RYUGU/CI CHONDRITES AS AN ENDMEMBER COMPOSITION OF THE CC RESERVOIR & AN ILLUSTRATIVE MIXING MODEL FOR CR, TI, & FE ISOTOPIC AND ELEMENTAL COMPOSITIONS OF CC CHONDRITES

T.E. Yap and F.L.H. Tissot, The Isotoparium, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA.

Introduction: Nucleosynthetic isotope anomalies constitute robust tracers of genetic links between Solar System materials, and have established that meteorites exhibit a fundamental dichotomy between non-carbonaceous (NC) and carbonaceous (CC) groups, broadly associated with the inner and outer Solar System, respectively [1-3]. Of all the CC meteorites, CI chondrites bear the closest resemblance to samples of Cb-type asteroid Ryugu returned by Hayabusa2 in chemistry, mineralogy, and isotope anomalies [4,5]. In Ti-Cr-O isotope space, for instance, Ryugu and CI chondrites together define an end-member composition of the CC reservoir. Based on the observation that Ryugu and CI chondrites exhibit indistinguishable Fe isotope anomalies, distinct nonetheless from those of other CC chondrites, it has recently been suggested that they derive from a third, rarely-sampled "CI" reservoir at greater heliocentric distances than the CC reservoir [6]. Here, we propose that the appearance of a genetic trichotomy in meteoritic heritages arises from the omission of CC achondrites in the Fe isotope data obtained and presented. Given that CC intra-reservoir variability in Ti-Cr-O isotope space extends to Fe, the CC achondrites are expected to bridge the Fe anomaly "gap" currently separating Ryugu and CI chondrites from the other CC chondrites.

To assert that Ryugu, CI chondrites, and CC chondrites derive from the same CC reservoir invites a discussion of how the relatively wide dispersion in Fe anomalies within the reservoir may be explained. To this end, we developed an illustrative mixing model for CC chondrites underpinned by previous studies. We explore how the Cr, Ti, and Fe isotope anomalies and concentrations of the CM, CV, CO, CK, and CR chondrite groups can be reproduced via admixing of four materials from three primordial nebular source regions: (i) elementally ordinary chondrite-like (OC-like) material, (ii) CI chondrite (Ryugu-like) material, (iii) isotopically CAI-like "dust," and CAIs *sensu stricto*.

Predictions Against a Genetic Trichotomy: To date, several achondrites have been classified as CC achondrites by virtue of Ti-Cr-O isotope systematics [7]. Note that two of them, Northwest Africa 2994 and Northwest Africa 3100 have been observed to possess rare and small relict chondrules, and may be more appropriately termed "highly-equilibrated chondrites" [8]. In Ti-Cr-O isotope space, the CC achondrites generally populate the region between Ryugu/CI chondrites (means of μ^{54}Cr ~141.0, μ^{50}Ti ~186.0, Δ^{17}O ~0.5) and the other CC chondrites (means of μ^{54}Cr ~106.7, μ^{50}Ti ~299.4, Δ^{17}O ~ -2.7), defining means of ~132.5, ~212.8, and ~ -1.6, respectively. Ryugu, CI chondrites, CC achondrites, and CC chondrites clearly define a single cluster and trend in Ti-Cr-O isotope space.

We performed linear regressions through Ryugu, CI chondrites, and CC chondrites in both Fe-Cr and Fe-Ti isotope spaces, obtaining slopes of ~ -0.47 and ~0.18, respectively. The measured μ^{54}Cr and μ^{50}Ti of the CC achondrites are then projected onto these regression lines to predict their μ^{54}Fe, and position them in Ti-Cr-Fe isotope space. The predicted μ^{54}Fe obtained from Fe-Cr space range from ~1.3 to ~26.1, with a mean of ~12.5 ± 1.2 (2SE). Those from Fe-Ti space range from ~2.3 to ~12.8, with a mean of ~6.4 ± 1.7 (2SE). Both predicted means fall between the mean μ^{54}Fe of Ryugu and CI chondrites (~1.5) and that of the CC chondrites (~23.0). There is substantial overlap between the ranges of predicted μ^{54}Fe from both spaces, especially in account of errors in the μ^{54}Cr and μ^{50}Ti of the CC achondrites (**Fig. 1**). Our simple exercise suggests the inclusion of Fe isotope anomalies from the CC achondrites will remove the

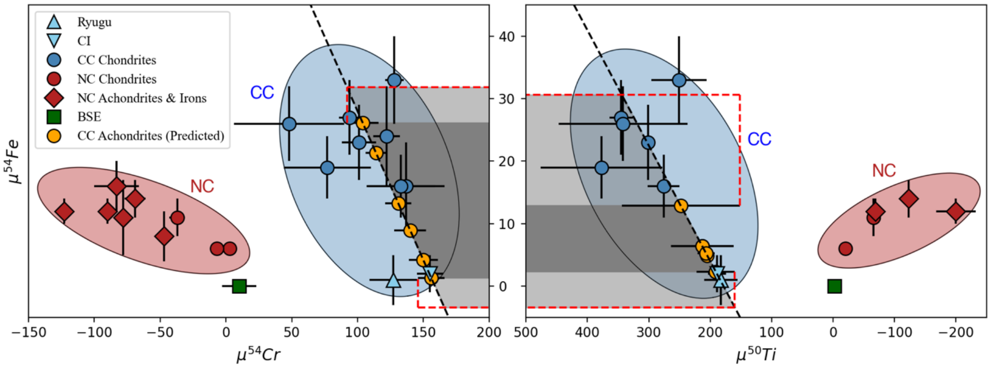

Fig. 1. *Predicted μ^{54}Fe values of CC achondrites in plots of (left) μ^{54}Fe vs. μ^{54}Cr and (right) μ^{54}Fe vs. μ^{50}Ti. Dark (light) grey bands highlight the range of predicted μ^{54}Fe values (including uncertainties).*

need to invoke a trichotomy in the description of meteoritic genetic heritages, and thus isotopically-distinct reservoirs in the early Solar System.

Mixing Model for CC Chondrites: Previous studies have collectively suggested that CC chondrites constitute admixtures of NC-like (i.e., OC-like or enstatite chondrite (EC)-like), CI-like, and isotopically CAI- or AOA-like components in addition to actual CAIs [*e.g.*, 3,9,10]. Notably, systematic investigation of isotope anomalies in multi-element space show that CAIs *sensu stricto* are inadequate in reproducing CC bulk anomalies when incorporated in NC-like material [3]. It has been demonstrated that Ti and Cr isotope anomalies and concentrations in CC chondrites may be explained with a mixing model involving the admixture of OC/EC material, CI material, and CAIs [11]. However, such a model is incapable of reproducing CC chondrite Fe isotope anomalies and concentrations, owing to the low Fe concentration in CAIs. In fact, we are unaware of any models that quantitatively explain CC chondrite isotopic and elemental variability for more than two elements.

We propose a mixing model in which the final isotopic and elemental composition of each CC group may be interpreted as a culmination of three mixing events — mixing between the OC-like and CI components into so-called precursor components (**Fig. 2A**), mixing between precursor components and CAI-like dust into so-called pre-CAI components (**Fig. 2B**), and the addition of CAIs to the pre-CAI components (**Fig. 2C**). The particular order in which these components are combined is, of course, irrelevant to the final proportions of the four end-member components in each CC group. We assume (i) the OC-like component lies along a straight line connecting the OC and CI chondrites, at a fiducial μ^{50}Ti of -500, and (ii) the CAI-like dust components have Fe/Ti ratios as well as Fe and Ti concentrations equivalent to those of their respective precursor components. The OC-like component is identified with an end-member composition of NC intra-reservoir variability. In multi-element space, it is clear that CI chondrites *sensu stricto* do not constitute the other end-member (e.g., consider Zr anomalies) of the NC reservoir. This unsampled end-member has been hinted at by [12] and may be isotopically CI-like for several elements (e.g., Cr, Ti, Fe). Our analysis, results, and evaluations of internal consistency will be detailed in [13], where our findings are also discussed in the context of the large-scale isotopic architecture and evolution of the early Solar System. Errors on calculated parameters are derived through Monte Carlo simulations. Overall, we find that CC chondrites collectively consists of roughly equal parts OC-like (mean of ~29.2%) and CI (mean of ~32.1%) material, with slightly higher amounts of CAI-like dust (mean of ~36.8%). This implies that the latter constitutes a major component of the CAI nebular source region, which likely formed close to the young Sun before being transported radially outwards through viscous spreading of the forming disk [3, 14,15]. While we predict Ryugu and CI chondrites do not define a reservoir of their own, they may nonetheless represent a primordial nebular component to which NC-like and CAI-like (including CAIs *sensu stricto)* material was incorporated to form the CC chondrites.

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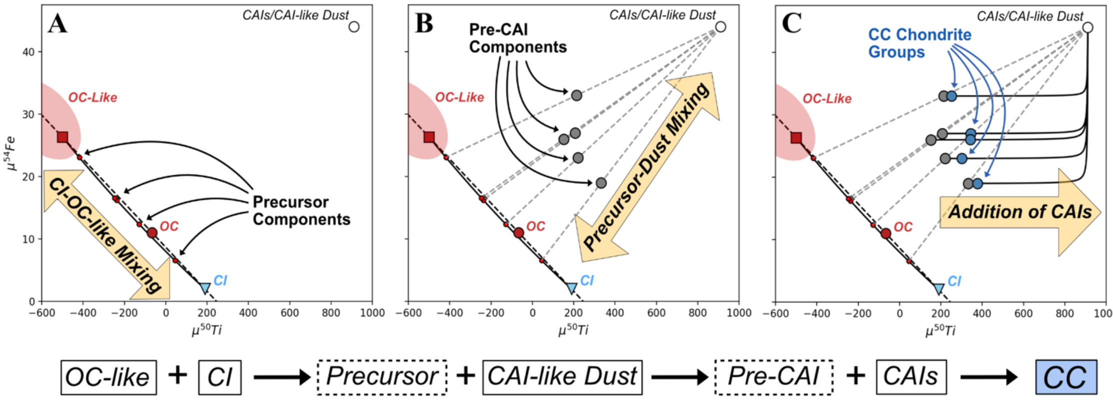

Fig 2. *Steps to recreating the CC chondrites in our mixing model, involving (A) mixing between CI and OC-like material, (B) mixing between the precursor components and the CAI-like dust, and (C) the addition of CAIs to the pre-CAI components.*