



# The oxidation state and mass of the Moon-forming impactor



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## ABSTRACT

Physical simulations of the origin of the Moon have, until recently, centred on impact, about 100 M.yr after the origin of the solar system, of a Mars-like body (10–20% Earth mass) on a near fully-accreted protoEarth. Although this model provides an explanation of the distribution of mass and moment of inertia of the Earth–Moon system it has recently been found that modification of the initial conditions greatly expands the range of permissible impactor masses. Here we take an alternative approach and consider how the oxidation state and mass of the impactor affect the chemical compositions of the product Earth and Moon. We apply the constraints that silicate Moon is richer in FeO than silicate Earth (9–13% as opposed to 8.05%), that their Hf/W ratios are both  $\sim 25$  and that they are virtually identical in isotopes of O, Ti, Si, Ni, Cr and W. We then grow protoEarth using a standard accretionary model which yields the correct mantle abundances of Ni, Co, W, Mo, Nb, V and Cr, and add to this body different masses of impactor. The impactor is assumed to be either highly oxidised ( $\sim 18\%$  FeO), highly reduced ( $\sim 0.3\%$  FeO) or undifferentiated and chondritic. In order to satisfy the isotopic constraints silicate Moon is assumed to be derived principally from silicate protoEarth.

We find that an oxidised or chondritic impactor of  $\sim 0.15 M_E$  can satisfy the isotopic constraints (most importantly  $\epsilon^{182}W$ ), FeO contents and Nb/Ta of Earth and Moon, but leads to implausibly low Hf/W of  $\sim 12$ – $16$  in silicate Earth and  $\sim 4$ – $6$  in silicate Moon. This is because the Moon requires more impactor mantle, with low Hf/W, than Earth to reach its higher FeO content. In contrast, impact of a similar mass (10–20%  $M_E$ ) of highly reduced, Mercury-like impactor on an oxidised protoEarth ( $\sim 10.7\%$  FeO in mantle) satisfies the isotopic constraints, FeO contents, Nb/Ta and Hf/W of silicate Earth and Moon given a small amount of post-impact re-equilibration of terrestrial mantle with impactor core. The presence of a small S-rich lunar core is consistent with this reduced impactor scenario. We conclude that the geochemical properties of Earth and Moon strongly favour a reduced impactor of 10–20%  $M_E$ .

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## 1. Introduction

Models of the conditions of terrestrial accretion and differentiation (e.g. Rubie et al., 2011; Wade and Wood, 2005) rely on the composition of bulk silicate Earth (BSE) (Allègre et al., 1995; McDonough and Sun, 1995), experimental measurements of the partitioning of elements between liquid silicate and segregating liquid metal core and the assumption that refractory elements are in CI chondritic proportions in the bulk Earth. Although models differ in detail, there is general agreement that pressures of core segregation became high (30–50 GPa) and some argue for increasing oxidation state during accretion, as expressed by an increasing FeO content of BSE (O'Neill, 1991a, 1991b; Rubie et al., 2011, 2015; Wade and Wood, 2005). The Moon-forming impact is

generally equated with addition of  $\sim 15\%$  of an oxidised, volatile-rich impactor to Earth (O'Neill, 1991b) a model which is consistent with the abundances of moderately volatile elements in BSE and with the isotopes of moderately volatile Ag. In the latter case the  $^{107}Ag/^{109}Ag$  ratio depends on the short-lived  $^{107}Pd$ – $^{107}Ag$  isotopic system ( $t_{1/2} = 6.5$  M.yr) and Schönbachler et al. (2010) showed that silicate Earth is CI chondritic in Ag isotope ratio. This result is only consistent with the accretionary timescale derived from the short-lived  $^{182}Hf$ – $^{182}W$  system if moderately volatile Ag was added very late in accretion, plausibly with about 15% of a CI-chondrite-like impactor (Schönbachler et al., 2010).

As the chemical similarities between Earth and Moon became clear during the 1970's and 1980's, geochemical models of lunar origin called for the Moon to be made, in the aftermath of a giant impact, of material dominantly from protoEarth (Ringwood, 1986; Wänke and Dreibus, 1983). When hydrodynamic simulations of the impact were made, however (Canup, 2004; Canup and Asphaug, 2001) the mass distribution and angular momentum of the

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**Table 1**  
“Target” composition values.

	Body			Reference
	Chondrite	Earth	Moon	
Hf/W	1.11 1.18	25.8 26 + 2/–3	24.9	McDonough and Sun (1995) Palme and O'Neill (2003) König et al. (2011) Münker (2010) Kleine et al. (2009)
FeO		8.05%	9–13%	McDonough and Sun (1995) Wänke et al. (1977) Jones and Palme (2000)
Nb/Ta	19.9 ± 0.6 17.65	14.0 ± 0.3	17.0 ± 0.8	Münker et al. (2003) McDonough and Sun (1995)
$\epsilon^{182}\text{W}$	0 <sup>a</sup>	1.9 2.03 ± 0.04 (Isua) 1.89 ± 0.01 (post-archaen)	1.9  $\epsilon_{\text{Earth}} + 0.27 \pm 4$	Kleine et al. (2009) Willbold et al. (2011) Kruijer et al. (2015)
$\Delta^{17}\text{O}$			Earth +12 ± 3 ppm Earth –1 ± 5 ppm	Herwartz et al. (2014) Young et al. (2016)
$\epsilon^{50,48,46}\text{Ti}$	0	0	0	Leya et al. (2003)
Mn, V Cr		Terrestrial Mantle = Lunar Mantle		O'Neill (1991a, 1991b)
V (ppm)		82	~Earth	Drake et al. (1989)
Cr (ppm)		3010	~Earth	Ringwood et al. (1987)
Mn (ppm)		1020	~Earth	
V (ppm)		82		McDonough and Sun (1995)
Cr (ppm)		2625		
Mn (ppm)		1045		
Ni (ppm)		1960	~0.3 Earth	Walter et al. (2000)
Co (ppm)		105	~Earth	McDonough and Sun (1995)
W (ppm)		12	~Earth	König et al. (2011)

<sup>a</sup>  $\epsilon^{182}\text{W}$  of Earth and Moon relative to Chondrite which is assigned a value of 0.

Earth–Moon system was generated with impactors of 10–20% of Earth mass and it was found that the Moon was produced from an accretion disc dominated by impactor rather than terrestrial material. The latter result is broadly consistent with the significant differences in composition of silicate Earth and silicate Moon. The BSE has an FeO content of 8% (McDonough and Sun, 1995) and an Nb/Ta of 14 (Münker et al., 2003) whereas silicate moon has values of 9–13% (Table 1) and 17 respectively (Münker et al., 2003). More recent trace element and isotopic data have shown, however that BSE and the Moon are essentially identical in Hf/W (Kleine et al., 2004; König et al., 2011) (Table 1) and in isotopes of O, Cr, Ti, Ni and W (Herwartz et al., 2014; Kleine et al., 2004; Regelous et al., 2008; Trinquier et al., 2008). These latter observations are extremely difficult to reconcile with models of the Moon being dominated by material from the impactor (e.g. Canup and Asphaug, 2001) implying, in agreement with the earlier hypotheses, that Earth and Moon were both made substantially of the same precursor materials. Although vapour-phase oxygen isotopic re-equilibration between Earth and Moon in the aftermath of the giant impact has been suggested (Pahlevan and Stevenson, 2007; Pahlevan et al., 2011) similar isotopic re-equilibration of involatile elements such as Ti, Ni and W is difficult to envisage. The implication, if the impactor was 10–50% of Earth Mass is that the moon was made from a similar mixture of protoEarth and impactor as the Earth itself (Young et al., 2016). This is a line of inquiry which we will pursue here. By making the assumption that there are similar proportions of impactor and protoEarth in both bodies we implicitly address most of the isotopic similarities between Earth and Moon. One similarity which, as will be shown, is difficult to reproduce, is that of  $\epsilon^{182}\text{W}$ . We will show that this provides strong constraints on the amounts of protoEarth and impactor in the 2 bodies as well as on the requirement for post-impact core equilibration with Earth's mantle.

Recent simulations of the Moon-forming impact have expanded the possible range of impactor mass consistent with the physical properties of the Earth–Moon system into two end member scenarios. The first of these involves a small impactor (~2 to 5% of Earth Mass, Cuk and Stewart, 2012), colliding with a rapidly spinning proto-Earth while the second is a collision between two bodies of similar size (Canup, 2012). Either end-member can, under certain circumstances reproduce the physical properties of the Earth–Moon system and generate a Moon-forming disc predominantly from the proto-Earth's mantle. As we will show below, however, neither end-member is consistent with all the chemical properties of Earth and Moon and the most plausible impactor size, from the standpoint of chemical properties, remains close to the “canonical” value of 0.15M<sub>E</sub>. In this work our aim was to make chemical models of the proto-Earth (pre-impact) and of the impactor, which lead to the observed chemical and isotopic characteristics of the silicate Earth and Moon after the impact. We aimed to do this by constructing each body from different proportions of protoEarth and impactor without resorting to the hypothesis of vapour-phase re-equilibration of the Earth–Moon system in the aftermath of the Giant Impact.

## 2. Accretion of the protoEarth

Before the giant impact the protoEarth had, based on the models discussed above, grown to between 50 and 95% of its current mass. Although the timescale of accretion to this point is constrained by the  $^{182}\text{Hf}$ – $^{182}\text{W}$  system to be greater than ~30 Ma after CAI formation (Kleine et al., 2004) there are considerable uncertainties attached to this figure. These uncertainties depend on the degree of metal–silicate equilibration before and after the impact and the size of the impactor. Siderophile  $^{182}\text{W}$  was generated during radioactive decay of short-lived lithophile  $^{182}\text{Hf}$  ( $t_{1/2} = 9 \text{ M.yr}$ )

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