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METEORITES AND THEIR PARENT BODIES:
EVIDENCE FROM OXYGEN ISOTOPES

ROBERT N. CLAYTON

*Enrico Fermi Institute and Departments of
Chemistry and Geophysical Sciences
University of Chicago, Chicago, Illinois 60637*

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As a result of the heterogeneous distribution of the isotopes of oxygen in the early solar nebula, the various planets, asteroids and meteorites have isotopic labels which permit recognition of samples derived from common sources. It is thus possible to see genetic associations between meteorite classes, such as group II E irons with H-group ordinary chondrites, and enstatite meteorites with the Earth and Moon. These associations help in defining the complexity of the parent bodies, and in determining their region of origin within the solar system.

INTRODUCTION

In order to understand the implications of all of the detailed measurements which are made on meteorites, we must somehow establish their "field relations" within the solar system. We need to identify their parent bodies, and reconstruct their histories of condensation and accretion. Oxygen isotope "fingerprints" provide a unique method giving information on the number of parent bodies represented by the meteorites. The solar nebula was not completely homogenized with respect to the isotopes of oxygen prior to condensation and accretion of the planets and meteorite parent bodies (Clayton *et al.*, 1973). Materials which condensed in different regions or at different times acquired variable proportions of a component enriched in ^{16}O . This isotopic "fingerprint" remains with the material, and no amount of chemical processing or mass-fractionation can eradicate it.

There are two possible explanations for the isotopic heterogeneity of the nebula: pre-solar solid grains enriched in ^{16}O , or a nucleosynthetically processed gas injected into the nebula followed by rapid condensation. The highest concentrations of the ^{16}O -rich component are found in high-temperature condensate minerals in C3 carbonaceous chondrites. This observation is consistent with the pre-solar grain hypothesis if these grains were refractory minerals which served as condensation nuclei for the solar system condensates. If the ^{16}O -rich component was introduced into the solar nebula from a nearby supernova explosion, then the high-temperature condensates in C3 meteorites were probably formed in the outermost parts of the solar nebula near the supernova shock front.

The oxygen isotopic compositions of the major stony and stony-iron meteorites are shown in Figure 1, on a graph of $^{17}\text{O}/^{16}\text{O}$ versus $^{18}\text{O}/^{16}\text{O}$. The oxygen isotopic compositions of matter in the early solar system were modified by at least two processes: (1) addition of the ^{16}O -rich component, which displaces the composition toward the lower left of the graph, along a line of unit slope; (2) mass-dependent isotopic fractionation associated with chemical or physical processes, which displaces the composition along a line of slope 1/2, in either direction, depending on the particular process. The heavy line in Figure 1 is the locus of compositions of terrestrial materials, and illustrates the effect

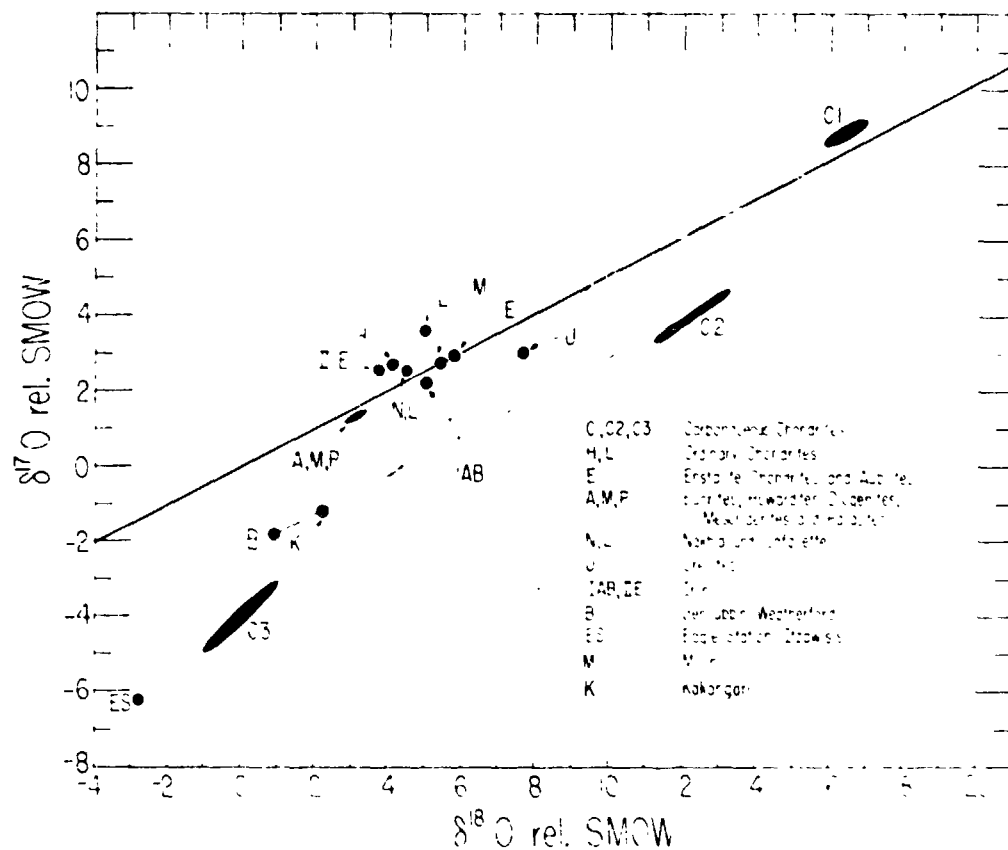


Fig. 1. Oxygen isotopic compositions of various meteorite groups. Ordinate is $^{17}\text{O}/^{16}\text{O}$, and abscissa is $^{18}\text{O}/^{16}\text{O}$, both expressed as permil (parts per thousand) deviations from an arbitrary terrestrial standard (SMOW). The heavy line with slope 1/2 is the locus of all terrestrial materials, which spread along the line due to mass-dependent isotopic fractionation. The mean value for the Earth is probably indistinguishable from that for the Moon. The dashed line with unit slope is the extrapolation of the ^{17}O mixing line observed in separated phases of C3 chondrites, most of which are off-scale to the lower left of this figure. Analytical uncertainties in the data are somewhat smaller than the plotted points.

of mass-fractionation processes within a single planet. The actual range of observed isotopic compositions on Earth is about six times as great as the span of Figure 1. The dashed line in Figure 1 is the mixing line of unit slope which is generated by individual inclusions and mineral samples from several C2 and C3 meteorites (Clayton *et al.*, 1977). The observed range of compositions extends well off the diagram to values of $\delta^{18}\text{O}$ of -40. The variations in composition of all of the other meteorites are presumably due to a

combination of these two processes of mixing and fractionation. Thus meteorites lying above the terrestrial line (C1, ordinary chondrites, IIE irons) contain less of the ^{16}O -rich component than the Earth, whereas the C2, C3 carbonaceous chondrites and most of the differentiated meteorites contain more than the Earth.

It should be considered whether a planet or meteorite parent body might, as a consequence of heterogeneous accretion, be internally heterogeneous with respect to oxygen isotopes (in addition to the obvious effects of isotopic fractionation). The evidence from terrestrial and lunar samples strongly indicates that all materials sampled have come from a single homogenized reservoir, as would be expected for such large differentiated bodies. At the other extreme, it is known that C2 and C3 carbonaceous chondrites are isotopically heterogeneous on a submillimeter scale. The evidence bearing on homogeneity in parent bodies of other meteorites is less direct. For example, all L and LL chondrites appear to be derived from a common reservoir, possibly a single parent body, and all H chondrites are derived from some other reservoir, also possibly a single parent body. It is obviously impossible, in principle, to distinguish between two noninteracting regions of a single parent, on the one hand, and two distinct parents on the other. However, lacking any evidence in favor of large-scale internal heterogeneities, I shall assume that isotopically distinct source reservoirs imply different parent bodies.

In the following sections, the various major meteorite groups will be discussed, with particular reference to the interrelationships among groups and the inferences with respect to their parent bodies.

CARBONACEOUS CHONDRITES

It can be seen in Figure 1 that the C1, C2, and C3 meteorites occupy three distinct regions of the oxygen isotope diagram. The C2s are a special case, since they are composed of approximately equal amounts of high-temperature anhydrous silicates (olivine and pyroxene) and a low-temperature phyllosilicate matrix. The region of Figure 1 labeled C2 is for the matrix material; the data for olivine and pyroxene are distributed along the ^{16}O mixing line determined by the minerals from C3 meteorites. C1 and C2 matrix materials are distinct from one another and, interestingly, lie on opposite sides of the terrestrial fractionation line. They clearly represent different source regions. Since both types are thought to be very primitive solar system materials, and since many asteroids appear to be similar to C1 or C2 meteorites, it is to be hoped that observations of asteroids can be improved to allow distinction between these two types of material.

The difference in isotopic compositions between C1 and C2 matrix requires that they be formed from nebular gases of different isotopic compositions, separated either in space or in time. Since both C1 meteorites and C2 matrix consist of hydrous silicates formed at low temperatures, probably by interaction with water vapor in a nebular gas, the isotopic difference between the two groups implies gaseous regions of the nebula with different ^{16}O abundances. The C1 material could be derived from the same source as the H-group ordinary chondrites, since these two groups appear to lie along a common fractionation line. There is no group of chondrites bearing a similar relation to the C2 matrix material. However, the unique chondrite Kakangari and the achondritic parts of Bencubbin and Weatherford may have such a relationship. In each case, the temperature effect on the isotopic fractionation between gas and solids would account for the enrichments in heavy isotopes in the low-temperature phyllosilicates relative to the higher-temperature olivine and pyroxene. (Note that no low-temperature phyllosilicate counterpart to the L-group chondrites has yet been observed.)

Although the C3 meteorites are isotopically heterogeneous on a submillimeter scale (Clayton *et al.*, 1977), their bulk isotopic compositions are very similar to one another, and only subtle differences between the subclasses C30 and C3V are detectable. Determination of the location and mode of origin of these meteorites is of the utmost importance in deducing solar system history, since they are the principal hosts of the nucleosynthetic

isotope anomalies in oxygen, magnesium, calcium, barium and neodymium (Clayton *et al.*, 1977; Lee *et al.*, 1977; Lee *et al.*, 1978; McCulloch and Wasserburg, 1978). In the case of the anomalies in minor elements, their observation in C3 meteorites may simply reflect more favorable conditions for preservation. However, in the case of the oxygen anomaly, the bulk meteorites show a greater ^{16}O -excess than any others, with the exception of the unusual pallasites Eagle Station and Itzawisis. The C4 meteorites Karoonda and Coolidge have oxygen isotopic compositions which are essentially the same as the C3s. The internal isotopic fractionation among minerals in C4s is consistent with metamorphic recrystallization at a temperature near 600°C (Clayton *et al.*, 1977).

A few carbonaceous chondrites have unique isotopic compositions, and do not fall within the three main groups. Al Rais and Renazzo, commonly classed as C2, have distinct compositions unlike the C2 group. Mokoia, usually classed as C3, has an isotopic composition which appears transitional between C3 and C2.

In addition to macroscopic carbonaceous chondrite meteorites, fragments of similar material have been observed as inclusions in other meteorites (Wilkening, 1978). Some of these have been found to have isotopic compositions different from the main carbonaceous chondrite groups, although most are rather similar to the C2 group chemically and isotopically (Clayton and Mayeda, 1978a). Thus, it would appear that conditions for production of C2-like material occurred in many places in the solar system; the observation of many asteroids with C2-like surfaces (Chapman *et al.*, 1975) is, of course, consistent with this observation.

ORDINARY CHONDRITES

Two distinct source reservoirs are required for the ordinary chondrites: one for the H group, another for the L and LL groups. The latter two are not resolved from one another, and could be chemical differentiates from the same source. The two reservoirs are displaced from one another in the direction of ^{16}O mixing, implying condensation under similar conditions from two isotopically distinct parts of the nebula.

Possible association of H-group chondrites with C1 chondrites has been discussed above. They may also have been derived from the same oxygen reservoir as the silicates in type IIE irons (Clayton and Mayeda, 1978b). There is no genetic association between the ordinary chondrites and any of the achondrites. In fact, where chondritic and achondritic fragments are found together in brecciated meteorites, they are found to have distinctly different oxygen isotope abundances, thus requiring derivation from separate parent bodies (Clayton and Mayeda, 1978a).

ACHONDRITES, MESOSIDERITES AND PALLASITES

Most of the differentiated stony and stony-iron meteorites fall into a single group in the oxygen-isotope diagram. This class includes the eucrites, howardites and diogenites, as well as the mesosiderites and pallasites. It also includes the well-studied achondrite Angra dos Reis, the igneous differentiation of which was complete 4.55 Gy ago (Lugmair and Marti, 1977; Wasserburg *et al.*, 1977). Were all of these meteorites derived from the same parent body? Differences in initial $^{87}\text{Sr}/^{86}\text{Sr}$ imply that they were not. Nevertheless the uniformity of oxygen isotopic composition requires that this large group of differentiated meteorites was derived from a common reservoir in the nebula.

A few achondrites form smaller, separate isotopic classes. The ureilites form a single group with isotopic compositions more like carbonaceous chondrites than achondrites. Nakhla and Lafayette, presumably fragments of the same parent, have a unique isotopic composition not obviously related to other groups. Shergotty and Zagami likewise form a separate group. Bencubbin and Weatherford are metal-rich breccias with a distinct and complex isotopic

signature. Eagle Station and Itzawisis are highly unusual in both chemical and isotopic compositions relative to other pallasites. Their parent body appears to have formed with an exceptionally large complement of high-temperature condensates, labeled with the 160 -excess recognized first in the C3 chondrites (Clayton and Mayeda, 1978b).

The aubrites are discussed in the next section.

ENSTATITE CHONDRITES AND ACHONDRITES

The enstatite chondrites and aubrites form a single class (Clayton *et al.*, 1976), consistent with derivation from a common parent body, as has been suggested on chemical grounds by Wasson and Wai (1970). This raises doubts about either the association of the E spectral type of asteroids with the aubrites (Zellner *et al.*, 1977) or the RF and RR spectral type with the enstatite chondrites (McCord, 1978). Such problems are not unexpected due to the lack of characteristic features in the reflectance spectrum of enstatite (Gaffey, 1976).

A remarkable aspect of the oxygen isotopic composition of the enstatite chondrites is that it is very near that of the Earth and Moon. The composition appears to lie squarely on the terrestrial fractionation line, perhaps a little enriched in the heavy isotopes relative to terrestrial mantle rocks. It is curious that the Earth should be so similar in isotopic composition to this meteorite group, since the high degree of reduction of the enstatite chondrites would appear to require their condensation in a region of the nebula in which the C/O ratio was significantly greater than elsewhere (Larimer, 1975). Further chemical and isotopic studies of enstatite chondrites are important to investigate their relationships to the inner planets.

IRON METEORITES

Type IIE irons, which contain coarse-grained silicate minerals, may have a common parentage with the H-group ordinary chondrites, as discussed above. The type IAB irons are breccias containing silicate rock fragments of chondritic composition (Bild, 1977). They fall in a single group in the oxygen isotope diagram, which may be related to the enstatite chondrite group by 160 addition. This association with the enstatite chondrites is also suggested by the low iron content of the mafic silicates in the IAB meteorites. Perhaps these meteorites are good candidates for the RF-type asteroids.

PROSPECTS FOR REMOTE ISOTOPIC ANALYSIS OF ASTEROIDS

The problems in performing sufficiently accurate $^{180}/^{170}$ and $^{170}/^{160}$ measurements without sample return are formidable. Although 160 is abundant, the heavier isotopes are not. Resolution of the different meteorite classes, for example H chondrites from L chondrites, requires a precision in the $^{170}/^{160}$ ratio of better than 5×10^{-4} . Since the absolute value of this ratio is only 4×10^{-4} , the measurement requires determination of 170 concentrations to better than 2×10^{-7} relative to 160 . Mass spectrometry is the only feasible technique, and the elimination of interfering species, such as hydrides, would be exceptionally difficult without the chemical processing used in laboratory analyses. Techniques without chemical sample preparation, such as laser-probe or ion-probe mass spectrometry fall far short of the necessary precision in terms of both random and systematic errors. There is no obvious *fundamental* limitation to such remote isotopic analysis, but a very large amount of instrument development would be a prerequisite.

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DISCUSSION

- VEVERKA: Why are the H and L chondrites represented by a single point, whereas the C chondrites are represented by an extended area?
- CLAYTON: That is what we observe. The Cs really do appear to spread out over some range along the fractionation direction due to small differences in the formation temperatures of the minerals. Because the Cs are formed at lower temperatures, the isotope effects are large and a change of 10 or 20 degrees in condensation temperature would give you a substantial spread. Ten or 20 degrees at the condensation temperatures of the Hs and Ls would give a very much smaller spread.
- FANALE: Are the data here spurious in the sense that what is analyzed is really a physical mixture of ^{18}O -enriched C1 material and ^{18}O -deficient C3 material, which would give points for C2s lying along some mixing line?
- CLAYTON: We have gone to a lot of effort to try to be sure that these things are free of impurities, and I think we have satisfied ourselves that we have done that pretty well. We have also managed in one case to do an analysis on a carbonate phase of a C2, where

there is one percent of calcite. That point lies quite a long way from the matrix but is on the same fractionation line as the matrix. So there is pretty good evidence, I think, that these are not mechanical mixtures and that they acquired this composition by interaction with a gaseous material that lies somewhere along the fractionation line.

FANALE: Is it possible, at least in the case of carbonaceous chondrites, that the ^{18}O -enrichment is due to a nonthermal activation process during an interaction with more ^{18}O -rich vapor at high vapor pressures? Or did we really have a homogeneous nebula where at the surface of a progenitor body, such as Ceres, there was preferential escape of ^{16}O from the base of the exosphere leaving a surface which was, therefore, ^{18}O -enriched?

CLAYTON: You ask whether the low temperature minerals could have been formed from ordinary chondrite material by low temperature exchange with an ^{18}O -enriched gas. I would say that is a possibility, particularly if the gas is a large reservoir compared to the meteorites, so that they ended up with no memory of their original composition. There is one thing that leads us to think that something like that might be going on. In samples from other meteorites we saw points that were near the dashed line for C3s (in Figure 1) and we started taking apart some of the C3 meteorites which contain a lot of iron-rich anhydrous silicates. We find that the olivines with different chemical compositions move up and down the dashed line and as we get to the most iron-rich we have at least one point that is on the fractionation line to the C2 matrix region. I can't cite any similar evidence, connecting C1s with anything else. Your second possibility was that everything was once homogeneous and was subsequently enriched in ^{18}O . Presumably you would have to start with very ^{18}O -deficient material like C3 meteorites. I think it's highly unlikely that all of the planets and the Moon and everything were made by that kind of alteration, at least based on what we have seen so far in Allende which is just a few grams of very peculiar C3 matrix in a very peculiar chemical state. I would be more inclined, so that you don't have to move so many atoms, to say that the materials like the C1 and C2 chondrites are normal and that C3 material is abnormal.

MCCORD: If the instrumentation did exist for doing oxygen isotope analysis on the surface of an asteroid, what sort of sample handling would you require?

CLAYTON: If the analysis were done by some kind of a laser probe or an ion probe mass spectrometer, no sample preparation is needed. We are working here on the development of an ion microprobe mass spectrometer, not for extraterrestrial analysis, but for terrestrial analysis, and sample preparation there simply involves using a polished rock surface. We do have to put on a conducting coating to keep it from charging up. That is the only preparation we need.