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Response to the comment by G. Dreibus and H. Wänke on "Comparative geochemistry of basalts from the Moon, Earth, HED asteroid, and Mars: Implications for the origin of the Moon" (2001) *Geochim. Cosmochim. Acta* 65, 979–997

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The central theses of our work (Ruzicka et al 1998, 2001) are that the composition of the Moon is not unique in the solar system, that it resembles the composition of the parent body of HED meteorites (likely the asteroid 4-Vesta) to a remarkable extent, and that geochemical data do not support an origin of the Moon by rotational fission (Binder, 1986) or small-impact collisional ejection (Ringwood, 1986, 1990). Furthermore, the data are consistent with a giant-impact origin for the Moon (Hartmann and Davis, 1975; Hartmann, 1986; Cameron, 1986, 1997, 2000; Canup and Asphaug, 2001) only if the Moon largely inherited the composition of the impactor.

Few researchers dispute the idea that the Moon and HED parent body have similar abundances of many volatile (e.g., Na and K) and siderophile elements (e.g., W). The controversy (Dreibus and Wänke, 2002) centers instead on the interpretation of geochemical data for a few key elements, including Ni, Co, Cr, and Mn. According to Wänke and colleagues, for these elements the composition of the Moon and Earth are similar, but very different for the Moon and HED parent body (Dreibus et al 1977, 1979; Wänke and Dreibus, 1986). Various authors have reached similar conclusions for Cr and Mn (Drake et al 1989; Ringwood, 1989; Ringwood et al 1990; O'Neill 1991) and for Ni and Co (Ringwood and Seifert, 1986; Ringwood, 1989; O'Neill, 1991), using either the modelled abundances of Wänke and colleagues, or approaches similar to these researchers. In contrast, based on correlated (albeit non-linear) abundances for these elements, we argue that Ni, Co and Cr abundances are similar for the Moon and HED asteroid, and different for the Moon and Earth. In contrast to Wänke and Dreibus (1986), we also argue that Mn data do not necessarily imply special conditions for the formation of the Earth and Moon.

The different interpretations stem in part from the different methodologies and samples used. We based conclusions on geochemical data for analogous basaltic samples from each planetary body, and inferred the compositions of the source regions, which could correspond to large portions of the mantles of the parent objects. For lunar samples we concentrated on mare basalts, as opposed to KREEP basalts or aluminous basalts. This was because the latter appear to represent unusual differentiates and/or impact-melt rocks, which are not analogous to the basalts from other objects. In contrast, Wänke and colleagues based their conclusions on derivative compositions of the Moon, HED asteroid, Earth, and Mars, estimated from models that differed from one object to the other, that varied depending on the element being considered, and that were based on different types of rocks, including impact breccias, volcanic rocks, and plutonic rocks.

The Ni, Co, Cr, and Mn abundances modelled for the HED asteroid (Dreibus et al 1977; Dreibus and Wänke, 1980) depend strongly on the assumed composition and proportion of an olivine-rich mantle component that has not yet been sampled. This olivine-rich component could have a composition similar to lunar dunite (Dreibus et al 1977), pallasitic olivine (Dreibus and Wänke, 1980), or something else altogether. The proportion of this olivine-rich component is also uncertain as it depends on the nature of the protolith. Dreibus et al (1977) and Dreibus and Wänke (1980) assumed a protolith similar to CI-chondrites, but significantly different parent body compositions are obtained for protoliths similar to ordinary chondrites or enstatite chondrites (Ruzicka et al 1997). A different choice for the composition and proportion of the HED mantle component will change the model Ni, Co, Cr, and Mn abundances in the HED asteroid.

For the Moon, the bulk composition inferred by Wänke and coworkers was inferred mainly from the composition of highland breccias, which are acknowledged to be contaminated by meteoritic debris. The abundances of these elements in the Moon were derived by making assumptions about the proportion and composition of the components (KREEP, anorthosite, Mg-rich component) out of which the breccias are assumed composed, and depend on the composition of the assumed protolith (e.g., CI-chondrites) (Wänke et al 1977a, 1977b, 1978). Incorrect assumptions about any of these will lead to an incorrect derivative composition for the Moon. For Ni and Co, the bulk composition of the Moon estimated by Wänke et al (1978) was obtained only after additional assumptions were made regarding the amount and type of meteoritic contamination. Whether or not these models lead to a valid bulk lunar composition is debatable.

In contrast, we argue that the compositions of eucrite and mare basalts themselves show good evidence for being controlled by igneous fractionation of mafic minerals (mainly olivine and pyroxene) from protoliths with similar Ni, Co, and Cr abundances. Although the Ni and Co abundances of eucrites are lower than that in mare basalts, the Ni-MgO and Co-(MgO+FeO) systematics for eucrites and all mare basalts fall on the same trend, and this trend is displaced from the compositions shown by terrestrial basalts and komatiites. On plots

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showing Cr-Mg and Cr-Mg# systematics, mafic and ultramafic volcanic rocks from the Moon, Earth, HED asteroid, and SNC parent body (likely Mars) tend to lie on parallel, offset trends, except that of Moon and HED asteroid, which have overlapping values (Ruzicka et al 1998, 2001). For Ni, Co, and Cr, our analysis suggests that it is the Earth that differs in composition from the Moon, rather than the HED asteroid. Using similar datasets and reasoning, Righter et al (2000) independently concluded that Ni/Mg and Ni/Cr (and Ir/Mg and Ir/Cr) values in the lunar and terrestrial mantles are different. Although it is possible that differences in oxygen fugacity resulted in different Cr abundances in basalts from different objects (Dreibus and Wänke, 2002), this does not explain the similar Cr abundances in lunar and eucritic basalts, and there is no direct evidence that a significant amount of Cr was present in the 2+ valence state in any of these objects.

Finally, although Mn abundances in mare basalts overlap those of terrestrial basalts, they are distinct and non-overlapping in terms of an FeO/MnO - MnO diagram, with a spread between the two as great or greater than between eucrites and SNC meteorites. Different Mn abundances in planetary basalts can arise depending on small differences in temperature of magmatic fractionation and melt composition (Ruzicka et al 2001), owing to a D-value for Mn that straddles unity (Irving, 1978). Thus, the distinctly different Mn abundances between mare and eucritic basalts are not necessarily diagnostic of source region compositions. Values of FeO/MnO are probably more diagnostic, and in this regard, we agree with Wänke et al (1977a) that different FeO/MnO values for terrestrial and lunar samples imply that "the Moon cannot in a simple way be a broken-off piece of the Earth."

The similar O-isotopic compositions (Clayton and Mayeda, 1975; Wiechert et al 2001) and Cr-isotopic compositions (Lugmair and Shukolykov, 1998) of the Earth and Moon support the idea that the Moon and Earth formed in a similar part of the solar nebula, but do not require the derivation of the Moon from the Earth. Tungsten-isotopic data, which have been used with some caveats to constrain the timing of the postulated Moon-forming giant impact (Lee et al 1997; Halliday et al 2000), can be interpreted instead to indicate that the Moon originated before core formation on Earth (Jones and Palme, 2000). The latter interpretation would present potential problems for any model that postulates derivation of the Moon from the Earth, for it could mean that too much metal would end up in the Moon. It would also be a problem for forming the Moon from the Earth via a giant impact, because one would expect that rapid core formation would be initiated by the high temperatures accompanying such a cataclysmic event.

In summary, we find no compelling evidence that the composition of the Moon is specially linked to that of the Earth, or that it reflects special formation conditions. On the contrary, it appears that among planetary objects for which we have basalt samples, the Moon's composition is not extraordinary. Besides the Moon and HED asteroid, the angrite parent body also appears to be strongly depleted in siderophile and volatile elements (Mittlefehldt et al 1998). Thus, among five planetary bodies, overall chemical characteristics may be similar among the three smaller ones, and more distinct in the two true planets.

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