

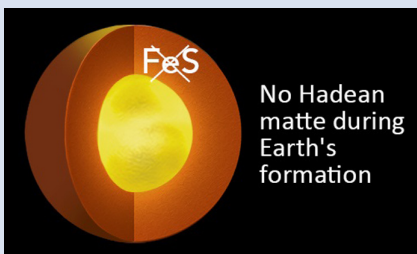
Earth's deep magma ocean never reached sulfide saturation

I. Blanchard^{1*}, J. Siebert², E. Kubik³, A. Minchenkova³, L. Calvo², N. Wehr²



<https://doi.org/10.7185/geochemlet.2506>

Abstract



No Hadean
matte during
Earth's
formation

The chondritic abundances of highly siderophile elements in the Earth's mantle have been proposed to result from the combination of pervasive exsolution and segregation of sulfide from the magma ocean, along with late accretion. Therefore, evaluating the sulfur storage capacity (*i.e.* sulfur solubility) of the deep magma ocean is key to understanding the late stages of Earth's formation. Here, we have investigated the effects of high pressure and high temperature on the solubility of sulfur in the deep primordial magma ocean by melting and equilibrating a pyrolytic glass with pure FeS in a laser-heated diamond anvil cell. Chemical analysis of the run products show that significant amounts of sulfur can be stored deep in the magma ocean (~1 wt. %). We developed a thermodynamic parameterisation predicting the solubility of sulfur at sulfide saturation (SCSS) depending on pressure, temperature and silicate composition. We show that SCSS always exceeds the amount of sulfur present in the mantle due to metal-silicate partitioning, consistent with previous work. Consequently, it appears that Earth's magma ocean likely never reached sulfur saturation, thereby preventing the segregation of a sulfide-rich melt, also referred as the "Hadean matte".

Received 27 September 2024 | Accepted 17 January 2025 | Published 20 February 2025

Introduction

The formation of Earth's main reservoirs, the metallic core and the surrounding silicate mantle, occurred early in Earth's history. During the first few tens of million years, the Earth was covered by a deep magma ocean with pressure and temperature conditions exceeding 40 GPa and 3000 K respectively (Li and Agee, 1996; Siebert *et al.*, 2012). These conditions led to the separation of siderophile (iron-loving) from lithophile elements (silicate-loving) to form the core and the mantle, respectively. Understanding how the Bulk Silicate Earth (BSE) composition was established is of primary importance, and is directly linked to our comprehension of the Earth's differentiation as well as the accretion process and the nature of Earth's building blocks.

Sulfur is a key element for understanding Earth's formation. It has been proposed that the mantle's signature in Highly Siderophile Elements (HSEs) could be explained by HSE segregation into a sulfide matte exsolved from the magma ocean towards the end of accretion (O'Neill, 1991; Rubie *et al.*, 2016). For this hypothesis to hold, the magma ocean must have reached sulfur saturation, enabling the segregation of a sulfide matte. The solubility of sulfur at sulfide saturation (SCSS) in molten silicate has been the subject of numerous studies, focusing mainly on the effects of the silicate composition on SCSS (Liu *et al.*, 2007; Fortin *et al.*, 2015; Namur *et al.*, 2016). Recently, the effects of pressure (P) and temperature (T) have been studied (Laurenz *et al.*, 2016; Blanchard *et al.*, 2021; Steenstra *et al.*, 2022), but either at limited P-T conditions (Laurenz *et al.*, 2016; Blanchard *et al.*, 2021) or using basalt as starting composition,

which might not be relevant in the context of the Earth's formation (Steenstra *et al.*, 2022).

In this work, we have used a laser-heated diamond anvil cell (LH-DAC) to replicate the high P-T conditions of Earth's differentiation in the laboratory. We have equilibrated a pyrolytic melt with pure FeS and showed that sulfur solubility in silicate melt remains high under these conditions. Additionally, we have also used a basaltic composition to compare our results with those reported by Steenstra *et al.*, (2022). Our experimental results, along with data from the literature, were used to parameterise a model predicting the evolution of sulfur saturation in a deep magma ocean. We show that SCSS remains significantly high throughout the accretion process, with mean values around 3000 ppm.

In contrast, sulfur content in the mantle produced from metal-silicate partitioning is always much lower (<600 ppm; Suer *et al.*, 2017). Hence, it seems unlikely that sulfur saturation was achieved during Earth's differentiation. This challenges the Hadean Matte hypothesis and suggests that alternative mechanisms should be considered to explain the budget of HSEs of the mantle.

Methods

We synthesised five samples between 53 and 72 GPa and 3800 to 4050 K using a laser-heated diamond anvil cell. Synthetic pyrolytic and basaltic glasses were melted and equilibrated with pure FeS. Experimental runs were subsequently recovered using Focused Ion Beam (FIB) and analysed using scanning electron

1. Institut de Minéralogie de Physique de la Matière et de Cosmochimie, Sorbonne Université, CNRS, Paris, France
2. Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, Paris, France
3. Bayerisches Geoinstitut, Universität Bayreuth, Bayreuth, Germany
* Corresponding author (email: ingrid.blanchard@sorbonne-universite.fr)

Table 1 Summary of experimental conditions.

Starting Material	Experiment	P (GPa)	T (K)	ΔIW	SCSS (wt. %)
Pyrolite + FeS	SCSS1	64 ± 5	4000 ± 300	-1.31	1.02 ± 0.27
Pyrolite + FeS	SCSS2	61 ± 5	4000 ± 300	-1.27	1.12 ± 0.36
Pyrolite + FeS	SCSS3	72 ± 5	4050 ± 300	-1.64	1.15 ± 0.15
Basalt + FeS	SCSS4	53 ± 5	3800 ± 300	-0.92	0.83 ± 0.31
Pyrolite + FeS	SCSS5	53 ± 5	3800 ± 300	-1.42	0.93 ± 0.25

microscopy energy dispersive X-rays. More details of the experimental and analytical procedures are given in the [Supplementary Information](#). [Table 1](#) summarises experimental conditions while [Table S-1](#) gives the full chemical analysis of each run.

Experimental Results

Each run consisted of a spherical sulfide blob surrounded by a quench silicate melt (see [Figs. 1, S-1](#)). The silicate melt of experiments performed using pyrolite as starting glass (SCSS1, 2, 3 and 5) or basaltic glass (SCSS4) fall in the range of terrestrial peridotites or basalts respectively. The amount of sulfur in the silicate melt from SCSS4 is slightly lower than in the other experiments, although the experimental runs look similar (see [Fig. 1](#)). The sulfide phase contains between 25 and 29 wt. % sulfur, along with roughly 6 to 10 wt. % oxygen, and 0.58 to 1.17 wt. % Si. This oxygen concentration is similar to that observed in previous metal-silicate partitioning diamond anvil cell experiments containing no sulfur. The concentration of silicon in sulfide is similar to observations from [Steenstra et al. \(2022\)](#), but much lower than in experiments containing no sulfide (e.g., [Blanchard et al., 2017](#); [Fischer et al., 2020](#); [Huang et al., 2021](#)). Traces of Mg and Al were also detected in the sulfide (see [Table S-1](#)). Overall, the compositions of the sulfide phases are similar, regardless of whether the starting material was pyrolytic or basaltic glass. We calculated the redox conditions of our experiments relative to the iron-wüstite buffer (IW; see [Supplementary Information](#)), and derived values between -0.9 to -1.41, consistent with previous diamond anvil cell experiments on other systems (e.g., [Siebert et al., 2012](#); [Blanchard et al., 2022](#)). No chemical or textural differences were observed between samples for which the temperature was maintained for either 10 or 120

seconds, suggesting that equilibrium is likely achieved in a very short time.

Thermodynamics

The solubility of sulfur in a magma ocean is intrinsically linked to the evolution of SCSS with pressure and temperature. To date, no study has focused on the effects of P and T in a system relevant for Earth's formation, specifically a pyrolytic magma ocean. Apart from the effects of pressure and temperature, it is well documented that the composition of the silicate itself has an impact on SCSS ([Liu et al., 2007](#); [Fortin et al., 2015](#); [Namur et al., 2016](#)). Among the most important elements influencing SCSS, experimental works have shown that iron (FeO) and silicon (SiO₂) play major roles ([O'Neill and Mavrogenes, 2002](#); [Wykes et al., 2015](#); [Smythe et al., 2017](#); [Blanchard et al., 2021](#)). Recent use of machine learning has confirmed that Si and Fe in silicate are indeed among the most important parameters influencing SCSS ([ZhangZhou et al., 2024](#)). While other components might also play a role, we chose not to overload our regression with parameters that are potentially not well constrained. Hence, we modelled SCSS following:

$$\ln S_{SCSS} = a + \frac{b}{T} + c \frac{P}{T} + \frac{d}{T} \times X_{FeO} + \frac{e}{T} \times X_{SiO_2} \quad \text{Eq. 1}$$

with X_{FeO} and X_{SiO_2} as the mole fraction of FeO and SiO₂ respectively. We combined more than 200 data from the literature that cover a wide range of pressure (1 bar to 72 GPa), temperature (1573 to 4300 K) and silicate composition. Details of the selection is given in the [Supplementary Information](#), and the final data set used for our parameterisation is provided in the [Supplementary Information](#).

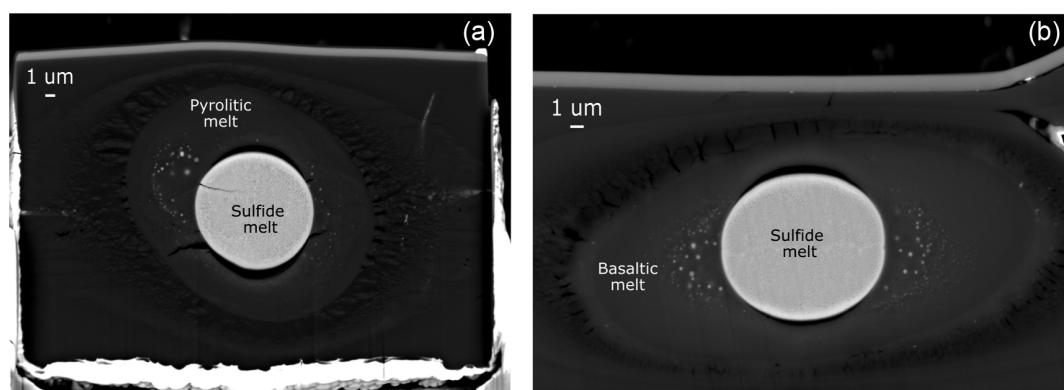


Figure 1 Backscattered images of two typical recovered runs. **(a)** Sample SCSS5 synthesised using pyrolytic glass as starting material, whereas **(b)** was synthesised with basaltic glass (SCSS4). Both runs were equilibrated at 53 GPa and 3800 K.

We obtain the following equation, with uncertainties in brackets:

$$\ln S_{SCSS} = 11.3 (0.2) - \frac{4562 (599)}{T} - 70(12) \frac{P}{T} + \frac{9740 (783)}{T} \times X_{FeO} - \frac{5211 (570)}{T} \times X_{SiO_2} \quad \text{Eq. 2}$$

Equation 2 shows that SCSS decreases with increasing pressure and X_{SiO_2} and increases with increasing T and X_{FeO} . The effects of pressure and temperature that we derive from this study are coherent with previous ones from [Laurenz *et al.* \(2016\)](#) and [Steenstra *et al.* \(2022\)](#) who did not explicitly propose an effect of silicate composition. Nevertheless, it is not possible to directly compare our coefficients with theirs, since the regression used is not the same.

Other models that include compositional effects previously predicted stronger effects of pressure (−190 and −265.8 for [Blanchard *et al.*, 2021](#) model 2 and [Smythe *et al.*, 2017](#) respectively), and either a stronger temperature term (−14683 in [Smythe *et al.*, 2017](#)) or even positive ones (18159 in the model 2 from [Blanchard *et al.*, 2021](#)).

In [Figure S-3](#), we compare the SCSS values measured in the experimental runs with those calculated from [Equation 2](#). This figure highlights the excellent agreement between our model and experimental data, despite the wide P–T compositional range studied here.

We also tested the effect of including only high P–T data to derive the evolution of SCSS. This is discussed in the [Supplementary Information](#).

Discussion

The solubility of sulfur at sulfide saturation (SCSS) predicted from this work ([Eq. 2](#)) can be used to better understand the behaviour of sulfur during Earth's formation and differentiation.

The behaviour of sulfur in the Earth's magma ocean is of great importance, because many elements are chalcophile (sulfur-loving), hence their fate during episodes of melting is directly linked to that of sulfur. We have calculated SCSS as a function of pressure and temperature in a different context. First, we present in [Figure 2a](#) and [2b](#) the evolution of SCSS along an adiabatic temperature profile for a magma ocean with a basal pressure of 80 GPa and 20 GPa ([Miller *et al.*, 1991](#)) respectively. For models that have a composition dependency, we used the composition of the PUM (Primitive Upper Mantle) from [Palme and O'Neill \(2014\)](#). From this figure, we observe that models of SCSS built from relatively low P–T experiments have a much more dramatic evolution, with higher starting SCSS values evolving toward much lower ones at high pressure. This is especially true for the 80 GPa adiabat, where for instance the [Laurenz *et al.* \(2016\)](#) model starts at values way higher than 1.5 wt. % of sulfur of SCSS to finish at 35 ppm at 80 GPa. Conversely, models built with both low and high P–T experiments (this study; [Steenstra *et al.*, 2022](#)) show a decrease (especially for 80 GPa adiabat), but it is much less intense. In our case, we predict an evolution of SCSS from about 11750 ppm at 0 GPa to about 4060 ppm at 80 GPa adiabat. For the 20 GPa adiabat, our study predicts almost a flat evolution (from about 6400 to about 5200 ppm), coherent with predictions from [Steenstra *et al.* \(2022\)](#). Again, models obtained from large volume press experiments predict a much stronger decrease of SCSS with pressure ([Laurenz *et al.*, 2016](#); [Smythe *et al.*, 2017](#); [Blanchard *et al.*, 2021](#)), with almost an order of magnitude difference for [Laurenz *et al.* \(2016\)](#). All in all, we predict for both low and high pressure adiabat high values of SCSS (>2500 ppm), in contrast to previous models obtained at lower P–T conditions.

It has been suggested that at the end of accretion, an episode of Hadean Matte occurred, during which ponds of FeS segregated from the magma ocean, due to the saturation of the magma ocean in sulfur ([O'Neill, 1991](#)). Using our formalism, we can now assess whether the terrestrial magma ocean ever reached sulfur saturation over the course of its existence.

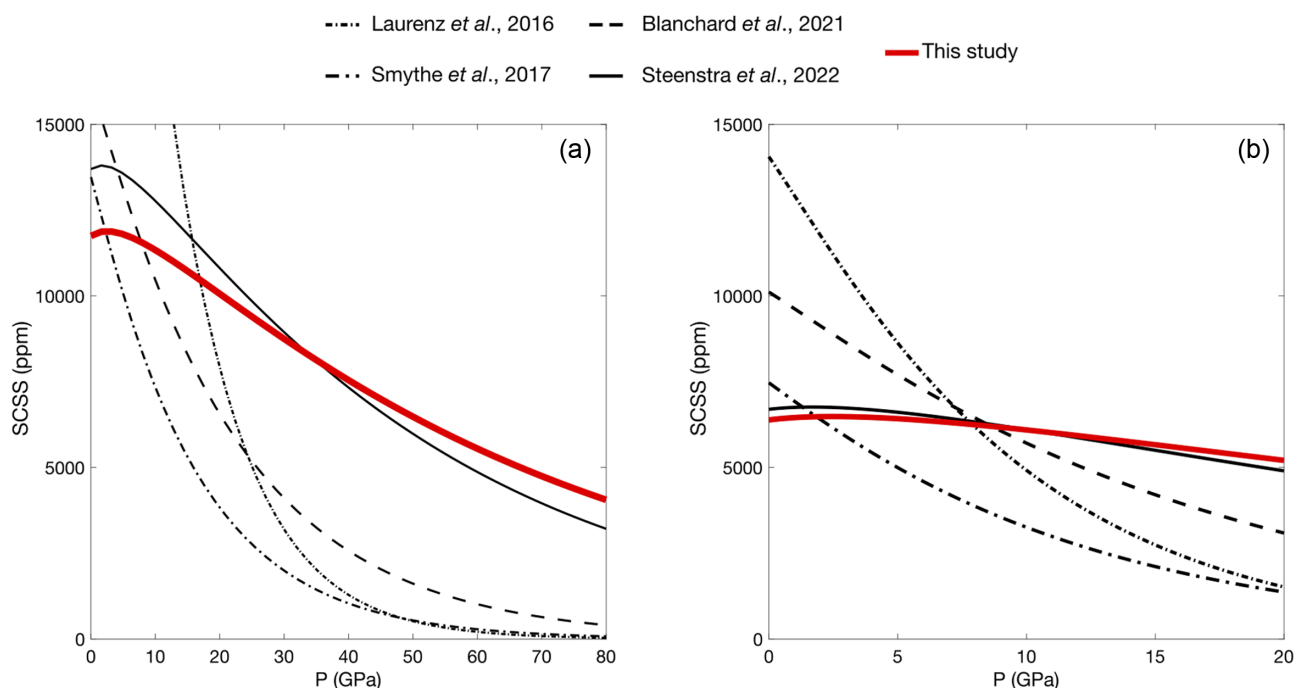


Figure 2 Evolution of SCSS as a function of pressure for 80 GPa adiabat (a) and 20 GPa adiabat (b). For models that are composition dependent, we used Primitive Upper Mantle composition by ([Palme and O'Neill, 2014](#)).

The parameterisation derived in Equation 2 was used in a core formation model to assess the evolution of SCSS during the magma ocean phase on Earth. The temperature of the magma ocean was fixed as the arithmetic mean of the mantle liquidus proposed by Fiquet *et al.* (2010) and Andrault *et al.* (2011), and the depth of the magma ocean was fixed at 40 % of the mantle's depth at each stage. The core formation model was discretised into 100 steps, each representing the accretion of 1 % of Earth's mass. We have also tested the effect of changing fO_2 over the course of accretion by changing the amount of FeO, since the redox path of Earth's formation is a matter of debate (*e.g.*, Siebert *et al.*, 2013; Rubie *et al.*, 2016). Three different scenarios were tested: one where the fO_2 is increasing over the course of accretion from IW-4.5 to IW-2.3, one where fO_2 decreases from IW-1.3 to IW-2.3, and one constant fO_2 of IW-2.3. Figure 3 presents the evolution of SCSS with the accreted fraction of the Earth, following Equation 2, and changing fO_2 conditions as detailed previously. The composition of the silicate is fixed to the composition of the Primitive Upper Mantle proposed by Palme and O'Neill (2014) in the case of the constant fO_2 , and the amount of FeO is varied for the two other redox paths. Given the importance of FeO in the evolution of SCSS (see Eq. 2), we additionally varied its abundance on the mantle on the two other redox paths through the course of accretion.

Rubie *et al.* (2016) were first to define empirically an effective pressure that describes SCSS and equilibration pressure for the entire magma ocean ($P_{eq-s} = k_S \times P_{CMB}$), provided that the corresponding temperature is between the liquidus and solidus of peridotite. It was shown by Steenstra *et al.* (2022) that k_S can range from 0.3 to 0.9 without impacting the evolution of SCSS, so we did not try to vary this value. Here, we used a constant value of 0.4, as suggested by Rubie *et al.* (2016). To assess whether the magma ocean ever reached SCSS, we compared the estimation of sulfur concentration at saturation with the residual amount of sulfur in the magma ocean due to metal-silicate partitioning during core formation. Figure 3 shows the amount of sulfur in the mantle predicted from metal-silicate partitioning experiments by Suer *et al.* (2017). We tested two homogeneous accretion scenarios: one where the magma ocean fully

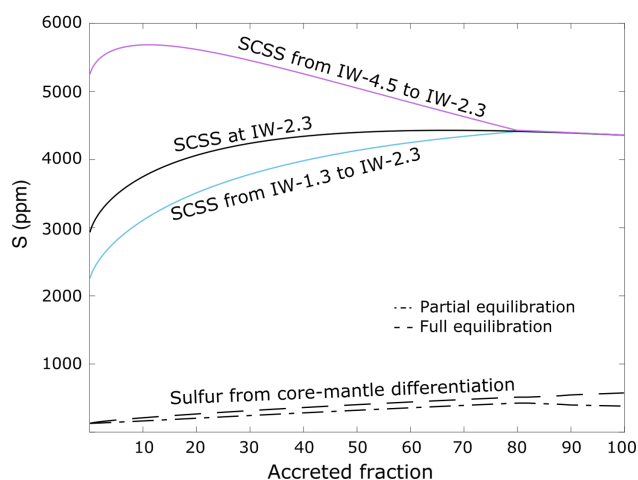


Figure 3 Comparison between the evolution of SCSS over the course of accretion from Equation 2, and the amount of sulfur in the magma ocean linked to core-mantle differentiation for both partial and full metal-silicate equilibration from Suer *et al.* (2017). The evolution of SCSS over the course of accretion is shown at constant fO_2 (black solid curve), in an oxidised scenario (purple curve), and in a reduced scenario (blue curve).

equilibrates with the forming core, and another where partial equilibration occurs between the magma ocean and the core (Deguen *et al.*, 2014). In this second scenario, equilibration is complete during the first 80 %, but becomes partial during the later stages of accretion when larger bodies are accreted (Suer *et al.*, 2017).

Regardless of the extent of equilibration, the model suggests that a maximum of about 500 ppm of sulfur can be stored in the magma ocean linked to core-mantle differentiation. This is far below the estimated SCSS, which is shown to be always higher than 2500 ppm, irrespective of the evolution of redox over the course of accretion (see Fig. 3). This is also true using a model derived only from high P-T experiments (see Supplementary Information, and Fig. S-4).

It has been proposed that oxygen can influence the partitioning of sulfur between metal and silicate (*e.g.*, Gendre *et al.*, 2022). We could not include the effect of oxygen on SCSS due to insufficient data. However, extrapolating data from Gendre *et al.* (2022) obtained at relatively low P-T conditions (<12 GPa and <2473 K) to core formation conditions would only strengthen our conclusions, as the presence of oxygen in the metallic phase enhances the siderophilicity of sulfur.

As can be seen in Figure 3, we predict a high SCSS during the whole course of accretion, with values above 2500 ppm, but a low concentration of sulfur predicted from metal-silicate partitioning experiments (<500 ppm). Previous experiments and models proposed by Steenstra *et al.*, (2022) are comparable to our results, although they predict slightly lower values of SCSS at the end of accretion (about 3500 ppm). In addition to a significant increase of the investigated pressure range, the main difference with our results is that we incorporate new high P-T data points with the effects of FeO and SiO_2 present in the silicate on SCSS. These results suggest that saturation of the magma ocean in sulfur was probably never reached over the course of accretion.

These estimations differ significantly from those of Rubie *et al.* (2016), who proposed up to about 7000 ppm of S in the mantle at the end of accretion. The difference stems from major differences in the accretion models. Rubie *et al.* (2016) considered that a large part of planetesimals that built the Earth were undifferentiated (fully oxidised). The evolution of SCSS they proposed is based on relatively low P-T experiments, that are very rich in HSEs (Laurenz *et al.*, 2016). Interactions of HSEs with sulfur are poorly constrained, but given that HSEs are chalcophile, their presence in the metallic phase of the runs could influence sulfur behaviour. Laurenz *et al.* (2016) propose a strong decrease of SCSS with increasing pressure, leading to sulfur saturation in a deep enough magma ocean. Consequently, Rubie *et al.* (2016) proposed that during the course of accretion, the magma ocean experienced at least one episode of sulfide liquid segregation, which stripped HSEs from Earth's mantle. They suggested that a subsequent episode of late accretion is mandatory to reproduce supra-chondritic Pd/Ir and Ru/Ir ratios observed in today's mantle, and remove the excess of HSEs (Becker, 2006; Walker *et al.*, 2015). In light of our new high P-T experiments, we suggest that sulfide saturation was likely never reached during Earth's accretion (see Fig. 3). Hence, the proposition that HSE's mantle signatures can be explained by sulfide segregation early in the Earth's history appears unlikely.

Recent work have proposed that a significant decrease in the metal-silicate partitioning of platinum during core formation might explain abundance of this HSE in today's mantle (Suer *et al.*, 2021), rather than a combined effect of sulfide saturation and a late arrival of this element.

Acknowledgments

We would like to thank Edgar Steenstra, an anonymous reviewer and the editor of this paper, Ambre Luguët, for their constructive and helpful comments. We thank James Badro for laser heating the samples. The LHDAC lab is supported by the LabEx UnivEarthS, ANR-10-LABX-0023 and ANR-18-IDEX-0001. Parts of this work were supported by IGP multidisciplinary programme PARI, and by Paris-IdF region SESAME Grant no. 12015908. We acknowledge Anja Schreiber from GFZ who extracted the FIB lamellae, Stephan Borensztajn from IGP who helped us with SEM analyses. JS acknowledges support from the French National Research Agency (ANR project VolTerre, grant No. ANR-14-CE33-0017-01) and support from the Institut Universitaire de France.

Editor: Ambre Luguët

Additional Information

Supplementary Information accompanies this letter at <https://www.geochemicalperspectivesletters.org/article2506>.



© 2025 The Authors. This work is distributed under the Creative Commons Attribution Non-Commercial No-Derivatives 4.0

License, which permits unrestricted distribution provided the original author and source are credited. The material may not be adapted (remixed, transformed or built upon) or used for commercial purposes without written permission from the author. Additional information is available at <https://www.geochemicalperspectivesletters.org/copyright-and-permissions>.

Cite this letter as: Blanchard, I., Siebert, J., Kubik, E., Minchenkova, A., Calvo, L., Wehr, N. (2025) Earth's deep magma ocean never reached sulfide saturation. *Geochem. Persp. Let.* 34, 6–10. <https://doi.org/10.7185/geochemlet.2506>

References

- ANDRAULT, D., BOLFAN-CASANOVA, N., NIGRO, G.L., BOUHIF, M.A., GARBARINO, G., MEZOUAR, M. (2011) Solidus and liquidus profiles of chondritic mantle: Implication for melting of the Earth across its history. *Earth Planetary Science Letters* 174, 181–191. <https://doi.org/10.1016/j.epsl.2011.02.006>
- BECKER, H., HORAN, M.F., WALKER, R.J., GAO, S., LORAND, J.-P., RUDNICK, R.L. (2006) Highly siderophile element composition of the Earth's primitive upper mantle: Constraints from new data on peridotite massifs and xenoliths. *Geochimica Cosmochimica Acta* 70, 4528–4550. <https://doi.org/10.1016/j.gca.2006.06.004>
- BLANCHARD, I., SIEBERT, J., BORENSZTAJN, S., BADRO, J. (2017) The solubility of heat-producing elements in Earth's core. *Geochemical Perspective Letters* 1–5. <https://doi.org/10.7185/geochemlet.1737>
- BLANCHARD, I., ABEYKON, S., FROST, D.J., RUBIE, D.C. (2021) Sulfur content at sulfide saturation of peridotitic melt at upper mantle conditions. *American Mineralogist* 106, 1835–1843. <https://doi.org/10.2138/am-2021-7649>
- BLANCHARD, I., RUBIE, D.C., JENNINGS, E.S., FRANCHI, I.A., ZHAO, X., PETITGIRARD, S., MIYAJIMA, N., JACOBSON, S.A., MORBIDELLI, A. (2022) The metal–silicate partitioning of carbon during Earth's accretion and its distribution in the early solar system. *Earth Planetary Science Letters* 580, 117374. <https://doi.org/10.1016/j.epsl.2022.117374>
- DEGUEN, R., LANDEAU, M., OLSON, P. (2014) Turbulent metal–silicate mixing, fragmentation, and equilibration in magma oceans. *Earth Planetary Science Letters* 391, 274–287. <https://doi.org/10.1016/j.epsl.2014.02.007>
- FIQUET, G., AUZENDE, A.L., SIEBERT, J., CORGNE, A., BUREAU, H., OZAWA, H., GARBARINO, G. (2010) Melting of peridotite to 140 gigapascals. *Science* 329, 1516–1518. <https://doi.org/10.1126/science.1192448>
- FISCHER, R.A., COTTRELL, E., HAURI, E., LEE, K.K.M., LE VOYER, M. (2020) The carbon content of Earth and its core. *Proceedings National Academy of Sciences U.S.A.* 117, 8743–8749. <https://doi.org/10.1073/pnas.1919930117>
- FORTIN, M., RIDDLE, J., DESJARDINS-LANGLAIS, Y., BAKER, D.R. (2015) The effect of water on the sulfur concentration at sulfide saturation (SCSS) in natural melts. *Geochimica Cosmochimica Acta* 160, 100–116. <https://doi.org/10.1016/j.gca.2015.03.022>
- GENDRE, H., BADRO, J., WEHR, N., BORENSZTAJN, S. (2022) Martian core composition from experimental high-pressure metal–silicate phase equilibria. *Geochemical Perspective Letters* 21, 42–46. <https://doi.org/10.7185/geochemlet.2216>
- HUANG, D., SIEBERT, J., BADRO, J. (2021) High pressure partitioning behavior of Mo and W and late sulfur delivery during Earth's core formation. *Geochimica Cosmochimica Acta* 310, 19–31. <https://doi.org/10.1016/j.gca.2021.06.031>
- LAURENZ, V., RUBIE, D.C., FROST, D.J., VOGEL, A.K. (2016) The importance of sulfur for the behavior of highly-siderophile elements during Earth's differentiation. *Geochimica Cosmochimica Acta* 194, 123–138. <https://doi.org/10.1016/j.gca.2016.08.012>
- LI, J., AGEE, C.B. (1996) Geochemistry of mantle–core differentiation at high pressure. *Nature* 381, 686–689. <https://doi.org/10.1038/381686a0>
- LIU, Y., SAMAHA, N., BAKER, D.R. (2007) Sulfur concentration at sulfide saturation (SCSS) in magmatic silicate melts. *Geochimica Cosmochimica Acta* 71, 1783–1799. <https://doi.org/10.1016/j.gca.2007.01.004>
- MILLER, G.H., STOLPER, E.M., AHRENS, T.J. (1991) The equation of state of a molten komatiite 2. Application to komatiite petrogenesis and the Hadean mantle. *Journal of Geophysical Research* 96, 849–864. <https://doi.org/10.1029/91jb01203>
- NAMUR, O., CHARLIER, B., HOLTZ, F., CARTIER, C., MCCAMMON, C. (2016) Sulfur solubility in reduced mafic silicate melts: Implications for the speciation and distribution of sulfur on Mercury. *Earth Planetary Science Letters* 448, 102–114. <https://doi.org/10.1016/j.epsl.2016.05.024>
- O'NEILL, H.S.C. (1991) The origin of the Moon and the early history of the Earth—A chemical model. Part 2: The Earth. *Geochimica Cosmochimica Acta* 55, 1159–1172. [https://doi.org/10.1016/0016-7037\(91\)90169-6](https://doi.org/10.1016/0016-7037(91)90169-6)
- O'NEILL, H.S.C., MAVROGENES, J.A. (2002) The Sulfide Capacity and the Sulfur Content at Sulfide Saturation of Silicate Melts at 1400°C and 1 bar. *Journal of Petrology* 43, 1049–1087. <https://doi.org/10.1093/ptrology/43.6.1049>
- PALME, H., O'NEILL, H.S.C. (2014) Cosmochemical Estimates of Mantle Composition, in: *Treatise on Geochemistry* 2nd Edition. Elsevier Ltd., pp. 1–39. <https://doi.org/10.1016/B978-0-08-095975-7.00201-1>
- RUBIE, D.C., LAURENZ, V., JACOBSON, S.A., MORBIDELLI, A., PALME, H., VOGEL, A.K., FROST, D.J. (2016) Highly siderophile elements were stripped from Earth's mantle by iron sulfide segregation. *Science* 353, 1141–1144. <https://doi.org/10.1126/science.aaf6919>
- SIEBERT, J., BADRO, J., ANTONANGELI, D., RYERSON, F.J. (2012) Metal–silicate partitioning of Ni and Co in a deep magma ocean. *Earth Planetary Science Letters* 321–322, 189–197. <https://doi.org/10.1016/j.epsl.2012.01.013>
- SIEBERT, J., BADRO, J., ANTONANGELI, D., RYERSON, F.J. (2013) Terrestrial accretion under oxidizing conditions. *Science* 339, 1194–1197. <https://doi.org/10.1126/science.1227923>
- SMYTHE, D.J., WOOD, B.J., KISEEVA, E.S. (2017) The S content of silicate melts at sulfide saturation: New experiments and a model incorporating the effects of sulfide composition. *American Mineralogist* 102, 795–803. <https://doi.org/10.2138/am-2017-5800CCBY>
- STEENSTRA, E.S., LORD, O.T., VITALE, S., BULLOCK, E.S., KLEMME, S., WALTER, M. (2022) Sulfur solubility in a deep magma ocean and implications for the deep sulfur cycle. *Geochemical Perspective Letters* 22, 5–9. <https://doi.org/10.7185/geochemlet.2219>
- SUER, T.A., SIEBERT, J., REMUSAT, L., MENGUY, N., FIQUET, G. (2017) A sulfur-poor terrestrial core inferred from metal–silicate partitioning experiments. *Earth Planetary Science Letters* 469, 84–97. <https://doi.org/10.1016/j.epsl.2017.04.016>
- SUER, T.-A., SIEBERT, J., REMUSAT, L., DAY, J.M.D., BORENSZTAJN, S., DOISNEAU, B., FIQUET, G. (2021) Reconciling metal–silicate partitioning and late accretion in the Earth. *Nature Communications* 12. <https://doi.org/10.1038/s41467-021-23137-5>
- WALKER, R.J., BIRMINGHAM, K., LIU, J., PUCHTEL, I.S., TOUBOUL, M., WORSHAM, E.A. (2015) In search of late-stage planetary building blocks. *Chemical Geology* 411, 125–142. <https://doi.org/10.1016/j.chemgeo.2015.06.028>
- WYKES, J.L., O'NEILL, H.S.C., MAVROGENES, J.A. (2015) The effect of FeO on the sulfur content at sulfide saturation (SCSS) and the selenium content at selenide saturation of silicate melts. *Journal of Petrology* 56, 1407–1424. <https://doi.org/10.1093/ptrology/egv041>
- ZHANGZHOU, J., LI, Y., CHOWDHURY, P., SEN, S., GHOSH, U., XU, Z., LIU, J., WANG, Z., DAY, J.M.D. (2024) Predicting sulfide precipitation in magma oceans on Earth, Mars and the Moon using machine learning. *Geochimica Cosmochimica Acta* 366, 237–249. <https://doi.org/10.1016/j.gca.2023.11.029>