Understanding early Solar System processes: An oxygen isotope perspective.

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Introduction: Oxygen isotope analysis has become an indispensable tool in the study of early Solar System processes [1], in large part as a result of the pioneering studies of Clayton and coworkers [2,3,4,5]. The high levels of precision available with the laser fluorination technique have significantly improved the range and scope of such investigations. As a result, high precision oxygen isotope measurements provide critical information about the processes that operated both in the nebula and subsequently on a diverse range of parent bodies, from small primitive asteroids to planetary-sized bodies.

Slope 1 variation: The discovery that primitive meteorites and their constituents display non mass-dependent variation, with a slope of close to 1 on an oxygen three-isotope diagram, was a fundamental breakthrough in meteoritical science [2]. However, the nature of the underlying process that produced this variation remains poorly understood. While self-shielding of CO, either in the early solar nebula [6, 7], or the precursor molecular cloud [8], is the currently favoured mechanism, alternative models have recently been proposed [9,10].

An important aspect of this problem relates to the significance given to various reference lines on oxygen three-isotope diagrams. The most widely used is the Carbonaceous Chondrite Anhydrous Mineral (CCAM) line, which has a slope of 0.94 and was derived from analysis of Allende CAIs [5,11]. However, the fundamental significance of the CCAM has been questioned and instead a line of slope 1 (Y&R line) proposed as more representative of the primordial variation [12]. The fact that a highly ^{17,18}O-enriched phase (δ^{17}O and δ^{18}O ≈180‰) in Acfer 094 plots on the extension of the Y&R line, lends additional support to this proposal [13].

The results of recent high precision laser fluorination studies of CR chondrites [14], and primitive achondrites [15,16], provide new information relevant to this problem (Fig. 1). Both the winonaites and acapulcoite-lodranite clan define distinct arrays on Fig.1, with slopes of 0.53 and 0.61 respectively. Chondrule-bearing winonaites (NWA 725, NWA 1052, NWA 1463, Dho 1222, Mt. Morris (W)), which may be close to the parental composition of the group, plot at the end of the array closest to the Y&R line. The CR chondrites display a similar relationship, with the least aqueously altered samples plotting close to the Y&R line and the progressively more altered ones furthest away from it [14]. In particular, the Antarctic CR chondrite QUE 99177 (Fig. 1) contains abundant amorphous material and appears to have suffered relatively little aqueous alteration [17]. Thus, the oxygen isotope composition of the precursor material to both the winonaites and CR chondrites is better defined by the Y&R line than the CCAM.

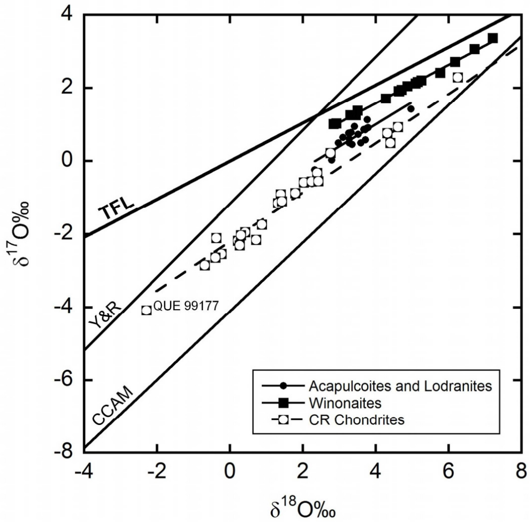

Fig. 1 Oxygen isotope composition of the CR chondrites, winonaites and acapulcoite-lodranite clan in relation to the CCAM and Y&R lines. TFL: Terrestrial Fractionation Line. Data [5, 14, 16].

Chondrules in Allende: To examine further the relationship between the Y&R and CCAM lines we have undertaken a laser fluorination study of Allende chondrules (Fig. 2). 25 chondrules, varying in mass from 0.2 to 3.4 mg, were extracted by gentle crushing and hand picking from a relatively pristine sample of Allende. These define a linear array with a slope of 0.97, which is distinct from the CCAM line (Fig. 2). Based on ion microprobe analyses of phenocryst phases in Acfer 094 chondrules, a further slope 1 line has recently been proposed, known as the Primary Chondrules Mineral line (PCM) [18] (Fig. 2). This line is clearly distinct and steeper than the line defined by chondrules in Allende. Since chondrules in Acfer 094 are relatively pristine [18], these relationships lend support to the suggestion that primary slope values decrease with increasing degrees of secondary alteration [12]. In addition, differing constituents in the same meteorite, i.e. Allende CAIs and chondrules, define differing slope values, which again may reflect a variable response to secondary alteration.

Even despite these variations it is clear that primary slope values vary only slightly from unity. In contrast, slope values of between ~0.6 and 1.8 have been measured in CO photodissociation experiments [19]. As a result, there is currently a debate about the extent to which self-shielding was responsible for the primordial oxygen isotope variation found in primitive meteorites [20]. In contrast, analysis of captured solar wind from Genesis concentrator samples indicates that the Sun has a composition of $\delta^{18}O$ = -58.5‰ and $\delta^{17}O$ = -59.1‰ [21]; values which are consistent with the predictions of the self-shielding model [6].

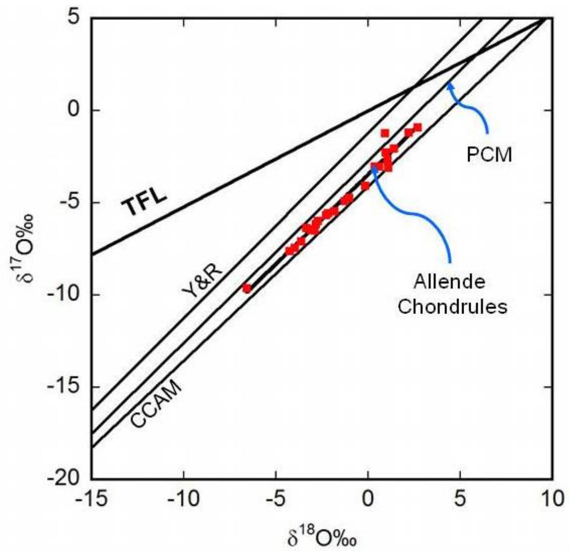

Fig. 2 Laser fluorination analyses of Allende chondrules compared to various reference lines (see text for details).

Deciphering parent body processes: Oxygen isotope analysis provides an important means of assessing the extent to which various meteorite groups, and by implication their parent bodies, underwent melting and hence isotopic homogenization [1,4]. Thus, the differentiated achondrites (HEDs, mesosiderites, pallasites, SNCs, angrites and lunar rocks) show extremely limited $\Delta^{17}O$ variation when compared to chondrites. The primitive achondrites (winonaites, brachinites, acapulcoite and lodranites) show intermediate levels of oxygen isotope variation [22] and are generally regarded as being either highly metamorphosed chondrites, or partial melt residues [23].

High precision oxygen isotope analysis has been particularly successful at helping to define the relationships between the various achondrite groups. Thus, on the basis of their differing $\Delta^{17}O$ values, it has been possible to resolve the angrites, HEDs and main-group pallasites and so demonstrate that each is from a distinct parent body [24,25]. Due to their similar petrography and mineralogy, an oxygen isotope analysis is often required to resolve the winonaites from the acapulcoites and lodranites [26].

Oxygen isotope analysis has convincingly demonstrated that basaltic achondrites are derived from multiple parent bodies [27, 28]. However, the extent to which impact mixing processes may contribute to the observed isotopic diversity requires further evaluation.

Genetic links between apparently distinct meteorite groups may be revealed by similarities in their oxygen isotope compositions. A possible example is the relationship between the CV and CK chondrites. While CKs tend to be of a higher metamorphic grade than the CVs, both share a range of common characteristics. In particular, very similar oxygen isotope compositions. Both groups may be derived from a common parent asteroid, that was subsequently disrupted to form the Eos asteroid family [29].

Conclusions: High-precision oxygen isotope analysis is a powerful technique that provides important insights into the processes that operated in the solar nebular and on early-formed asteroids.

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