THE FRACTURE STRENGTH OF METEORITES: ITS IMPLICATION FOR THEIR FRAGMENTATION

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***Abstract*:** The vibrational fracturing rate (VFR), cutting rate (CR), porosity and density were measured for shock-melted LL chondrites in the Yamato-79 collection and some achondrites in order to study the fracture strength (the degree of lithification) of meteorites quantitatively. The VFR's show very small values for these LL chondrites and diogenite Yamato-74013, that is, these meteorites are hard to break. Yamato-790964 is the most porous of these LL chondrites, but its VFR value is the smallest. We also examined the shape and mass distribution of Antarctic meteorites in order to investigate whether difference in the fracture strength is reflected in these data. There are subtle differences of axial ratio (b/a), although the number of the meteorites examined in this study is too small and the differences are not statistically significant. The top ten in the mass distribution of L chondrites in the Antarctic collection are all L6, whereas L6 is the weakest of all the petrologic types in fracture strength. This result implies that L6 chondrites were larger than the other petrologic types of L chondrites in space.

1. Introduction

Collision is considered one of the most important processes in the growth of planetesimals or in the evolution including the surface brecciation of meteorite parent bodies, as well as in the impact cratering on the surface of planets. Although the collision process is dependent on sizes or relative impact velocities of mutually impacting bodies, fracture strength (or the degree of lithification) is also one of key properties of colliding bodies. Because the extraterrestrial materials now observed are evidently lithified to some extent, it is also important at what time and how the planetesimals ($\sim 10^{18}$ g; GOLDREICH and WARD, 1973) or meteorites were lithified in the early stages of the evolution of the solar system.

We have already proposed a new strength measure named 'vibrational fracturing rate (VFR)' in order to study quantitatively the degree of lithification of meteorites (FUJII *et al.*, 1980). By using the vibrational fracturing rate method, we have already shown the differences of relative strength among H, L, LL and C chondrites quanti-

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tatively (FUJII *et al.*, 1981b). In addition to these results, we have measured, for this study, the vibrational fracturing rates for shock-melted LL chondrites and some achondrites, and have measured the cutting rates of these meteorites for comparison. We will discuss the relationship between the results of the vibrational fracturing rate and the mass spectrum or shape of Antarctic meteorites.

2. Experimental

2.1. Vibrational fracturing rate (VFR) measurement

The ground surface of a sample was excavated with a 2 mm-diameter steel rod by using an ultrasonic machine which vibrates vertically at 19.5 kHz. Water was continuously supplied but no grinding powder was used. The rate of excavation under a constant normal stress ($\sim$0.5 MPa) was measured by a differential transformer and recorded on a strip chart. The vibrational fracturing rate (VFR) is defined as the rate of the excavation (*e. g.* in mm/min). The VFR of calcite or olivine was used as a standard. The experimental procedures were the same as those described in detail by FUJII *et al.* (1980, 1981b). Samples of meteorites were embedded in resin and cut to make at least a 5×5 mm flat surface. The VFR measurements were made several times on one side of each sample and the average of these measurements was taken as the VFR of the sample.

The meteorite samples were supplied by the National Institute of Polar Research. Yamato-790519, Yamato-790723 and Yamato-790964 in the Yamato-79 collection are classified as the shock-melted LL chondrites by YANAI *et al.* (1981). Three achondrites, polymict eucrite ALH-765 (MIYAMOTO *et al.*, 1979), diogenite Yamato-74013 (TAKEDA *et al.*, 1978) and ureilite ALH-77257 (TAKEDA *et al.*, 1980) were also used for this study.

By using the Archimedian principle, density and porosity were measured for a fragment of these meteorites from the same specimen as that used for the vibrational fracturing rate measurements. The method used is the same as that described in FUJII *et al.* (1981b).

2.2. Cutting rate (CR) measurement

Cutting rate (CR) was measured for these meteorites by using a rotating diamond blade 0.8 mm thick and 100 mm in diameter. Cutting rate was measured by a differential transformer at the cutting depth of the sample as a function of time under dry condition. The flat surface of a sample was held against the diamond blade by using a lever system. For experimental convenience, we took a constant normal load of 100 g. Rotation speed of the diamond blade was kept constant at 8 s/turn. The method to measure the cutting rate is described in more detail in FUJII *et al.* (1981a). The sample used for cutting rate measurement is another side of the cut sample used for the vibrational fracturing rate measurement.

2.3. Shape of meteorite

HASEGAWA (1981) has already examined the shape of Antarctic meteorites which is described by the axial ratio. FUJIWARA *et al.* (1978) and HASEGAWA (1981) proposed a method to describe the fragment shape quantitatively, that is, the shape is specified by the axial ratio (b/a) and (c/a), where a, b, c are the longest, intermediate and the shortest axial lengths, respectively. The shape of meteorites seems to be dependent on their strength as well as the nature of high velocity impact processes which they suffered (HASEGAWA, 1981). In order to compare the shape of the meteorites with our results of the VFR measurements, we examined their shape, taking into consideration the class of the meteorites. The data of the axial lengths are collected for the Antarctic meteorites which have been already classified into meteorite classes. The data of the axial length of the Yamato-73, -74, -75 and -79 and Allan Hills-76 collections are from the Catalog of Yamato Meteorites (YANAI, 1979) and Meteorites News (Natl Inst. Polar Res., 1982), and those for the Allan Hills-77, -78 and -79 collections are from the Antarctic Meteorite Newsletter (NASA, 1981).

3. Results and Interpretations

Table 1 summarizes the results of vibrational fracturing rate (VFR), cutting rate (CR), porosity and bulk density measured for the meteorites. The results of VFR for the H, L, LL5, LL6 and Allende meteorites are from FUJII *et al.* (1981b). The CR results for these meteorites are converted into the values in the case of normal load of 100 g on the basis of those reported by FUJII *et al.* (1981a). We use the value measured for olivine as a standard, because the actual values of VFR and CR are affected by

Table 1. Vibrational fracturing rate (VFR), cutting rate (CR), porosity and density of meteorites.

		VFR[1)] (mm/min)	CR[2)] (mm/min)	Porosity (%)	Bulk density (g/cm^3)
Y-790519	(LL)	0.0094	0.044	7	3.11
Y-790723	(LL)	0.0095	0.044	8	3.03
Y-790964	(LL)	0.0070	0.051	16	2.78
Y-74013	(Di)	0.0034	0.041	1	3.44
ALH-765	(Eu)	0.021	0.086	7	2.92
ALH-77257	(Ur) (m)	0.045	0.046	6	3.15
	(i)	0.0053			
ALH-77233	(H4)*	0.010	0.051	5	3.45
ALH-77182	(H5)*	0.010	0.064	15	2.97
ALH-77115	(H6)*	0.012	0.069	(8)[4)]	(3.11)[4)]
Y-74191	(L3)*	0.011	0.074	—	—
ALH-77230	(L4)*	0.014	0.059	1	3.44
ALH-77254	(L5)*	0.021	0.050	(18)	(2.88)
ALH-77231	(L6)*	0.110	0.121	(3)	(3.66)
ALH-78105	(L6)*	0.225[3)]	0.127	4	3.44
ALH-78109	(LL5)*	0.260[3)]	0.208	20	2.72
Y-75258	(LL6)*	0.230	0.178	(33)	(2.38)
Allende	(C3)* (m)	0.360–0.760[3)]	0.213	26	2.68
	(i)	0.040			
Olivine		0.019	0.042		

* From FUJII *et al.* (1981a, b).

1) Values are obtained under normal stress of 0.5 MPa.

2) Values for normal load of 100 g.

3) VFR becomes unmeasurably high after a few minutes' experiment.

4) Parentheses indicate less accurate data (specimen weight, <150 mg), uncertainty of bulk density is more than a few percent.

the conditions of measurement (FUJII *et al.*, 1981a, b), and the meteorites studied in this study are as hard as olivine. Ureilite ALH-77257 (m) and (i) in Table 1 indicate different portions measured on the same meteorite. Although wide variations of VFR are observed in this sample surface, a great part of the sample shows the VFR value in the range of about 0.07–0.02 mm/min. A small area (about 1.5 mm in diameter) of the surface, probably on a crystal-grain contained in the sample shows the value (i) of VFR. The VFR for the bulk of ALH-77257 would be represented by (m).

Figure 1 shows the logarithmic ratios with a minus sign of VFR of the samples studied (V) to that of olivine (V_0). Shock-melted LL chondrites, Y-790519, Y-790723 and Y-790964 show the lowest VFR of ordinary chondrites. Yamato diogenite, Y-74013 shows a very low VFR value.

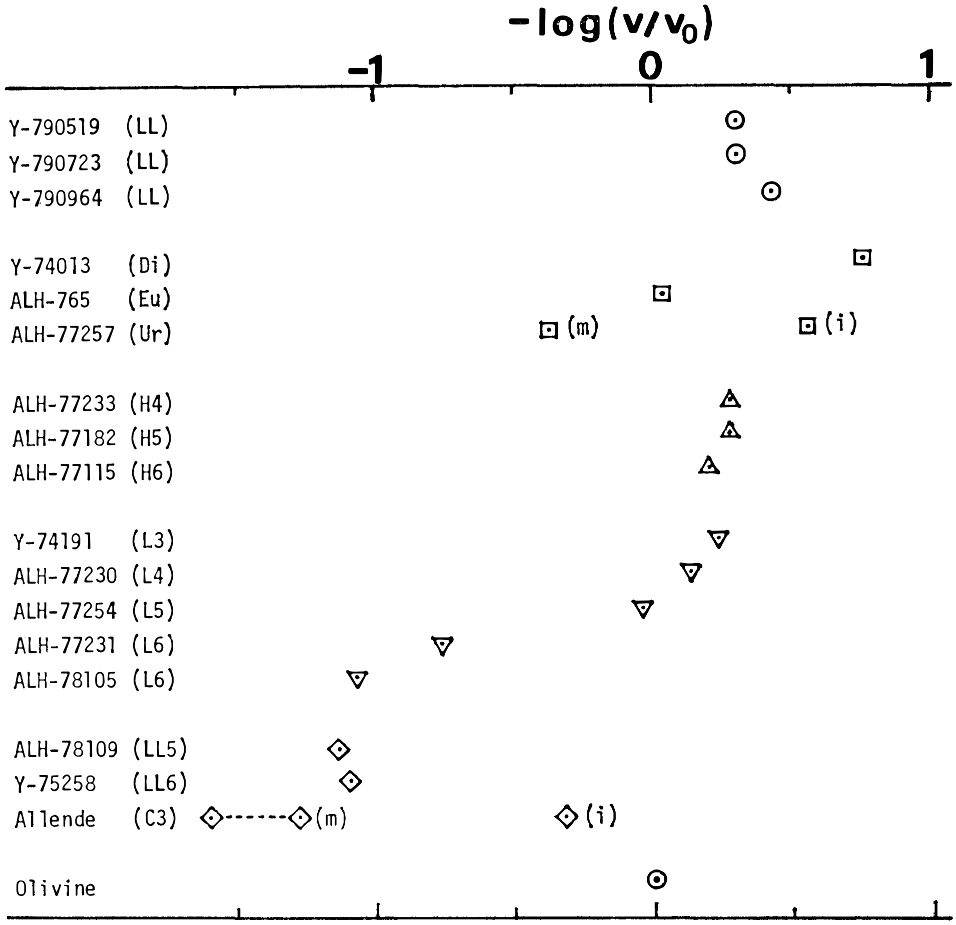

Fig. 1. Logarithmic ratios, $-\log (V/V_0)$, of the vibrational fracturing rate of meteorites (V) and that of olivine (V_0).

Figure 2 shows the logarithmic ratios with a minus sign of CR of the samples studied (U) to that of olivine (U_0). The CR and VFR results are mutually related (FUJII *et al.*, 1981a), although the range of the variation in the values of CR for the meteorite samples is about 10 times smaller than that of VFR.

Among the shock-melted LL chondrites, differences in the values of porosity are found (Table 1). The largest value of porosity for Y-790964 is consistent with the re-

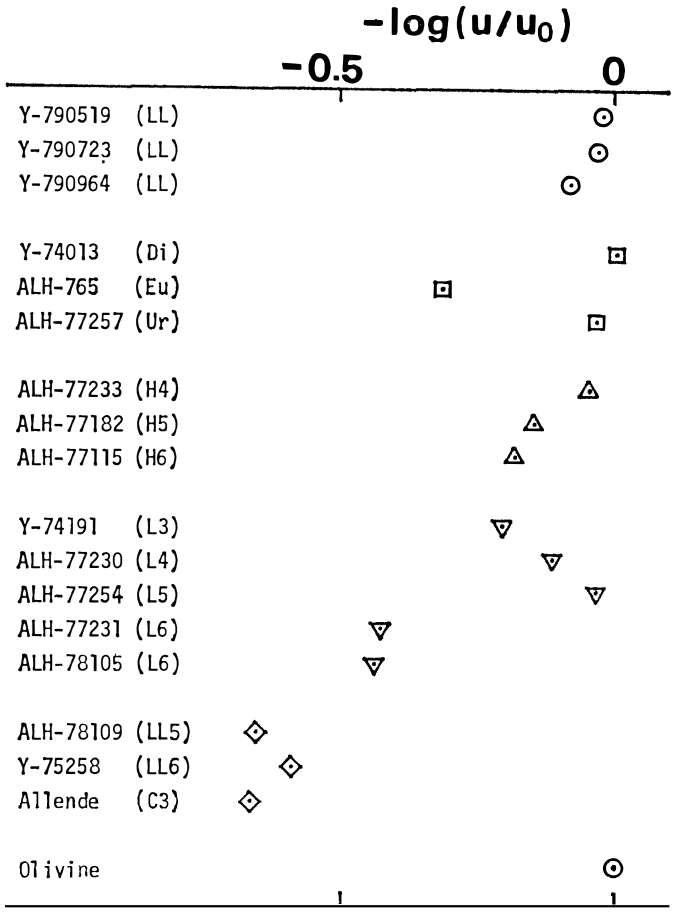

Fig. 2. Logarithmic ratios, $-\log (U/U_0)$, of the cutting rate of meteorites (U) and that of olivine (U_0).

Table 2. The average axial ratio of Antarctic meteorites.

	⟨b/a⟩			⟨c/a⟩
	JPN	USA	Total	Total
H4	0.778 (15)	0.789 (18)	0.784 (33)	0.547 (17)
H5	0.723 (17)	0.695 (32)	0.704 (49)	0.476 (32)
H6	0.753 (16)	0.765 (15)	0.759 (31)	0.531 (15)
ΣH	0.758 (50)	0.734 (67)	0.745 (117)	0.507 (67)
L3	—	0.639 (12)	0.689 (15)	0.504 (11)
L4	0.732 (7)	—	0.732 (7)	—
L5	0.796 (7)	—	0.743 (11)	—
L6	0.774 (23)	0.698 (39)	0.726 (62)	0.536 (43)
ΣL	0.761 (53)	0.681 (55)	0.720 (108)	0.524 (57)
ΣLL	—	—	0.660 (13)	0.468 (13)
Iron			0.718 (18)	0.414 (16)
Eucrite*			0.727 (24)	0.420 (13)
Diogenite			0.792 (28)	—
Ureilite			0.785 (6)	—
ΣC			0.761 (10)	

Number in parentheses denotes the number of sample.
Σ indicates the sum of petrologic types.
* including howardites.

sults of the petrographic study by SATO *et al.* (1982). The smallest porosity of the Y-74013 diogenite among the meteorites studied is also consistent with its recrystallized granoblastic texture common in Yamato diogenites (TAKEDA *et al.*, 1975, 1978, 1979, 1981).

The results of the shape of meteorites are listed in Table 2. The average axial ratios $\langle b/a \rangle$ and $\langle c/a \rangle$ in every meteorite class are shown when the number of meteorites classified is more than 5. ΣH includes H3, H4, H5, H6 and H-group not yet classified into petrologic type. The same is true for ΣL. The $\langle b/a \rangle$ of ΣH seems to be slightly higher than that of ΣL. Because the standard deviation of (b/a) is about 0.15, this difference is not statistically significant. No correlation among petrologic types is observed. The distribution of axial ratio (b/a) of representative meteorite groups are shown in Fig. 3. The number of samples in the meteorite groups is too small to discuss in detail. Figure 3 also shows the distribution of (b/a) in H and L chondrites more than 100 g in weight. It is interesting that the distribution of (b/a) in iron meteorites shows a bimodal pattern.

Figure 4 shows the integral mass spectra for the H, L, LL, diogenites, eucrites and iron meteorites. Flatness of spectra in the range of small mass (<100 g) seems to be due to the few small meteorites so far classified. HASEGAWA (1981) indicated that mass

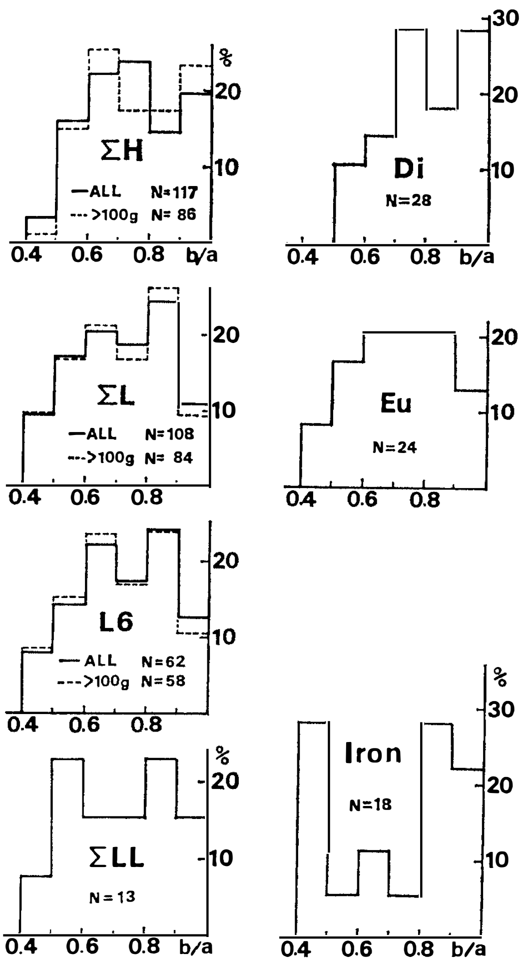

Fig. 3. Distribution of axial ratios (b/a) for some meteorite classes in the Antarctic collection. ΣH: H chondrites of all petrologic types; ΣL: L chondrites of all petrologic types; ΣLL: LL chondrites of all petrologic types; Di: Diogenites; Eu: Eucrites (including howardites); Iron: Iron meteorites.

Σ represents the sum of petrologic types. Dotted lines denote the distributions of (b/a) for the meteorites more than 100 g in weight.

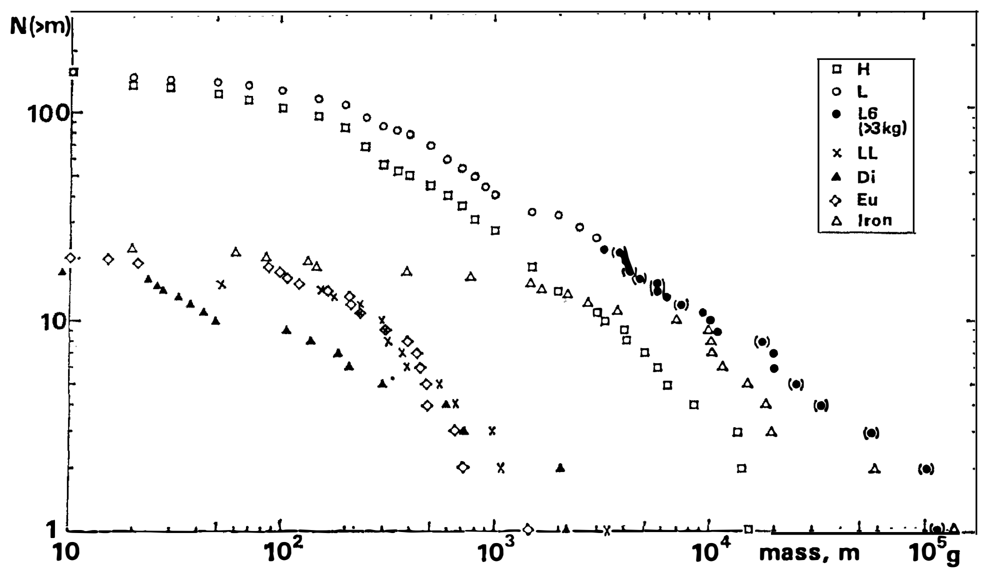

Fig. 4. Integral mass spectra (cumulative number) for some meteorite classes in the Antarctic collection. H: H chondrites of all petrologic types; L: L chondrites of all petrologic types; LL: LL chondrites of all petrologic types; Di: Diogenites; Eu: Eucrites (including howardites); Iron: Iron meteorites. Solid circles denote L6 chondrites more than 3 kg in weight. Solid circles in parentheses denote pieces of the ALH-769 L6 chondrite.

spectra of fragments of meteorite showers may be represented by a power law and that the steeper mass spectrum may correspond to the larger equivalent E/M_t value, where E, M_t are impact energy and target mass, respectively. There is no significant difference in the exponents of mass spectra between H and L chondrites in the mass range of 10^2 to 10^4 g. When the ALH-769 L chondrite which is the largest L chondrite of the Antarctic collection consisting of 33 pieces is excluded, the slopes of L and H chondrites are equivalent (ITO *et al.*, 1982).

4. Discussion

4.1. Vibrational fracturing rate and cutting rate

The shock-melted LL chondrites in the Yamato-79 collection are dark-colored stones with fine-grained glassy texture (YANAI *et al.*, 1981; SATO *et al.*, 1982). These chondrites are considered to be surface regolith materials of the LL parent body that were subjected to various degree of shock melting, crystallization from a melt, shock recrystallization and brecciation due to intense impacts, and were eventually consolidated into a coherent rock (YANAI *et al.*, 1981). The presence of vesicles and glass which may have been produced by shock heating is the characteristic feature of these chondrites. The brown glass and fine-grained glassy materials fill interstices of laths of euhedral pyroxene crystals and mineral fragments (SATO *et al.*, 1982). Very low value of VFR for these LL chondrites can be explained by the glassy materials which fill interstices of mineral fragments (Table 1). Y-790964 has the greatest amount of vesicles and glass among these three LL chondrites and may have experienced the most intense shock-melted recrystallization (SATO *et al.*, 1982). Y-790964 is the most porous of these LL chondrites (Table 1), but its VFR value is the smallest.

Polymict eucrite ALH-765 is considered to be the product of brecciation processes on the surface of a howardite parent body (MIYAMOTO *et al.*, 1979), and shows relatively high VFR compared with that of the Y-74013 diogenite (Table 1). Twenty-nine recrystallized diogenites including Y-74013 have been found in the Yamato meteorite field (YANAI, 1979; TAKEDA *et al.*, 1975, 1978, 1979). On the basis of their mineralogical studies, TAKEDA *et al.* (1981) has proposed that these diogenites are pieces of a single fall. These diogenites show recrystallized and granoblastic texture of orthopyroxene unlike that of common diogenites (TAKEDA *et al.*, 1979). The low values of VFR and porosity for Y-74013 are consistent with its texture and considered to be due to the recrystallized condition.

The ALH-77257 ureilite consists almost entirely of anhedral to subhedral olivine ($\sim$80%) and pyroxene ($\sim$15%). ALH-77257 is fairly coarse-grained, with olivine grains up to 3 mm. All grain boundaries are almost evenly filled with dark carbonaceous material, in which trace amounts of troilite and iron metal are scattered (MASON, 1978; TAKEDA *et al.*, 1979). TAKEDA *et al.* (1979) reported that the ALH-77257 ureilite is resistant to cutting, but is relatively brittle. The high VFR of ALH-77257 (m) seems to be in harmony with the brittleness of this meteorite (Table 1). The difficulty in cutting is probably due to diamond grains in the ureilite. Contrary to this fact, our CR of ALH-77257 is relatively high and similar to that of olivine. This discrepancy can be explained by the following reason. In our CR measurements, the sample is cut with a rotating diamond blade to a depth of only $\sim$200 microns. The material cut with the blade is probably a crystal grain (olivine) in ALH-77257 because the meteorite is fairly coarse-grained.

The VFR values are roughly proportional to those of CR for the corresponding meteorites but a few exception (Table 1). For example, the VFR value of Y-790964 is the lowest of three shock-melted LL chondrites, but its CR value is the highest. The range of variations among the CR values is smaller than that of VFR. As was shown in Table 1 and Fig. 2, the CR values for all the meteorites except for the Y-74013 diogenite are larger than that of olivine. Namely, all the meteorites measured in this study are easier to cut with the blade than olivine. This relation, however, does not hold true of the values of VFR. This result of the CR values may be dependent on the difference in physical properties between the crystal (olivine) and mineral assemblages (meteorite). The differences between the VFR and CR seem to be partially dependent on the following reason: In VFR measurements, fragments of the sample itself acted as grinding powder vertically hitting the sample surface within the water layer because no grinding powder was used; in CR measurements, the sample surface is abraded by the diamond grains planted in the rotating blade, and the CR is probably related to abrasion properties and/or grain-to-grain adhesion (FUJII *et al.*, 1981a). General correspondence between the VFR and CR, however, suggests that there should exist some physical mechanism to relate the strength of these meteorites.

4.2. *The shape and mass distribution of meteorites*

Meteorites seem to have experienced many impacts at various stages of their history. The shape of meteorites and their mass distribution are considered to be influenced significantly by impacts. In fact, on the basis of the results of the shape and mass distribution of meteorites, HASEGAWA (1981) has already shown that the distribution of (b/a) is similar to that obtained for basalt fragments in a laboratory impact experiment. By measuring the VFR and CR, we recognized that there are some differences in the fracture strength of each meteorite class. We, therefore, investigated whether the differences of this physical property are reflected in the shape and mass distribution of meteorites on the basis of the data on the Antarctic meteorites which have been already classified into meteorite classes.

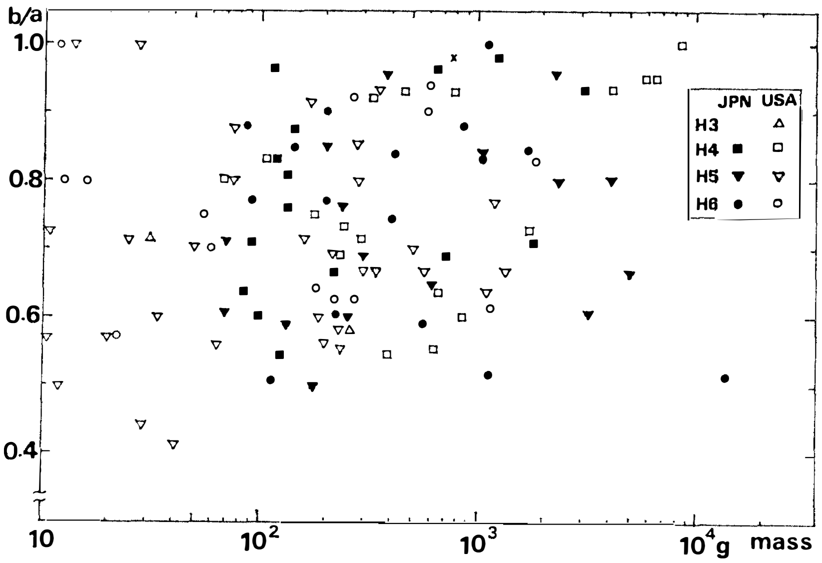

Fig. 5. Axial ratio (b/a) vs. mass of H chondrites. Solid and open symbols denote the H chondrites in the Japan and U.S.A. collection, respectively. × indicates an H chondrite which has not yet been classified into petrologic type.

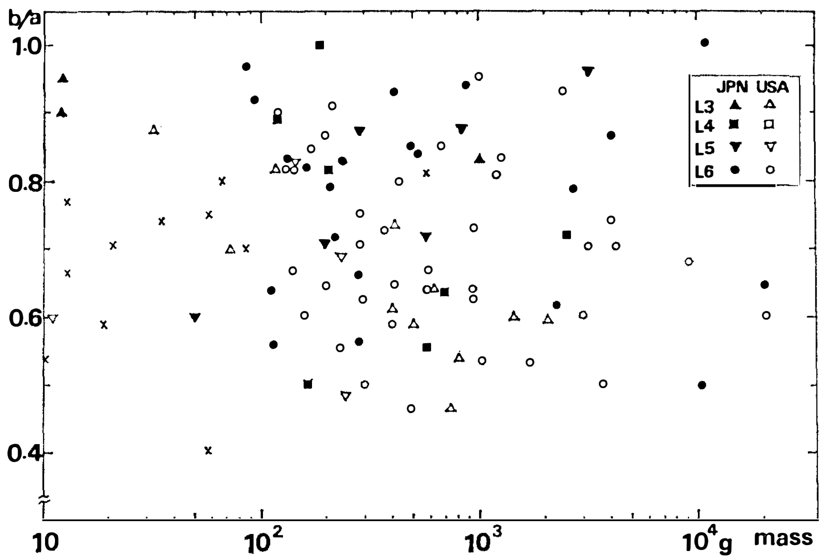

Fig. 6. Axial ratio (b/a) vs. mass of L chondrites. Solid and open symbols denote the L chondrites in the Japan and U.S.A. collection, respectively. × indicates an L chondrite which has not yet been classified into petrologic type.

As shown in Table 1, the values of <b/a> for ordinary chondrites in the USA collection have a tendency to show smaller values than those of the corresponding Japan (JPN) collection. In order to make the reason for these differences clear and to examine the changes of the value of (b/a) with the mass of the meteorite sample, we plotted the distribution of (b/a) *vs.* the mass of the meteorites (Figs. 5–7). Among the ordinary chondrites which have been already classified, Figs. 5 and 6 showed that (1) we can not find a significant difference in number of the chondrites which have large mass (>1 kg) between the USA and JPN collections; (2) the small H chondrites ($<\sim 80$ g) in the USA collection are larger in number than those in the JPN collection. There is no correlation between the shape and mass of meteorites (Figs. 5–7). Figure 8 shows the comparison of the distributions of (b/a) in H and L chondrites of more than 100 g in weight between the JPN and USA collections. Some differences are found between the JPN and USA collections. The populations for H and L chondrites collected may differ from each other. These differences may be caused by the method to measure the length of axes, probably the definition of b.

As was pointed out by Hasegawa (1981), the shape of Yamato diogenites is round and their mass spectrum is flat compared with that of chondrite showers. We examined the shape of eucrites (and howardites) for comparison. As is shown in Fig. 3, the shape of eucrites seems to be similar to that of chondrites. The samples of eucrites with (b/a) <0.6 appear to be larger in number than those of diogenite, although this result is not statistically significant. The VFR value of the Yamato diogenite is about ten times smaller than that of the eucrite, and about a hundred times smaller than that of LL chondrites. The roundness of the shape of Yamato diogenites may be dependent on their hardness represented by VFR or CR measurement.

It is interesting that in L chondrites the top twenty in the mass distribution are all classified L6, but this is not so for H chondrites (Figs. 4, 5, 6). The largest L chondrite in the Antarctic collections is ALH-769 which is L6 (Yanai, 1979). This L6 chondrite

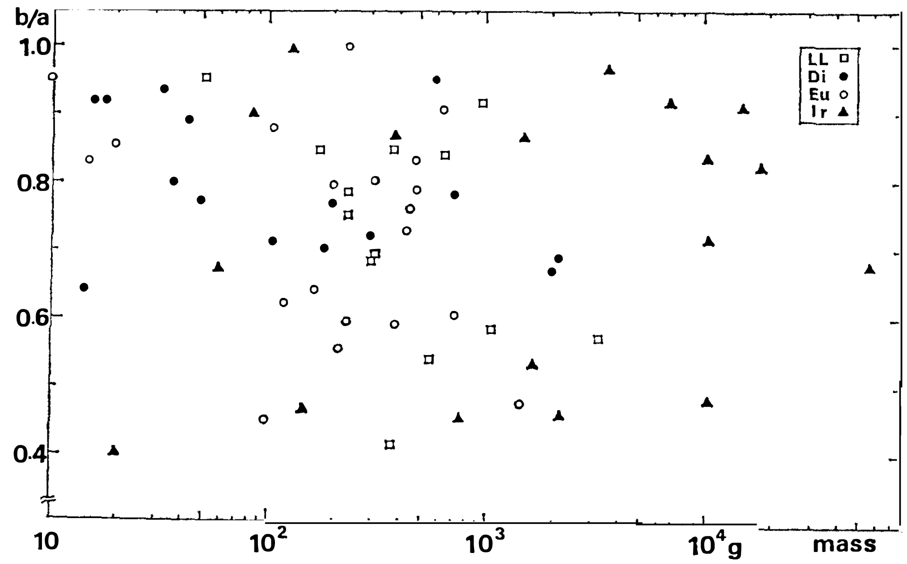

Fig. 7. Axial ratio (b/a) vs. mass of meteorites. LL: LL chondrites of all petrologic types; Di: Diogenites; Eu: Eucrites (including howardites); Ir: Iron meteorites.

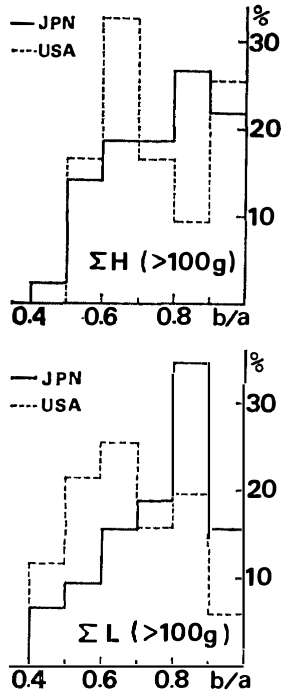

Fig. 8. Comparison of the distribution of axial ratio (b/a) for H or L chondrites more than 100 g in weight in the Japan collection with those in the U.S.A. collection (dotted lines).
ΣH: H chondrites of all petrologic types; ΣL: L chondrites of all petrologic types. Σ represents the sum of petrologic types.

consists of 33 pieces and its total mass is about 407 kg (YANAI, 1979). Even if we exclude ALH-769 (or regard it as one meteorite), the top ten in mass distribution are all L6. Our VFR and CR measurements revealed that the fracture strength of L6 is fairly weak compared with other petrologic types of L chondrites (Table 1). Taking into consideration the nature of destruction by impact phenomena, this result seems to be unusual. The possible reasons to explain this result are: (1) In the Antarctic collection the ratio of the number of L6 to that of L group is large; (2) in large-scale impacts, a weaker fracture-strength body produces larger fragments than a stronger one does; and (3) L6 chondrites are larger than other petrologic types of L chondrites in space.

In the Antarctic collections the ratio of the number of L6 to that of all the L chondrites (L6/ΣL) is about 0.66. If we regard ALH-769 as one meteorite, the ratio is about 0.58. The L6/ΣL ratio compiled by WASSON (1974) is about 0.71. Consequently, the Antarctic meteorite collections seem not to be exceptional on the basis of the number data alone. If we assume the L6/ΣL ratio is 0.7 and that the mass distribution of L6 is the same as that of the other petrologic types, the probability that the top ten of the mass distribution will be all L6 is very low ($\sim$0.03).

The results of laboratory experiments to support reason (2) have not yet been reported as far as we know. Laboratory impact experiments should be carried out by using the target or projectile with various physical properties (for example, L6 or the other petrologic types) to examine both the shape and mass distribution of the fragments produced.

Reason (3) seems to be plausible. The L6 chondrites now observed are relatively large, although the L6 chondrite is significantly weaker than other petrologic types of L chondrites (Table 1). The L6 chondrite is not particularly strong against weathering.

It is suggested, therefore, that L6 chondrites have relatively larger weight than other petrologic types of L chondrites in space.

ANDERS (1978) discussed the origin of stony meteorites from their trapped solar-wind gases. He proposed that the L chondrite parent body was completely shattered in a collision about 500 Ma ago, that the L chondrites falling on Earth may be a relatively unbiased sample of this body, and that the high proportion of strongly heated meteorites implies a high input of kinetic energy per unit mass, and hence a high projectile/target mass ratio.

If the chance of the succeeding minor collisions was similar in the average for every type of the L chondrite, then the distribution of size of the L6 type was produced probably at the major collision. In the core-type fragmentation by the high-velocity impact (FUJIWARA *et al.*, 1977), the central part of the parent body is expected to remain as relatively large cores. Therefore, the L6 chondrites may be located at the middle of their parent body under the assumption of an onion-shell model for the L chondrite parent body. This condition is favorable to the internal heating model for the ordinary chondrite parent body (MIYAMOTO *et al.*, 1981).

ITO *et al.* (1982) have explained the significance of the statistical approach of meteorites to deduce the information about the histories of meteorites in space. The statistical approach has been difficult because the number of meteorite samples were limited. The discovery of the Antarctic meteorites will develop the statistical analyses on the physical properties of meteorites, although the number of meteorites examined in this study is still small. Much future studies are required.

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