STABLE-ISOTOPE ANOMALIES: THE DICHOTOMOUS NATURE OF SOLAR SYSTEM MATERIALS AND LIMITS ON MIXING WITHIN THE NASCENT SOLAR SYSTEM.

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Introduction: Among primitive meteorites (chondrites), carbonaceous chondrites represent a distinctive subset; and not just vis-à-vis carbon. "Carbonaceous" traits [1] include: ^{16}O-rich oxygen isotopic composition (except in the case of CI); CI-or-higher mean ratio of refractory elements to the major lithophile element Si; relatively high abundance of refractory inclusions (except in CI); and high matrix/chondrule abundance ratio. The term carbonaceous is "somewhat of a misnomer" [1]. Carbonaceous chondrites of high petrologic types are C-poor compared to noncarbonaceous chondrites of types near 3.0 [2,3]. In this work, "carbonaceous" is used in the traditional meteoritical sense, connoting kinship with CI, etc., but not really much about carbon.

The full significance of the carbonaceous / noncarbonaceous distinction has only recenty become manifest, as the collective fruit of many excellent isotopic studies, enumerated in Table 1, and reviewed by [20,21]. Carbonaceous materials (chondrites plus a few differentiated meterorites) represent a solar system reservoir that is fundamentally distinct, not just versus other chondrites, but also versus nearly all differentiated materials. Not shown in Table 1 are many meteorite types for which neither ε^{50}Ti nor ε^{54}Cr has yet been determined. I have also exploited the rich legacy of oxygen isotopic data from R. N. Clayton's lab [e.g., 22, 23], augmented by recent sources [e.g., 14]. My studies have also extended to the still small data base for ε^{62}Ni [24, 25; ε^{62}Ni poses particularly difficult analytical challenges], which in general correlates with ε^{50}Ti.

Origins of the isotopic variations, and special significance of ureilites: For the Ti, Cr and Ni isotopic ratio anomalies exploited here, the variations observed are far too great to be the result of mass fractionation, so they probably reflect incomplete, and/or impermanent, mixing of stellar-nucleosynthetic ejecta [4,5,26,27]. In the CI1 Orgueil, enrichments in ^{54}Cr are linked with presolar Cr-oxides, most likely spinels, of order 10-100 nm in size [26,27]. Within the CV3 Allende, Trinquier et al. [5] found remarkable heterogeneity in ε^{50}Ti, mainly between chondrules and CAI. The origin of the Δ^{17}O diversity remains controversial [21]. Oxygen is a major element, whereas presolar grains are trace components and rarely feature ^{16}O enrichment [28], so Δ^{17}O diversity clearly did not stem from presolar nanoparticles of the type found by Dauphas et al. [26]. In any case, Δ^{17}O, ε^{50}Ti, ε^{54}Cr and ε^{62}Ni, all can potentially provide important constraints on mixing in the nascent solar system.

Table 1. "Truth table" listing of source/availability for ε^{50}Ti and ε^{54}Cr data for planetary materials.

		ε^{50}Ti	ε^{54}Cr
Carbonaceous chondrites			
	CI	4, 5	10, 12-15
	CM	5	10, 12-15
	CO	5	10, 12-15
	CV	4, 5	10, 12-15, 19
	CR	4, 5	12,13,14,15
	CB	5	10, 12
	CK	5	12, 16
	Tagish Lake	5	14
Noncarbonaceous chondrites			
OC	H	4, 5	12, 16
	L	5	12, 16
	LL	5	12, 16
EC	EH	5	12, 15, 16
	EL	N	12, 16
	E-Itqiy	5	N
	R (Rumuruti-like)	N	16
	GRO 95551	N	16
Differentiated materials			
	Angrites	5	12
	Aubrites	N	12
	HEDs	4, 5	12
	Earth	4	12
	Moon	5, 6	16
	Mars (SNC)	4, 5	12, 16
	Mesosiderites	4, 5	12
	Main Group pallasites	5	12, 16
	Eagle Station pallasites	N	10
	NWA 011/NWA 2976	5	7
	Ureilites	4, 5	8,9,11,17,18
	IIE iron meteorites	N	12
	IIIAB iron meteorites	N	12, 16

Abbreviation: N = no data available. Also, all references are shown in abbreviated format, without [brackets].

Any one type of differentiated meteorite will generally show limited variation in these isotopic ratios. Ureilites are exceptional, with O-isotopic variations that closely resemble the CCAM line (Δ^{17}O ranges from –2.4 to –0.2 ‰), and correlate with bulk composition [22,20]. Ureilites also contain on avg. 3 wt% bulk C [e.g., 2], so it has been generally assumed that they were descended from carbonaceous-chondritic precursor matter [e.g., 29; many other references are cited in ref. 20]. In any case, ureilites stand out as one variety of differentiated meteorite for which it would be inappropriate to average all data before plotting.

Isotopic bimodality: Figs. 1 and 2 show ε^{54}Cr plotted vs. ε^{50}Ti and vs. Δ^{17}O. Similar diagrams have been published previously by Trinquier et al. [5, 12] and Qin et al. [17]. The CB data are shown as CB* with a grey fill, because no single CB has yet been analyzed for both ε^{54}Cr and ε^{50}Ti, or for both ε^{54}Cr and Δ^{17}O.

The large data sets used here show an obvious bimodality, remarkable not only for the strength of the clustering, but also in other ways. In both Figs. 1 and Fig. 2, among carbonaceous chondrites there is a clear trend, aligned approximately perpendicular to the direction of the noncarbonaceous cluster. Thus, no realistic extension of the carbonaceous chondrite isotope-compositional distribution can be expected to incorporate the other materials. Ureilites not only show *non*-carbonaceous affinity [18], they plot at the *far end* of the noncarbonaceous field in Fig. 1. Other "surprising"

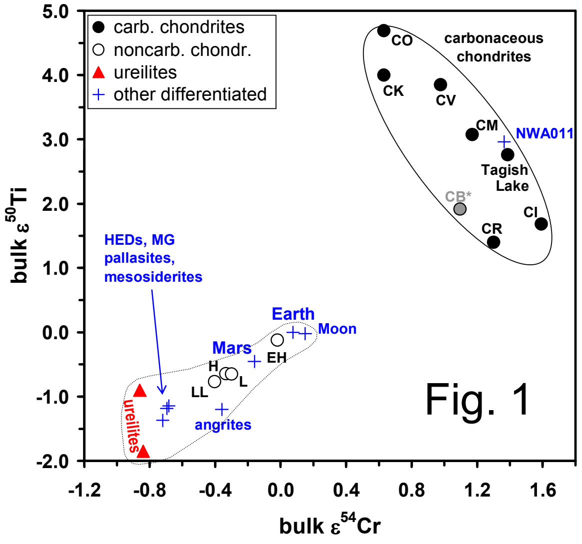


Fig. 1

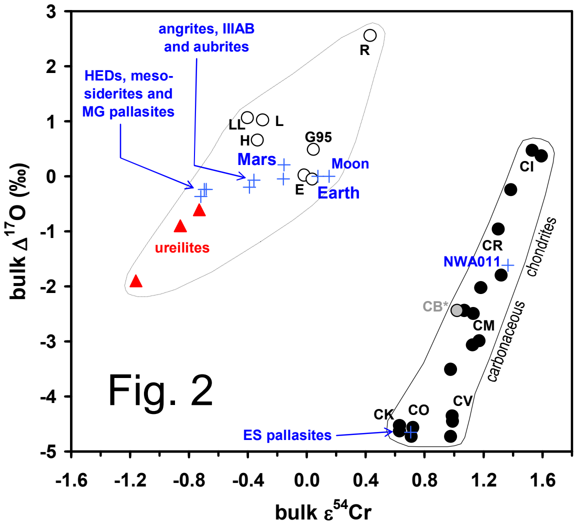


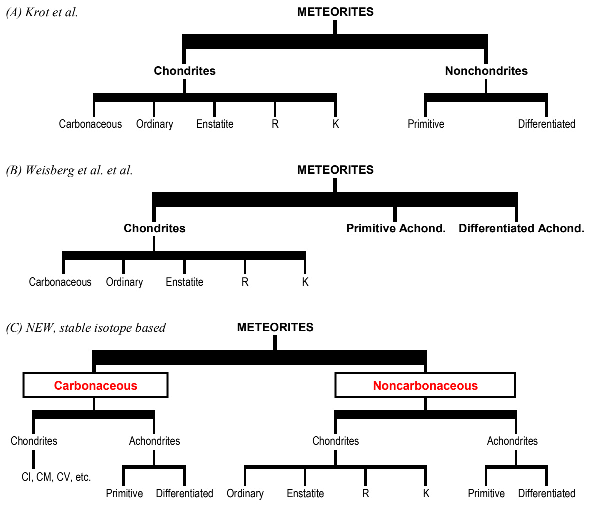
Fig. 2

isotopic compositions, such as for NWA 011 and Eagle Station pallasites, which are differentiated and yet of carbonaceous affinity, and GRO 95551 ("G95"), an anomalous chondrite, do *not* conflate the two clusters.

Discussion: The bimodality implies that ***the top-level classification of planetary materials needs to be reconsiderd*** (Fig. 3). The inapt terms carbonaceous and especially noncarbonaceous ought to be replaced (e.g., by *ectopic* and *entopic*; with Greek connotations outwardly located and inwardly located, respectively).

The bimodality is conceivably merely an extreme manifestation of the effects of episodic accretion in the protoplanetary nebula [15,30]. However, a simpler explanation is that the bimodality corresponds to a division between materials that originally accreted in two vastly different regions of the solar system. NWA 011 and the ES pallasites notwithstanding, carbonaceous planetesimals were less likely than noncarbonaceous planetesimals to undergo major heating; probably because carbonaceous planetesimals tended to accrete at greater radial distance from the Sun [31]. Walsh et al. [32] have inferred that as a consequence of radial migration and mass growth of the giant planets, the belt region underwent a complex evolution that culminated in a significant inward migration of planetesimals from the outer solar system, into mainly the outer belt. I [20,21] suggest that the isotope-geochemical bimodality arose because carbonaceous materials originally accreted in the outer solar system, and the noncarbonaceous materials in the inner solar system; with very limited (early) mixing between these two reservoirs.

Fig. 3 TOP-LEVEL CLASSIFICATION OF SOLAR SYSTEM MATERIALS



In Figs. 1-2, the planets (Earth, Moon and Mars) plot within, or at the fringe of, the noncarbonaceous fields. By lever-rule modeling [21], the proportion of carbonaceous matter in the Earth is almost certainly less than 32%, and in Mars less than 18%.

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