ATOM PROBE TOMOGRAPHY IN PLANETARY SCIENCE.

L. Daly[1*], [1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK (luke.daly@glasgow.ac.uk).

Introduction: Atom probe tomography (APT) is an atomic-scale technique that is capable of measuring the composition (major, minor, trace and isotopes) as well as nano-scale chemical variations and the position of atoms within a sample in 3 dimensions within small volumes (100x100x1000 nm) [1]. As such APT has the potential to be a powerful tool in geology and planetary science [2]. APT has been used in material science for over 52 years, however, the first application on an extraterrestrial sample wasn't until 1992 and even then, focused on the conductive FeNi metal [3]. It was not until the development of the laser assisted atom probe, where the ionization energy is provided by an ultraviolet laser [4] that non-conductive materials in meteorites such as silicates, oxides, sulphides and carbonates could be analysed. Here I will provide an overview of the APT technique, how it works, what type of information can be obtained, how samples are prepared and summarise the current planetary science applications.

Sample preparation: APT samples are extracted from meteorites using a focused ion beam (FIB) where a 10-20 µm long and 2 µm wide triangular prism is cut out of the sample using FIB [5]. After this lift out, 1 µm sections of the prism are then welded to a pre-prepared post using a gas injection system coupled with the ion beam. The sections are then further milled using an annular milling pattern to generate the needle shape until the apex of the tip is <100 nm in diameter with a half shank angle generally <10 ° [5]. Recently FIB lift out procedures have been developed to target interfaces and submicrometre particles such as the 'button method' [6], as well as new approaches to prepare the sample in situ to avoid extraction such as the Satellite dish method [7].

Current APT applications in planetary science: APT is being applied to a rapidly broadening number of extraterrestrial materials. Particular attention has been afforded to pre-solar grains, especially nanodiamonds in carbonaceous chondrites in the search for the carrier phase of the Xe-HL pre-solar signal [8-10]. APT is the only technique with the sensitivity to measure the carbon isotopic ratios of these nanodiamonds and if analytical instrument biases such as CH formation can be overcome could be used to measure the isotopic ratios of pre-solar grains *in situ* [11]. The capability of APT to measure isotope abundances is also important from a geochronological perspective. The U-Pb decay system has been successfully applied to nanostructures in zircon, baddeleyite and lunar meteorites to unpick their impact and metamorphic history [12-14]. In addition, a recent, robust approach has been developed to extract Re-Os isotope systematics by APT [15] and is being applied to calculate the formation age of refractory metal nuggets (RMN) in carbonaceous chondrites to determine whether some may have a pre-solar origin [16]. The ability of APT to measure trace elements has been used to detect Sulphur in RMN that suggest some were originally 'free-floating' in the disk and migrated large distances early in the solar systems history [17], as well as element redistribution in apatite in Lunar KREEP basalts caused by shock metamorphism [18]. This capability has also been used to measure Fe-nanoparticles and vesicles [18] and directly detect water [20] in space weathered surfaces throughout the Solar System. The 3D tomography of APT datasets has been used to reveal nanoscale phase separations on Mars [21, 22], Itokawa [23] and in chondritic carbonates [24] generated by shock and thermal metamorphism, as well as in iron meteorites to better constrain their magnetic properties [25]. Targeted lift outs have revealed cation migration in water-rock reaction surfaces in Martian meteorites with implications for how these reactions progress [26].

Summary: APT can provide a vast array of nanoscale information from spatial to isotope abundances at an atomic level. However, the true interpretive power of APT is revealed at the end of a correlative set of analyses across several length scales [e.g. 6, 25] from remote sensing, to hand sample, to thin section, to electron microscopy, to transmission electron microscopy, culminating in atom probe tomography.

References: [1] Kelly T.F., and Larson D.J., (2012) *Annual Review of Materials Research,* 42, 1-31. [2] Saxey D. W. (2018) *Scripta Materialia*, 148, 115-121 [3] Miller M.K., & Russel K.F. (1992) *Surface Science*, 266, 411-445. [4] Larson D. J., (2013) *Local Electrode atom probe tomography*. [5] Thompson K., et al., (2007) *Ultramicroscopy*, 107(2)131-139. [6] Rickard W., et al., (in review) *Ultramicroscopy*. [7] Halpin J.E., et al., (2019) *Ultramicroscopy*. [8] Isheim D., et al., (2013) *Microscopy and Microanalysis*, 19(S2), 974-975. [9] Heck P.R., et al., (2014) *Meteoritics & Planetary Science*, 49, 453-467. [10] Lewis J.B., et al., (2015) *Ultramicroscopy*, 159, 248-254. [11] Lewis J.B., et al., (2018) *Metsoc*, 6269. [12] Montalvo S. D., et al., (2019) *Chemical Geology*, 507, 58-95. [13] White L. D. et al., (2017) *Nature Communications*, 8, 15597. [14] White L. F., et al., (2019) *Geoscience Frontiers*. [15] Daly L., et al., (2018) *Geostandards and Geolanalytical Research*, 42(3) 279-299. [16] Daly L., et al., (2019) *LPSCL*, 1514. [17] Daly L., et al., (2017) *Geology*, 45(9), 847-850. [18] Černock, A., et al., (2019) *LPSCL*, 2228. [19] Greer J., et al., (2017) *Metsoc*, 6137. [20] Daly L., et al., (this meeting) *Metsoc*. [21] Daly L. et al., (2018) *Metsoc*, 6237. [22] White L. F., et al., (2018) *Contributions to Mineralogy and Petrology,* 173(10), 87. [23] Timms N. E., et al., (2018) *6th Symposium of Solar System Materials.* [24] Daly L., et al., (2018) *Metsoc,* 6239. [25] Einsle J. F. et al., (2018) *Proceedings of the National academy of Sciences*, 115(49), E11436-E11445. [26] Daly L., et al., (2019) *LPSCL*, 1521.