Fate of carbon during the formation of Earth's core

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Scientific background

- The element carbon can be both **volatile** and **siderophile**. It is **ubiquitous** in today's Earth, being present in its atmosphere, its surface, its mantle and presumably its core.

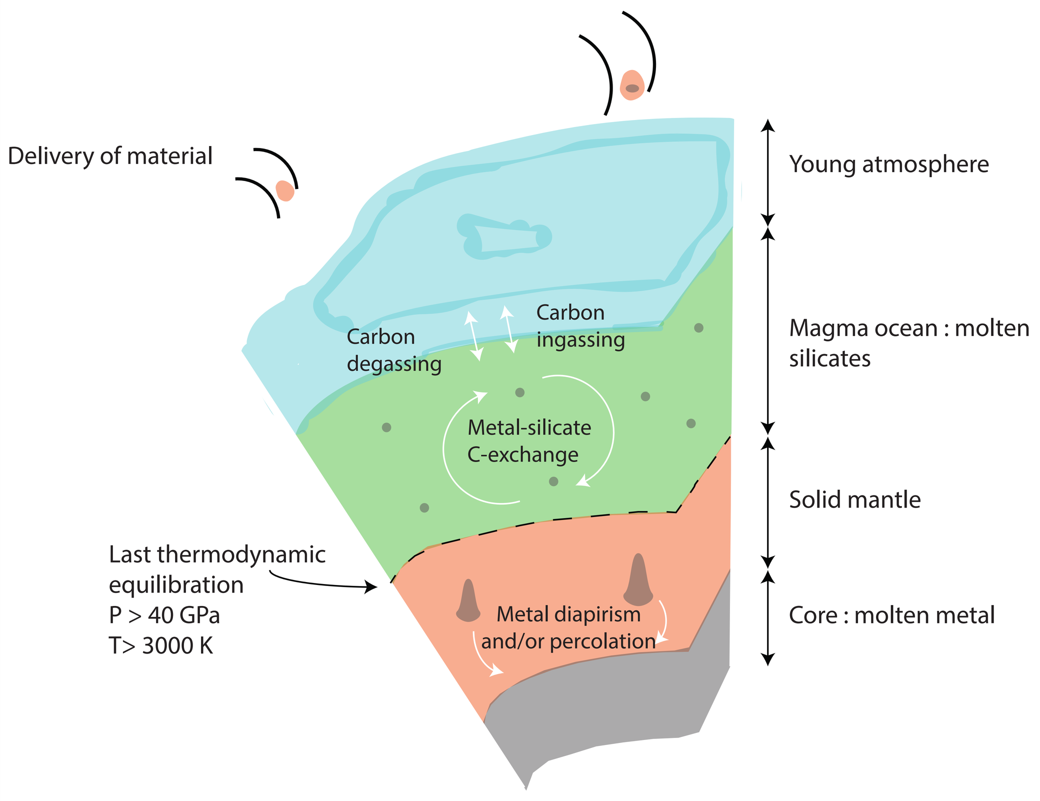
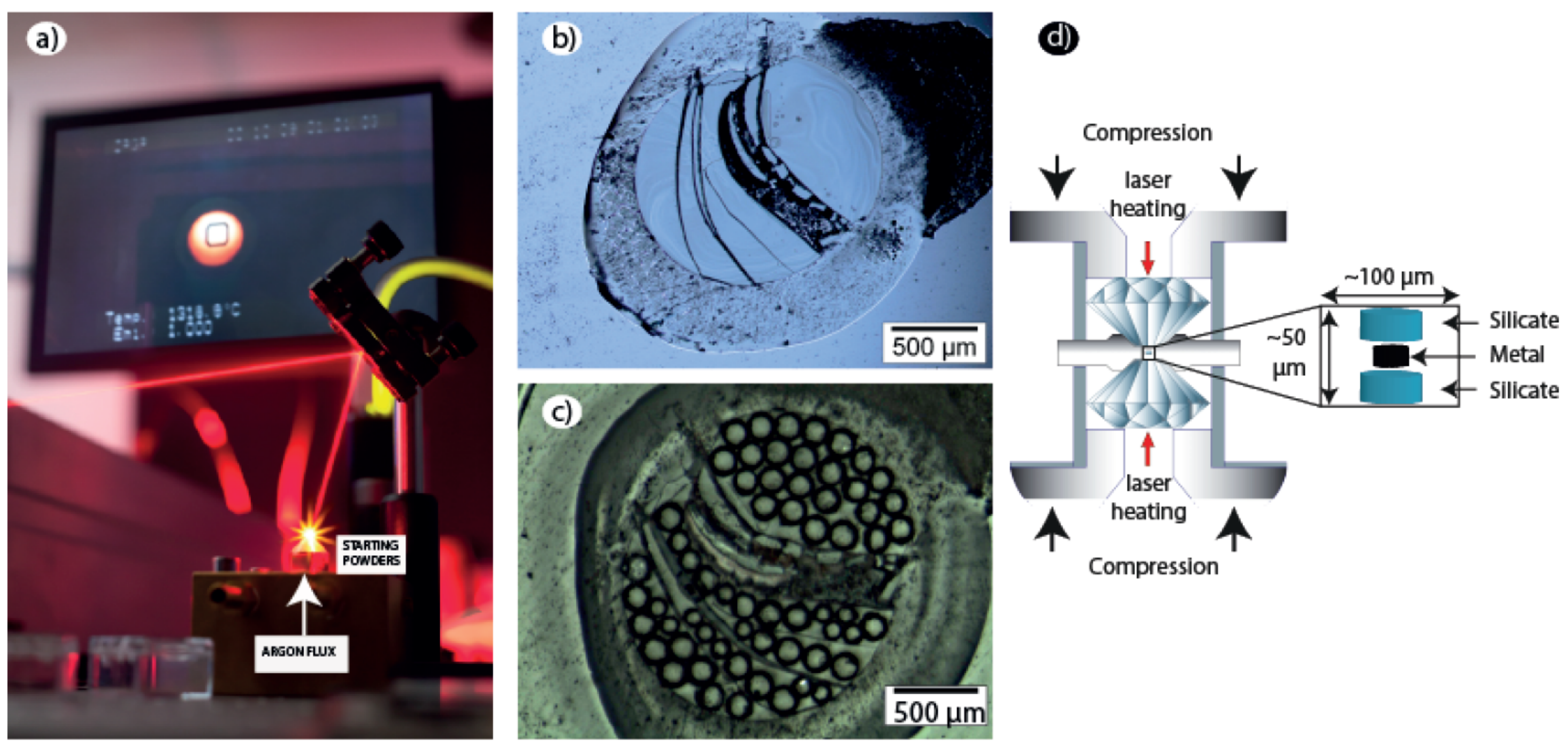


Illustration of the differentiation of the Earth during which carbon was involved in different processes that led to nowadays abundances:
- metal-silicate partitioning;
- degassing and ingassing to the atmosphere;
- delivery of volatile-rich material.

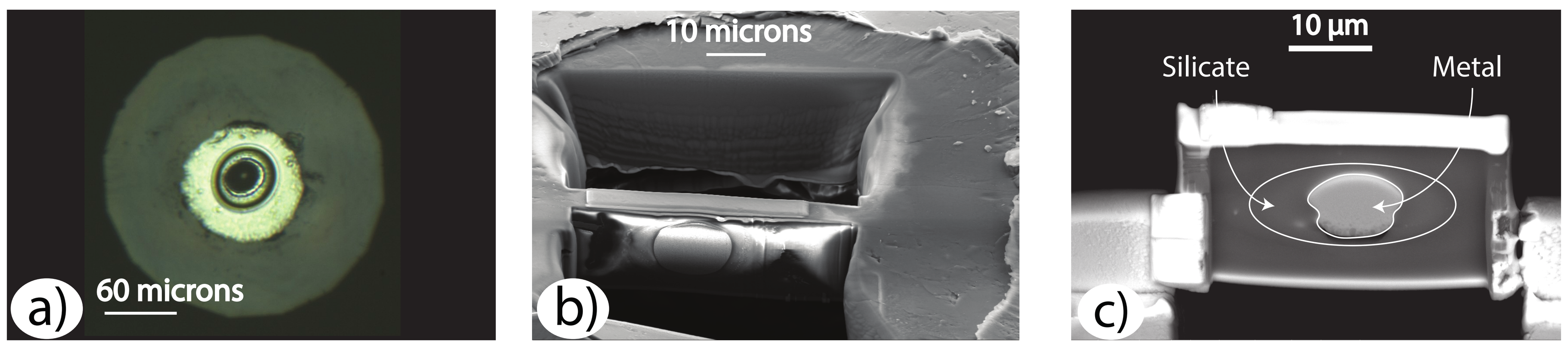
- In order to understand the abundance of carbon in today's mantle, we performed **high pressure and high temperature experiments** recreating the condition of the last thermodynamic equilibrium between the proto-core and the proto-mantle [1].

Methods & Analyses

- Composition of the starting material : **basaltic glass** made with aerodynamic levitation + **^{13}C-rich iron alloy** made with piston-cylinder.



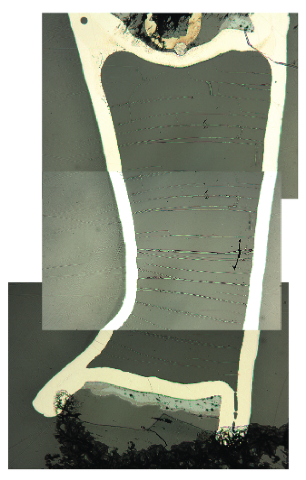
- a) Picture of the aerodynamic levitation furnace. b) Silicate starting material after polishing down to 20 µm thickness. c) Picture of the silicate disk showing the disks cutted with laser. d) Diagram illustrating the geometry of our experiments.

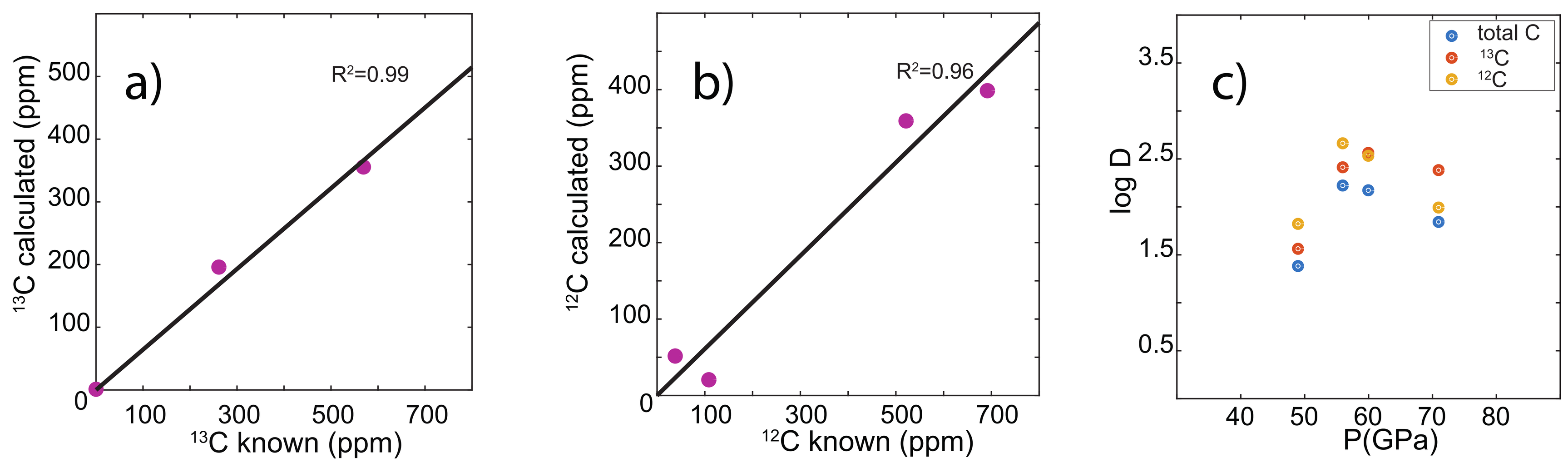


- Recovery process after quench of LH-DAC experiments. a) Optical image through diamonds showing the laser spot in black. b) Excavation of the sample using ion beam. c) Final aspect of the sample with the two separate phases clearly visible: the metal and silicate.

- **EPMA analyses to assess the amount of major elements in both the metal and the silicate**
Fabrication of a carbide standard (Fe_3C) with piston cylinder following the method of [2] checked with XRD and EPMA.

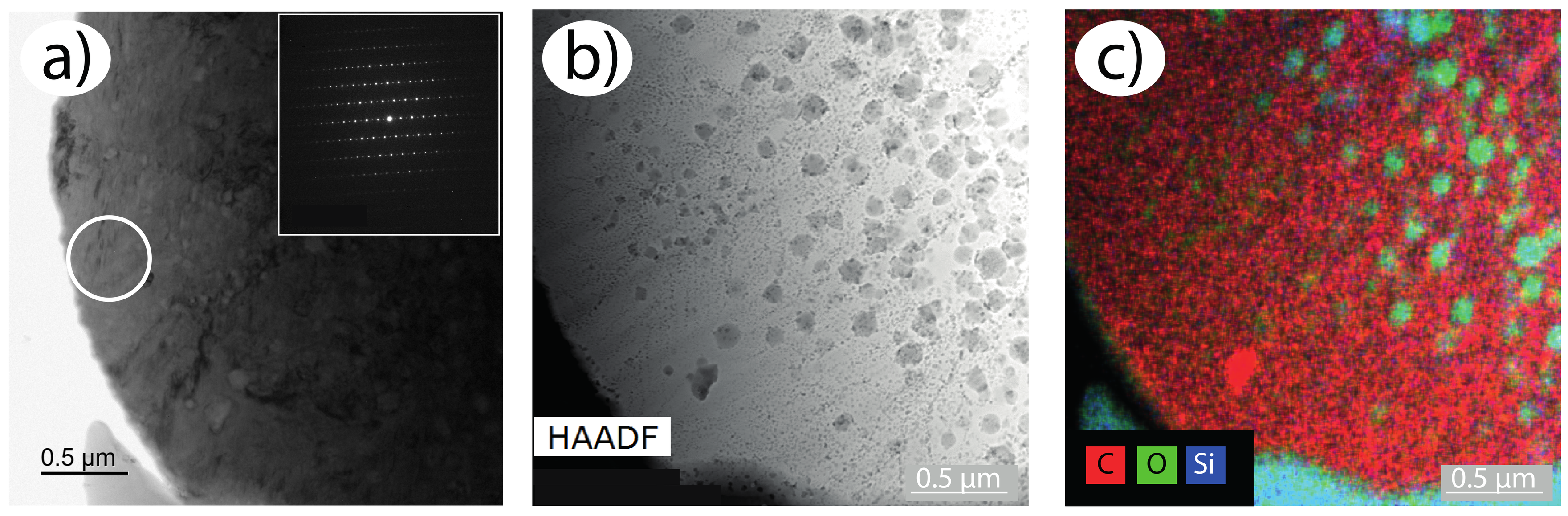
- **nanoSIMS analyses to assess the amount of C in the silicate**
Fabrication of standards using piston-cylinder following the method of [3]. We synthesised two ^{13}C doped basaltic glasses for which composition was checked using FTIR and EPMA. We also used two meteorites (D'Orbigny and ALV 981-R23c).





- a) and b) Measure of our standards using nanoSIMS facility (Milton Keynes, UK) for both ^{12}C and ^{13}C. c) Differences in D_C using either ^{12}C, ^{13}C or total carbon measured with nanoSIMS. This illustrates that there is ^{12}C contamination in our samples. This most likely comes from the starting material that showed to contain both ^{12}C and ^{13}C as can be seen from FTIR and nanoSIMS measurements.

- **TEM analysis to infer the structure and obtain EDS maps of the metallic phase.**



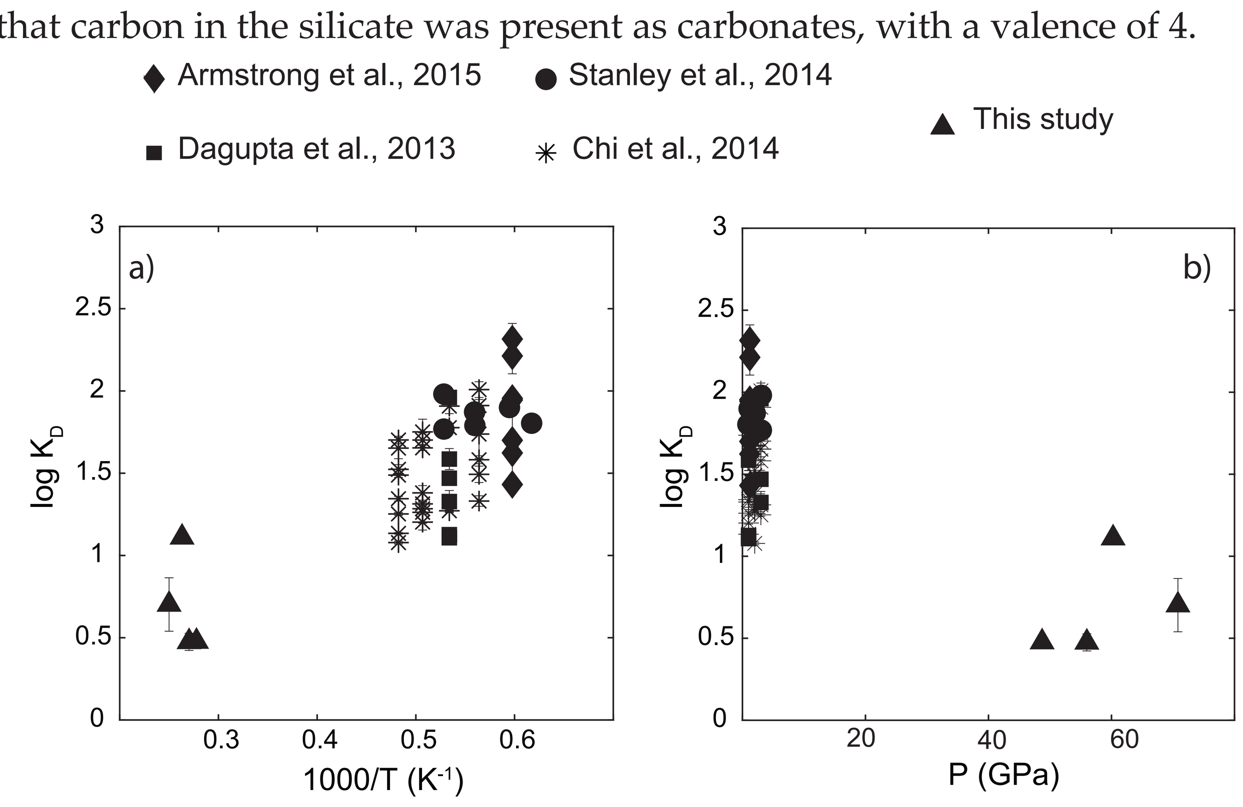
a) **Bright field image and diffraction pattern** of the metallic phase of one of our recovered run highlighting the presence of **stoechiometric Fe_7C_3** (also observed with EELS). b) **Dark field image** of the same sample along with c) **EDS map** of the zone that displays the presence of O- (and Si-) rich exsolutions.

Results & Conclusions

We calculated the partition coefficient (D) and the equilibrium constant (K_D) of carbon between metal and silicate using the total amount of carbon ($^{12}C+^{13}C$) such as :

$$D_C = \frac{X_C^{metal}}{X_{CO}^{silicate}} \qquad K_D = \frac{D_C}{(D_{Fe})^{n/2}} \qquad \log K_D = 0.3(\pm 0.2) + \frac{3822(\pm 860)}{T}$$

We assumed that carbon in the silicate was present as carbonates, with a valence of 4.

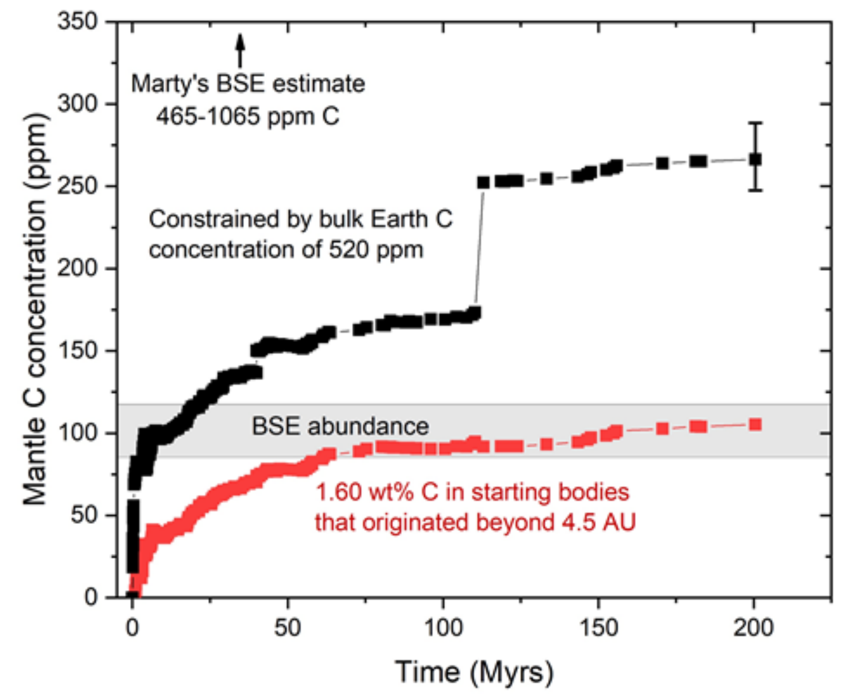


Our results highlight that **carbon becomes less siderophile at P-T conditions of core formation** than at relatively low P-T condition. Nevertheless, carbon stays siderophile with **D ~ 100**.

MODEL Multistage core–mantle differentiation model coupled with N-body accretion simulations, extension to Rubie et al., 2015/16

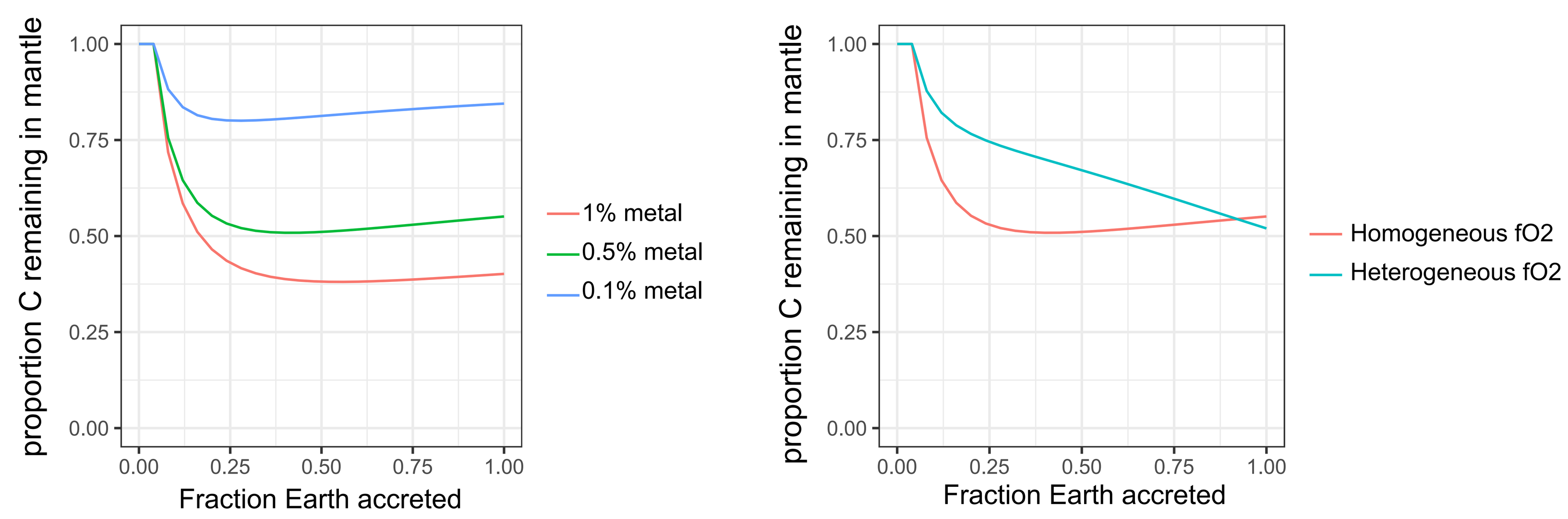
Includes dynamics of the protoplanetary disk ([10])
C = CI abundance (3.45 wt%) for bodies formed after 4.5 AU, C = 0 otherwise
fO_2 varies with heliocentric distance
Final giant impact at about 112 Myrs

Overabundance of C in the mantle. Due to overestimation of starting C? Could disproportionation of Fe^{2+} have extracted C to the core [11]?



C sequestration by pervasive late-stage metal fractionation: our results suggest that Earth's mantle is over-abundant in C at end of accretion. Late-stage pervasive metal saturation would strip excess C from mantle. Pressure-driven FeO disproportionaiton has been demonstratedi n both solid (Frost et al., 2003) and liquid (Armstrong et al., 2019) silicate at > 25 GPa.

Calculation: can easily remove ~50% C from mantle if 0.5wt.% Fe precipitated at IW-2.4 (same answer from homogeneous and heterogeneous fO2 evolution). Even 0.1 wt.% Fe removes 20% of mantle C.



CONCLUSIONS
- Core formation conditions in the lab using state-of-the-art experimental and analytical techniques
- Carbon is still siderophile at P-T conditions of core formation, but becmes less siderohile with increasing depth in planet
- Combined accretion and differentiation model based on N-body simulation predicts 2-3x too much C in Earth's core
- Late-stage pressure-driven metal precipitation event can remove excess C to BSE levels

References
[1] Li, & Agee (1996) Nature, 381(6584), 686; [2] Dasgupta et al. (2013) GCA, 102, 191-212; [3] Yoshioka et al. (2015) Am. Min., 100(7), 1641-1644; [4] Armstrong et al. (2015) GCA, 171, 283-302; [5] Stanley et al. (2014) GCA 129, 54-76; [6] Chi et al. (2014) GCA, 139, 447-471; [7] Dasgupta & Hirschmann (2010) EPSL 298(1-2), 1-13; [8] Hirschmann (2016) Am. Min., 101(3), 540-553; [9] Marty (2012) EPSL 313, 56-66; [10] Rubie et al. (2016) Science, 353(6304), 1141-1144; [11] Armstrong et al. (2019) Science, 365(6456), 903-906.