TITANIUM ISOTOPE SOURCE RELATIONS AND THE EXTENT OF MIXING IN THE EARLY SOLAR SYSTEM EXAMINED BY INDEPENDENT COMPONENT ANALYSIS. Robert C. J. Steele* and Patrick Boehnke, Department Earth, Planetary, and Space Sciences, UCLA, Los Angeles, California, 90095; *r.steele@uclmail.net

Introduction: Investigation of the isotopic compositions of early Solar System materials yields evidence for the nucleosynthetic precursors of the Solar System. For refractory elements with greater than three isotopes, for example Ti, Ni and Mo, the variation in anomalies over different bulk meteorite groups and normal calcium, aluminium rich inclusions (CAIs) are highly correlated [1, 2, 3]. This has been suggested to show mixing between reservoirs with different nucleosynthetic origins [1, 2, 3].

There are, however, exceptions to these systematic correlations, most notably the FUN (fractionated with unknown nuclear effects) CAIs and the population of hibonite grains from CM chondrites. Hibonite grains and FUN CAIs are relatively poorly understood populations of refractory inclusions found in primitive chondrites. These populations exhibit some of the largest isotope anomalies observed in materials found within the Solar System yet their origins remain unexplained. Hibonite, the focus of this study, is a highly refractory mineral and is thought to possibly be one of the first solids to have formed within the Soar System either by condensation or as a refractory residue [4].

Several hibonite populations have been observed, see [4, 5]. They are possibly related to each other and the Solar System because their O isotopic compositions are within what is considered to be the Solar System range [6, 7]. Broadly they can be split into two groups based on isotopic characteristics and petrology. The first, characterised by platy crystals (PLACs) and blue aggregates (BAGs), show large mass-independent stable isotopic anomalies coupled with little or no evidence for extant short-lived radionuclides (SLRs) [4, 8]. While the second, comprising spinel hibonite spherules (SHIBs), show smaller mass-independent anomalies but evidence for SLRs, for example either canonical or supra-canonical ^{26}Al [4, 8, 7]. The stable isotope anomalies are thought to represent pre-Solar signatures but it is not known whether the events in which the hibonites formed occurred within the Solar System at some point prior to general chemical and isotopic homogenisation of the proto-solar nebula, or if they were formed outside the Solar System and so are not isotopically related to the wider Solar System. Therefore it is clearly of great importance to asses the relation of the isotopic variations observed in the hibonites to the variation observed in other Solar System materials.

The isotopic composition of Ti has been studied extensively in both hibonites and bulk meteorites and normal CAIs. Titanium is a major element in hibonites and of reasonable high abundance in most meteorites ($\geq$ 500 ppm [9]). Moreover, Ti has five stable isotopes produced with varying efficiency by different nucleosynthetic environments, making it suitable as a tracer of nucleosynthetic source relations and mixing in the proto-Solar nebula.

The Ti isotope variations among the hibonites have proven somewhat enigmatic. The hibonite grains exhibit some of the largest isotopic anomalies seen for any element with ^{50}Ti enrichments of up to 25 % [8] and deficits of up to 10 % [10], however, there are no consistent correlations in these data, see figure 1. Various studies [11, 12, 8] have investigated the number of likely sources by attempting to fit the data to a plane. They find that the data do fit on a plane meaning that four or more sources are required produce the variation. The bulk meteorite data, however, show very consistent variation through the meteorite groups characterised by a correlation between $\varepsilon^{46}\text{Ti}_{\frac{49}{47}}$ and $\varepsilon^{50}\text{Ti}_{\frac{49}{47}}$ [1]. This correlation has been shown to be consistent with input from the O/Ne zone of an type II supernova (SNII) [2, 13].

Methods: We have re-examined the Ti isotope compositions of hibonite grains in the light of the more recent Ti isotope compositions published for bulk chondrites and normal CAIs [1]. The previous ion probe studies of hibonite grains normalised data for mass-dependent fractionation using the ^{46}Ti/^{48}Ti normalisation. The more recent measurements of bulk meteorites, however, observed isotopic compositions which were most consistent with correlated anomalies on the isotopes ^{46}Ti and ^{50}Ti, therefore, they adopted a ^{47}Ti/^{49}Ti normalisation. Thus, the first step was to renormalise the hibonite data in order to make the data from the two groups comparable, this was published in the previous LPSC meeting [14]. The renormalisation has been extended to include uncertainties for individual data points, rather than a representative average for each study. These were obtained from a Monte Carlo simulation varying around the uncertainties of the original data with 10000 repeats, see figure 1.

We have examined the relationships between hibonites and bulk meteorites by using independent component analysis (ICA), an established technique in signal processing that has only rarely been applied in geochemistry or cosmochemistry [18, 19]. Independent component analysis is a method of blind source separation by which a multivariate dataset can be deconvolved into independent subcomponents [20]. We have

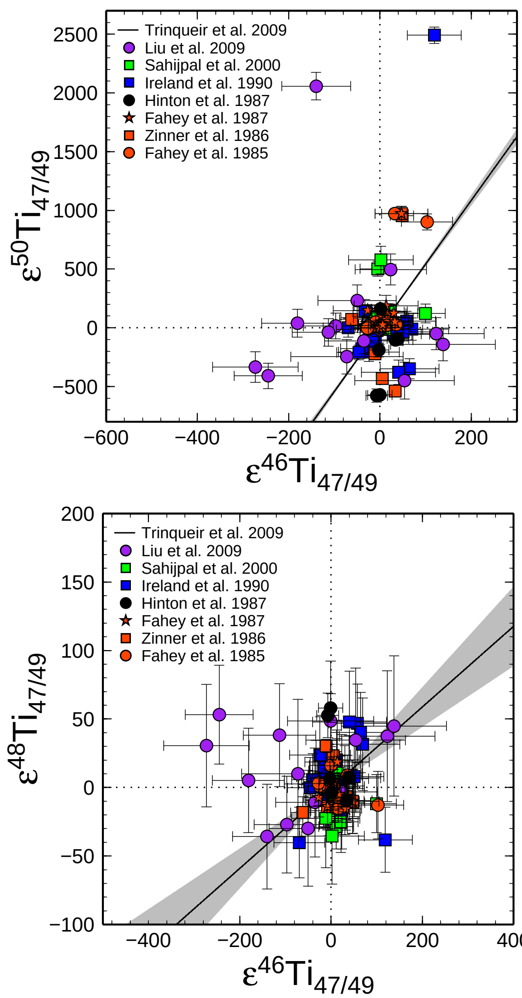

Figure 1: Titanium isotope data from [7, 15, 8, 10, 12, 16, 17] renormalised from $^{46}Ti/^{48}Ti$ to $^{47}Ti/^{49}Ti$. Also shown is the correlation observed in bulk meteorites from [1].

extended the traditional ICA technique to include uncertainties [21]. This new method offers a powerful tool to examine the mixing of sources in isotopic data and has potential for use in wider cosmochemical and geochemical data. The ICA returns the compositions of independent components, or vectors, required to fully describe the variation of the data. That is the compositions of the sources required to have mixed based on the variation present. These compositions describe a slope along which a significant proportion of the isotopic variation can be explained. These slopes could represent one source mixing to the origin (Solar) composition, or two sources mixing either side, therefore, the number of sources is at least the number of components plus one. As discussed in [20] the ICA algorithm is based on the assumptions that the sources are statistically independent and a mixed along linear trends, for a full description of ICA see [22].

Results: From the ICA we find that two components are required to explain the bulk meteorite data because there is small but significant variation in $\varepsilon^{48}Ti_{\frac{49}{47}}$. The two components that describe the bulk meteorite Ti isotope variation are very well defined because the bulk meteorite data are very precise and describe a tight correlation, in fact a plane, in three dimensions. The slope we find between $\varepsilon^{50}Ti_{\frac{49}{47}}$ and $\varepsilon^{46}Ti_{\frac{49}{47}}$ is within error of the slope observed by [1] determined by York regression [23]. The results of the ICA show that there are three components required to fully explain the hibonite data. Due to the noise in the hibonite data the components describing the variation in this dataset are much less well defined, however, all three components which describe the hibonite data are resolved, at the 95 % confidence interval, from both the components which describe the bulk meteorite data.

Discussion: The Ti isotope anomalies in hibonite represent the largest Ti isotope anomalies found in Solar System materials but they comprise a very small total mass of anomalous Ti and so their significance for Ti isotope variation in the bulk Solar System is not clear. The bulk meteorites are less anomalous by a factor of 200 but represent much more than 200 times the Ti and so represent the bulk of anomalous Ti in the Solar System. The findings from the ICA suggest that these two reservoirs of anomalous Ti are not related by simple mixing as the dominant source in the bulk meteorites is not present as one of the components observed in the hibonite grains. This finding can be reconciled in one of two ways, firstly the hibonite grains may not be from the Solar System and may be pre-Solar grains which formed in an environment with similar O isotope compositions to the Solar System. Secondly, this finding may be evidence of a second, unrecorded, event which created the Ti source of the bulk meteorites by mixing two or more of the hibonite sources. These two hypotheses may be tested by comparison with other elements (for example, Ca). More Ti, and other element, isotope data in hibonite grains are required to further investigate this.

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