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Surface morphological features of boulders on Asteroid 25143 Itokawa

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ABSTRACT

On the sub-kilometer S-type asteroid, 25143 Itokawa, some boulders on rough terrains seem to be exposed without any powdery material covering. Based on surface morphological features, there are two major types of boulders: one has rounded edges and corners (rounded boulders), while the other has angular edges and corners (angular boulders). The surface features of the rounded boulders suggest that they have hardness heterogeneity and that some may be breccias. The angular boulders appear to be more resistant to impact disruption than the rounded ones, which may be due to a difference in lithology. The major constituents of Itokawa may be LL chondrite-like brecciated lithology (rounded boulders) along with a remarkable number of boulders suggesting that lithology is atypical among LL chondrites (angular boulders). Some of both types of boulders contain intersecting and stepped planar foliations. Comparison with meteorite ALH76009 suggests that the planar foliations may be marks where rocks were torn apart. As lithified breccias cannot be formed on present-day sub-kilometer-sized Itokawa, it is reasonable that boulders with various lithologies on Itokawa were formed on its large ancestor(s). The rubble-pile structure of Itokawa suggested by its low density ($\sim$1.9 g/cm^3) indicates that boulders on Itokawa are reassembled fragments formed by catastrophic disruption of large ancestor(s).

1. Introduction

Because of accretion in the early solar nebula, asteroids have experienced various processes such as thermal metamorphism and/or aqueous alteration, impact shock events, catastrophic disruption, and reassembly. It is believed that the majority of meteorites were derived from asteroids; thus, meteorite researchers have estimated histories of asteroids based on petrology, mineralogy, chemistry, and isotopic signatures of meteorites. The in situ observation of rocks on the surface of an asteroid is also a method for estimating its history. However, such direct observation of rock textures by a spacecraft could not be accomplished to date. Even the highest-resolution images obtained by the NEAR Shoemaker spacecraft could not reveal rock textures of the surface material of Asteroid 433 Eros in detail because of limited spatial resolution (Robinson et al., 2002).

The sub-kilometer asteroid, 25143 Itokawa, which is the target asteroid of the Japanese Hayabusa spacecraft, is covered with numerous boulders and cobbles (Saito et al., 2006). Although the finest material observed on Itokawa is resolution-limited (highest resolution: 6.0 mm), typical boulders and cobbles on the rough terrains of Itokawa are stacked without burying by fines (Miyamoto et al., 2007). Miyamoto et al. (2007) also noted the apparent lack of a powdery material covering that obscures the surface morphological features of boulders and cobbles. They proposed some causes of the deficiency of the powdery material: electrostatic levitation and removal of the fines by solar radiation pressure, restricted accumulation after impact due to the higher ejection velocity of the fines, and segregation of the fines into the interior

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of the asteroid. Even though a very thin powdery material covering may exist, it does not conceal the surface textures of boulders and cobbles on Itokawa. Accordingly, we could perform direct observation of the surface morphological features of boulders and cobbles on Itokawa's surface.

The relative abundances of olivine and low-Ca pyroxene and their FeO contents, and elemental abundances of the surface material of Itokawa were obtained by in situ measurements by the near-infrared spectrometer, NIRS-Hayabusa (Abe et al., 2006; Hiroi et al., 2006), and the X-ray fluorescence spectrometer, XRS-Hayabusa (Okada et al., 2006; Arai et al., 2008), respectively. Based on near-infrared reflectance spectra, the surface of Itokawa is estimated to be LL5 or LL6 chondrite-like material (Abe et al., 2006; Hiroi et al., 2006). The XRS-Hayabusa data did not rule out the presence of primitive achondrite-like materials on Itokawa's surface (Okada et al., 2006; Arai et al., 2008). Observation of surface morphological features of large boulders on Itokawa would provide another perspective for discussing its constituents. We used several brecciated LL chondrites, a fragile L/LL chondrite, and an L chondrite with a unique surface morphological feature to discuss the surface morphological features of the boulders on Itokawa. There are no primitive achondrites sufficiently large to facilitate a comparison between their surface features and those of the boulders. From the description on surface features of the boulders and cobbles on Itokawa and comparison with the meteoritic samples, we discuss the lithology of the boulders and cobbles, and their origins.

2. Images used in this study

Three close-up images of regions of rough terrain were taken by the telescopic Optical Navigation Camera with the V-band filter (also known as the asteroid multiband image camera, AMICA; Saito et al., 2006) from heights of 60 to 160 m from Itokawa's surface during the touch-down rehearsal on November 12, 2005, Coordinate Universal Time (UTC). These images were used for the observation of the surface morphological features of unconsolidated boulders and cobbles in the rough terrain of Itokawa (Fig. 1). The squares labeled "2A", "2C", and "2E" in Fig. 1 correspond to the fields of view of three high-resolution images shown in Fig. 2A, C, and E, respectively. The high-resolution images corresponding to squares "2A", "2C", and "2E" are ST 2539437177, ST 253944467, and ST 2539451609, respectively (Table 1). They are situated at the east side of a smooth terrain (MUSES-C region) and near the rim or the inside of a crater candidate #4 (LINEAR region) proposed by Hirata et al. (2009) (Fig. 1). North is downward

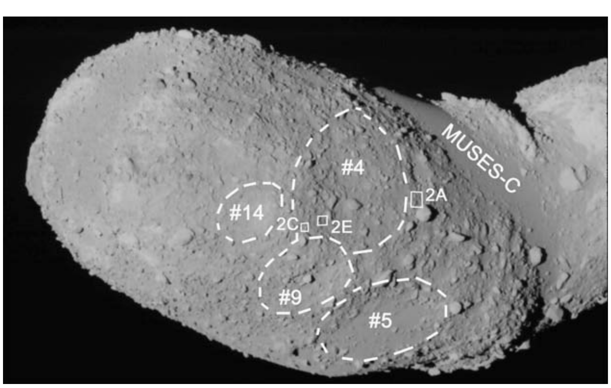

Fig. 1. Positional relationships of high-resolution images used in this study plotted on a part of the global image of Itokawa. Three boxes with numbers correspond to the areas in Fig. 2. The image IDs of Fig. 2A–C are ST 2539437177, ST 2539444467, and ST 2539451609, respectively. In this figure, the geographic north of Itokawa points downward. The MUSES-C region and four crater candidates #4, 5, 9, and 14 by Hirata et al. (2009), is also indicated. The image ID of this figure is ST 2506694595.

in all the images used in this study. A single pixel in each of the original images corresponds to about 11.3, 6.0, and 7.8 mm, respectively. The image resolutions are sufficiently high to allow a description of the surface morphology and texture of ~40-cm-sized boulders. The brightness and contrast of the images are modified to enhance the visibility of the particles (Miyamoto et al., 2007). The top parts of the original images are obscured because of the polarizer (Saito et al., 2006).

3. Surface morphological features of boulders

3.1. Major surface morphological features of boulders on Itokawa

Three high-resolution images of Itokawa's surface used in this study are shown in Fig. 2. The fields of view of all the images are covered with unconsolidated boulders and cobbles. Miyamoto et al. (2007) reported the following two characteristics about the unconsolidated boulders and cobbles in the three images: (1) the smaller boulders and cobbles are not isolated on the top of boulders without being supported by other boulders and cobbles. (2) As may be suggested by the majority of the boulders having wide and relatively flat surfaces facing upward, their position and orientation are stable against local gravity (Fig. 2). Miyamoto et al. (2007) proposed reallocation of boulders and cobbles after their accumulation and/or deposition. Therefore, we could observe surface morphological features of boulders using these images.

Boulders on Itokawa's surface can be categorized into two major types based on their surface morphological features: rounded and angular boulders. Boulders having rounded edges and corners and wavy surfaces in Fig. 2A, C, and E, respectively, are depicted in light gray in their corresponding schematic line drawings (Fig. 2B, D, and F). We call them "rounded" boulders, although they may be classified as subangular to rounded if we use the terminology of sedimentary geology (e.g., Pettijohn, 1974). Rounded boulders occupy about 80% of the total area in Fig. 2A and C and about 50% of the total area in Fig. 2E, for which the corresponding line drawing is shown in Fig. 2F. Typical rounded boulders are shown in Fig. 3.

Boulders with sharp edges and corners are depicted in dark gray in their corresponding line drawings (Fig. 2B, D, and F) and are prominent (about 40% of the total area) in Fig. 2E and F (Table 2). We use the term "angular" for boulders with sharp edges and corners. Typical angular boulders are shown in Fig. 4. By comparing surface morphological features of a large rounded boulder in Fig. 3C and a large angular one in Fig. 4A, it is observed that the latter has sharper edges and corners than the former.

3.2. Surface morphological features of rounded boulders

Some rounded boulders show remarkable surface morphological features (Fig. 3). Protrusions are obvious in the boulders in Fig. 3A and E. The majority of the rounded boulders have surface morphological features similar to those shown in Fig. 3B and C. The boulders in Fig. 3C and D show patches with areas ~50 cm × 50 cm across, indicated by arrows. We can delineate the outline of the patch on the boulder in Fig. 3C, although its surface morphology is similar to its surroundings. A patch on the boulder in Fig. 3D is darker than its surroundings, which suggests different chemical composition and/or different abundance of material that causes darkening. The boulder shown in Fig. 3E, which has surface morphological features similar to those in Fig. 3A, seems to be overlaid by other boulders (two examples are labeled "a" and "b").

In Fig. 2E, rounded boulders seem not to be predominant; however, the center to the middle-right edge of the image is occupied by an area with features similar to those of the boulders in Fig. 3A and E. This area is brighter than the surroundings, and its

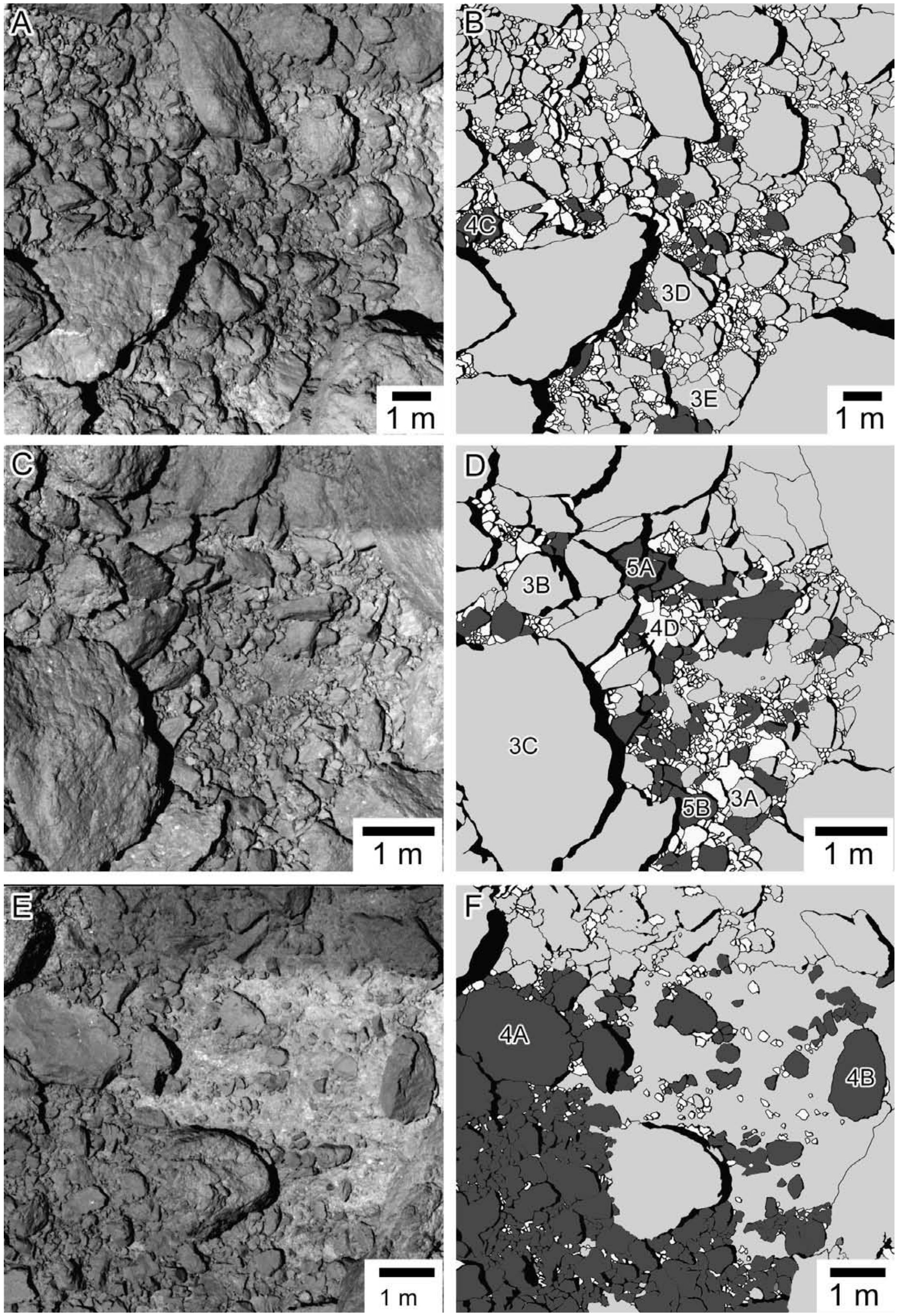

Fig. 2. Distribution of boulders having different surface morphological features. (A), (C), and (E) are the high-resolution close-up images shown in Fig. 1. (B), (D), and (F) are line drawings corresponding to (A), (C), and (E), respectively. Light gray boulders in (B), (D), and (F) are those having surface morphological features shown in Fig. 3. Dark gray boulders in the figures are those having features shown in Fig. 4. Boulders shown in Figs. 3–5 are labeled in Fig. 2B, D, and F. Open boulders in Fig. 2B, D, and F are difficult to classify due to their small sizes and/or poor features. The upper fifth of Fig. 2A, C, and E is obscured due to the polarizer mounted on AMICA-Hayabusa.

appearance is similar to the bright interstices among the protrusions in Fig. 3E. It appears that a large boulder containing protrusions similar to those in Fig. 3E is incompletely buried by neighboring boulders. Similarly, the boulder in Fig. 3E may be incompletely buried, and a small portion of it may appear on Itokawa's surface.

3.3. Surface morphological features of angular boulders

In Fig. 2A and C, there are relatively small angular boulders (>50 cm in diameter) with flat surfaces, as seen in their line drawings (Fig. 2B and D). Large angular boulders (Fig. 4A and B) coexist

Table 1
Descriptions of photographs used in this study.

Film no.	Figure no.	Global position	Point resolution (mm)
ST 2539437177	2A	Neighbor of Komaba	11.3
ST 2539444467	2C	Between Arcoona and Komaba	7.8
ST 2539451609	2E	Ditto	6.0

Table 2
Relative area ratios in the three images.

Figure no.	Global position	Rounded	Angular	Unclassified
2A	Neighbor of Komaba	83	4	13
2C	Between Arcoona and Komaba	79	11	10
2E	Ditto	55	42	3

with large rounded ones near the center of Fig. 2E. These angular boulders have not only sharp edges and corners but also relatively flat and featureless surfaces. Some white speckles on the widest flat surface of the boulder in Fig. 4A are probably remnants of micrometeoroid impact, by which fresh interiors unweathered by space weathering are exposed (Miyamoto et al., 2007). The boulder in Fig. 4A is brighter than that in Fig. 4B. The difference may reflect different chemical composition and/or different abundance of material that causes darkening.

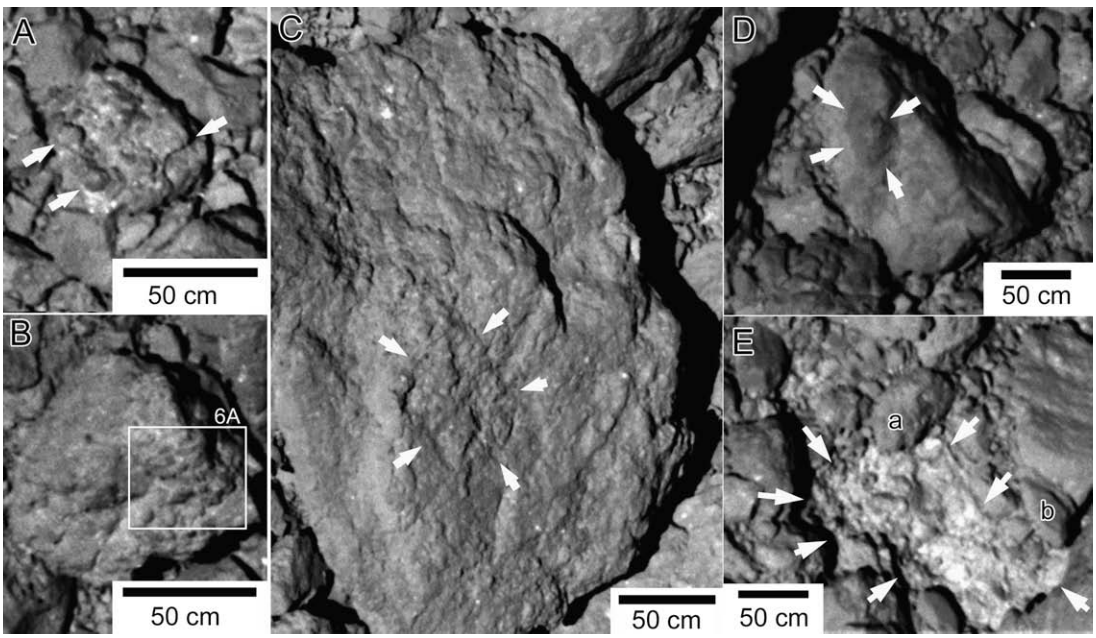

Fig. 3. Rounded boulders on Itokawa. Boulders in (A)–(C) have bumps 3–20 cm in size on their surfaces. (A) A protrusion indicated by an arrow pointing left seems to have been detached from the boulder. Two remarkable protrusions are also indicated by two arrows pointing right. (B) A boulder displaying protrusions on its surface. A box labeled "6A" is the area of Fig. 6A. (C) There seems to be a ~50-cm-sized patch on this boulder, which is indicated by arrows. (D) This boulder has a dark patch (indicated by arrows). (E) A boulder that has surface morphological features similar to those in Fig. 3A. In this case, the boulder is situated below the surrounding boulders indicated by arrows. Two boulders, "a" and "b", are apparently on this boulder.

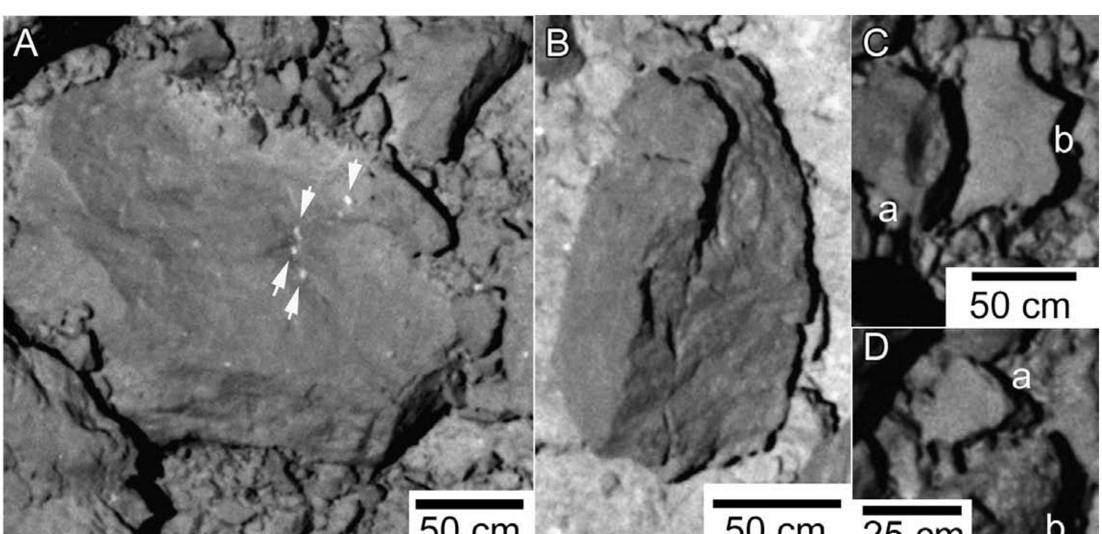

Fig. 4. Angular boulders on Itokawa. (A) and (B) Boulders have sharper edges and corners than the surrounding boulders. Both boulders lack undulations on their surfaces. Some white speckles are indicated by arrows on the surface of the boulder in A. (C) Boulder "b" is brighter than boulder "a". (D) Boulder "a" has a brighter and flatter surface than boulder "b". Boulder "b" belongs to the rounded boulders.

Angular boulders tend to be more abundant among smaller boulders (less than about 1 m across) and cobbles (Figs. 2 and 4C and D) than among large boulders (larger than a few meters across). Obvious brightness variations can be observed among small angular boulders and cobbles, as shown in Fig. 4C. Boulder "b" is much brighter than cobble "a". Among small angular boulders and cobbles, bright angular ones tend to be flatter than the others, as shown in boulder "b" in Fig. 4C and "a" in Fig. 4D.

3.4. Boulders having intersecting planar foliations

The above two types of boulders include boulders that have characteristic intersecting and stepped planar foliations (Fig. 5A and D). In the case of these boulders, both are angular. Each stepped planar foliation is labeled in Fig. 5B and E. Fig. 5C and F are schematic illustrations of these boulders, although there are ambiguities in drawing these illustrations because we do not have their stereo images.

4. Discussion

4.1. Two types of boulders and their inferred physical properties

Rounded boulders with undulating surfaces occupy about four-fifths of the total areas in Fig. 2A and C, and about half of the total area in Fig. 2E (Figs. 2 and 3; Table 2). More than half of them have abundant subangular to rounded protrusions with dimensions of 3–20 cm or sometimes patches with dimensions of up to ~50 cm

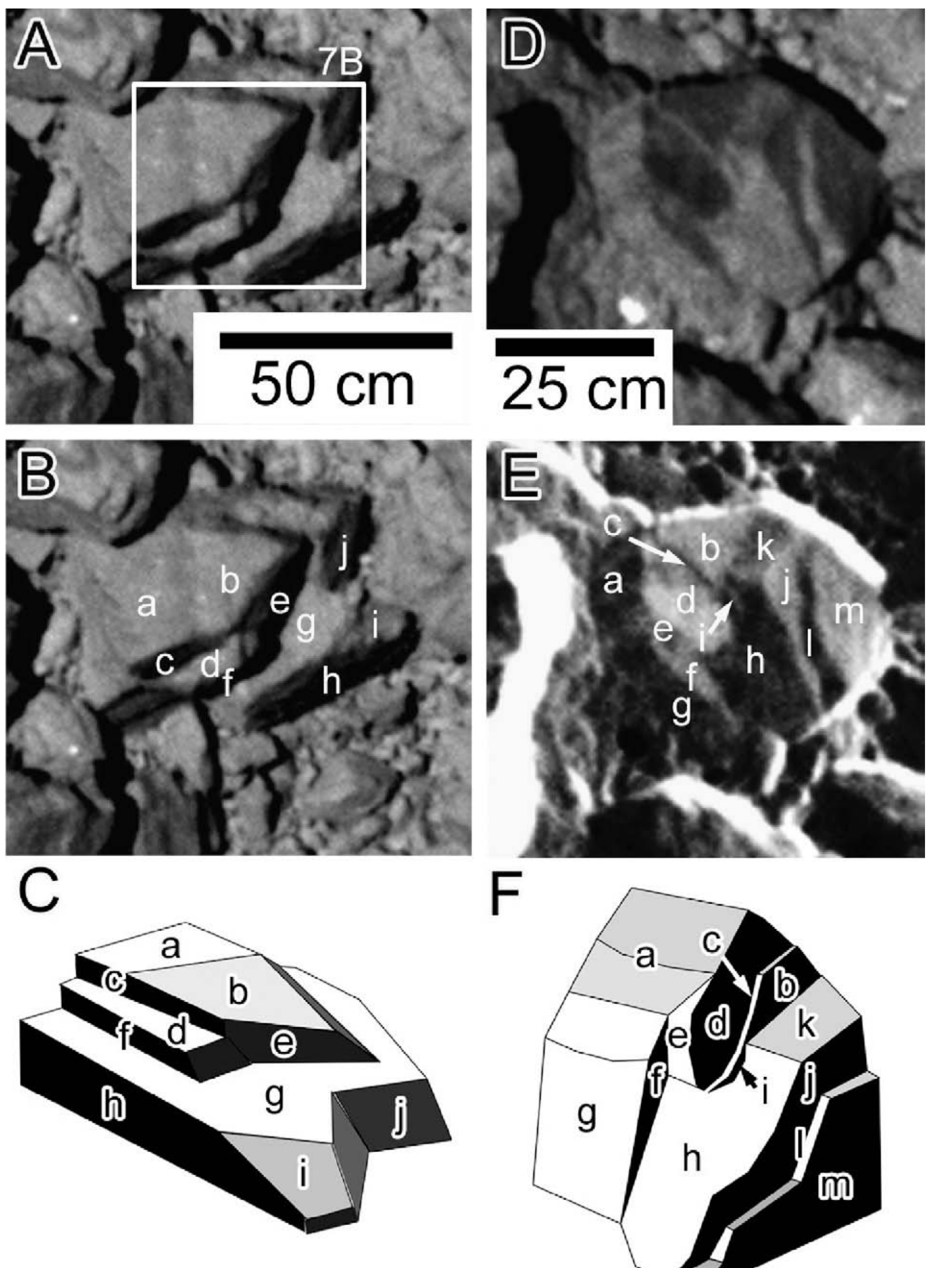

Fig. 5. Boulders containing intersecting and stepped planar foliations on Itokawa. (A) A boulder in Fig. 2C. A box labeled "7B" is the area of Fig. 7B. (B) Each stepped planar foliation in (A) is labeled from "a" to "j". (C) A schematic illustration to show the shape of the boulder in (A). Labels of the steps are indicated in the illustration. (D) Another boulder in Fig. 2C. (E) Each stepped planar foliation in (D) is labeled from "a" to "m". In this figure, an inverted black and white image is used to facilitate shape recognition. (F) A schematic illustration to show the shape of the boulder in (D). Labels of the steps are indicated in the illustration.

(Fig. 3). These features indicate that these rounded boulders contain physical (hardness) or petrographic heterogeneity, and strongly suggest that they are breccias. Their rounded surface morphology may result from their fragility to external force and from their internal structure. They may be composed of small regions with different transmittance of a compressive stress wave. Such heterogeneity prevents coherent transmission of a compressive stress wave that would make sharp flat surfaces and result in undulating outlines with rounded edges and corners. The surface flatness of the rounded boulders are various. It may be related the degree of lithification because more lithified boulders would be more homogeneous in hardness.

Angular boulders are prominent in Fig. 2E (Table 2). What causes the difference in surface morphological features between the rounded and angular boulders? One possible cause is different degrees of impact erosion. However, both types of boulders experienced remarkable space weathering (Figs. 3 and 4). Therefore, this is not the main cause of the differences in shape. Another possible cause is the difference in lithology. If the angular boulders have homogeneous and coherent lithology, they would have a large flat plane resulting from shock due to coherent transmission of a compressive stress wave. Therefore, we believe that different lithologies are more plausible than different exposure times to space. Nakamura et al. (2008) proposed that the flat shapes of the angular boulders are indicative of their formation by spallation processes based on shock experiments. Our observation and interpretation are consistent with their interpretation.

The surface of Itokawa has ferromagnesian silicate mineralogy similar to that of LL5 or LL6 chondrites based on in situ measurements of near-infrared reflectance spectra (Abe et al., 2006; Hiroi et al., 2006). However, there are no LL5 or LL6 chondrites with homogeneously hard interiors, as inferred from the surface morphological features of the angular boulders. Because impact melted rocks, such as the Y790964 LL chondrite (Yamaguchi et al., 1998), have a higher fracture strength than that of the other LL chondrites (Miyamoto et al., 1982), they may represent one possible lithology of the angular boulders.

4.2. Comparison of textures of rounded boulders with those of meteorites

We compare a rounded boulder shown in Fig. 3B and brecciated and unbrecciated LL and L/LL chondrites on the same scale (Fig. 6). For comparison, a part of Fig. 6A was enlarged, and the enlarged image was interpolated by the bicubic method in the software Adobe Photoshop CS®. Dark and light inclusions or patches in the boulder (Fig. 6A) are similar in size to clasts in two brecciated meteorites: the Y75258 LL6 and Paragould LL5 chondrites (Fig. 6B and C). Undulations on the rounded boulder seem comparable to those of the fragile L/LL4 chondrite Bjurböle (Fig. 6D). The heterogeneity of hardness within the boulder may be comparable with that of Bjurböle. The similarity in size of these features between the boulder and the meteorites would support that the rounded boulders contain breccias and that some of them are as fragile as the Bjurböle meteorite.

4.3. Comparison of surface morphological features of the boulders containing intersecting planar foliations with a unique L chondrite ALH76009

The boulders containing intersecting planar foliations belong to both rounded and angular boulders (Fig. 5). Because flat surfaces can be formed by the spallation process (Nakamura et al., 2008), polygonal boulders shown in Fig. 5 could be formed by the same process. However, it seems difficult to make boulders with the stepped intersecting planar foliations in Fig. 5A and D only by spallation. These boulders would contain weak planes in their interiors, at which the boulders could be separated easily, before they attained their present forms.

Fig. 7 shows a large mass of the ALH76009 L6 chondrite. It is a fragile meteorite having a notable morphology with two intersecting planar foliations, indicated by A and B. Except for these foliations, the meteorite has a rounded outline, which resulted from its fragility. A close look at the planes revealed that these flat planes are shock veins. They are composed of thin (<5 mm in thickness) glassy planes. The later-formed shock vein "a" blocks off the shock vein labeled "b". The morphology of this meteorite clearly shows that the meteorite was broken along the veins before entering the Earth's atmosphere. When compared with a boulder shown in Fig. 5B on the same scale, the dimensions of the flat planes of the meteorite are comparable with the planar foliations of the boulder. Therefore, if we assumed that the physical processes forming planar foliations in sub-meter-sized boulders and those in large meteorites are the same, intersecting planar foliations on the boulders may be the marks where rocks were torn apart at shock veins. Such

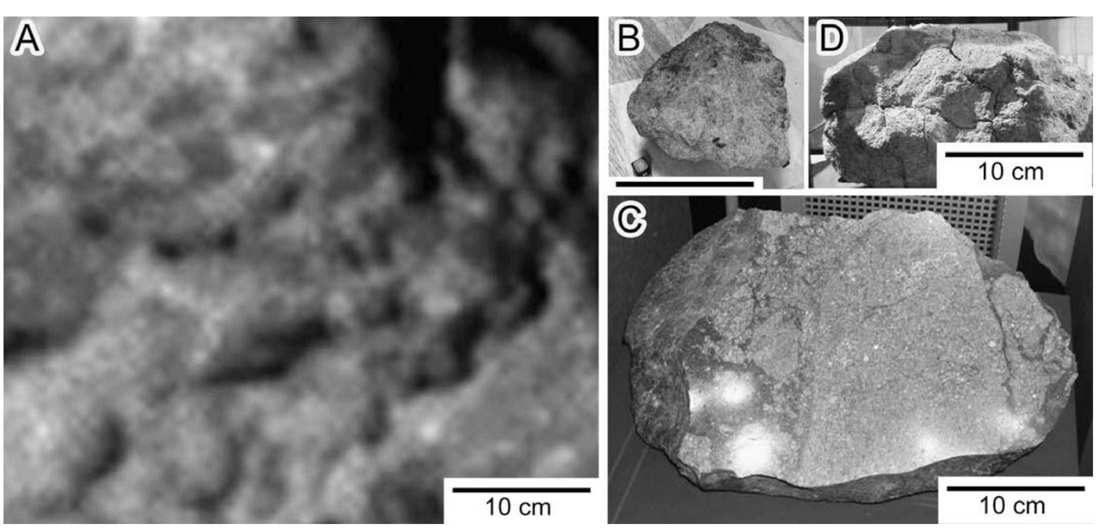

Fig. 6. An enlarged image of a rounded boulder and brecciated LL and unbrecciated L/LL chondrites are displayed on the same scale. (A) An enlarged image of the rounded boulders in Fig. 3B. (B) Y75258 LL6. This meteorite is a sample in the collection at the National Institute of Polar Research, Japan. (C) The Paragould LL5 chondrite has abundant dark material that fills the interstices of angular fragments. Halations of spotlights appear in this photo because this meteorite has a polished flat surface. This meteorite is a sample in the collection at the Smithsonian Museum of Natural History, USA. (D) The Bjurböle L/LL4 chondrite is a famous fragile meteorite with surface morphology similar to some of the rounded boulders in Figs. 2 and 3. This meteorite belongs to the collection at the University of Helsinki, Finland.

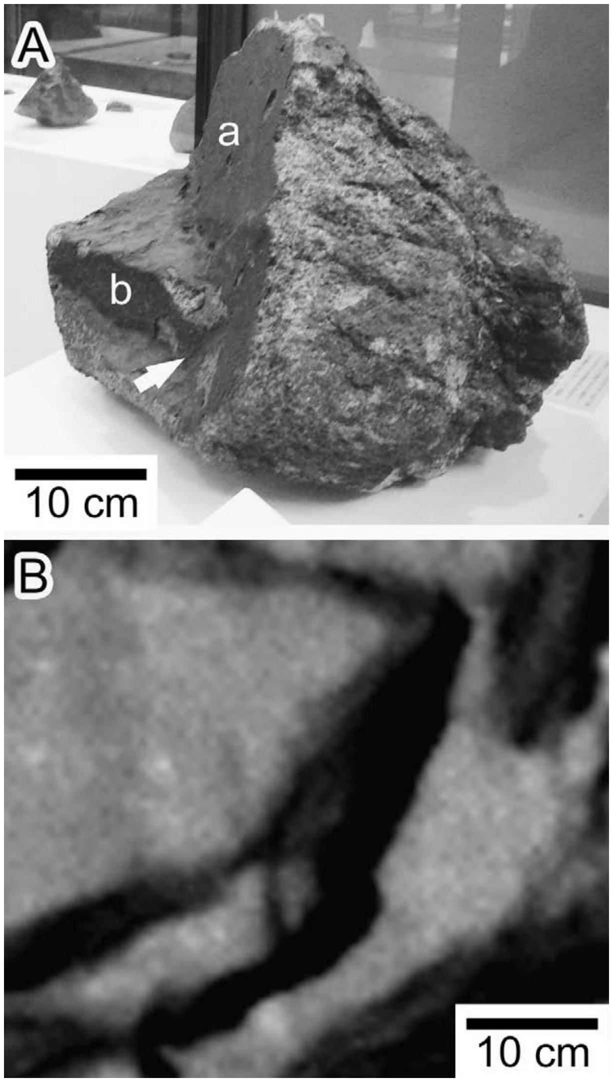

Fig. 7. A unique faceted meteorite ALH76009 L6 chondrite (A) and an enlarged image of a boulder with stepped planar foliations in Fig. 5B at the same scale (B). (A) The planes "a" and "b" are split at thin (<5 mm thick) shock veins. Because the surface of the planes is covered with fusion crust, this meteorite should have had these flat planes even before or during atmospheric entry (photo at the exhibition hall at the National Institute of Polar Research, Japan). An arrow indicates the intersection of two crosscutting shock veins. (B) The dimensions of the stepped planar foliations are comparable to the planes on the surface of ALH76009.

shock veins may have been formed during shock events on the precursor(s) of Itokawa.

4.4. Origins of boulders on Itokawa

Many ordinary chondrites are fragmental or regolith breccias that were lithified after metamorphism. Fragmental and regolith breccias occupy about 50% and 6% of LL chondrites, in contrast to 10% and 15% for H chondrites and 15% and 3% for L chondrites, respectively (Keil et al., 1994; Bischoff et al., 2006). Abundant probable breccias among the rounded boulders may be consistent with the idea that the surface material of Itokawa has LL5 or LL6 chondrite-like olivine and pyroxene mineralogy based on NIRS-Hayabusa data (Abe et al., 2006). Because quite variable metallographic cooling rates of each metal grain have been obtained even in a thin section of an ordinary chondrite breccia, constituents in a meteorite breccia may have been derived from various depths of an asteroid (Scott and Rajan, 1981). This leads to the idea that catastrophic disruption and reassembly of an S-type asteroid could create such extensive mixing of the constituents of a meteorite, although some might have been formed during cratering events on asteroids (e.g., Keil et al., 1997; Scott, 2002; Scott and Wilson, 2005; Bischoff et al., 2006). This idea seems to be consistent with the coexistence of boulders with probably different lithologies in close proximity on Itokawa's surface.

Scott and Wilson (2005) proposed that 10–50 km S-type asteroids like Eros, Gaspra, and Ida were initially accreted as very porous, gravitational aggregates after catastrophic disruption. They would have been consolidated by shock melt and pressure-welded Fe–Ni metal grains during impact events after filling their interior voids by fine-grained material through seismic shaking. Subsequent large impacts would shatter them and lead to formation of smaller rubble-pile asteroids. Lithification of such small asteroids (0.6–6 km in size) does not proceed because they are too small to form abundant shock melts by impact processes. If this scenario is true, rounded boulders having surface morphological features suggestive of breccias on Itokawa may have been formed on large (>10 km in diameter) ancestor(s) by consolidation of thick unconsolidated regolith, as on Eros (50–100 m: McCoy et al., 2002).

Surface morphological features of the angular boulders suggest that they are coherent rocks harder than the rounded ones. LL chondrite impact melt rocks that experienced almost complete melting (Yamaguchi et al., 1998) may be a candidate for the angular rocks. This estimation seems consistent with the argument by Arai et al. (2008), who suggested the presence of partially melted LL chondrite-like material based on XRS-Hayabusa data. Moreover, Abell et al. (2007) proposed that the surface material of Itokawa is similar to pigeonite-rich primitive achondrite-like material based on Earth-based observations. Almost complete melting of ordinary chondrites must have occurred on parent bodies much larger than present-day Itokawa, irrespective of internal heating due to ^{26}Al decay and impact heating, because extensive melting needs higher temperature and longer heating duration than lithification of breccias (Keil et al., 1997; Folco et al., 2005). Therefore, the variety of inferred lithologies of the boulders on Itokawa's surface must have resulted from geological activity on large ancestor(s) of Itokawa. The rubble-pile structure of Itokawa, inferred from its low density ($\sim$1.9 g/cm^3) and a bulk porosity of $\sim$40% (Fujiwara et al., 2006), also suggest catastrophic disruption of large ancestor(s) of Itokawa and reassembly of fragments.

5. Conclusions

We performed observations of the surface morphological features of boulders on Itokawa. The observations could be performed because of a deficiency of powdery coverings on the surface of boulders. Two major types of boulders were distinguished: rounded and angular boulders. Rounded boulders seem to be heterogeneous in strength. Some have surface morphological features suggestive of breccias. Angular boulders have surface morphological features suggestive of compact and coherent interiors. They may have different lithology from the rounded ones. Both types of boulders contain intersecting planar foliations. Previously existing shock veins might have served as fissures where rocks were torn apart. These observations may be consistent with the idea that the major constituents of Itokawa have LL chondrite-like brecciated lithology along with a remarkable number of boulders suggesting lithology atypical among LL chondrites. Based on theoretical considerations, lithified breccias cannot be formed on present-day sub-kilometer-sized Itokawa. It is reasonable that boulders with various lithologies on Itokawa were formed on its large ancestor(s). The rubble-pile structure of Itokawa also suggests the catastrophic disruption of large ancestor(s) of Itokawa and the formation of Itokawa through reassembly of fragments. Our observation is important in understanding geological processes on small bodies.

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References

Abe, M., and 12 colleagues, 2006. Near-infrared spectral results of Asteroid Itokawa from the Hayabusa spacecraft. Science 312, 1334–1338.

Abell, P.A., Vilas, F., Jarvis, K.S., Gaffey, M.J., Kelley, M.S., 2007. Mineralogical composition of (25143) Itokawa 1998 SF_{36} from visible and near-infrared reflectance spectroscopy: Evidence for partial melting. Meteor. Planet. Sci. 42, 2035–2182.

Arai, T., Okada, T., Yamamoto, Y., Ogawa, K., Shirai, K., Kato, M., 2008. Sulfur abundance of Asteroid 25143 Itokawa observed by X-ray fluorescence spectrometer onboard Hayabusa. Earth Planets Space 60, 21–31.

Bischoff, A., Scott, E.R.D., Metzler, K., Goodrich, C.A., 2006. Nature and origins of meteorite breccias. In: Lauretta, D., McSween, H.Y. (Eds.), Meteorites and the Early Solar System II. University of Arizona Press, Tucson, pp. 679–712.

Folco, L., Burbine, T.H., D'Orazio, M., 2005. Surface mineralogy changes induced by impact melting on ordinary chondritic parent asteroids: Clues from the DaG 896 meteorite. Mem. Soc. Astron. Ital. Suppl. 6, 116–121.

Fujiwara, A., and 21 colleagues, 2006. The rubble-pile Asteroid Itokawa as observed by Hayabusa. Science 312, 1330–1334.

Hirata, N., and 10 colleagues, 2009. A survey of possible impact structures on 25413 Itokawa. Icarus 200, 486–502.

Hiroi, T., Abe, M., Kitazato, K., Abe, S., Clark, B.E., Sasaki, S., Ishiguro, M., Barnouin-Jha, O.S., 2006. Developing space weathering on the Asteroid 25143 Itokawa. Nature 443, 56–58.

Keil, K., Haack, H., Scott, E.R.D., 1994. Catastrophic fragmentation of asteroids: evidence from meteorites. Planet. Space Sci. 42, 1109–1122.

Keil, K., Stöffler, D., Love, S.G., Scott, E.R.D., 1997. Constraints on the role of impact heating and melting in asteroids. Meteor. Planet. Sci. 32, 349–363.

McCoy, T.J., Robinson, M.S., Nittler, L.R., Burbine, T.H., 2002. The near Earth asteroid rendezvous mission to Asteroid 433 Eros: A milestone in the study of asteroids and their relationships to meteorites. Chem. Erde 62, 89–121.

Miyamoto, H., and 14 colleagues, 2007. Regolith migration and sorting on Asteroid Itokawa. Science 316, 1011–1014.

Miyamoto, M., Fujii, N., Ito, K., Kobayashi, Y., 1982. The fracture strength of meteorites: Its implication for their fragmentation. Mem. Natl. Inst. Polar Res. 25, 331–343.

Nakamura, A.M., and 13 colleagues, 2008. Impact process of boulders on Itokawa surface as fragments from collisional disruption. Earth Planets Space 60, 7–12.

Okada, T., Shirai, K., Yamamoto, Y., Arai, T., Ogawa, K., Hosono, K., Kato, M., 2006. X-ray fluorescence spectrometry of Asteroid Itokawa by Hayabusa. Science 312, 1338–1341.

Pettijohn, F.J., 1974. Sedimentary Rocks, third ed. Harper and Raw, New York. p. 628.

Robinson, M.S., Thomas, P.C., Veverka, J., Murchie, S.L., Wilcox, B.B., 2002. The geology of 433 Eros. Meteorit. Planet. Sci. 37, 1651–1684.

Saito, J., and 33 colleagues, 2006. Detailed images of Asteroid 25143 Itokawa from Hayabusa. Science 312, 1341–1344.

Scott, E.R.D., 2002. Meteorite evidence for the accretion and collisional evolution of asteroids. In: Bottoke, W.F., Jr., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 697–709.

Scott, E.R.D., Rajan, R.S., 1981. Metallic minerals, thermal histories and parent bodies of some xenolithic, ordinary chondrite meteorites. Geochim. Cosmochim. Acta 45, 53–67.

Scott, E.R.D., Wilson, L., 2005. Meteoritic and other constraints on the internal structure and impact history of small asteroids. Icarus 174, 46–53.

Yamaguchi, A., Scott, E.R.D., Keil, K., 1998. Origin of unusual impact melt rocks, Yamato-790964 and -790143 (LL-chondrites). Antarct. Meteor. Res. 11, 18–31.