Earth’s volatile contents established by melting and vaporization

C. Ashley Norris & Bernard J. Wood

The silicate Earth is strongly depleted in moderately volatile elements (such as lead, zinc, indium and alkali elements) relative to CI chondrites, the meteorites that compositionally most closely resemble the Sun1. This depletion may be explained qualitatively by accretion of 10 to 20 per cent of a volatile-rich body to a reduced volatile-free proto-Earth2,3, followed by partial extraction of some elements to the core1. However, there are several unanswered questions regarding the sources of Earth’s volatiles4,5, notably the overabundance of indium in the silicate Earth. Here we examine the melting processes that occurred during accretion on Earth and precursor bodies and report vaporization experiments under conditions of fixed temperature and oxygen fugacity. We find that the pattern of volatile element depletion in the silicate Earth is consistent with partial melting and vaporization rather than with simple accretion of a volatile-rich chondrite-like body. We argue that melting and vaporization on precursor bodies and possibly during the giant Moon-forming impact6–8 were responsible for establishing the observed abundances of moderately volatile elements in Earth.

Earth accreted from asteroidal and protoplanetary bodies over a timescale of 30–100 Myr (ref. 9). On the basis of observations of igneous, metallic and achondritic meteorites, it is assumed that many of these asteroidal components formed within a few million years of the origin of the Solar System and underwent an early phase of melting and vaporization, with heat sources such as the decay of 26Al (ref. 9). For example, volatile-poor Vesta seems to have formed within 4 Myr of the origin of the Solar System and to have undergone melting, volatile loss10 and volcanism for a further 35 Myr (ref. 11). During Earth’s protracted accretion, unmelted and previously melted, variably volatile-depleted bodies were added in impacts that became progressively more violent, terminating with the giant impact (or impacts) that led to the formation of the Moon9,12. Modelling of the accretion process and applying constraints on the basis of the partitioning of siderophile elements between core and silicate mantle leads to the conclusion that Earth was periodically covered by a ‘magma ocean’ of molten silicate13–15. Models of the giant impact also suggest that it led to wholesale melting of the silicate Earth, extremely high surface temperatures with partial vaporization of the silicate melt12,15, and the generation of a proto-lunar disk of melt and vapour. Some volatile loss can take place from this proto-lunar disk by hydrodynamic escape17. Atmospheric loss from Earth during the magma-ocean phase18 and loss of moderately volatile Zn (refs 8, 19) and K (ref. 7) from the Moon are confirmed by recent isotopic measurements.

As anticipated from the previous discussion, the silicate Earth is strongly depleted in moderately volatile elements such as Pb, Tl, Zn, Sb, Bi and Ag relative to the solar composition as represented by CI chondrites. Figure 1 illustrates these depletions in a graph of element concentration in the silicate Earth1, normalized to abundance in CI chondrites, plotted against a measure of element volatility. This measure is assumed, following general practice, to correlate with the temperature at which 50% of the element would be condensed from a gas of solar composition19. For comparison, we show the depletion pattern of CV carbonaceous chondrites21, meteorites that are also volatile-depleted relative to CI chondrites and that have never undergone planetary processes of melting and core formation.

From Fig. 1 it can be seen that, although there is a general trend of declining relative abundance both in the silicate Earth and in CV chondrites with increasing volatility (decreasing condensation temperature), there are many elements that, in the silicate Earth, fall below the trend. Such cases are frequently ascribed to extraction into the core, the elements being dissolved either in segregating Fe-rich metal22 during accretion or in a putative sulphide ‘Hadean matte’ in the final stages of core formation2. Therefore, for example, elements such as Au, Cu, Ag and S are known to partition strongly into both molten Fe metal22 and liquid FeS at elevated temperature, whereas the more abundant Na, K, B and F show negligible tendencies to follow Fe and FeS into the core. Core formation has clearly reduced the concentrations of relatively non-volatile elements such as Fe, Ni, Mo and W in the silicate Earth23, so it is reasonable to apply the same principle to the volatile elements shown in Fig. 1. However, this approach to understanding the chemical composition of the silicate Earth implicitly relies on the assumption that the moderately volatile elements were added to Earth during accretion by a body with a mass of 10%–20% that of Earth that had CI-chondrite-like ratios of these elements. Late arrival of such a body seems to be the most reasonable explanation of the Pd/Ag and 107Ag/109Ag ratios of the silicate Earth3. This body has also been suggested to have been the Moon-forming impactor2. Further depletions as shown for Au, Ag and

Figure 1 | Concentrations in the bulk silicate Earth of moderately volatile elements. Concentrations are plotted against the temperature at which 50% of the element would be condensed at a pressure of 10−8 bar from a gas of Solar System composition24, and are expressed relative to concentrations in CI chondrite meteorites21 (normalized to a concentration ratio of Mg of 1.0). Elements studied here are shown as filled coloured symbols (see legend). Open squares refer to elements not specifically addressed by our study. Open circles refer to all elements in CV chondrites. Error bars, 1 s.d. The arrow labelled ‘increasing partitioning into the core’ refers to one possible way of explaining high depletions of elements such as S, Se, Tl, Bi and Ag.
other elements are then ascribed to the aforementioned core-forming processes. However, despite the flexibility of the approach in terms of the conditions (pressure, temperature and metal composition) of core formation, which can be varied to match the depletion pattern, the abundances of numerous elements remain difficult to explain. In, for example, has a much lower condensation temperature than Zn and is more siderophile and more chalcophile than Zn, yet is relatively more abundant in the silicate Earth. In is also much more abundant in the silicate Earth than Tl, despite having a similar condensation temperature (Fig. 1) and being more siderophile and more chalcophile. Cs is strongly depleted despite not partitioning into either metal or sulfide. The same applies to the halogens. Cu and Ag have virtually identical partitioning into sulfide and metal and very similar condensation temperatures, yet Cu is substantially more abundant than Ag. Therefore, the pattern of abundance shown in Fig. 1 cannot be explained solely by the addition of volatiles in a CI-chondrite-like body followed by partial core formation. Of the other processes involved in the formation and differentiation of Earth, melting on precursor bodies and on the protoplanet must have led to partial vaporization of the most volatile elements, and it is this process that we consider here.

To measure the loss of volatile elements to the vapour phase directly, we constructed a 1-atm gas mixing furnace with stirring apparatus (see Methods and Extended Data Tables 1 and 2). The device is capable of stirring a 4.5-cm³ crucible of silicate melt at temperatures of up to 1,700 °C in an entirely gas-tight assembly. Flowing CO/CO₂ mixtures were used to control oxygen fugacity (f_O₂). The crucible and stirrer mechanism are made of high-purity nickel and products were drop-quenched into a water bath at the end of the experiment. The silicate starting material was a natural basalt from the Reykjanes Ridge, Iceland, which was crushed, ground and mixed with a trace element mixture of oxide powders to yield concentrations of 300–500 μg g⁻¹ per element.

Volatil-loss experiments were performed at 1,300 °C and a range of log(f_O₂) values from −7 to −13. This f_O₂ range represents values from just less than that of the Ni–NiO buffer, down to 2.3 logarithmic units below that of the Fe–FeO buffer. The former (upper) value is characteristic of the modern mantle; the latter (lower) value corresponds to the case of molten peridotitic mantle in equilibrium with Fe and hence simulates conditions during core formation.

All products presented as a mass of homogeneous black glass containing no observable gas bubbles.

Major element compositions of the products were determined using a scanning electron microscope (SEM) with an energy-dispersive detector (Extended Data Table 1). Trace element concentrations were measured using laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; Methods and Extended Data Table 2). Samples were inspected for homogeneity using an SEM with back-scattered electron (BSE) imaging, X-ray mapping, and repeated spot analysis using an energy-dispersive spectrometer (EDS). In all cases, the major element composition of the samples appeared to be homogeneous to the precision of these techniques (approximately 2% relative standard deviation, r.s.d.). Repeated trace element analysis using LA-ICP-MS showed that most elements were homogeneous to better than the single-spot precision, approximately 5%–10% r.s.d. In the high concentration range of 400–500 μg g⁻¹, the intra-spot variation was less than 5% r.s.d. for Ag, Ga, In, Mo, Pb, Sn, W and Zn; that of Bi, Cd, Cu, Ge, Sb and Tl was in the range 10%–15% r.s.d. Unsurprisingly, the most depleted samples at an abundance of 1–10 μg g⁻¹ had larger intra-spot variation and greater uncertainty for each point. The most variable elements were Bi, Ge and Sb (25% r.s.d.), then Ag, Cd, Sn and Zn (10%–15% r.s.d.), with the rest exhibiting less than 10% r.s.d.

Over the duration of the experiment, volatile elements partitioned into the gas phase and were flushed from the furnace by the constant stream of CO₂ gas. For these volatile-loss experiments, the surface of the melt was continuously replenished by the stirring mechanism and diffusion of the element in the melt can be neglected as a kinetic factor.

![Figure 2](image-url) Concentrations of selected elements in product silicate glasses. Concentrations are normalized to starting concentrations, for a time series performed at 1,300 °C and an oxygen fugacity of 10⁻⁷ atm. This oxygen fugacity is about 0.3 logarithmic units below the Ni–NiO buffer. The order of volatility is Cd > Ag > Cu > In > Zn, in marked contrast to the anticipated relative volatilities from the condensation temperatures of Fig. 1. Error bars, 1 s.d. The open circle indicates the starting point for all elements; curves are arbitrary ‘by eye’ fits.

In Fig. 2 we show a time series of experiments performed at f_O₂ = 10⁻⁷ atm (0.3 logarithmic units below the Ni–NiO buffer). As can be seen, loss is continuous with time and, under these conditions and in contrast to condensation (Fig. 1), In is less volatile than Cu and Ag.

![Figure 3](image-url) Volatility factors as a function of oxygen fugacity. These experiments were performed at 1,300 °C. Volatility factors were calculated from the ratios of initial to final concentrations of the elements after 60-min reaction in the constantly stirred melt. Indicative error bars (left) of ±10% and ±20% are greater than 1 s.d. for virtually all elements and conditions (see text).
To compare volatile loss from the silicate melt for each element, we define a ‘volatility factor’ $F_M$ of trace element $M$ to be the final concentration of the trace element divided by the initial concentration in the starting mixture. Low values correspond to high volatility. To determine the relative volatilities of the elements and their dependence on oxygen fugacity, it was necessary to fix the time during the experiment at which volatility factors were compared. This time must be one at which most elements exhibit some volatility and at which the order of the elements when ranked by volatility is unchanging with time. It must not be so long that some of the elements of interest are no longer detectable by our analytical method. From Fig. 2 it is clear that the correct volatility order is established in 10–30 min and that some elements are almost completely lost after 3 h, even at the relatively oxidizing $\text{log}(f_{O_2})$ value of $-7$. Given these constraints, we opted to compare volatility factors after 60 min. This was simply a convenient time and was not chosen with any particular hypothesis in mind. All of the volatility factors shown in Fig. 3 therefore refer to experiments of 60-min duration.

The volatility factors of trace elements are plotted against oxygen fugacity in Fig. 3. There is a clear increase in volatility with decreasing oxygen fugacity, indicating that the gas species are more reduced than the oxide species in the melt.

In young solar systems, the nebular H$_2$-rich gas is believed to disperse after about 3 Myr (ref. 26), meaning that, thereafter, the conditions of melting induced by radioactive decay and impacts are set by the solid silicate and metal components equilibrated within the planetary or protoplanetary body. In the case of Earth, Mars and Vesta, the oxygen fugacity imposed by core–melt equilibrium would be in the range 1–3 logarithmic units below Fe–FeO equilibrium$^{14,27}$. This means that at 1,300°C oxygen fugacities of $10^{-11}$–$10^{-13}$ atm would be appropriate for estimating volatilities from molten or partially molten silicate bodies undergoing core formation. Under these conditions, as shown in Fig. 3, In is less volatile than Cu, Zn, Pb and Ag, all of which have higher condensation temperatures (Fig. 1). The principal reason for this result is that solar gases have high concentrations of H$_2$S and H$_2$O, and In has stable gaseous S and OH species (InS, In$_2$S and InOH), which stabilize it in the gas phase. These gas species are absent from our experiments. Their presence in a solar gas nevertheless provides a clue to the origin of the In ‘anomaly’. This anomaly is readily explained if the moderately volatile element contents of the silicate Earth were established by melt–vapor reactions during melting after the disappearance of the nebular gas. Such reactions might reasonably have been established on small precursor bodies for which gravitational escape would have been possible or conceivably during the Moon-forming impact when instabilities in the silicate vapour may have induced substantial loss of the Earth–Moon atmosphere$^{17}$.

In Fig. 4 we plot the silicate Earth abundances of the elements that we have studied against volatility factors under conditions of 1,300°C and $\text{log}(f_{O_2}) = -13$ and $-11$. As can be seen, the pattern of depletion agrees closely with the volatility factors that we measured under conditions appropriate for core formation on precursor bodies and Earth. In, Cu and Zn all have similar volatilities, consistent with their similar relative abundances in the silicate Earth, whereas Sn is more volatile and Cd, Ag and Ge much more volatile than Zn, also consistent with their relative abundances. The plateau in abundance for low volatility factors in Fig. 4 are at abundances close to 1%. This value implies that low concentrations have been augmented by a chondritic component believed to have delivered $2\% \pm 1\%$ of Earth’s C, H and some noble gases$^{28}$ and/or the ‘late veneer’, which delivered approximately 0.5% of Earth’s highly siderophile elements after core formation ceased$^{29}$.

In conclusion, we have shown that the pattern of volatile element abundance in the silicate Earth (Fig. 4) is much more consistent with measured volatilities from silicate melt at low oxygen fugacities than it is with volatilities (condensation temperatures) in a solar gas (Fig. 1). The data strongly suggest that the pattern of volatile element depletion was established by melt–vapour reaction (evaporation and re-condensation) in the absence of the reducing nebular gas. We envisage these processes taking place on small molten precursor bodies where gravitational escape of volatiles is likely, or possibly in the Earth–Moon system after the giant impact.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 8 February; accepted 4 July 2017.

1. Palme, H. & O’Neill, H. in Treatise on Geochemistry Vol. 3, Ch. 1, 1–39 (Elsevier, 2014).
2. O’Neill, H. S. The origin of the Moon and the early history of the Earth—a chemical model, Part 2: the Earth, Geochim. Cosmochim. Acta 55, 1159–1172 (1991).
3. Schönbeihr, M., Carlson, R. W., Horan, M. F., Mock, T. D. & Hauri, E. H. Heterogeneous accretion and the moderately volatile element budget of Earth. Science 328, 894–897 (2010).
4. Wang, Z. C., Laurencz, V., Pettitgard, S. & Becker, H. Earth’s moderately volatile element composition may not be chondritic: evidence from In, Cd and Zn. Earth Planet. Sci. Lett. 435, 136–146 (2016).
5. Witt-Eickschen, G., Palme, H., O’Neill, H. S. C. & Allen, C. M. The geochemistry of the volatile trace elements Ag, Cd, Ga, In and Sn in the Earth’s mantle: new evidence from in situ analyses of mantle xenoliths. Geochim. Cosmochim. Acta 73, 1755–1778 (2009).
6. Canup, R. M. & Asphaug, E. Origin of the Moon in a giant impact near the end of the Earth’s formation. Nature 412, 708–712 (2001).
7. Wang, K. & Jacobsen, S. B. Potassium isotopic evidence for a high-energy giant impact origin of the Moon. Nature 538, 487–490 (2016).

8. Paniello, R. C., Day, J. M. D. & Moynier, F. Zinc isotopic evidence for the origin of the Moon. Nature **490**, 376–379 (2012).
9. Kleine, T. et al. Hf-W chronology of the accretion and early evolution of asteroids and terrestrial planets. Geochim. Cosmochim. Acta **73**, 5150–5188 (2009).
10. Moynier, F. et al. Planetary-scale strontium isotopic heterogeneity and the age of volatile depletion of early Solar System materials. Astrophys. J. **758**, 45 (2012).
11. Roszkar, J. et al. Prolonged magmatism on 4 Vesta inferred from Hf-W analyses of eucrite zircon. Earth Planet. Sci. Lett. **452**, 216–226 (2016).
12. Cuk, M., Hamilton, D. P., Lock, S. J. & Stewart, S. T. Tidal evolution of the Moon from a high-obliquity, high-angular-momentum Earth. Nature **539**, 402–406 (2016).
13. Li, J. & Agee, C. B. Geochemistry of mantle–core differentiation at high pressure. Nature **381**, 686–689 (1996).
14. Wade, J. & Wood, B. J. Core formation and the oxidation state of the Earth. Earth Planet. Sci. Lett. **236**, 78–95 (2005).
15. Rubie, D. C. et al. Accretion and differentiation of the terrestrial planets with implications for the compositions of early-formed Solar System bodies and accretion of water. Icarus **248**, 89–108 (2015).
16. Anup, R. M. Simulations of a late lunar-forming impact. Icarus **241**, 433–456 (2004).
17. Genda, H. & Abe, Y. Modification of a proto-lunar disk by hydrodynamic escape of silicate vapor. Earth Planets Space **55**, 53–57 (2003).
18. Tucker, J. M. & Mukhopadhyay, S. Evidence for multiple magma ocean outgassing and atmospheric loss episodes from mantle noble gases. Earth Planet. Sci. Lett. **393**, 254–265 (2014).
19. Kato, C., Moynier, F., Valdes, M. C., Dhaliwal, J. K. & Day, J. M. D. Extensive volatile loss during formation and differentiation of the Moon. Nat. Commun. **6**, 7617 (2015).
20. Lodders, K. Solar System abundances and condensation temperatures of the elements. Astrophys. J. **591**, 1220–1247 (2003).
21. Wasson, J. T. & Kallemeyn, G. W. Compositions of chondrites. Phil. Trans. R. Soc. Lond. A **325**, 535–544 (1988).
22. Wood, B. J., Kiseeva, E. S. & Mirolo, F. J. Accretion and core formation: the effects of sulfur on metal–silicate partition coefficients. Geochem. Cosmochim. Acta **145**, 248–267 (2014).

Acknowledgements This research was supported by grants from the European Research Council (267764) and the Science and Technology Facilities Council (UK) to B.J.W. and a Studentship to C.A.N. from the STFC. We thank D. Dingwell and his group in Munich for advice on furnace design and G. Fitton (Edinburgh) for donating the basalt.

Author Contributions C.A.N. constructed the furnace, performed the experiments and analyses, and contributed to writing the manuscript. B.J.W. conceived the project, provided guidance and wrote a substantial part of the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to B.J.W. (bernie.wood@earth.ox.ac.uk).

Reviewer Information Nature thanks S. Jacobsen, F. Moynier and E. Young for their contribution to the peer review of this work.

23. McDonough, W. F. & Sun, S.-s. The composition of the Earth. Chem. Geol. **120**, 223–253 (1995).
24. Mills, N. M., Agee, C. B. & Draper, D. S. Metal–silicate partitioning of cesium: implications for core formation. Geochem. Cosmochim. Acta **71**, 4066–4081 (2007).
25. Wood, B. J., Bryndzia, L. T. & Johnson, K. E. Mantle oxidation state and its relationship to tectonic environment and fluid speciation. Science **248**, 337–345 (1990).
26. Evans, N. J. II et al. The Spitzer c2d legacy results: star-formation rates and efficiencies; evolution and lifetimes. Astrophys. J. Suppl. Ser. **181**, 321–350 (2009).
27. Righter, K. & Drake, M. J. Core formation in Earth’s Moon, Mars, and Vesta. Icarus **124**, 513–529 (1996).
28. Marty, B. The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. Earth Planet. Sci. Lett. **313–314**, 56–66 (2012).
29. Wang, Z. C. & Becker, H. Ratios of S, Se and Te in the silicate Earth require a volatile-rich late veneer. Nature **499**, 328–331 (2013).
METHODS

To directly measure the loss of volatile elements to the vapour phase, we constructed a 1-atm gas mixing furnace with stirring apparatus. This device is capable of stirring a 4.5-cm³ crucible of silicate melt at temperatures up to 1,700 °C. In situ stirring mechanisms have previously been integrated into gas-mixing furnaces, but our design features an entirely gas-tight assembly and a rapid quenching mechanism. The furnace tube is made from high-purity alumina with heating elements of molybdenum disilicide. The crucible and stirrer mechanism are made of high-purity nickel. The purity of the nickel was verified by LA-ICP-MS (see Methods section ‘Analysis’) to contain <3 μg g⁻¹ of the trace elements of interest, except for Cu, which was slightly elevated at 30 μg g⁻¹ but still well below the concentration in the sample. Experiments were quenched in a water bath upon conclusion.

The starting material was made from natural basalt dredged from Reykjanes Ridge, Iceland, crushed in a Fritsch steel-jaw rock crusher before being ground to a fine grey powder using a Tama agate disk mill. To ensure a sufficient supply of material, approximately 500 g of material was crushed. A trace element mixture was formulated to target final compositions of 300–500 μg g⁻¹ per element, weighed out from reagent-grade oxide powders. The trace element mixture was ground with a quarter of the powdered basalt in an agate mortar. The remainder of the basalt was added in three stages and ground together with the initial mixtures in a large agate mortar. In total, 60 g of the starting material was prepared and stored in a desiccator to maintain dryness.

To determine the trace element composition of the starting mixture, a portion of sample was melted and quenched to a glass in a high-pressure piston cylinder experiment. This experiment was run at 1.5 GPa and 1,500 °C in a graphite capsule for 5 min. The product was mounted in acrylic, ground and polished with diamond paste before analysis by EDS and LA-ICP-MS (see below for analytical method). The composition of the starting mixture is shown in Extended Data Tables 1 and 2.

Volatile-loss experiments were performed at 1,300 °C and a range of log(fo₂) values from −7 to −13. The oxygen fugacity of the experiments was controlled using a constant CO/CO₂ gas mixture, apportioned according to the tables in ref. 31. We verified the oxygen fugacity before and after each experiment using a solid zirconia potentiometric oxygen sensor.

For each experiment, 3 g of material was weighed out, pressed into a 12-mm-diameter pellet with a 10-t press and placed inside the crucible. The crucible is keyed into the top of an alumina pedestal, which is inserted into the hot furnace from below. A second key between the pedestal and the base of the furnace ensures that the crucible resists the turning moment from the stirrer. The assembly takes 1–2 min to come to temperature, with the sample melting at around 1,250 °C. The stirrer was inserted from above, penetrating the molten sample by approximately 8 mm, and the furnace sealed. The stirrer was driven with a d.c. motor via a pulse-width modulated motor controller. At 20% output power, the stirrer rotates constantly at 30 r.p.m. All experiments used the same stirring rate.

At the end of the experiment, the stirrer was stopped and a trapdoor in the bottom of the furnace opened, allowing the pedestal and assembly to fall freely into a water bath.

All of the experiments presented as a mass of homogenous black glass containing no observable gas bubbles. Most samples filled at least half of the 4.5-cm³ crucible, with a small amount of material fracturing and breaking free into the water bath. Analysis of any loose shards showed the same composition as the water bath. All data supporting the findings of this study are available within the paper and its Extended Data. Source Data for Figs 1–4 are available in the online version of the paper.
Extended Data Table 1 | Major element compositions (in wt %) of starting material (EBT1) and product glasses from experiments F006 to F019

| Experiment | Mix | Duration (min) | Temperature (°C) | log(fO2) | N | MgO (c) | CaO (c) | Na2O (c) | K2O (c) | NiO (c) | Total (c) | Total (c) |
|------------|-----|----------------|------------------|----------|---|--------|--------|--------|-----|-------|---------|---------|
| Starting   | EBT1| 0              | N/A              | N/A      | 5 | 8.90   | 0.05   | 12.28  | 0.04 | 1.96   | 0.06    | 0.07   | 0.01    | 0       | 0       | 99.8    | 0.5     |
| F006       | EBT1| 10             | 1300             | -7       | 10| 8.66   | 0.02   | 12.27  | 0.03 | 1.83   | 0.02    | 0.13   | 0.01    | 0.58    | 0.02    | 100.0   | 0.5     |
| F007       | EBT1| 30             | 1300             | -7       | 10| 8.69   | 0.03   | 12.19  | 0.03 | 1.88   | 0.02    | 0.12   | 0.01    | 0.88    | 0.02    | 100.0   | 0.3     |
| F008       | EBT1| 60             | 1300             | -7       | 11| 8.51   | 0.15   | 12.46  | 0.10 | 1.70   | 0.21    | 0.11   | 0.01    | 1.05    | 0.03    | 100.0   | 0.6     |
| F010       | EBT1| 180            | 1300             | -7       | 10| 8.40   | 0.04   | 12.34  | 0.04 | 1.71   | 0.03    | 0.12   | 0.01    | 2.56    | 0.09    | 100.0   | 0.3     |
| F012       | EBT1| 5              | 1300             | -9       | 10| 8.76   | 0.04   | 12.31  | 0.05 | 1.90   | 0.02    | 0.13   | 0.02    | 2.19    | 0.09    | 100.0   | 1.2     |
| F013       | EBT1| 30             | 1300             | -9       | 10| 8.56   | 0.12   | 12.32  | 0.04 | 1.74   | 0.14    | 0.14   | 0.01    | 0.90    | 0.02    | 100.0   | 0.5     |
| F014       | EBT1| 60             | 1300             | -9       | 10| 8.75   | 0.03   | 12.28  | 0.05 | 1.88   | 0.03    | 0.10   | 0.02    | 0.84    | 0.03    | 100.0   | 0.5     |
| F015       | EBT1| 30             | 1300             | -11      | 10| 8.72   | 0.14   | 12.16  | 0.05 | 1.93   | 0.03    | 0.10   | 0.02    | 0.68    | 0.26    | 100.0   | 1.2     |
| F018       | EBT1| 60             | 1300             | -11      | 10| 8.57   | 0.07   | 12.19  | 0.05 | 1.74   | 0.06    | 0.10   | 0.02    | 1.56    | 0.03    | 100.0   | 0.6     |
| F019       | EBT1| 60             | 1300             | -13      | 10| 8.73   | 0.05   | 12.31  | 0.03 | 1.95   | 0.04    | 0.08   | 0.02    | 0.69    | 0.11    | 100.0   | 0.8     |

1σ refers to 1 standard deviation and N to the number of analyses. EBT1 and F006 to F019 are experiment identifiers.
| Experiment | N  | Ag (c) | Bi (c) | Cd (c) | Cr (c) | Cu (c) | Ga (c) | Ge (c) | In (c) |
|------------|----|--------|--------|--------|--------|--------|--------|--------|--------|
| Starting   | 41 | 328.6  | 10.1   | 203.3  | 17.1   | 355.0  | 43.4   | 600.6  | 88.4   |
| F008       | 134| 223.9  | 54.9   | 49.7   | 21.3   | 91.1   | 41.7   | 542.8  | 60.3   |
| F010       | 38 | 13.7   | 1.2    | 2.3    | 0.3    | 0.8    | 0.1    | 711.7  | 28.0   |
| F012       | 31 | 295.7  | 9.2    | 47.9   | 4.3    | 90.0   | 3.9    | 443.0  | 14.1   |
| F013       | 31 | 247.3  | 1.7    | 71.5   | 1.6    | 133.9  | 11.5   | 574.6  | 22.6   |
| F014       | 31 | 64.9   | 5.0    | 34.3   | 15.4   | 25.0   | 4.0    | 712.6  | 20.0   |
| F015       | 30 | 163.1  | 60.9   | 72.7   | 30.5   | 96.0   | 25.7   | 590.6  | 48.9   |
| F018       | 31 | 41.4   | 2.1    | 14.9   | 0.8    | 6.6    | 0.6    | 595.3  | 18.3   |
| F019       | 63 | 7.1    | 6.2    | 1.7    | 1.4    | 6.6    | 2.9    | 700.6  | 120.1  |

| Experiment | N  | Mo (c) | Pb (c) | Sb (c) | Sn (c) | Tl (c) | V (c)  | W (c)  | Zn (c) |
|------------|----|--------|--------|--------|--------|--------|--------|--------|--------|
| Starting   | 41 | 394.5  | 40.3   | 45.0   | 20.1   | 482.6  | 17.3   | 333.7  | 6.7    |
| F008       | 134| 483.9  | 51.5   | 443.9  | 21.5   | 224.2  | 85.9   | 164.2  | 25.2   |
| F010       | 38 | 492.3  | 25.0   | 463.4  | 33.2   | 218.4  | 39.6   | 155.7  | 9.8    |
| F012       | 31 | 579.6  | 26.4   | 153.5  | 18.4   | 11.7   | 6.8    | 57.8   | 6.5    |
| F013       | 31 | 477.1  | 13.3   | 485.0  | 23.4   | 332.7  | 30.2   | 215.7  | 10.5   |
| F014       | 31 | 402.4  | 14.0   | 297.9  | 28.4   | 101.0  | 34.1   | 64.3   | 5.5    |
| F015       | 30 | 441.0  | 113.2  | 426.4  | 54.8   | 206.3  | 94.5   | 112.9  | 11.1   |
| F018       | 31 | 442.9  | 12.7   | 164.5  | 6.8    | 5.7    | 0.4    | 66.6   | 2.8    |
| F019       | 63 | 245.2  | 134.8  | 52.7   | 44.9   | 1.1    | 0.5    | 12.8   | 11.5   |