Preliminary results from sulfide Hayabusa particle RB-CV-0234

Devin L. Schrader[1] and Thomas J. Zega[2]

[1]*Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA (devin.schrader@asu.edu),*

[2]*Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA (tzega@lpl.arizona.edu)*

Introduction: We performed initial analyses of the sulfide Hayabusa particle RB-CV-0234, and compared it to our results from LL3–6 chondrite sulfides [1,2], with the goal of further constraining the formation and alteration conditions of asteroid Itokawa. Preliminary analysis by JAXA's Hayabusa examination team via scanning electron microscope (SEM) determined that RB-CV-0234 (25.9 µm in diameter) consists of FeS, Fe, FeNiS, and CuS, making it an ideal target potentially containing both pyrrhotite group sulfides [$(Fe,Ni,Co,Cr)_{1-x}S$] and the rare Ni-rich sulfide, pentlandite [$(Fe,Ni,Co,Cr)_{9-x}S_8$].

Sulfides are important to study as their compositions, textures, and crystal structures can be used to constrain oxygen fugacity of formation, shock stage, and aqueous-, thermal-, and cooling-histories [e.g., 3–8]. The pyrrhotite group sulfides are largely nonstoichiometric and have a range of compositions ($0<x<0.125$) and distinct crystal structures (polytypes). The stoichiometric end members are 2C (troilite; FeS, hexagonal) and 4C (Fe_7S_8, monoclinic) pyrrhotite. There are also pyrrhotites of intermediate compositions with $0<x<0.125$ (all hexagonal); including the non-integral NC-pyrrhotites and the integral 5C (Fe_9S_{10}), 6C ($Fe_{11}S_{12}$), and 11C ($Fe_{10}S_{11}$) pyrrhotites [e.g., 9–11]. Geothermometry of pyrrhotite-pentlandite intergrowths in meteorites shows that most formed via primary cooling from high temperature or thermal metamorphism [e.g., 12–14]. Sulfides in the LL4 to LL6 chondrites typically equilibrated between 600 and 500°C, consistent with formation during cooling after thermal metamorphism [14]. However, geothermometry of pyrrhotite-pentlandite intergrowths from an LL5–6 impact melt-breccia indicated that the sulfides were annealed at ≤230°C, likely after an impact event [12]. Analyses of Hayabusa particles have identified asteroid 25143 Itokawa as LL4–6 chondrite material (~10% LL4 and ~90% LL5–6) [e.g., 15–18] that was thermally metamorphosed between ~780 and 840°C [15]. Itokawa particles were found to record shock stages between S2 and S4, with most particles around S2 [19,20]. Sulfides in Hayabusa particles [e.g., 15,21,22] may record additional and/or complementary information on the formation conditions of asteroid Itokawa.

Samples and Analytical Procedures: We mounted RB-CV-0234 on an epoxy bullet, following the methods of [21], and microtomed the sample in preparation for analysis and sample extraction using the FEI Helios NanoLab 660 focused-ion-beam-SEM (FIB-SEM) at the University of Arizona (UAz). The visible particle surface was 25.0 × 10.2 µm after microtoming. X-ray element maps and high-resolution images of the microtomed RB-CV-0234 were obtained with the FIB-SEM prior to extraction of a ~12.4 × 11.2 µm section from one end of the whole particle, which was then thinned to electron transparency (<100 nm) following the methods of [23]. The FIB section was then analyzed using the 200 keV aberration-corrected Hitachi HF5000 scanning transmission electron microscope (TEM) at UAz.

Results: FIB-SEM X-ray element maps showed that the microtomed surface of RB-CV-0234 consisted entirely of pyrrhotite. However, X-ray element maps of the extracted FIB section, determined via TEM analysis, revealed a grain of pentlandite (4.8 × 1.3 µm) at the bottom of the section (**Fig. 1**). The FIB section contains a single large grain of pyrrhotite and a single smaller grain of pentlandite. Selected-area electron-diffraction (SAED) patterns of the pyrrhotite and pentlandite grains index to 2C pyrrhotite (troilite) and pentlandite along the [110] zone axis (i.e., they are crystographically oriented), respectively.

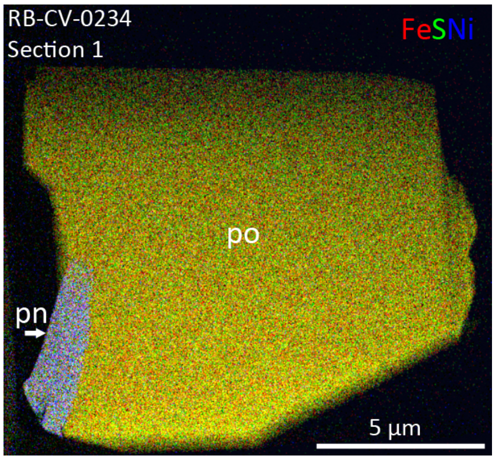

Fig. 1. Composite TEM X-ray element map (RGB=FeSNi) of RB-CV-0234 FIB Section 1; where po = pyrrhotite and pn = pentlandite.

Discussion: The preliminary results from the first FIB section from RB-CV-0234 are most consistent with it being a sulfide from an LL6 chondrite, similar to the sulfides from Saint-Séverin studied by [1]. We infer this because, based on results from the LL3–6 chondrite sulfides we previously studied via FIB-TEM [1,2], only sulfide grains in Saint-Séverin (LL6, S2 [24]) contain a similar pentlandite/pyrrhotite morphology (i.e., blocky pentlandite in pyrrhotite) and 2C pyrrhotite (troilite) with pentlandite [1]. The other LL chondrites we studied contained either a distinct morphology (e.g., pentlandite lamellae) and/or multiple polytypes of pyrrhotite [1,2]; perhaps indicating higher degrees of shock as troilite in ordinary chondrites is known to display shock indicators, such as fizzed and polycrystalline troilite [e.g., 8]. This conclusion is consistent both with the petrographic types represented in Hayabusa particles (10% LL4 and 90% LL5–6 [15,17,18]) and the most likely shock stage of Hayabusa samples (S2; [19,20]). Additional planned FIB section extractions from RB-CV-0234 will allow us to test this conclusion and investigate if the sulfide contains any evidence of space weathering [e.g., 22]. We plan to determine the compositions of both the pentlandite and the pyrrhotite via quantitative energy-dispersive X-ray spectroscopy with the TEM at UAz [25], and determine the sulfide's geothermometry to constrain its thermal history (i.e., if the sulfide was annealed at low temperature, or cooled from high temperature [e.g., 12,14]).

Acknowledgements: We thank JAXA for the loan of the Hayabusa particle used in this study through the 5th International Announcement of Opportunity, and NASA grant NNX17AE53G (DLS PI, TJZ Co-I) for funding this research.

References

[1] Schrader D. L. and Zega T. J. 2017. Abstract #6347. 80th MetSoc. [2] Schrader D. L. and Zega T. J. 2018. Abstract #2621. 49th LPSC. [3] Arnold R. G. 1967. Can. Min. 9:31. [4] Kissin S. A. and Scott S. D. 1982. Econ. Geol. 77:1739. [5] Raghavan V. 2004. J. Phase Equilib. 25:373. [6] Wang H. et al. 2006. J. Sulfur Chem. 27:1. [7] Harries D. and Langenhorst F. 2013. Meteorit. Planet. Sci. 48:879. [8] Bennet M. E. and McSween Jr. H. Y. 1996. Meteorit. Planet. Sci. 31:255. [9] Morimoto N. et al. 1975. Econ. Geo. 70:824. [10] Wang H. et al. 2006. J. Sulfur Chem. 27:1. [11] Harries D. et al. 2011. Am. Min. 96:716. [12] Jamsja N. and Ruzicka A. 2010. Meteorit. Planet. Sci. 45:828. [13] Schrader D. L. et al. 2015. Meteorit. Planet. Sci. 50:15. [14] Schrader D. L. et al. 2016. Geochim. Cosmochim. Acta 189:359. [15] Nakamura T. et al. 2011. Science 333:1113. [16] Noguchi T. et al. 2014. Earth, Planets, and Space 66:124. [17] Tsuchiyama A. et al. 2011. Science 333: 1125. [18] Tsuchiyama A. et al. 2014. Meteorit. Planet. Sci. 49:172. [19] Noguchi T. et al. 2011. Science 333:1121. [20] Zolensky M. E. et al. 2012. Abstract #1477. 43rd LPSC. [21] Berger E. L. and Keller L. P. 2015. Microscopy Today 23:18. [22] Harries D. and Langenhorst F. 2014. Earth, Planets, and Space 66:163. [23] Zega T. J. et al. 2007. Meteorit. Planet. Sci. 42:1373. [24] Rubin A. E. 2004. Geochim. Cosmochim. Acta 68:673. [25] Zega T. J. et al. 2018. Abstract #2084. Microsc. Microanal. 24 (Suppl. 1).