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GENETIC RELATIONS AMONG
METEORITES AND PLANETS

R. N. CLAYTON

On the basis of $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios, meteorites and planets can be grouped into at least nine categories, as follows (in order of increasing ^{16}O): (1) type L and LL ordinary chondrites; (2) type H ordinary chondrites, type IIE irons, and C1 carbonaceous chondrites; (3) the nakhlites and Shergotty; (4) the earth, moon, and enstatite chondrites and achondrites; (5) basaltic achondrites, hypersthene achondrites, mesosiderites, pallasites and type IAB irons; (6) the ureilites; (7) C2 carbonaceous chondrite matrix, Bencubbin, Weatherford, and Kakangari; (8) C3 carbonaceous chondrites; (9) pallasites Eagle Station and Itzawisis. Objects of one category cannot be derived by fractionation or differentiation from the source materials of any other category, but must represent samples of different regions of an inhomogeneous solar nebula. The isotopic classification, together with major-element abundances, provides a powerful method for recognition of interrelationships of the various meteorites and their parent bodies.

INTRODUCTION

Suppose that the atoms in various regions of the solar nebula, prior to the condensation and accretion of the planets, had been labelled with some identifying mark so that they could later be recognized in spite of their intervening complex chemical histories. We would then have a means of discerning between bodies which had formed in different regions of the nebula, and of recognizing groups of objects which had formed in a common region of the nebula. In the latter case, it should then be possible to proceed by conventional cosmochemical methods to deduce the sequence of chemical and physical processes which caused differentiation within the group, since its members evolved from a common source. Just such a tracer seems to have been present in the solar nebula in the form of presolar grains, highly enriched in ^{16}O, which were incorporated in various proportions into matter which condensed in different parts of the nebula (Clayton et al. 1973; 1976).

The ^{16}O-rich component was first observed in minerals which are believed to be the earliest high-temperature condensates from the hot solar nebula: the anhydrous iron-free oxides and silicates found in the carbonaceous chondrites. The primitive nature of these condensates was inferred from their chemical and mineralogical compositions, which correspond closely to the phases which should first condense from the nebula if thermodynamic equilibrium prevailed (Grossman, 1972). This interpretation was supported by the observation that the condensates in the Allende carbonaceous chondrite contain the least radiogenic (and hence most prim-

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itive) strontium of any solar system samples yet measured (Gray *et al*. 1973).
These early condensates are found sometimes as isolated crystals set in a matrix
of fine-grained hydrous silicates formed at lower temperatures, and sometimes as
aggregates and inclusions as large as one or two centimeters in diameter. In both
types of occurrence, the high-temperature minerals are found to have ^{16}O excesses,
relative to "ordinary" oxygen, which range up to 5%. This is a very substantial
fraction, considering that oxygen is the most abundant element in the minerals.

It has been suggested that the ^{16}O-excesses were introduced into the solar
nebula in the form of presolar grains, which were refractory compounds in which the
oxygen was essentially pure ^{16}O, presumably derived from a single nucleosynthetic
event (Clayton *et al*. 1973). This problem is discussed further elsewhere in this
symposium (Clayton 1976). It is sufficient for the purposes of the present paper
simply to note that the different proportions of ^{16}O in the various solar system
bodies provide the labels we need to recognize which bodies were derived from common
regions in the nebula and which were formed in other regions.

The variations in oxygen isotopic composition in the carbonaceous chondrites
are so large that the effects of ^{16}O addition on the ratios of $^{18}O/^{16}O$ and $^{17}O/^{16}O$
are much greater than the variation in these ratios which are commonly observed in
natural materials, and which result from the isotopic mass-dependence of rates and
equilibrium constants. In fact, while the $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios in the carbon
ceous chondrites vary by about 5%, the $^{18}O/^{17}O$ ratios are almost constant. Howeve
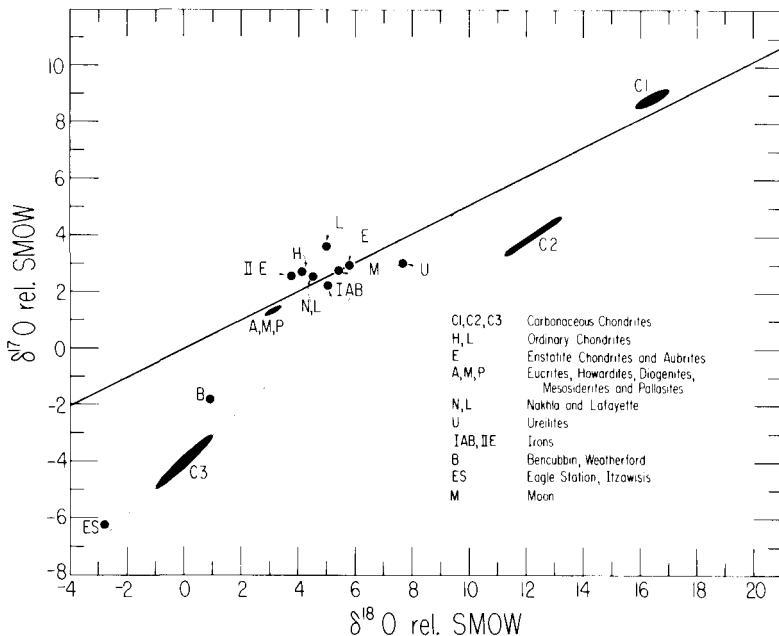

Figure 1.   Plot of $^{17}O/^{16}O$ vs $^{18}O/^{16}O$ (expressed as parts-per-thousand deviations
from the arbitrary terrestrial standard, SMOW) for various meteorite
groups and for the moon. The solid line with slope 1/2 is the locus of
points for terrestrial samples, which vary due to mass-fractionation
processes. The mean value for the whole earth is probably indistinguish-
able from the value for the moon. The dashed line is the mixing line
between "ordinary" oxygen and the ^{16}O-rich component, as determined by
measurement of high temperature minerals in carbonaceous chondrites
(Clayton et al ., 1976).

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for most of the remaining meteorite groups, the magnitudes of the variations in ratios caused by ^{16}O addition are comparable to the variations caused by mass-dependent isotopic fractionations, so these two effects must be sorted out. This can be done effectively on a graph of $^{17}O/^{16}O$ vs. $^{18}O/^{16}O$. Mass-fractionation processes, whether chemical or physical, cause displacements along a line with a slope close to 1/2, reflecting the relative mass differences in the two ratios. If there had been no influence of nuclear processes in the oxygen of the solar system, all samples of meteorites and planets would fall on a single line on this graph. In fact, they do not fall on one line, but occupy a substantial region of the diagram reflecting the operation of both mass-fractionation and ^{16}O additions.

If samples of pairs or groups of meteorites or planets lie on the same slope-1/2 mass fractionation line, they may have been derived from the same reservoir of matter in the solar nebula, presumably at about the same distance from the center. Equally as important as establishing genetic relationships is the establishment of separate classes which are not directly related. Perhaps the most significant example is that of the ordinary chondrites. For years various proposals have been made for differentiation processes to make high-iron (H-group) chondrites from low-iron (L-group) chondrites or vice-versa. The fact that these groups lie on two distinct fractionation trends in the oxygen isotope diagram shows that one group cannot have been derived from the other by differentiation processes alone, or by addition or removal of metallic iron.

OBSERVATIONS AND DISCUSSION

Fig. 1 summarizes the isotopic data available at the present time. Detailed data on individual meteorites and on separated mineral phases of chondrites and achondrites are given by Clayton et al. (1976). Data on separated phases of C2, C3 and C4 carbonaceous meteorites are reported by Clayton et al. (1977). The minimum number of oxygen isotope groups is given in Table 1; some of these may be subdivided in future as the analytical resolving power improves.

TABLE 1

OXYGEN ISOTOPE GROUPS

(In order of increasing fraction of ^{16}O-rich component)

1. L, LL chondrites

2. H. Chondrites, II E irons, Cl carbonaceous chondrites

3. Shergotty, Nakhla, Lafayette

4. Earth, moon, enstatite chondrites, enstatite achondrites

5. Basaltic achondrites, hypersthene achondrites, mesosiderites, pallasites, IAB irons

6. Ureilites

7. C2 matrix, Bencubbin, Weatherford, Kakangari

8. C3 carbonaceous chondrites

9. Eagle Station, Itzawisis

Several close associations are recognizable, and indicate derivation of certain meteorite types from a common source material, and possibly from a common parent body. A large number of differentiated meteorites fall in a tight cluster on the

oxygen isotope plot. They include the basaltic achondrites (eucrites and howardites the hypersthene achondrites (diogenites) the mesosiderites and most of the pallasites. These are a particularly interesting group of meteorites, since they appear to have undergone their initial melting, differentiation *and solidification* very early in solar system history (Allegre *et al.* 1975).

The enstatite chondrites and enstatite achondrites (aubrites) have indistinguishable isotopic compositions. Their highly reduced state relative to other meteorites has led some authors to postulate an origin in a region of the nebula with enhanced C/O ratio (Larimer 1975). No indication of extreme conditions is shown by the oxygen isotope abundances.

The earth and moon also have isotopic compositions which are identical within the uncertainty which results from our incomplete sampling of the earth's mantle. This is evidence in favor of formation from a common source material, rather than by mixture of a variety of primitive components such as are found in the carbonaceous chondrites. The earth-moon relationships have been discussed in more detail elsewhere (Clayton and Mayeda 1975).

The iron meteorites have probably been derived from the cores of planetesimals with rocky exteriors. Several classes of irons can be recognized from their trace-element abundances (see review by Scott and Wasson, 1975). For those iron meteorites which contain silicate, phosphate or oxide minerals, it may be possible to inter-relate the oxygen isotope groups and the iron groups, and thus reconstruct the parent bodies. Two examples are seen in Table I and Fig. 1: the group IIE irons (Colomera and Weekeroo Station) could be related by fractionation processes to the H-group ordinary chondrites; the group IAB irons (Campo del Cielo, Landes, Linwood, Woodbine) form a single oxygen isotope group which may lie on the same isotope fractionation trend as the differentiated stony meteorites.

Eagle Station and Itzawisis are two pallasites which are chemically distinguishable from the other pallasites in having the most iron-rich olivine and the most nickel-rich metal (Buseck and Goldstein 1969). They have oxygen isotopic compositions totally unlike other stony-irons, and are the most ^{16}O-rich of any meteorites yet analyzed. They are evidently samples of the same parent body, which incorporated an exceptionally large proportion of ^{16}O-rich refractory material (Clayton *et al.* 1976).

Another pair of unusual meteorites is Bencubbin and Weatherford, which are brecciated and shocked stony-irons, and which were earlier classed with the mesosiderites. Their oxygen isotopic compositions are unusual and very similar to one another, again implying a common parent body distinct from that of the mesosiderites. They lie on an extrapolation of the fractionation line of the matrix material of C2 carbonaceous chondrites, but this may be coincidental, as no obvious connection is known between these groups. Bencubbin provides an interesting example of a polymict breccia, in that it contains fragments of different rock types, including achondritic, ordinary chondritic and carbonaceous chondritic material (Lovering, 1962). These all have quite distinct oxygen isotopic compositions, not on a common fractionation line, indicating their earlier history in separate parent bodies. Similar observations have been reported for a C2 fragment in an H-group chondrite (Plainview) and an ordinary chondrite fragment in an enstatite achondrite (Cumberland Falls) (Clayton *et al.* 1976). This provides clear evidence that collisions between planetesimals can produce rocks containing macroscopic fragments of both bodies involved in the collision. These fragments do not always correspond to known meteorite types, so that they provide a broader sampling of solar system material than is given by whole meteorites. The occurrence of stony polymict breccias with multiple origins implies that caution should be used in interpreting the association between iron groups and oxygen groups, described above, since some of these may also be breccias with the metal and silicate portions having unrelated origins (Wasson 1970).

The C1 carbonaceous chondrites are commonly accepted as the least fractionated meteoritic material, and have chemical abundances of most elements in solar pro-

portions (Anders, 1971). They, as well as the fine-grained matrix minerals of the C2 carbonaceous chondrites, are thought to have accreted from solar nebular condensates at low temperatures (<400 K) (Larimer and Anders, 1967). Although the number of isotopic analyses is limited, it is evident in Fig. 1 that the C1 and C2 materials are different from one another. The C1 rocks could, however, have been derived from a source in common with the H-group chondrites.

SUMMARY

The data discussed in this paper include results from all of the major classes of meteorites. However, further analyses of unusual or unique meteorites, and of small foreign lithic fragments in meteorites, should extend the range of observed compositions. The classification of meteorites by oxygen isotopic composition has provided no conflicts with previous classification based on chemical and mineralogical compositions, but provides a new basis for examining interrelationships among groups, and a new approach to deduction of the properties of the parent bodies.

On the basis of the evidence available, there is no simple relationship between oxygen isotopic composition and chemical or mineralogical composition, such as might have resulted if there had been a monotonic trend in the ^{16}O content as a function of distance from the center of the nebula. A more complicated variation, probably in time as well as in space, is implied by the observations.

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DISCUSSION

EBERHARDT: Do all the different petrological classes of H and L chondrites lie on the same individual fractionation line?

CLAYTON: This is the case for the samples analyzed, which are almost all from petrologic classes 5 and 6. There are only one or two analyses of classes 3 and 4.

DICKEL: What was the total range of isotopic abundance over the whole solar system?

CLAYTON: The largest $^{18}O/^{16}O$ ratios are found in the Cl carbonaceous chondrites, and the smallest yet observed are in two unusual pallasites, Eagle Station and Itzawisis. The total range in $^{18}O/^{16}O$ is about 3% and is a combination of both mass-fractionation and ^{16}O admixture. Variations of as much as 6% are observed in separated mineral components of meteorites.

BRECHER: Would you take the coincidence of oxygen isotopic fractionation for the Moon and the Earth, as evidence in support of their formation in the same nebular region i.e., rule out some capture hypotheses for lunar origin? If you do, how do you explain the similar abundance of ^{16}O in Cl and H-type chondrites? These cannot be presumed to have formed in the same region, in view of pronounced chemical and mineralogical differences.

CLAYTON: Yes, evidence favors formation of Moon and Earth from similar material. Though H and Cl chondrites lie on the same fractionation line, their differences can be attributed to different temperatures at formation.