Moderately volatile element behaviour at high temperature determined from nuclear detonation

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Abstract

The first nuclear detonation, at the Trinity test site, is an analogue for high temperature volatile loss during planet formation processes. We report Cu isotope and abundance data, comparing them with Zn and K isotopes in trinitite glasses sampled with distance from the detonation centre. Copper concentrations drop, and isotopic compositions become ~0.3 ‰ higher with proximity to the detonation. Relative sensitivity to high temperature evaporative isotopic fractionation processes occur in the order: Zn > Cu >> K. Lower volatility of K relative to Cu and Zn results from its low activity coefficient in silicate melts. Lunar mare basalt and some tektite Cu, Zn and K isotope compositions can be modelled using empirical fractionation factors (α) derived from trinitite. Combined with isotopic variations measured in mare basalts, the results support volatile loss during a magma ocean phase for the Moon.

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Introduction

The moderately volatile elements (MVE), including Cu, Zn and K, trace volatile behaviour in planetary bodies. The MVE have 50 % nebular condensation temperatures (TC_{50}) at solar nebula conditions (10^{-4} bar) of between 1134 K and 665 K (Lodders, 2003), and have low element-element bond energies (Albarède *et al.*, 2015). Stable isotope MVE compositions have been utilised to examine fractionation effects induced by evaporation or condensation, and to assess stable isotope differences between Earth and the Moon (*e.g.*, Paniello *et al.*, 2012; Day and Moynier, 2014; Boyce *et al.*, 2015; Wang and Jacobsen, 2016; Dhaliwal *et al.*, 2018).

An advantage of examining the MVE relative to more volatile compounds such as H_2O is that they generally occur in sufficient quantity within rock-forming minerals and glasses that their isotopic composition can be precisely measured. Copper ($TC_{50} = 1037$ K) is a useful tracer of planetary volatile histories, being both moderately volatile and chalcophile during planetary processes (*e.g.*, Moynier *et al.*, 2017). Copper isotopic fractionations (expressed as $\delta^{65}Cu = ([^{65}Cu/^{63}Cu]_{sample}/[^{65}Cu/^{63}Cu]_{SRM976} - 1) \times 1000$) of planetary materials do not match predicted kinetic isotopic fractionation factors, but are instead consistent with subdued fractionation factors

approaching unity (Moynier *et al.*, 2017). A problem in interpreting volatile element isotope fractionation has been that laboratory experiments are unable to reproduce large scale volatile processes, making empirical assessment of volatile element loss during planet formation challenging. This is particularly troubling since debate surrounds the extent of volatile loss experienced by planets and when this occurred (Paniello *et al.*, 2012; O'Brien *et al.*, 2014; Wang and Jacobsen, 2016).

To examine the behaviour of Cu during high temperature processes, and to compare it with two other MVE, we investigated melted glasses (trinitite) formed during nuclear detonation at the Trinity Test site, New Mexico, USA. During this event, local conditions exceeded 8430 K, leading to vapourisation of the arkosic eesced sand substrate (Supplementary Information). Temperature estimates for the explosion are above those anticipated for typical basaltic eruption temperatures. The conditions of formation were likely to be reducing since the absolute $\log fO_2$ (bar) defined by the FMQ buffer is -6.3 at 1673 K, but is -1.8 at 2273 K. In contrast, air has $\log fO_2 = -0.68$ at both temperatures, resulting in reducing conditions relative to solid-solid buffers.

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Samples and Methods

Trinitite samples collected with known distances from the detonation and that have previously been examined for Zn (Day *et al.*, 2017) and K isotopes (Chen *et al.*, 2019) were studied. These samples include trinitite taken within 10 m of ground zero (IF), at 100 m (IG) and at 200 ± 50 m (T3). Sample T3 had the least amount of trinitite glass, and we use this sample to establish background Cu abundance and $^{65}\text{Cu}/^{63}\text{Cu}$ at the Trinity test site, as it has a similar composition to ‘unmelted’ sand (Bellucci *et al.*, 2014). The 10 m sample, IF, formed at 1663 K and cooled within 17 minutes of emplacement, whereas the 100 m sample, IG, formed at 1593 K, cooled within five minutes of emplacement (Meshik *et al.*, 2008). Peripheral sample T3 formed at lower temperatures and higher rates of cooling.

To assess Cu elemental or isotopic heterogeneity, a systematic procedure of crushing and leaching/etching was performed on trinitites (Supplementary Information). The final Cu cuts after chemistry, representing 99 ± 1 % of Cu in the sample, were analysed for isotopic composition using a Thermo Fischer Neptune Plus Multi-Collector Inductively-Coupled-Plasma Mass-Spectrometer (MC-ICP-MS) at the Institut de Physique du Globe de Paris following procedures in Sossi *et al.* (2015), and detailed in the Supplementary Information. To correct for instrumental mass bias, isotope measurements were doped with Ni to correct for matrix effects and calculated using the standard sample bracketing protocol relative to the NIST SRM976 standard, whereby variations in Cu ratios are defined using the delta notation ($\delta^{65}\text{Cu}$).

Copper Isotope and Abundance Data for Trinitite

The T3 trinitite, furthest from the centre of the nuclear detonation, has a typical BSE $\delta^{65}\text{Cu}$ value and higher Cu content than the IF and IG samples. When plotted as Cu content *versus* $\delta^{65}\text{Cu}$ (Figure 1), the IF and IG residues, etchates and leachates form negatively correlated trends, only disturbed by the IG HCl leach. Hydrochloric acid is effective at leaching sulfide or metal, and we posit that isotopically heavy metal particulate from close to the detonating ‘Gadget’ was incorporated into IF, explaining the IF HCl Cu composition as well as anomalously high Pb in this sample (Day *et al.*, 2017). Exclusion of this sample leads to correlations for the residue, bulk, HF-HNO₃ etch and H₂O leach ($y = -0.057x + 2.39$; $R^2 = 0.95$) matching that of the IF sample ($y = -0.070x + 0.698$; $R^2 = 0.99$). In both cases, the isotopically lightest values occur in H₂O, and the heaviest values occur in the residue.

Lithium and Fe isotopes during leaching can be fractionated by >2 ‰ as a consequence of either diffusion driven isotopic fractionation (Li) or proton promoted dissolution (Fe) that are influenced by sample composition (Verney-Carron *et al.*, 2011; Revels *et al.*, 2015). Increasing reagent strength and prolonged time of exposure (>2 hours) also leads to increasing isotopic fractionation. The Cu isotope data for trinitites cannot be explained by laboratory induced fractionation effects. For example, no laboratory induced isotopic fractionation of Cu was observed in lunar sample 66095 using the same methods (Day *et al.*, 2019). Instead, the most extreme Cu isotope fractionation occurs in the mildest leaches and not in the more aggressive etches. The Cu, Zn and K data for trinitite therefore reflect sampling of distinct sub-reservoirs in samples.

Negative trends in Cu content *versus* $\delta^{65}\text{Cu}$ space (Figure 1) indicate that Cu is isotopically heavy in the silicate fraction of trinitite and is isotopically heaviest closest to the

nuclear detonation centre. Conversely, H₂O leaches appear to have sampled isotopically light Cu, perhaps preserved as soluble Cu salts, on the outer glass surfaces.

Isotopic Fractionation of Cu, Zn and K

There is a correlation of decreasing Cu content with proximity to the ‘Gadget’ (Fig. 2). A similar less well-constrained relationship has previously been observed for Zn and Pb (Day *et al.*, 2017), but is not so evident in trinitite K contents (Chen *et al.*, 2019). The relationship between distance from the nuclear detonation and $\delta^{65}\text{Cu}$ is less well-defined, and not as clear as $\delta^{66}\text{Zn}$, but is better defined than $\delta^{41}\text{K}$, where significant K isotope fractionation from the BSE value only occurs for IF trinitite. Therefore, the IF and IG trinitite samples are demonstrably isotopically heavier than either BSE or the T3 sample for Cu, as well as for Zn, and in the case of IF, for K (Table S-1) (Fig. 3). There is no evidence that there is sufficient isotopic or elemental heterogeneity in Earth materials, or the arkosic sand at the Trinity test site, for this variation to be natural. The only process explaining this relationship is high temperature evaporative fractionation.

Evaporation of volatile elements at high temperatures is thought to be a function of element condensation temperatures under nebular conditions, or bond-bond energies (Albarède *et al.*, 2015). However, for vapourisation or condensation processes that take place under distinct thermodynamic conditions, these temperatures bear limited relevance. This is because the condensed phase is a silicate liquid melting and vapourising at 1 bar total pressure, compared to condensation of solid metal and silicate minerals at low pressures in the H₂ atmosphere of the solar nebula (Norris and Wood, 2017; Sossi *et al.*, 2019). Trinitites allow empirical assessment of relative volatilities of MVE with mass differences of two. From relationships between $\delta^{65}\text{Cu}$ and $\delta^{66}\text{Zn}$ and $\delta^{65}\text{Cu}$ and $\delta^{41}\text{K}$ in Figure 3 it is possible to calculate the relative sensitivity of these isotope systems during high temperature evaporative fractionation. We obtain:

$$\delta^{66}\text{Zn} > \delta^{65}\text{Cu} > \delta^{41}\text{K}$$

In detail, the relationship is $1.5 \pm 1.2^{+2.5}_{-1.2}$ for $\delta^{66}\text{Zn}/\delta^{65}\text{Cu}$ and $1.9 \pm 1.6^{+2.2}_{-1.6}$ for $\delta^{65}\text{Cu}/\delta^{41}\text{K}$ using the relationships in Figure 3 and associated error envelopes.

Relative element volatilities during evaporation from trinitite can be compared with theoretical and experimental considerations of MVE evaporation from basaltic silicate melt. Both Cu and K are expected to exist as monatomic oxides in silicate melts (*i.e.* $\text{KO}_{0.5}$ and $\text{CuO}_{0.5}$) while their gas species, under nominally anhydrous conditions and high temperatures, are K^0 (g) and Cu^0 (g) (Lamoureux and Hildenbrand, 1984; Lamoureux *et al.* 1987). Therefore, partial pressures during evaporation should increase proportionally to $(f\text{O}_2)^{-0.25}$. Although Zn is also present in the gas as Zn^0 , its stable melt oxide species is ZnO(l) , conferring a dependence of $(f\text{O}_2)^{-0.5}$ on $p(\text{Zn})$ (Sossi *et al.*, 2019). Therefore, increasingly reducing conditions favour evaporation of Zn over Cu and K. Calculations of equilibrium partial pressures of gaseous elements over silicate melts requires knowledge of the activity coefficients of these elements in the condensed phase, assuming an ideal gas phase. The Cu activity coefficient in basaltic melts has been determined to be ≈ 10 –20 at 1300 °C, extending down to 3.5 at 1650 °C (Holzheld and Lodders, 2001; Wood and Wade, 2013), whereas that of Zn is slightly less than unity (Sossi *et al.*, 2019). By contrast, activity coefficients of alkali oxides in silicate melts are much less than unity (see discussion in

Figure 1 Copper content versus $\delta^{65}\text{Cu}$ in trinitite. Bulk silicate Earth (BSE) estimate from Savage *et al.* (2015).

Figure 2 (a) $\delta^{65}\text{Cu}$ and (b) Cu abundance in trinitite with distance from the 'Gadget' compared with Zn, Pb and K contents from the same samples (Day *et al.*, 2017; Chen *et al.*, 2019). BSE is from Savage *et al.* (2015).

Figure 3 Copper versus (a) Zn and (b) K isotopes in trinitite. Zinc and K data for trinitites from Day *et al.* (2017) and Chen *et al.* (2019). BSE Cu, Zn and K values are from Moynier *et al.* (2017) and Wang and Jacobsen (2016).

Sossi and Fegley, 2018). This key property stabilises them in the silicate melt, resulting in decreased volatilities compared to the nebular condensation temperature.

For $\text{KO}_{0.5}$, appropriate activity coefficients are $\approx 2 \times 10^{-4}$ (Hastie and Bonnell, 1985; Sossi *et al.*, 2019). Insofar as these values are applicable to trinitite melts, the equilibrium partial pressures of these species can be calculated in air ($\log f_{\text{O}_2} = -0.68$). Relative to their mole fraction in the condensed phase, their partial pressures at 1600 K and 1 bar total pressure are 1.06×10^{-5} bar for K, 1.58×10^{-4} bar for Zn and 8.84×10^{-5} bar for Cu, resulting in an expected order of volatility $\text{Zn} > \text{Cu} \gg \text{K}$, in agreement with observations. If the amount of an element (E) vapourised is proportional to its partial pressure (p) divided by its mole fraction (X), then:

$$f_{\text{vap}}^E = \frac{\frac{p(E)}{X(E)}}{\left(1 + \frac{p(E)}{X(E)}\right)}$$

Substituting the normalised partial pressures shows a broad match to the concentration of Cu remaining in sample IF ($7.4 - 12.1 \mu\text{g g}^{-1}$), $f_{\text{vap}}^{\text{Cu}} = 0.86$ (given an initial Cu content of $73.4 \mu\text{g g}^{-1}$), then $f_{\text{vap}}^{\text{Zn}} = 0.92$ and $f_{\text{vap}}^{\text{K}} = 0.37$. This treatment assumes that diffusion in the melt is sufficiently fast to keep pace with vapourisation. The other factor contributing to how

efficiently elements are lost from silicate melts is their diffusion coefficient through this medium. As Cu is the fastest diffusing element of the trio (Zn being the slowest; Ni and Zhang, 2017), this will promote loss of Cu relative to K and Zn, enhancing isotopic fractionation (Moynier *et al.* 2010).

Implications for the Formation of Tektites and the Moon

Volatile behaviour in trinitite glasses enables assessment of how high temperature evaporation processes may have acted on other planetary materials. In the first instance, we consider tektites. Tektites are glassy materials of various shapes and sizes that are considered to have formed from meteoroid-induced atmospheric air blasts that melted soils and upper crustal materials in certain regions during discrete events. Tektites show extreme $\delta^{66}\text{Zn}$ and $\delta^{65}\text{Cu}$ variations, being enriched in the heavier isotopes due to evaporative fractionation (Moynier *et al.*, 2009, 2010). Potassium isotopes are less extremely fractionated than for Cu or Zn isotopes, spanning the range of $\delta^{41}\text{K}$ observed in trinitites (*e.g.*, Jiang *et al.*, 2019). The results from trinitite are consistent with fractionation of Cu and Zn isotopes occurring in the tektites that is as great or greater than for the IF (10 m) trinitite sample. Limited K isotope fractionation is consistent with its low activity coefficient in silicate melts

Figure 4 Rayleigh distillation curves versus (a) Cu, (b) Zn and (c) K contents and isotopic compositions for trinitite glass, tektites and lunar samples. Curves are shown for different alpha fractionation (α) factors (1, 0.9998, 0.999, 0.998) established from trinitite, with $70 \mu\text{g g}^{-1}$ Cu, $30 \mu\text{g g}^{-1}$ Zn and $40000 \mu\text{g g}^{-1}$ K for estimated BSE isotopic compositions. Data are from this study, Day *et al.* (2017), and Chen *et al.* (2019) for trinitite. Tektite data are from Moynier *et al.* (2009, 2010), and Jiang *et al.* (2019), and lunar basalts data are from Paniello *et al.* (2012), Kato *et al.* (2015), and Wang and Jacobsen (2016) and references therein.

compared to Cu and Zn, hindering evaporation (e.g., Hastie and Bonnell, 1985). The variation in $\delta^{66}\text{Zn}$ in tektites is large, whereas the variation in $\delta^{65}\text{Cu}$ is well described by fractionation factors (α) of between 0.999 and 0.9998, similar to those required to explain Zn, Cu and K isotope fractionation at the Trinity nuclear test site (Fig. 4).

The other example we consider is MVE depletion in lunar samples. Shown in Figure 4 are Zn isotope data for mare basalts, and Cu and K isotope data for a variety of lunar samples, including mare basalts and some soils. The lunar samples are systematically enriched in the heavier isotopes of Zn, Cu and K relative to BSE. These isotope systems can all be explained by fractionation factors (α) of between 0.999 and 0.9998 for $^{66}\text{Zn}/^{64}\text{Zn}$, $^{65}\text{Cu}/^{63}\text{Cu}$ and $^{41}\text{K}/^{39}\text{K}$, corresponding to the empirical fractionation factors derived from trinitite, and far smaller than for evaporation into a vacuum. Lunar samples span a range in isotopic composition and contents of Zn, Cu and K, suggesting inhomogeneity in the Moon and MVE fractionation at high temperatures during magmatic evolution. Such variability is therefore inconsistent with MVE evaporative fractionation solely in a solid-vapour disk forming the Earth and Moon (Paniello *et al.*, 2012; Wang and Jacobsen, 2016), and also requires volatile loss during later lunar evolution, such as during a magma ocean phase (e.g., Day and Moynier, 2014; Boyce *et al.*, 2015; Day *et al.*, 2020) where partial pressures of degassing species may lead to accumulation at the surface, reducing the degree of isotopic fractionation to near-equilibrium values.

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Author Contributions

JD designed the research and wrote the article; JD, PS and FM collected the data; AM, OP and DP provided samples. All authors provided comments and suggestions on the article.

Additional Information

Supplementary Information accompanies this letter at <http://www.geochemicalperspectivesletters.org/article2014>.

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References

- ALBARÈDE, F., ALBALAT, E., LEE, C.T.A. (2015) An intrinsic volatility scale relevant to the Earth and Moon and the status of water in the Moon. *Meteoritics and Planetary Science* 50, 568–577.
- BELLUCCI, J.J., SIMONETTI, A., KOEMAN, E.C., WALLACE, C., BURNS, P.C. (2014) A detailed investigation of post-nuclear detonation trinitite glass at high spatial resolution: delineating anthropogenic vs. natural components. *Chemical Geology* 365, 69–86.
- BOYCE, J.W., TREIMAN, A.H., GUAN, Y., MA, C., EILER, J.M., GROSS, J., GREENWOOD, J.P., STOLPER, E.M. (2015) The chlorine isotope fingerprint of the lunar magma ocean. *Science Advances* 1, e1500380.
- CHEN, H., MESHIK, A.P., PRAVDIVTSEVA, O.V., DAY, J.M.D., WANG, K. (2019) Potassium isotope fractionation during the high-temperature evaporation determined from the Trinity nuclear test. *Chemical Geology* 522, 84–92.
- DAY, J.M.D., MOYNIER, F. (2014) Evaporative fractionation of volatile stable isotopes and their bearing on the origin of the Moon. *Philosophical Transactions of the Royal Society of London A* 372, 20130259.
- DAY, J.M.D., MOYNIER, F., MESHIK, A.P., PRAVDIVTSEVA, O.V., PETIT, D.R. (2017) Evaporative fractionation of zinc during the first nuclear detonation. *Science Advances* 3, p.e1602668.
- DAY, J.M.D., SOSSI, P.A., SHEARER, C.K., MOYNIER, F. (2019) Volatile distributions in and on the Moon revealed by Cu and Fe isotopes in the 'Rusty Rock' 66095. *Geochimica et Cosmochimica Acta* 266, 131–143.
- DAY, J.M.D., VAN KOOTEN, E.M.M.E., HOFMANN, B.A., MOYNIER, F. (2020) Mare basalt meteorites, magnesian-suite rocks and KREEP reveal loss of zinc during and after lunar formation. *Earth and Planetary Science Letters* 351, 115998.
- DHALIWAL, J.K., DAY, J.M.D., MOYNIER, F. (2018) Volatile element loss during planetary magma ocean phases. *Icarus* 300, 249–260.
- HASTIE, J.W., BONNELL, D.W. (1985) A predictive phase equilibrium model for multicomponent oxide mixtures part II. Oxides of Na–K–Ca–Mg–Al–Si. *High Temperature Science* 19, 275–306.
- HOLZHEID, A., LODDERS, K. (2001) Solubility of copper in silicate melts as function of oxygen and sulfur fugacities, temperature, and silicate composition. *Geochimica et Cosmochimica Acta* 65, 1933–1951.
- JIANG, Y., CHEN, H., FEGLEY, B. JR., LODDERS, K., HSU, W., JACOBSEN, S.B., WANG, K. (2019) Implications of K, Cu and Zn isotopes for the formation of tektites. *Geochimica et Cosmochimica Acta* 259, 170–187.
- KATO, C., MOYNIER, F., VALDES, M.C., DHALIWAL, J.K., DAY, J.M.D. (2015) Extensive volatile loss during formation and differentiation of the Moon. *Nature Communications* 6, 7617, doi: 10.1038/ncomms8617.
- LAMOREAUX, R.H., HILDENBRAND, D.L. (1984) High temperature vaporization behavior of oxides. I. Alkali metal binary oxides. *Journal of Physical and Chemical Reference Data* 13, 151–173.
- LAMOREAUX, R.H., HILDENBRAND, D.L., BREWER, L. (1987) High-temperature vaporization behavior of oxides II. Oxides of Be, Mg, Ca, Sr, Ba, B, Al, Ga, In, Tl, Si, Ge, Sn, Pb, Zn, Cd, and Hg. *Journal of Physical and Chemical Reference Data* 16, 419–443.
- LODDERS, K. (2003) Solar system abundances and condensation temperatures of the elements. *The Astrophysical Journal* 591, 1220.
- MESHIK, A., PRAVDIVTSEVA, O., HOHENBERG, C. (2008) Fission xenon in trinitites from the first nuclear test. APS April Meeting and HEDP/HEDLA Meeting, St. Louis, MO, 11 to 15 April 2008.
- MOYNIER, F., BECK, P., JOURDAN, F., YIN, Q.-Z., REIMOLD, U., KOEBERL, C. (2009) Isotopic fractionation of zinc in tektites. *Earth and Planetary Science Letters* 277, 482–489.
- MOYNIER, F., KOEBERL, C., BECK, P., JOURDAN, F., TELOUK, P. (2010) Isotopic fractionation of Cu in tektites. *Geochimica et Cosmochimica Acta* 74, 799–807.
- MOYNIER, F., VANCE, D., FUJII, T., SAVAGE, P. (2017) The isotope geochemistry of zinc and copper. *Reviews in Mineralogy and Geochemistry* 82, 543–600.
- NI, P., ZHANG, Y. (2017) Cu diffusion in a basaltic melt. *American Mineralogist* 101, 1474–1482.

- NORRIS, C.A., WOOD, B.J. (2017) Earth's volatile contents established by melting and vaporization. *Nature* 549, 507-510.
- O'BRIEN, D.P., WALSH, K.J., MORBIDELLI, A., RAYMOND, S.N., MANDELL, A.M. (2014) Water delivery and giant impacts in the 'Grand Tack' scenario. *Icarus* 239, 74-84.
- PANIELLO, R.C., DAY, J.M.D., MOYNIER, F. (2012) Zinc isotopic evidence for the origin of the Moon. *Nature* 490, 376-379.
- REVELS, B.N., ZHANG, R., ADKINS, J.F., JOHN, S.G. (2015) Fractionation of iron isotopes during leaching of natural particles by acidic and circum-neutral leaches and development of an optimal leach for marine particulate iron isotopes. *Geochimica et Cosmochimica Acta* 166, 92-104.
- SAVAGE, P.S., MOYNIER, F., CHEN, H., SHOFNER, G., SIEBERT, J., BADRO, J., PUCHTEL, I.S. (2015) Copper isotope evidence for large-scale sulphide fractionation during Earth's differentiation. *Geochemical Perspectives Letters* 1, 53-64.
- SOSSI, P.A., FEGLEY, B. (2018) Thermodynamics of element volatility and its application to planetary processes. *Reviews in Mineralogy and Geochemistry* 84, 393-459.
- SOSSI, P.A., HALVERSON, G.P., NEBEL, O., EGGINS, S.M. (2015) Combined separation of Cu, Fe and Zn from rock matrices and improved analytical protocols for stable isotope determination. *Geostandards and Geoanalytical Research* 39, 129-149.
- SOSSI, P.A., KLEMME, S., O'NEILL, H.S.C., BERNDT, J., MOYNIER, F. (2019) Evaporation of moderately volatile elements from silicate melts: experiments and theory. *Geochimica et Cosmochimica Acta* 260, 204-231.
- VERNEY-CARRON, A., VIGIER, N., MILLOT, R. (2011) Experimental determination of the role of diffusion on Li isotope fractionation during basaltic glass weathering. *Geochimica et Cosmochimica Acta* 75, 3452-3468.
- WANG, K., JACOBSEN, S.B. (2016) Potassium isotopic evidence for a high-energy giant impact origin of the Moon. *Nature* 538, 487-490.
- WOOD, B.J., WADE, J. (2013) Activities and volatilities of trace components in silicate melts: a novel use of metal-silicate partitioning data. *Contributions to Mineralogy and Petrology* 166, 911-921.