Chrome-spinel in Hayabusa particles: Recorders of Asteroid Itokawa's thermal history

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Introduction: Chrome-spinel, which includes chromite ($FeCr_2O_4$) and Cr-rich spinel ($[Mg,Fe][Al,Cr]_2O_4$), records both pre- and post-accretionary formation conditions while remaining resilient to extensive alteration (e.g., [1–5]). They are found in a wide variety of astromaterials, including chondrites, as well as Hayabusa [6] and Stardust [5] returned samples. The morphologies, chemical compositions, and O-isotope compositions of chrome-spinel minerals in returned samples provide important information on their primary formation conditions in the nebula (temperature, time, oxygen fugacity) and on the secondary alteration conditions on the parent body (thermal metamorphism).

Chrome-spinel and olivine in FeO-rich chondrules in carbonaceous and ordinary chondrites are very sensitive indicators of thermal metamorphism [1,4]. We compare the compositions, textures, and O-isotope compositions of chrome-spinel from asteroid 25143 Itokawa with those from ordinary chondrites to investigate correlations between formation mechanism, oxygen fugacity, and formation/alteration temperatures. Studying chrome-spinel in Hayabusa particles constrains the parent body formation and alteration conditions of asteroid 25143 Itokawa and provides information about the variety of material present on this asteroid (e.g., [6]).

Samples and analytical procedures: We were allocated three Hayabusa-returned particles during the Hayabusa AO7 (Table 1; Fig. 1a–c). Two of the allocated samples contain olivine-chrome-spinel pairs, while the third is solely chrome-spinel. All samples are large enough for multiple *in situ* O-isotope analyses.

Table 1. Hayabusa-returned samples for study.

Sample	Size (diameter)	Phases
RA-QD02-0316	117 × 51.5 µm	olivine, chr
RB-CV-0091	29.88 × 14 µm	olivine, chr
RB-CV-0262	39.2 × 23.3 µm	chr

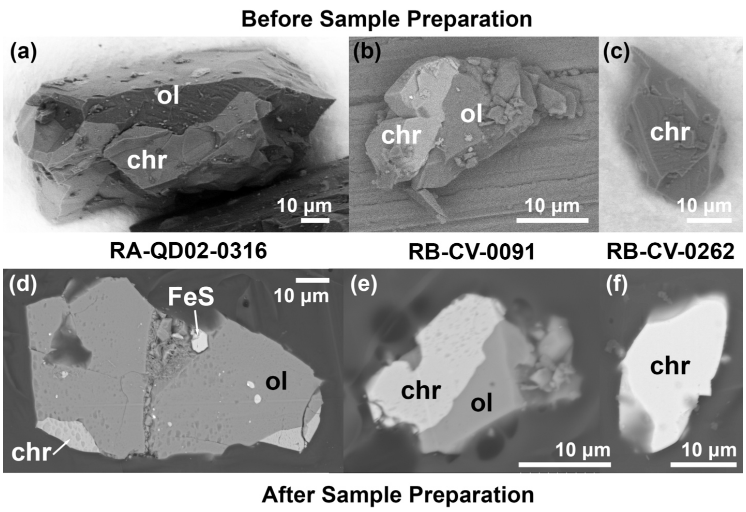

Figure 1. Hayabusa particles studied here (a, b, c) before, and (d, e, f) after sample preparation (i.e., mounting in epoxy and microtoming). (a–c) Backscattered electron (BSE) images modified from the JAXA Hayabusa particle catalogue used for preliminary identification of phases. (d–f) BSE images showing flat surfaces created by microtoming after mounting in epoxy. The orientation of RA-QD02-0316 changed slightly after mounting in epoxy, resulting in a smaller area of exposed spinel. Where chr = chrome-spinel, ol = olivine, and FeS = iron sulfide.

Sample preparation: The Itokawa samples were prepared at the University of Arizona's Lunar and Planetary Laboratory (LPL) following a modified version of the method presented in [7]: the particles were mounted on the top of epoxy bullets, which were then trimmed and sliced using a Leica EM UC7 ultramicrotome with two diamond knives (a trim knife and a cutting knife) to create flat surfaces that were suitable for microbeam analysis. The progressive excavation of each Itokawa grain was monitored using a Keyence VHX-7000 4K digital-optical microscope at LPL to ensure that overlying epoxy was removed to reveal

sufficient sample area for further analysis while preserving as much of the particle as possible. Analysis in 3D microscopy mode confirmed that the microtome method created smooth, flat surfaces ideal for EPMA and *in situ* O-isotope analysis.
Electron microscopy: The prepared samples were then carbon-coated and imaged in backscattered electron (BSE) mode in a Hitachi TM4000Plus II Tabletop scanning-electron microscope (SEM) at LPL Kuiper-Arizona Laboratory for Astromaterials Analysis facility (K-ALFAA) to verify that the microtome method created smooth, flat surfaces required for subsequent microprobe analysis (Fig. 1d–f). We then determined the major and minor element compositions of olivine and chrome-spinel in each of the Itokawa particles using the Cameca SX-100 EPMA at LPL K-ALFAA.

Results: *Olivine-spinel thermometry:* The olivine-spinel geothermometer was used to calculate closure temperatures for the two Itokawa particles that contain olivine and chrome-spinel mineral pairs (RA-QD02-0316 and RB-CV-0091). Quantitative compositional analyses were performed via EPMA at the edges of mineral pairs to determine the major and minor element compositions of both phases. Olivine-spinel temperatures were then determined using these data and an Excel version of the MELTS calculator [9]. Temperatures were determined at a pressure of 1 bar, which is a reasonable approximation for asteroids [10]. These calculations yielded closure temperatures of ~610 ± 50 °C (1 sigma, 1σ) to ~710 ± 50 °C for the different particles, which agree within a 2σ error. Assuming the olivine and spinel pairs in Itokawa particles originated from chondrules, these temperatures do not reflect the conditions of chondrule crystallization but rather closure temperatures after thermal metamorphism (e.g., [11]), consistent with temperatures recorded by olivine-spinel pairs in LL3.5–6 chondrites [8]. Temperatures indicative of crystallization in the chondrules of LL3.00–3.3 chondrites are typically >1000 °C [8].

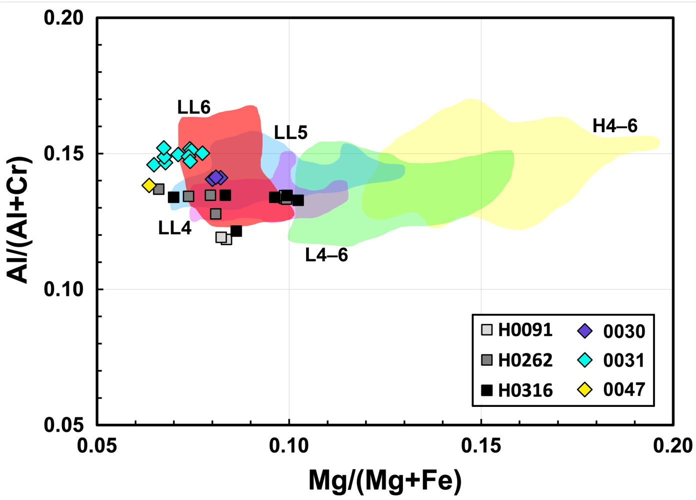

Figure 2. Chromite compositions for Hayabusa particles studied here (H0091, H0262, and H0316; squares) and from [6] (RA-QD02-0030, -0031, and -0047; diamonds) compared to those from ordinary chondrites (fields drawn from data in [6] and [8]).

Major and minor element compositions: The major and minor element compositions of each of the Itokawa chrome-spinels show that they have Cr/(Cr+Al) > 0.8, indicating that they are all chromite (i.e., $FeCr_2O_4$). Their Mg/(Mg+Fe) and Al/(Al+Cr) ratios cover a broader range than chromite compositions reported from three other Itokawa particles (RA-QD02-0030, -0031, and -0047) [6] (Fig. 2).
Since olivine-spinel geothermometry indicates that the Itokawa chromites studied here originate from thermally metamorphosed material, their compositions are compared with those from type 4–6 ordinary chondrites (LL, L, and H) (Fig. 2). The Itokawa chromites appear to be slightly less equilibrated than those previously reported by [6], which best match LL5 and LL6 chondrites, and cover similar compositions to chromites from LL4–6 chondrites (see comparison of OC data from [8] in Fig. 2).

Discussion: Due to the significant overlap between the major and minor element compositions of chromite from LL4–6 chondrites, it is not possible to match the Itokawa chromites studied here with specific petrologic types. Future work will include performing *in situ* O-isotope analyses of both olivine and chrome-spinel phases in each sample. This will enable us to constrain the specific meteorite petrologic type matches to the Itokawa chromites. However, the presence of Itokawa chromites covering the same range as LL4–6 chondrites is consistent with Itokawa being a breccia of LL4–6 materials [6].

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