# OXYGEN ISOTOPIC VARIATION OF THE TERRESTRIAL PLANETS.

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**Introduction:** Since the seminal work of Clayton and co-workers [1] it has been clear that there was oxygen isotopic heterogeneity in the most primitive materials in the solar nebula, with variations of up to 50‰ in $\delta^{18}O$ and over 25‰ in $\Delta^{17}O$[1] in materials formed or at least heavily processed within the nebula. In the terrestrial planets (Earth, Moon, Mars and the HED parent body (possibly Vesta)) the range in $\delta^{18}O$ values can remain very large, especially on geologically active bodies, particularly the Earth where low temperature reactions with water can play an important role in developing large isotopic variations. However, the variation that is now seen in $\Delta^{17}O$ is <1‰ [e.g. 3], with the variation from each body generally much less. This limited range in the $\Delta^{17}O$ values is generally believed to be the result of large volume homogenization during widespread heating/melting events during the history of these planets and large asteroids. However, variation still exists within and between the suites of rocks from each of the terrestrial planets, and this can provide valuable information on their origin, inter-relationship and evolution. In order to extract this information it is necessary to measure the oxygen isotopic composition of clean, well characteristed materials to very high precision.

We have undertaken a number of studies covering most the main sample suites from evolved planets or asteroids using a technique of laser ($CO_2$ laser @ 10.6μm) assisted fluorination ($BrF_5$) coupled to a high dispersion, high precision mass spectrometer (VG PRISM III). This offers analytical precision for $\delta^{18}O$ and $\delta^{17}O$ of 0.08 and 0.04‰ respectively, but as much of this uncertainty is related to gas handling fractionation the $\Delta^{17}O$ uncertainty is <0.025‰ [4] and allows us to determine mass fractionation lines with uncertainties down to ±0.013‰ [e.g. 5] – approximately 50 times smaller than the variation displayed by the terrestrial planets/asteroids.

**Oxygen Isotope Variation**: Within the limited range of $\Delta^{17}O$ values displayed by samples of the terrestrial planets three broad grouping could readily be discerned – Mars, the Earth/Moon and the basaltic meteorites (HEDs, angrites, plus various other meteorite types) [3] allowing discrimination of the groups, useful in the classification of new meteorites, and offering insight into the degree of homogenization and into the identification of the relative contributions of possible primitive precursors. High precision analyses have revealed considerable more detail to this initial picture. The SNC meteorites define a martian fractionation line with a $\Delta^{17}O$ value of +0.032 ± 0.01 [5]. The basaltic meteorites (HEDs and angrites) previously defined what appeared to be a single, albeit relatively poorly defined mass fractionation line. However, as shown in Figure 1 the HEDs define what appears to be a well defined fractionation line ($\Delta^{17}O$ = -0.24 ± 0.007) with the angrites ($\Delta^{17}O$ = -0.072 ± 0.007) now clearly resolved. In contrast, high precision measurements of lunar rocks by Wiechert et al [6] shows that there is no isotopic difference between the Earth and the Moon.

**Discussion**: While the oldest, and possibly least precise of the high precision data the SNC meteorites clearly define a single martian fractionation line. Virtually all martian meteorites have relatively young crystallization ages but the data set includes ALH 84001, a sample of ancient crust with a crystallization age of approx 4.5Ga. As such it is clear that homogenisation of any initial isotopic heterogeneity occurred within the first few tens of millions of years after formation [5]. Even more rapid melting and homogenization may be required for 4 Vesta (HEDs) as all but one (Pasamonte) of the eucrites and diogenites fall on a single mass fractionation line, despite the fact that there are several geologically distinct groups with different histories within the eucrites. The anomalous nature of Pasamonte was also detected by [7] who also reported two other meteorites with similar $\Delta^{17}O$ values – suggesting that infact some isotopic heterogeneity was retained within Vesta as cooling progressed. It may be that these anomalous eucrites are not from the same parent body, or were contaminated by impactor material or that homogenization was not complete.

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[1] Virtually all physical processes acting upon any homogeneous reservoir of oxygen, will have an impact on the $^{16}O/^{17}O$ ratio approximately 0.52 times that of the effect on the $^{16}O/^{18}O$ ratio – such that on a three isotope plot ($\delta^{17}O$ vs $\delta^{18}O$ ) any such suite of samples resulting from this reservoir would plot upon a line of slope 0.52 [2]. The $\Delta^{17}O$ value is defined as the offset from such a line defined by crustal and mantle rocks from Earth ($\Delta^{17}O = \delta^{17}O - (0.52*\delta^{18}O)$

Further detail on the geochemical similarities and differences between the oxygen isotope populations within suites of similar basaltic rocks will go a long way to helping to resolve this problem, but will also shed considerable light on the structure of this body as it formed.

The angrite meteorites are another suite of ancient basaltic meteorites. Geochemically distinct from the HEDs, they are now clearly resolved on the basis of oxygen isotopes as well. With very ancient crystallization ages homogenisation of the angrite parent body must have been very rapid. It should be noted that a fairly typical eucrite (Ibitira) has a $\Delta^{17}$O value indistinguishable from the angrites – which raises the question as to whether a geological relationship exists between the angrites and (at least) some of the eucrites.

Other examples of the use of high precision oxygen isotope analysis includes the complete similarity in the $\Delta^{17}$O value of the Moon and the Earth which has been taken to show that the Earth and Theia (putative Moon-forming Earth impactor) were formed from the same material, presumably at a similar heliocentric distance [6].

High precision oxygen isotopic measurements are required on a number of other groups with close associations with the basaltic meteorites (e.g. the mesosiderites) in order to determine if they have distinguishable isotopic reservoirs, and in combination with detailed geochemical data determine if these reservoirs originate on a single or discrete parent bodies.

**References:** [1] Clayton R. N. et al. (1973) *Science, 182,* 485-488. [2] Clayton R. N. et al. (1978) [3] Clayton R. N. and Mayeda T. K. (1996) *Geochim. Cosmochim. Acta, 60,* 1999-2017. [4] Miller M. F. et al. (1999) *Rapid Comm. Mass Spectrom., 13*, 1211-1217. [5] Franchi I. A. et al. (1999) *Meteoritics & Planet. Sci., 34,* 657-661. [6] Wiechert U. et al. (2001) *Science, 294*, 345-348. [7] Wiechert U. et al. (2004) *EPSL, 221,* 373-382.

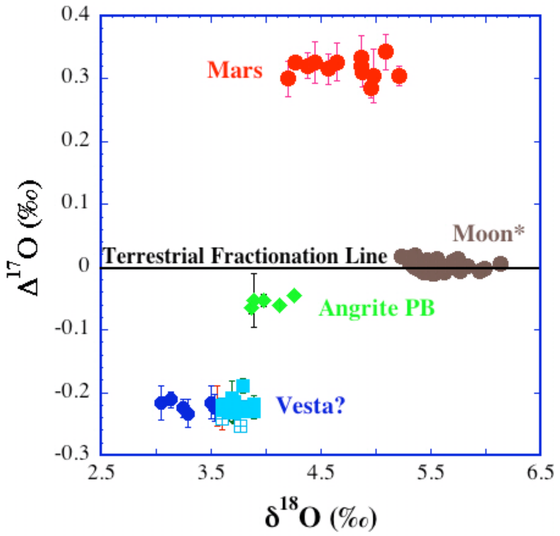

Figure 1 – Oxygen isotopic variation of the terrestrial planets. On this modified version of a three isotope plot mass fractionation lines (constant $\Delta^{17}$O) plot as horizontal lines. Terrestrial data not shown as this spans a very large range in $\delta^{18}$O but has a similar scatter to lunar and martian data sets [e.g. 5,7]. Lunar data from [6].