OXYGEN ISOTOPIC COMPOSITIONS OF LUNAR SOILS AND ALLENDE INCLUSIONS AND THE ORIGIN OF THE MOON, L. Grossman,* R.N. Clayton** and T.K. Mayeda,***
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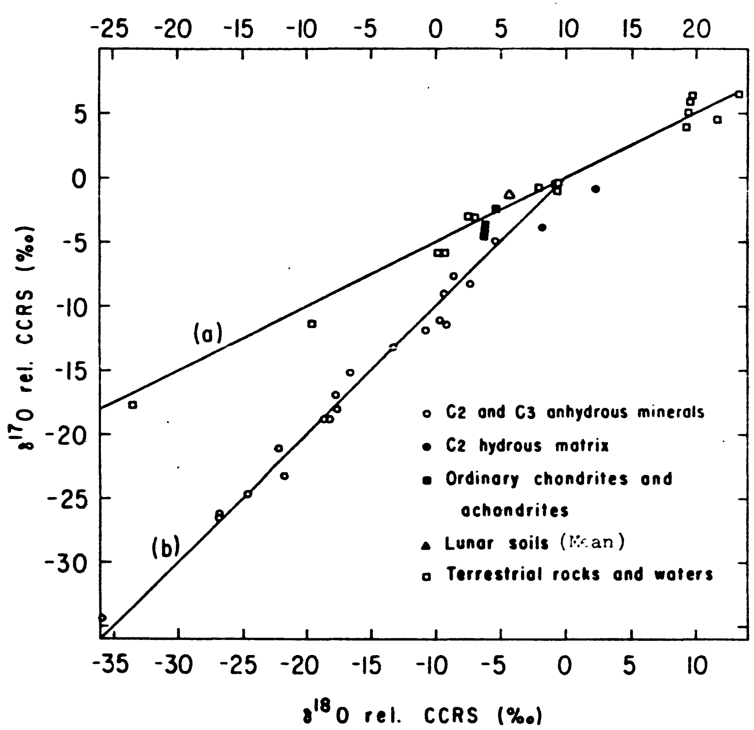
In order to account for the high refractory and low volatile element concentrations in lunar rocks compared to chondrites, several workers[1,2,3,4] have postulated that the moon is highly enriched in high-temperature solar nebula condensates such as the Ca-Al-rich inclusions in the Allende meteorite. Clayton et al.[5] and Grossman and Larimer[6] have criticized these models because of the vast difference in δO^{18} between lunar materials and Allende inclusions. In this paper we present the results of simultaneous measurements of δO^{18} and δO^{17} in lunar, terrestrial and meteoritic materials and discuss the origin of the moon in the light of these data.

Clayton et al.[7] showed that a graph of δO^{17} *vs.* δO^{18} of anhydrous minerals in C2 and C3 chondrites, including the refractory inclusions in Allende, is a straight line of slope +1, line b. The simplest interpretation of this linear array is that the oxygen in all the inclusions, regardless of their host meteorite or their mineralogy, consists of two components. One of these is probably pure O^{16} and the other has an isotopic composition close to "normal" solar system oxygen. The O^{16} may have been incorporated by the condensates as interstellar grains which escaped isotopic homogenization at the birth of the solar system or it may have been produced in and ejected from the early sun.



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In contrast to the data on the anhydrous inclusions, the oxygen isotopic compositions of ordinary chondrites and terrestrial materials fall along a line of slope +1/2, line a. This slope is expected for samples whose isotopic compositions are related through a series of chemical fractionation processes. The data for several lunar soils and soil breccias, shown in Table 1, have a mean value of $\delta O^{18} = 5.63\pm0.05$ and $\delta O^{17} = 3.8\pm0.2$ relative to SMOW and appear to be slightly depleted in O^{16} relative to points on line a. The oxygen isotopic composition of the lunar samples cannot be a simple mixture of oxygen from Allende inclusions and ordinary chondrites, nor can it be derived from any such mixture by fractionation processes.

Table 1

Oxygen Isotopic Compositions of Lunar Samples

Sample No.	Description	δO^{18}(SMOW)	δO^{17}(SMOW)
70019,10	Breccia	5.53	3.7
73221, 8	Soil	5.64	3.4
73281, 7	Soil	5.66	4.3
76501,14	Soil	5.68	4.1
79221,25	Soil	5.61	3.3
79261,17	Soil	5.64	3.7
12033,55	Soil	5.62	4.0

The scatter of the inclusion data about line b is larger than can be accounted for by analytical error and may be due to chemical isotope effects superimposed on the mixing line. The sum of the maximum deviations in δO^{18} on either side of line b for different inclusions is $3.7^{o}/oo$. If the sample richest in chemically fractionated O^{18} is assumed to have condensed at 1500°K,[8] then this difference implies a range in nebular equilibration temperatures of 1500-950°K, using the cosmothermometer of Onuma et al.[9]

If the amount of the O^{16} component in excess of that present in the lunar soils is subtracted from the inclusions, they plot along line a over a $3.7^{o}/oo$ range in δO^{18} centered near the intersection of lines a and b. The displacement of the δO^{18} of the lunar soils along a from this point can be related to the minimum difference between the mean condensation temperatures of inclusions and protolunar materials using the cosmothermometer. If the mean condensation temperature of the refractory inclusions in the meteorites is 1400°K, then the mean equilibration temperature of all the material which accreted to form the moon is 980^{+175}_{-135}°K. The oxygen isotopic composition of the moon is thus consistent with a large proportion of high-temperature condensates whose oxygen isotopic compositions are, however, quite unlike those of all observed Allende inclusions which are dramatically enriched in the O^{16} component relative to the lunar samples. The relatively low mean equilibration temperature of the moon is 200° below the condensation temperatures of nickel-iron and magnesium silicates at a total pressure of 10^{-4} atm, suggesting that these phases constitute part of the lower-temperature fraction. The very low concentrations of refractory siderophile elements (Ir, Os, Ru) in lunar rocks[4] compared to those predicted for high-temperature condensates[10] and observed in the Allende inclusions[4,10] indicate a very efficient post-accretional removal process, such as the gravity separation of an Fe or Fe-S melt.

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There is a suggestion in our data that the lunar points are displaced slightly from the terrestrial chemical line a. This may indicate that the moon is depleted in the 0^{16} component by about 2^{o}/oo relative to the earth.

There remains the problem of understanding why the Allende inclusions are so enriched in the 0^{16} component compared to the refractory condensates which accumulated to form the moon. This could be explained if the moon formed from materials that condensed at a smaller heliocentric distance than the Allende inclusions. Here, the initial nebular temperatures may have been sufficiently high to evaporate most of the pre-existing interstellar grains. The oxygen in the Allende meteorite is about 1% richer in the 0^{16} component than the moon. Condensation of Allende would remove less than 10% of the total oxygen from a gas of solar composition. Total evaporation of the interstellar grains in the region of the nebula where the moon accreted would thus dilute the 0^{16} component beyond detection. Alternatively, lunar accretion may have occurred in a part of the nebula where pre-condensation grain fractionation mechanisms may have been much more efficient than in the case of Allende. If the 0^{16} component has a solar origin, then its relative concentrations in the moon and Allende can be explained if the mean surface area/volume ratio of the Allende inclusions was higher than that of the grains which formed the moon at the time of 0^{16} ejection from the sun.

References:

1. Gast, P.W. (1972). The Moon 5, 121-148.
2. Anderson, D.L. (1973). Earth Planet. Sci. Lett. 18, 301-316.
3. Krähenbühl, U., Ganapathy, R., Morgan, J.W. and Anders, E. (1973). Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1325-1348. Pergamon.
4. Wänke, H., Baddenhausen, H., Dreibus, G., Jagoutz, E., Kruse, H., Palme, H., Spettel, B. and Teschke, F. (1973). Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1461-1481. Pergamon.
5. Clayton, R.N., Hurd, J.M. and Mayeda, T.K. (1973). Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1535-1542. Pergamon.
6. Grossman, L. and Larimer, J.W. (1974). Rev. Geophys. Space Phys. (in press).
7. Clayton, R.N., Grossman, L. and Mayeda, T.K. (1973). Science 182, 485-488.
8. Grossman, L. (1972). Geochim. Cosmochim. Acta 36, 597-619.
9. Onuma, N., Clayton, R.N. and Mayeda, T.K. (1972). Geochim. Cosmochim. Acta 36, 169-188.
10. Grossman, L. (1973). Geochim. Cosmochim. Acta 37, 1119-1140.