed from dusty regions grew into larger crystals of troilite at such places. The coexistence of a large pyroxene crystal with a core of dust inclusions and coarse troilites around the pyroxene (Fig. 10) supports this interpretation. The concentration of a silica mineral in the coarsest grain areas together with plagioclases and coarse troilites, suggests that SiO_2 was produced when the silicates were reduced to produce sulfides.

We cite the presence of chemical zoning at the rims of the very coarse-grained areas and around large chromite crystals as an evidence of partial melting. On the other hand, preservation of the chemical zoning suggests that the subsequent cooling was relatively rapid. The TEM observation that neither exsolution nor dislocation indicating low strain-rate deformation (MORI and TAKEDA, 1980) is present in the coarse orthopyroxenes supports this hypothesis. However, the duration of the high temperature stage must be long enough to form large-sized crystals of pyroxenes and troilites.

During the high temperature stage, the isotopic distribution must have been reset in the coarse-grained areas while leaving that of the fine-grained areas almost unchanged. The complex shock and thermal annealing histories may be the sources of the isotopic disturbances and redistribution of the rare-earth elements proposed by MASUDA *et al.* (1979) and NAKAMURA (1979). The young ^{40}Ar-^{39}Ar age obtained for a Yamato diogenite (KANEOKA *et al.*, 1979) may represent the impact event that produced partial melting.

It is clear from the above studies that the differences found in the rare-earth elements and isotope distribution between the different masses of the Yamato diogenites may be attributed to heterogeneous sampling and that we are dealing with pieces of a single fall. The fact that four of the Yamato diogenites found at different locations fit together in hand specimen, and that the unique Yamato diogenites are distributed in a limited area of the Yamato meteorite field, give strong support for the single fall.

Because the coarse-grained areas are easily broken, this portion may occupy a large fraction of some of the small samples distributed to the investigators.

In conclusion, the granoblastic texture and the parallel structures characteristic of the Yamato diogenites except Yamato-75032 may have been formed by recrystallization of a few very large crystals (probably several cm in diameter) by heavy shock processes, and subsequent thermal annealing. Coarse-grained areas may indicate intergranular melting and recrystallization. The concentration of the Ca and Fe cations at the rims of crystals in coarse-grained areas supports this hypothesis. Some differences found in rare-earth element abundance of the different masses of the Yamato diogenites may be the results of inhomogeneous sampling, and some isotope disturbances may be attributed to different degrees of shock processes and thermal annealings. We believe that we are dealing with pieces of a single fall, and that the unique Yamato diogenites with granoblastic textures are among the most heavily shocked diogenites.

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