

REE ABUNDANCE PATTERNS IN CAIs: IMPLICATIONS FOR NEBULAR PROCESSES;

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In an accompanying abstract [1] we have presented a new scheme for classifying CAIs according to their trace element abundances. Assuming that CAI abundances are representative of their abundances in the solar nebula (which is equivalent to assuming the same, although not necessarily 100 %, accretion efficiency for all CAIs), the high abundance of fractionated CAIs, i.e. ultrarefractory-depleted F_D 37 %, and ultrarefractory-enriched F_E 7 %, suggests that their formation was an important process throughout nebular regions where CAIs in Murchison and Allende formed.

By calculating the time required for a $1\mu\text{m}$ grain to scavenge Lu from the solar nebular vapor, Palme [2] argues that the formation of the F_E CAIs had to take at least four days, and probably substantially longer. He argues that the long timescale rules out transient heating processes, for example as caused by nebular lightning, as the heat source for these REE patterns. Accepting this argument, and the results of cooling rate experiments on synthetic CAI compositions [3] (because some "igneous" CAIs have fractionated patterns), we argue that the high abundance of F_D CAIs requires widespread heating over long (\geq week) time periods throughout the nebular regions where the CAIs formed. However, we emphasize that many of the F_D CAIs are fine-grained (e.g. Allende) or hibonite-bearing inclusions (e.g. Murchison) for which no cooling rate constraints are available. Furthermore, time periods of a week are short relative to the estimated nebular lifetime of $\sim 300,000$ years. If the time interval spanned by formation of Group II CAIs could be ascertained, the time scale for high temperatures in the nebula could be estimated.

Because formation of F_D patterns in perovskite (CaTiO_3) and in hibonite ($\text{CaAl}_{12}\text{O}_{19}$) requires gas-grain equilibration to stop at or only slightly below the hibonite and perovskite condensation temperatures (e.g. [4]), the *minimum* temperatures in these nebular regions (as a function of the assumed nebular total pressure) are 1730 K at 10^{-3} bars, 1548 K at 10^{-5} bars, and 1401 K at 10^{-7} bars for F_D patterns in hibonite, and 1677 K at 10^{-3} bars, 1529 K at 10^{-5} bars, and 1404 K at 10^{-7} bars for F_D patterns in perovskite [5, 6].

However, the constraints outlined above are applicable only if F_D patterns are solar nebula products. We note that there is an apparent discrepancy between the high temperatures required for formation of the fractionated patterns and the isotopic anomalies in Ca and Ti commonly found in these CAIs. Hibonite and perovskite are the most refractory Ca- and Ti-bearing condensates [5] and all the Ca and Ti are in the nebular gas at higher temperatures. Thus Ca and Ti would be isotopically homogenized on a short time scale by nebular mixing and by molecular diffusion instead of being isotopically anomalous as commonly observed in F_D CAIs where isotopic measurements have been made [7-10].

Murchison CAIs commonly have large ^{50}Ti isotopic anomalies. These are generally found in $\text{Uf}(011)$ crystal fragments, but large anomalies are also found in inclusions with F_D patterns (Fig. 1). Anomalies in ^{47}Ti , ^{49}Ti , and ^{50}Ti are *not* correlated and do not decrease in unison (Fig. 2) as would be expected if F_D inclusions formed by the progressive dilution of an exotic gaseous reservoir with normal Ti. Rather, F_D inclusions preserve at least as great a diversity of compositions even if a larger fraction are isotopically normal. The case of Murchison F_D inclusion 7-170 [9] is particularly notable since this is the only inclusion known that has a large ^{50}Ti depletion and a small excess of ^{49}Ti (in the ^{46}Ti - ^{48}Ti normalization scheme). It is not clear if the anomalies in ^{42}Ca , ^{43}Ca and ^{48}Ca behave similarly because the ^{42}Ca and ^{43}Ca anomalies are generally not resolvable from zero within 2σ error. In any case, dilution by nebular mixing of isotopically anomalous vapor cannot explain the observed Ti isotopic anomalies in F_D CAIs. A correlation that is prevalent in Murchison CAIs is that there are no inclusions with both large Ti isotopic anomalies and excess ^{26}Mg from the in situ decay of ^{26}Al at a level of $5 \times 10^{-5} \times ^{27}\text{Al}$. On the other hand, all F_D inclusions have $^{26}\text{Mg}^*$ at this level provided they do not have a large ^{50}Ti isotopic anomaly (Fig. 3). This clearly correlates isotopic and chemical systematics in CAIs from Murchison and cannot easily be explained by nebular condensation models.

Alternatively, as we and others have previously suggested [6, 10-13], the Ca and Ti isotopic anomalies in the F_D CAIs are the signature of presolar chemical processing. In these models, which have several advantages over nebular condensation models, the ultrarefractory REE could have been fractionated from the less refractory REE during condensation in an expanding stellar envelope with the subsequent depletion of the most volatile REE (Ce, Eu, Yb) occurring during partial vaporization of this presolar dust in the solar nebula. An attractive feature of this model is that both the Ca and Ti isotopic anomalies are inherited from presolar dust, which is incompletely vaporized and thermally processed in the solar nebula. This model can be tested experimentally using techniques such as Nd-Sm, La-Ce, or Lu-Hf dating to determine when the fractionation of the REE took place [6, 13].

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References: [1] Ireland and Fegley (1991) this conference. [2] Palme (1991) In *Protostars and Planets III*, submitted. [3] MacPherson *et al.* (1988) In *Meteorites and the Early Solar System*, p 746. [4] Ekambaram *et al.* (1984) *GCA* 48, 2089. [5] Kornacki and Fegley (1984) *J. Geophys. Res.* 89, B588. [6] Fegley and Ireland (1991) *Euro. J. Solid State Inorg. Chem.* in press. [7] Hinton *et al.* (1988) *GCA* 52, 2573. [8] Ireland *et al.* (1990) *GCA* in press. [9] Ireland (1988) *GCA* 52, 2827. [10] Ireland (1990) *GCA* in press. [11] Kornacki and Fegley (1986) *EPSL* 79, 217. [12] Wood (1981) *EPSL* 56, 32. [13] Kornacki and Fegley (1985) *LPS XVI*, 457.

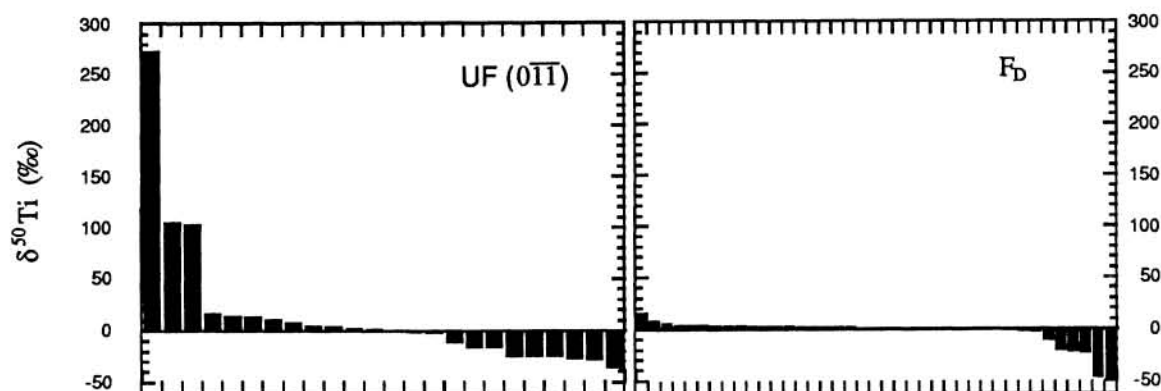


Figure 1. Large ^{50}Ti isotopic anomalies are found in F_D inclusions as well as inclusions with unfractionated patterns (such as $UF (0\bar{1}\bar{1})$ shown on the left).

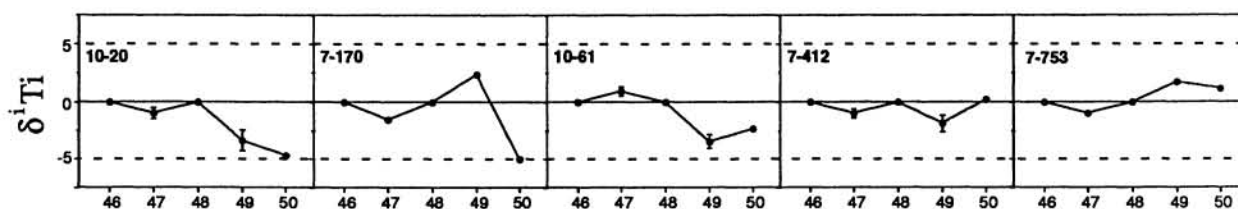


Figure 2. Ti isotopic anomalies in F_D inclusions. Anomalies in ^{47}Ti , ^{49}Ti , and ^{50}Ti are not correlated and do not decrease in unison as would be expected if F_D inclusions formed by the progressive dilution of exotic Ti in a gaseous reservoir. Rather, F_D inclusions display the same variability in their Ti isotopic compositions as the UF inclusions. (NB - ^{50}Ti anomalies + 10).

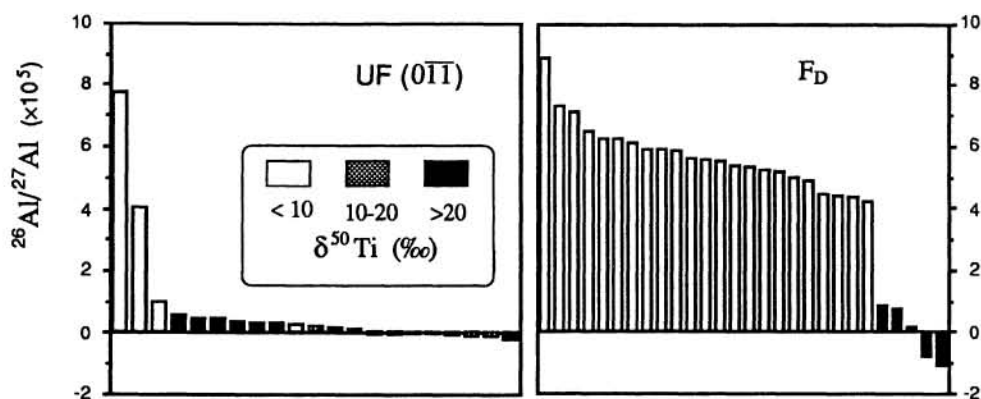


Figure 3. Inclusions that have large Ti isotopic anomalies never have excess ^{26}Mg . On the other hand, inclusions that have F_D patterns have excess ^{26}Mg unless they also have a large ^{50}Ti isotopic anomaly. Apparent negative values are mathematical artifacts from normalization and uncertainty of measurement.