Itokawa chondrule fragment preserves evidence of proto-planetary disk processing

N.E. Timms[1], F. Jourdan[1], W.D.A. Rickard[1], T. Nakamura[2], D.W. Saxey[1], D. Fougerouse[1], S.M. Reddy[1], L. Daly[3], P.A. Bland[1], Z. Quadir[1], R. Oike[2] and T. Yada[4]

[1]*Curtin University, Perth, GPO Box U1987, WA, Australia*

[3]*Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan*

[2]*University of Glasgow, Glasgow, G12 8QQ, UK*

[4]*Institute of Space and Astronautical Science, JAXA, Sagamihara, Kanagawa 252-5210, Japan*

(*correspondence: n.timms@curtin.edu.au)

Particles brought back from Itokawa provide a unique opportunity to study unaltered material in their original context (i.e. without glass hydration). Here we combine time of flight secondary ion mass spectrometry (ToF-SIMS), electron backscatter diffraction (EBSD), transmission electron microscopy (TEM), energy dispersive spectroscopy (EDS), $^{40}Ar/^{39}Ar$ geochronology, and Atom Probe Tomography (APT) to examine one of the few melt rock particles recovered from the Itokawa asteroid by the Hayabusa mission [1]. This particle (RB-CV-0082) comprises 5-30 μm long crystals of high-Ca Cr-bearing pyroxene, olivine within a quenched emulsion of variable composition silicate glass. The olivine (Fa = 26.7% via APT; 27.9% via EDS) is similar in composition to other olivine from equilibrated Itokawa particles. EBSD mapping reveals that the olivine and high-Ca pyroxene phenocrysts are crystalline and do not show any evidence of shock metamorphism or deformation. Furthermore, the high-Ca pyroxene form elongate clusters of grains that have a strong crystallographic and shape preferred orientation.

TEM imaging, EBSD and TOF-SIMS (≤50 nm spatial resolution) maps show two dominant glass compositions form interconnected globules, much of which is amorphous. These segregations are Si-Al-Na-K-O-rich and Ca-Fe-Mg-Ti-O-rich, and are plagioclase and pyroxene normative, respectively. Locally, nebulous segregations of Si-Al-Na-O-rich and crystalline Mg-Fe-Si-O-rich material are associated with partially- to totally-digested olivine grains. The glass also contains ~5%vol nano-vesicles (typically 10-300 nm across), and minor nano-scale crystals of troilite and merrillite. Within the Si-Al-Na-K-O-rich regions of the glass, the alkalis (including K relevant to $^{40}Ar/^{39}Ar$ dating) are further segregated into even finer lamellae, alternating over 100 nm length scales. Further nanoscale analyses by APT constrain the compositions of fine-scale domains within the particle, demonstrating that lamellae within Si-Al-Na-K-O domains comprise end-member orthoclase and albite normative compositions, consistent with antiperthite lamellae. The $^{40}Ar/^{39}Ar$ analysis of particle RB-CV-0082 indicates an approximate age of 4.5 Ga. However, the data show that the $^{40}Ar/^{39}Ar$ analysis is likely to be affected by recoil, precluding resolution of a precise age.

The texture of RB-CV-0082 is consistent with incipient flash melting, with complete digestion of feldspar and partial digestion of olivine and pyroxene. The various glass compositions are consistent with phase separation into conjugate immiscible liquids formed by spinodal decomposition upon cooling below the upper critical solution temperature in a multicomponent oxide system, preserved by rapid quenching [2]. Subsequent crystallization of the plagioclase-normative immiscible domains to plagioclase was followed by exsolution of Na and K- rich (antiperthite) lamellae upon cooling below the feldspar solvus.

It has been reported that the regolith from the Itokawa asteroid underwent long-term thermal annealing and subsequent impact shock [4]. It is possible that an impact event could have caused flash melting and quenching of a metamorphosed olivine-pyroxene-plagioclase parent rock responsible for the texture of this particle. This melting mechanism would help explain why the relict olivine composition is similar to that of normal Itokawa olivine while preserving interstitial fine-scale glass textures. However, the lack of shock microstructures in olivine and pyroxene grains, the crystallographic alignment of elongate (barred?) pyroxene, and extremely old $^{40}Ar/^{39}Ar$ age are more consistent with a porphyritic chondrule with mesostasis origin for the particle rather than an impact melt origin. As such, this particle provides more insight into chondrule formation within the proto-planetary disk than the history of the Itokawa parent body. Nevertheless, the preservation of such fine-scale microstructures and compositional variations in this particle imply that it has not been extensively texturally equilibrated via recrystallisation and grain growth at high temperatures associated with thermal metamorphism on the initial Itokawa parent body (as interpreted for the majority of the Itokawa particles). Therefore, this fragment was likely to have been sourced from near the surface of the Itokawa parent body prior to breakup. The preservation of nano-vesicles indicates that the timescales of flash heating and quenching were very short and did not result in the complete loss of volatiles, which has implications for volatile retention

through chondrule formation and processing within the proto-planetary disk, as well as accretion, processing and breakup of the asteroid parent body.

References

[1] Nakamura. T. et al. 2014. Abstract at Hayabusa 2014. [2] Hamann et al. (2017). Meteoritics & Planetary Science 1-39. [3] Jourdan. F. et al. 2017. Geology 45:819-822. [4] Nakamura. T. et al. 2011. Science 333:6046.