

COMPOSITION OF REFRACTORY METAL NUGGETS: IMPLICATIONS FOR THEIR ORIGINS. L. Daly¹, P. A. Bland¹, K. Evans¹, K. A. Dyl¹, L. V. Forman¹, P. W. Trimby², S. Moody², L. Yang², H.W. Liu², A. La Fontaine², J. M. Cairney², S. P. Ringer³ and M. Saunders⁴, ¹Department of Applied Geology, Curtin University, GPO Box U1987, Perth, WA, 6845, Australia. E-mail luke.daly@postgrad.curtin.edu.au, ²Australian Centre for Microscopy and Microanalysis and ARC Centre of Excellence for Design in Light Metals, The University of Sydney, NSW, 2006, Australia, ³Australian Institute for Nanoscale Science and Technology, and School of Aerospace, Mechanical & Mechatronic Engineering The University of Sydney NSW, 2006, Australia. ⁴ Centre for microscopy, Characterisation and Analysis, The University of Western Australia, WA 6009, Australia

Introduction: Refractory metal nuggets (RMNs) are composed primarily of Fe, Ni, and platinum group elements (PGEs). They are thought to form by condensation in the early Solar Nebula [1]. However, it has also been suggested that RMNs can form via crystallisation from a silicate melt [2]. Here we combine *in situ* analysis of RMNs, RMN compositions reported in the literature, and predicted compositions from a condensation model to define populations of RMNs based on their chemistry.

Methodology: 109 RMNs were analysed *in situ* from Allende, Murchison, Vigarano, ALH 77307, and Adelaide, using energy dispersive X-Ray spectroscopy (EDS) at the University of Sydney, Curtin University, and the University of Western Australia. These observations were supported by analyses from EDS during Transmission Kikuchi Diffraction (TKD), and EDS obtained in transmission electron microscopes (TEMs).

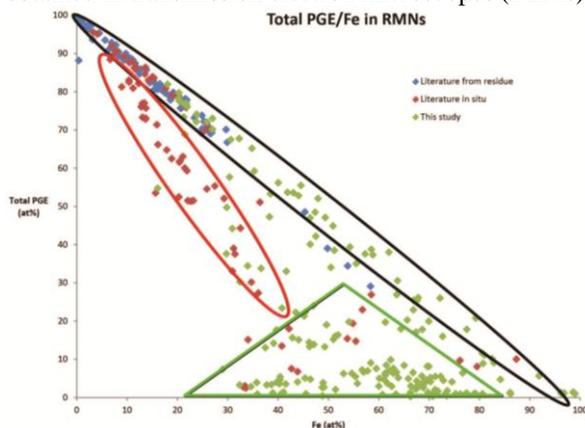


Figure 1: Total PGE/Fe in RMNs from this study and the literature. Showing a Fe mixing trend (black oval), a Ni mixing trend (red oval) and a low PGE region (green triangle).

An exhaustive literature search was performed in an attempt to include all published RMN compositions [1, 3-12], as well as RMNs thought to have formed via crystallisation in a silicate melt [2, 13], giving a sum total of 380 RMNs for this study.

All compositions have been converted to atomic percent and renormalised, only taking into account the elements Fe, Ni, Ru, Rh, Mo, W, Re, Os, Ir, and Pt.

RMN compositions were compared to a condensation model similar to that detailed in [1].

Results and discussion: Plots of total PGE vs Fe (Fig 1), and total PGE vs Ni (Fig 5) show three distinct trends which can be defined by a Fe mixing line, a Ni mixing line and a cluster of low PGE concentrations (Fig 1). To check this is not an artifact of data processing, the data was plotted by original wt%, meteorite, author, technique, and inclusion type; revealing no systematic errors due to these factors.

Plotting the data in a similar vein to [1] (Fig 2) indicates that RMNs do approximately follow a condensation trend.

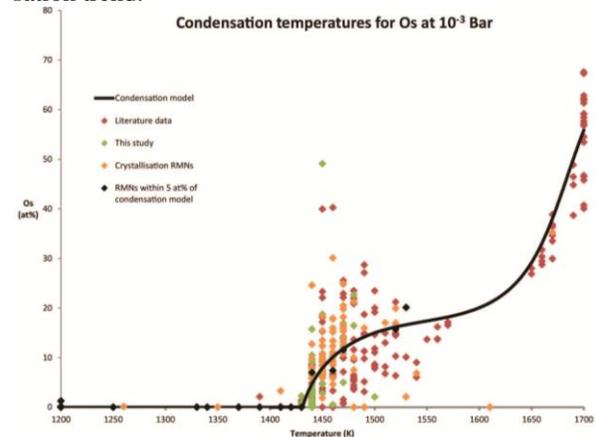


Figure 2: Composition of Os in RMNs compared to model condensation temperatures, RMNs within 5 at% of the condensation model for all elements are highlighted in black.

However, when the abundance of every element in each individual RMN was compared to the predicted composition from the condensation model, of the 380 RMNs analysed, only 29 were consistent to within 5 at% for every element. Of these 29, 22 were cosmic spherule-hosted RMNs from [13], which are thought to form by crystallisation. Of the remaining 7, only 2 had condensation temperatures >1500 K (Fig 2). In fact, when RMNs that formed via crystallisation are superimposed onto elemental plots (Fig 3) the spread is much more consistent with this mechanism of formation. Therefore, it is likely that most, if not all

RMNs formed by crystallisation, not condensation. Current condensation models cannot explain the full elemental composition of individual RMNs. This could be due to a lack of accurate activity coefficients for PGEs, this is required if we are to completely discount condensation as a possible mechanism for RMN formation.

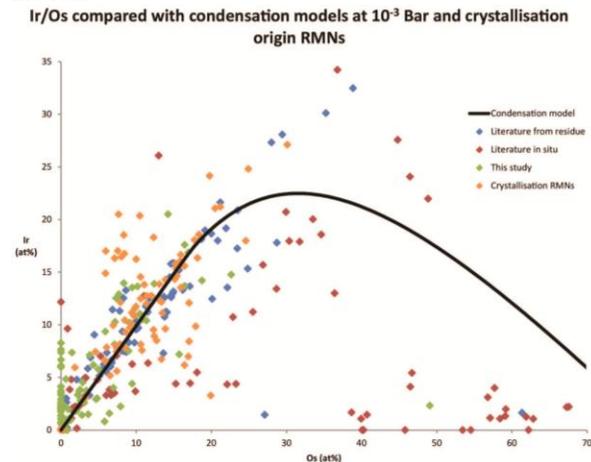


Figure 3: Ir/Os RMN compositions with condensation model and crystallisation RMNs. Indicating a crystallisation origin is more consistent with the spread of most RMN compositions.

Nevertheless, a crystallisation origin can only account for RMNs that follow the Fe mixing line (Fig 4).

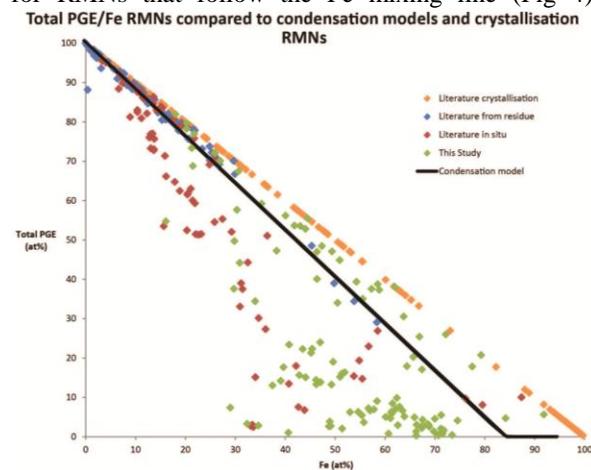


Figure 4: Total PGE/Fe with the condensation model and crystallisation RMNs. Indicating crystallisation or condensation cannot derive all RMNs.

Plotting RMNs relative to their host phase (Fig 5) reveals the low PGE cluster is dominated primarily by sulphide-hosted RMNs. Therefore, these grains are likely to have been affected by, if not formed due to sulphidation. However, the Ni mixing line remains an enigma. Fig 5 reveals the sulphide cluster is situated towards the end of the Ni mixing line. Therefore, the Ni trend and the sulphide cluster are potentially an expression of varying degrees of sulphidation of RMNs,

or sulphidation of RMNs with variable compositions produced by crystallisation; with Fe being replaced by Ni, dragging the Fe mixing line down towards the Ni mixing line.

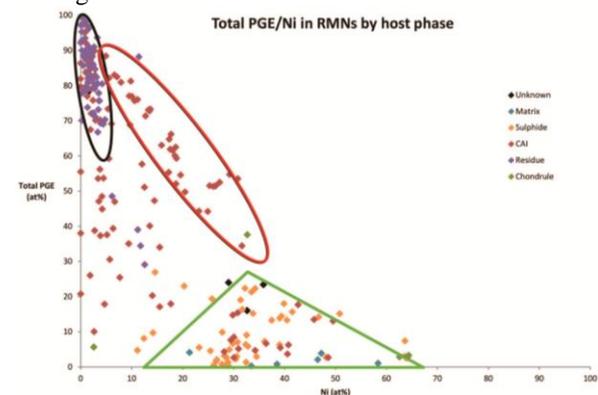


Figure 5: Total PGE/Ni RMNs by host. Indicating a relationship between the Ni mixing line (red) and the sulphide dominated region (green).

If every RMN can be interpreted as a product of crystallisation this presents a problem: RMNs are found in every component in carbonaceous chondrites [14]. This includes components which are not thought to have undergone igneous processes such as fluffy CAIs. This could call into question our current understanding of how these components form.

Conclusion: *In situ* analysis of RMN compositions reveals two populations of RMNs. The first follows a Fe mixing line, derived by crystallisation of RMNs from a silicate melt as described by [2]. The second follows a Ni mixing line produced by secondary sulphidation of crystallisation derived RMNs. A condensation origin for RMNs seems unlikely, but a crystallisation origin questions our current understanding of how meteoritic components form.

References: [1] Berg T. et al. (2009) *The Astrophys. Jour.*, 702, 172-176. [2] Schwander D. et al. (2015) *Met. & Planet. Sci.*, 50, 5, 893-903. [3] Bischoff A. & Palme H. (1987) *Geochim. et chosmochim. Ac.*, 51, 2733-2748. [4] Blander M. et al. (1980) *Geochim. et chosmochim. Ac.*, 44, 217-223. [5] Palme H. et al. (1994) *Geochim. et chosmochim. Ac.*, 58, 495-513. [6] Wark D.A. & Lovering J.F. (1976) *LPSC*, 7, 912 [7] Wark D.A. (1986) *Earth & planet. Sci. Let.*, 77, 129-148. [8] Palme H. et al. (1982) *Earth & planet. Sci. Let.*, 61, 1-12. [9] Wark D.A. & Lovering J.F. (1978) *LPI*, 9, 1214-1216. [10] Croat T.K. et al. (2013) *Met. & Planet. Sci.*, 48, 686-699. [11] Harries D. et al. (2012) *Met. & Planet. Sci.*, 47, 2148-2159. [12] Schwander D. et al. (2014) *Met. & Planet. Sci.*, 49, 1888-1901. [13] Rudraswami N.G. et al. (2014) *Geochim. et chosmochim. Ac.*, 131, 247-266. [14] Daly L. et al. (2014) *LPSC XLV*, Abstract #2071.