Earth and Planetary Science Letters 450 (2016) 337–345

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

# Secondary submicrometer impact cratering on the surface of asteroid 25143 Itokawa

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ARTICLE INFO

*Article history:*
Received 15 March 2016
Received in revised form 8 June 2016
Accepted 18 June 2016
Available online 12 July 2016
Editor: B. Marty

*Keywords:*
Hayabusa
asteroid
regolith
space weathering
impact cratering
exposure age

ABSTRACT

Particle RA-QD02-0265 returned by the Hayabusa spacecraft from near-Earth asteroid 25143 Itokawa displayed a unique abundance of submicrometer-sized (≤500 nm) impact craters, which are rarely observed among the Hayabusa samples. The particle consists of intensely twinned diopside that was subjected to a large-scale shock event before exposure to the space environment on the surface of 25143 Itokawa. Intense (sub-)micrometer-scale impact cratering may suggest a long surface exposure and, hence, a long residence time of regolith material on the surface of small asteroids, bearing implications for the dynamical evolution of these bodies. However, our combined FE-SEM and FIB/TEM study shows that the degree of solar wind-induced space weathering and the accumulation of solar flare tracks are not exceptionally different from other Hayabusa particles with surface exposure ages estimated to be less than 1 ka. A 500 nm wide crater on the surface of RA-QD02-0265 exhibits microstructural damage to a depth of 400 nm below its floor and contains residues of Fe–Ni metal, excluding a formation by space craft exhausts or curatorial handling. The geometrical clustering among the 15 craters is unlikely random, and we conclude that the craters have formed through the impacts of secondary projectiles (at least partially Fe–Ni metal) created in a nearby (micro-)impact event. Besides structural damage by the solar wind and deposition of impact-generated melts and vapors, secondary impact cratering on the submicrometer-scale is another potential mechanism to modify the spectral properties of individual regolith grains. The lack of extensively exposed regolith grains supports a dynamic regolith on the surface of 25143 Itokawa.



## 1. Introduction

In 2010 the Hayabusa spacecraft returned regolith material from the S-type near-Earth asteroid 25143 Itokawa, which is compositionally consistent with LL-type chondrites (Nakamura et al., 2011; Noguchi et al., 2011). Beside the regolith material collected on the lunar surface this is currently the second body in the solar system on which pristine surface material was directly sampled and returned to Earth.

Asteroids in the inner solar system lack significant atmospheres and are exposed to the action of space weathering (Chapman, 2004). The mechanisms of space weathering on 25143 Itokawa and other near-Earth asteroids include the irradiation by solar wind ions (Hiroi et al., 2006; Vernazza et al., 2009; Noguchi et al., 2011, 2014; Bradley et al., 2014), the impacts of macroscopic and microscopic meteoroids (Nakamura et al., 2012; Nagao et al., 2011; Langenhorst et al., 2014), thermal cycling and thermal alteration of the surface material (Delbo et al., 2014; Harries and Langenhorst, 2014), and mass re-distribution and shedding (Taylor et al., 2007; Nagao et al., 2011; Scheeres, 2015; Connolly et al., 2015). The effects observed on regolith grains returned comprise the formation of amorphous and nanocrystalline surface layers (Noguchi et al., 2011, 2014; Thompson et al., 2014; Keller and Berger, 2014; Harries and Langenhorst, 2014), the formation of melt and vapor-deposited surface layers (Noguchi et al., 2014; Thompson et al., 2014), shock metamorphic features such as high densities of lattice defects (Langenhorst et al., 2014), and grain abrasion (Tsuchiyama et al., 2011).

The entirety of effects observed and the mechanisms considered to be responsible for them offer unprecedented possibilities of insight into the dynamical evolution of the orbits of asteroids in near-Earth space (Connolly et al., 2015). A crucial datum in this endeavor is the age of the asteroid's surface and, therefore, the time

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http://dx.doi.org/10.1016/j.epsl.2016.06.033

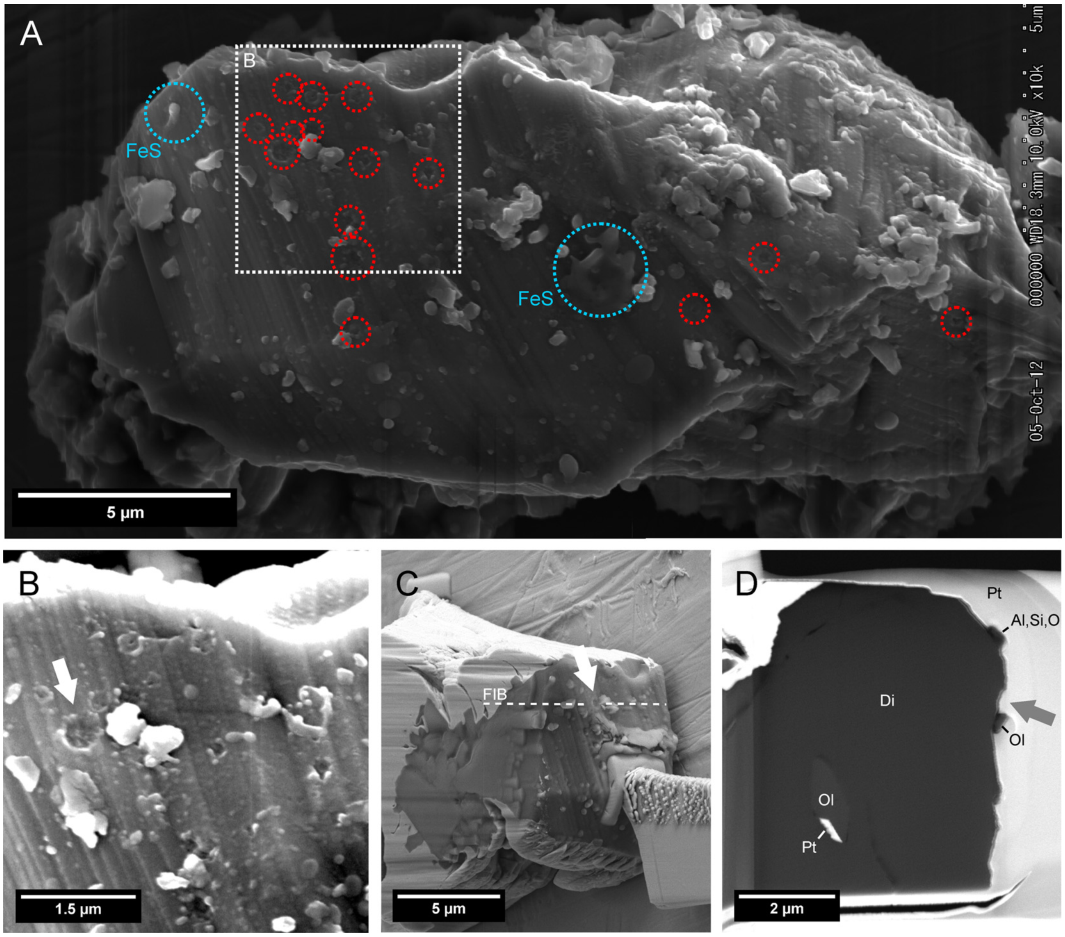


**Fig. 1.** SEM images of particle RA-QD02-0265. (A) Overview of the cratered surface showing the locations of submicrometer-sized craters and FeS splashes (circles). (B) Detail of the crater cluster with the largest, 500-nm crater marked by an arrow. (C) A slice of the particle after initial FIB preparation for EPMA. The surface shown in B is turned sideward, facing to the right. The arrow marks the 500-nm crater. Visible is the surface striation due to the intense twinning of diopside. The dashed line indicates the location of the FIB section through the 500-nm crater. (D) BSE image of the extracted FIB slice. The arrow marks the 500-nm crater.

scale of collision events and the re-distribution and loss of mass. However, a surface age cannot be defined uniquely, because the rates of processes allowing dating depend on depth in the regolith and the usually unknown rate of re-distribution of matter within it. Cosmic-ray produced $^{3}$He and $^{21}$Ne indicate a $1.5 \pm 0.4$ Ma residence time of a regolith grain of 25143 Itokawa in a shielding depth within the range of 1 to 10 cm (Meier et al., 2014). The densities of solar-flare induced particle tracks within individual regolith particles suggest exposures between 24 to 80 ka within depths of millimeters, but thin and not fully amorphous surface layers in the grains suggest that the direct exposure to the Sun was likely less than 1 ka for these grains (Keller et al., 2015).

A potential method of elucidating the exposure history of asteroidal regoliths is the determination of the number density of impact microcraters on regolith grains, which may be converted to an age of exposure at the uppermost regolith surface if the flux of micrometeoroids is known or can be inferred. Microcraters down to diameters of a few 100 nm have been described extensively from the lunar regolith (e.g., Brownlee et al., 1973; Schneider et al., 1973; Fechtig et al., 1974; Morrison and Zinner, 1977; Morrison and Clanton, 1979) and from the meteoritic regolith breccias Kapoeta (howardite; Brownlee and Rajan, 1973) and Murchison (CM2 chondrite; Goswami et al., 1976). Within the collection of regolith grains returned from 25143 Itokawa only 3 of the approximately 30 particles studied in detail show submicrometer-sized crater features (Matsumoto et al., 2016), which were initially described by Nakamura et al. (2012) and are associated with apparent melt particles adhering to the surface of the grains. Particle RA-QD02-0265 investigated in this study displays an unprecedented number of crater features on its surface (15 in total). We conducted our investigations in order to verify the impact origin of these features and to understand the shock and exposure history of this regolith grain.

## 2. Sample and methods

The particle RA-QD02-0265 (20 µm longest dimension, Fig. 1(A)) was found unexpectedly on a gold sample holder. Samples that unexpectedly occur on the slide glass or sample holders in the Hayabusa curation center are named ‘Extra’ samples and are separated from the normal samples. Some of the Extra samples were identified as particles lost during handling and re-named to the RA and RB designations. RA-QD02-0265 was initially designated Extra-0013 and did not match any particle previously lost. The re-naming and inclusion of Extra-0013 into the collection of normal samples was done after careful investigations by field-emission scanning electron microscopy (FE-SEM) and field-emission electron probe microanalysis (FE-EPMA), which confirmed the sample as mineralogically indistinguishable from other Hayabusa-returned regolith grains.

During the initial preparation at the JAXA extraterrestrial sample curation center the particle was fixed on a gold plate using an epoxy resin (Shell Chemical, EPON 815). After detailed study by FE-SEM (Hitachi S-4300SE/N) the particle was cut into two