RE-OS MODEL AGES FOR REFRACTORY METAL NUGGETS. L. Daly[1,2,3,*], P. A. Bland[1], D. W. Saxey[4], S. M. Reddy[1,4], S. Tessalina[5], D. Fougerouse[1,4], B.F. Schaefer[6], A. La Fontaine[3], W. D. A. Rickard[4], L. V. Forman[1], L. Yang[3], S. Moody[3], P. W. Trimby[3,7], N. D. Nevill[1], J. Cairney[3] and S. P. Ringer[3]. [1]Space Science and Technology Centre, School of Earth and Planetary Sciences, Curtin University, GPO Box U1987, Perth, WA 6845, Australia. [2]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK. [3]Australian Centre for Microscopy and Microanalysis and School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia. (*luke.daly@glasgow.ac.uk). [4]Geoscience Atom Probe, Advanced Resource Characterisation Facility, John de Laeter Centre, Curtin University, GPO Box U1987, Perth, WA 6845, Australia. [5]TIMS Facility, John de Laeter Centre, Curtin University, GPO Box U1987, Perth, WA 6845, Australia. [6]GEMOC, Department of Earth and Planetary Sciences, Maquarie University, 2109, NSW, Australia, [7]Oxford Instruments Nanoanalysis, High Wycombe, HP12 3SE, UK.

Introduction: Refractory metal nuggets (RMNs) are an enigmatic sub-micrometre refractory phase in primitive chondritic meteorites. RMN were discovered simultaneously in Ca-Al-rich inclusions (CAIs) by Palme & Wlotzka [1] and Wark & Lovering [2] in 1976. The refractory, metallic, and highly siderophile element (HSE) composition of RMNs comprising at. % abundances of Os, Re, Ir, Pt, Ru, Mo, Rh, W, Fe and Ni implies that they formed at high temperatures [3,4,5]. Therefore, RMNs are likely to be among the first solid phases to form in our solar system. As such, their chemistry [3,5,6], crystallography [7] and isotope systematics [3,8] can provide insights into the earliest time period of the solar system. For example, recent crystallographic studies have shown that RMNs are likely to form prior to their host inclusion [7]. Trace element geochemical analysis by atom probe tomography (APT) revealed minor amounts of S, a volatile element, within RMNs. This observation implies that RMNs were initially 'free floating' in the nebular, and likely migrated between a high temperature and low temperature regions of the protoplanetary disk [6], supporting the 'fiefdom' model of protoplanetary disk formation [9].

Finally, geochemical analysis of >100 RMNs *in situ* within a series of primitive chondritic meteorites reveal that RMNs are present within all chondritic components [5]. Additionally the heterogeneous chemistry of RMNs is inconsistent with known solar-nebula and parent body processes [5] such as condensation [3], crystallisation [10] or parent body alteration [11]. This leaves the possibility that an initial population of pre-solar RMNs/HSE-rich precursor phases, may have survived processing in the protoplanetary disk [5,6]. RMNs have also been observed in demonstrably pre-solar graphite [12], and RMN condensation is plausible in the circumstellar environment of asymptotic giant branch stars [13] supporting the idea that some RMNs may be pre-solar. However, to demonstrate a pre-solar origin for any material requires isotopic measurements. Unfortunately, precise isotope analysis of individual RMNs is challenging due to their micrometer-sub-micrometre size. To date, only a handful of isotope datasets on individual RMNs have been undertaken [3,8]. All values in these studies were consistent with a solar system origin [3,8]. Recent Ru isotope measurements of bulk RMN aliquots reveal that bulk RMN contain a slight r-process deficit that could be explained by late injection of material from a core-collapse supernova. These observations also support the idea that some RMNs may be pre-solar [14].

One important trait of RMNs is that they are Os-rich. Therefore, if a sufficiently sensitive approach could be applied, it would be possible to produce model ages for individual RMNs using the Re-Os isotope system.

Here we apply APT combined with a new approach to extract robust Re-Os isotopic information from Os rich Alloys [15], to measure the Re-Os isotope systematics and calculate model ages for 11 RMNs.

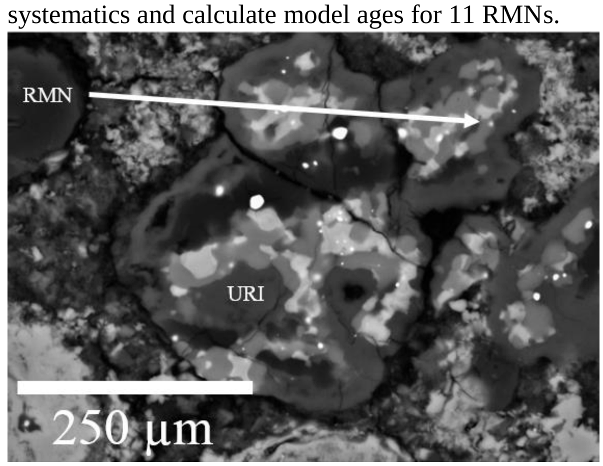

Figure 1. A backscatter electron image of an RMN bearing URI in ALH 77307. The RMNs are the bright regions. The labelled RMN is also shown in Figure 2 and 3. After Daly et al., [6]

Method: We identified 11 RMNs hosted within a range of chondritic components CAI, ultra refractory inclusions (URI), magnetite, amoeboid olivine aggregates (AOA) and sulphide rims around a chondrule) in five primitive carbonaceous meteorites (Allende, Vigarano, Adelaide, Murchison, Alan Hills (ALH) 77307) using scanning electron microscopy (e.g.

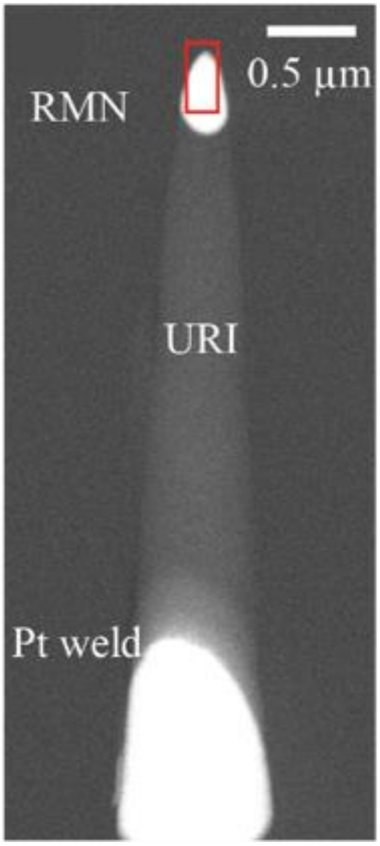

Figure 2. A backscatter electron image of the RMN in Figure 1 post extraction and milling to a needle like point by FIB techniques. The RMN is the bright grain situated at the apex of the tip with the host URI beneath. The specimen is attached to the Si post by a Pt weld. The red box indicates the approximate field of view of the atom probe analysis. (After Daly et al., [6])

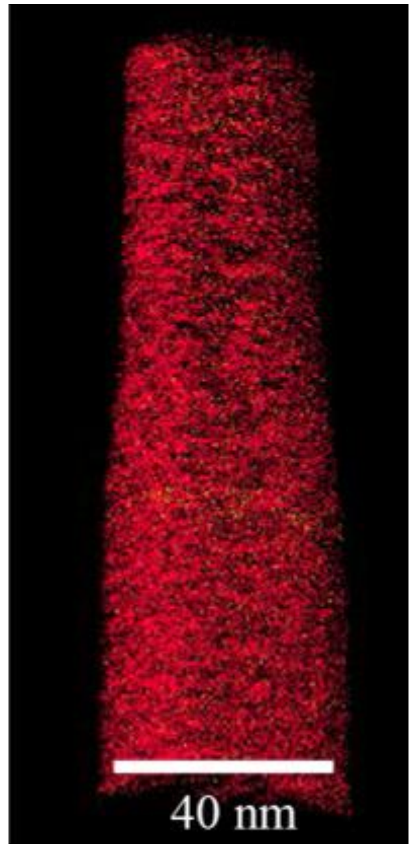

Figure 3. A 3 dimensional reconstruction of the atoms measured by atom probe analysis of the RMN in Figure 1 and 2. Each dot represents an individual atom detected during atom probe analysis. Re is represented by red dots and S by yellow dots. The sample is homogeneous with respect to its chemistry. This data set is typical for RMN in this study.

Figure 1). The RMNs were extracted and milled to needle like specimens for APT using focused ion beam (FIB) instruments at Sydney and Curtin University following the 'button' method targeting approach of Rickard et al., [16]. The RMNs were analysed on either the LEAP 4000XHR Geoscience atom probe at Curtin University or the LEAP 4000X Si at the University of Sydney (Figure 2). The data were processed using the IVAS software package. Re-Os isotopic information were extracted following the approach of Daly et al., [15] a new approach for extracting robust Re-Os isotopic information from metallic alloys by APT.

Results: The $^{187}Re/^{189}Os$ ratios and $^{187}Os/^{189}Os$ ratios extracted from the RMNs from CAIs, URIs, and AOAs using the new approach [15] plot on the solar system isochron and have model ages consistent with the age of the solar system. The RMNs hosted in magnetite inclusions also produce Re-Os isotope ratios that are consistent with a solar system origin. However, one RMN, hosted in a sulphide rim around a chondrule has an unusual Re-Os isotope ratio. The results and implications of this RMN and the broader implications of the other mode ages will be discussed at the meeting.

Discussion and conclusion: APT has been shown to be an ideal tool to extract robust isotopic information from geochronologically important isotope systems. In particular, APT is ideal for the analysis of sub-micrometre materials that are challenging to isotopically measure with established techniques. Through the provision of a robust standardised approach for APT isotopic analysis [15] we have safely applied this method to RMNs. Our data indicate that that all RMNs measured in this study that are hosted in typical refractory inclusions have calculated model ages that are within the analytical precision of the age of the Solar system, consistent with previous RMN isotope measurements [3,8]. This approach would be able to distinguish and date pre-solar RMNs.

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