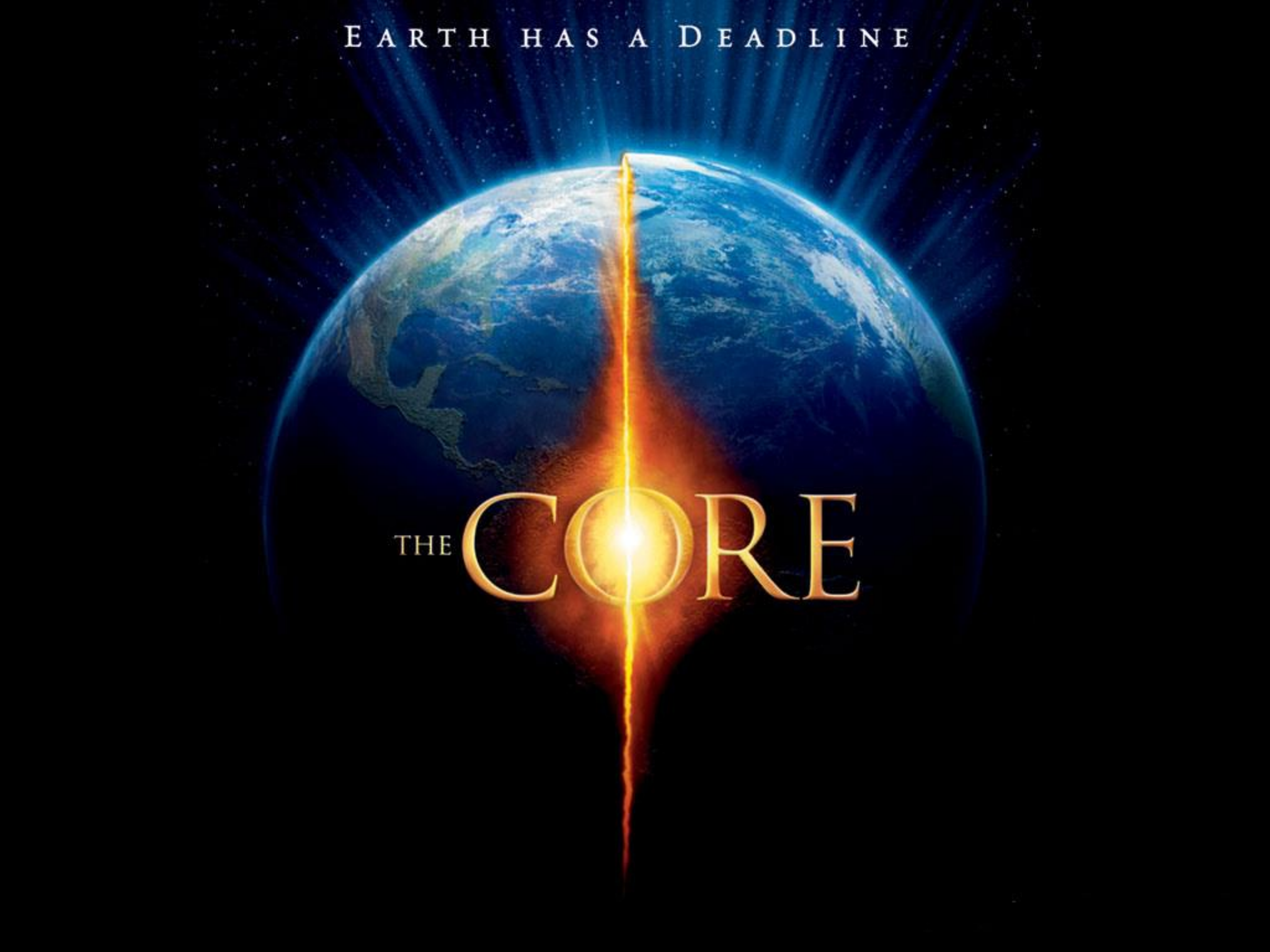
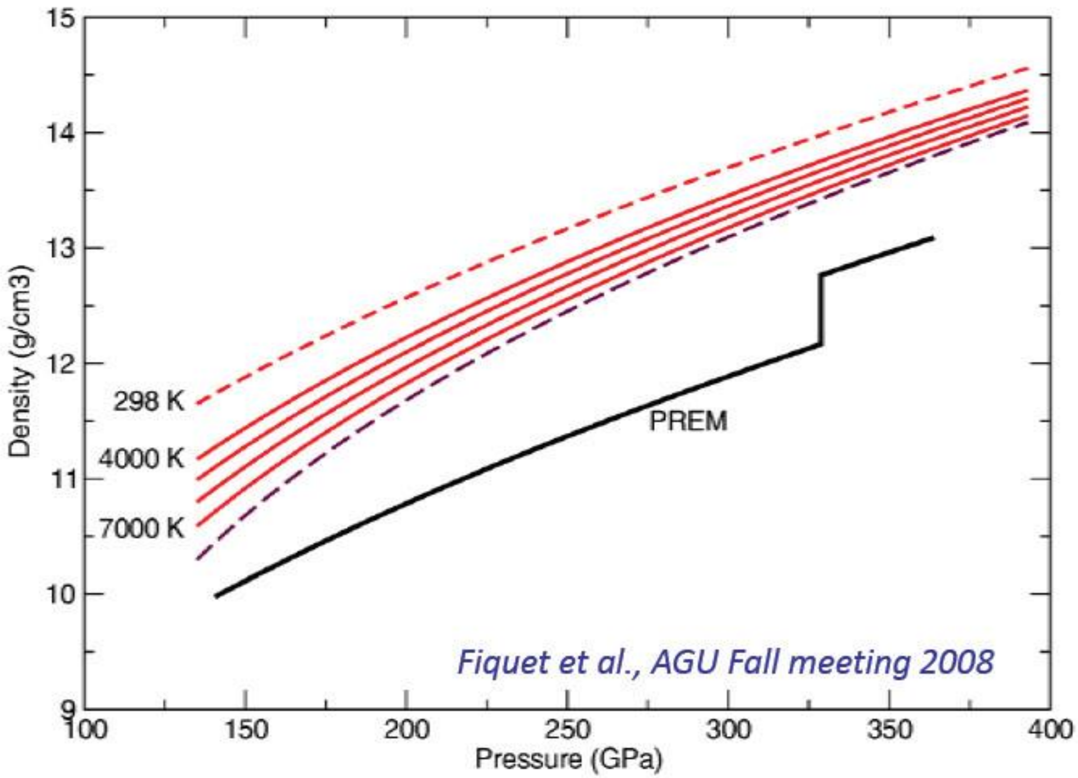
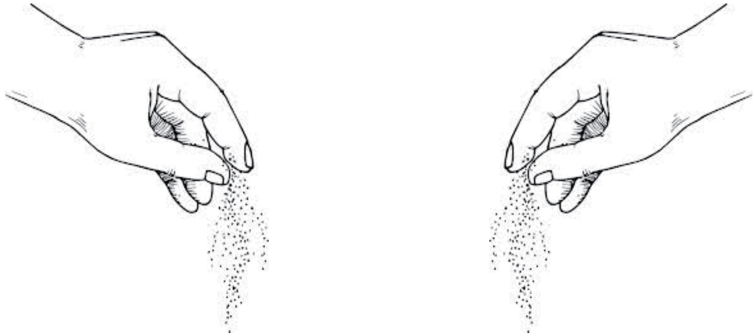
- Let’s try to apply that to the Earth’s core


EARTH HAS A DEADLINE
THE CORE



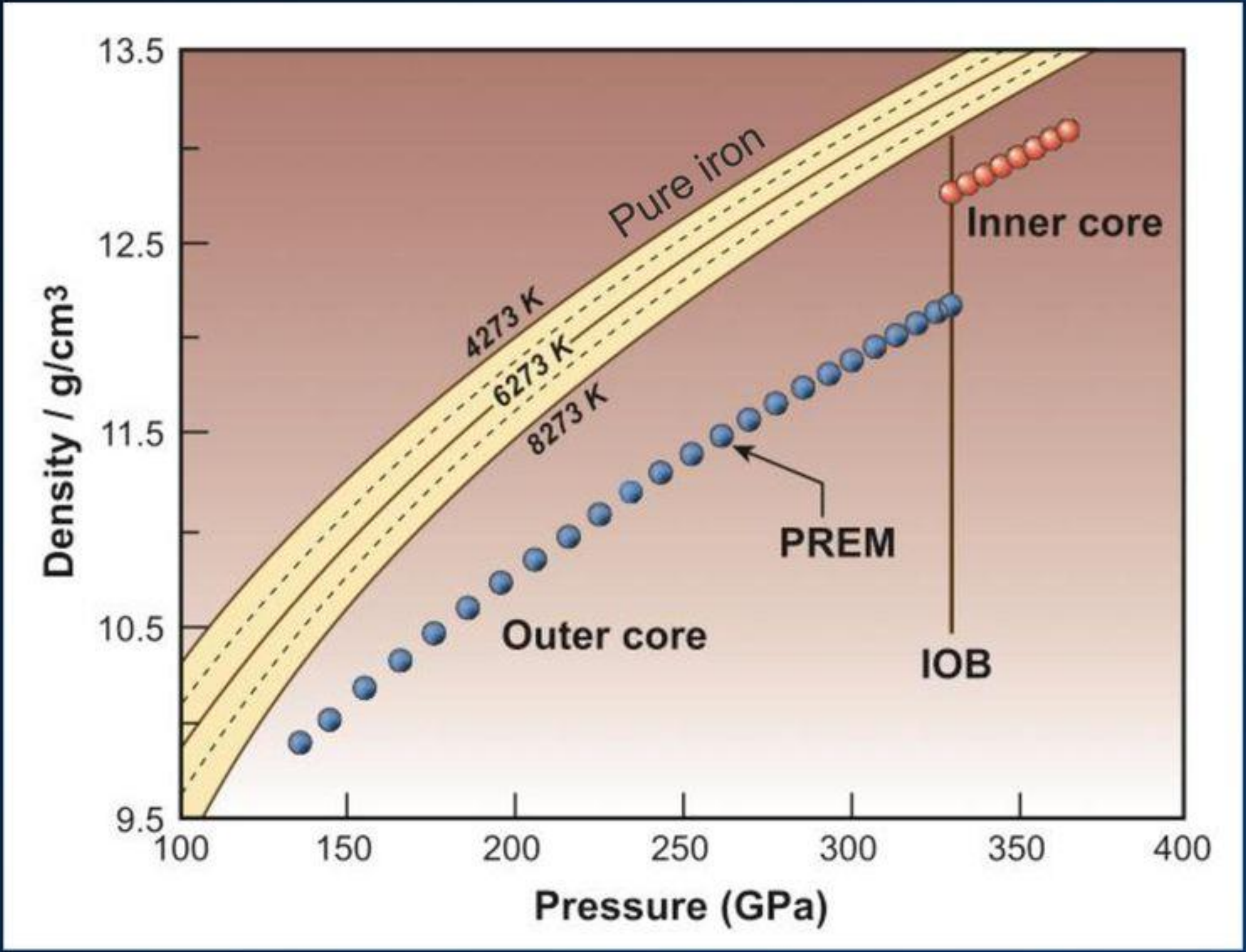
The Earth's core is less dense than pure iron



Addition of « lighter elements »

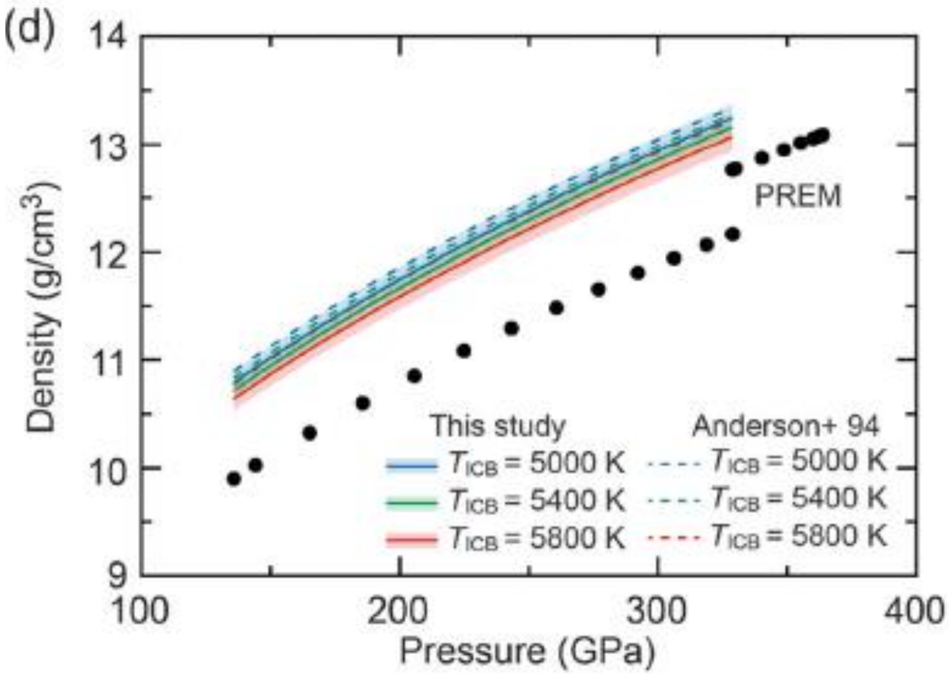
Light Elements in the Core

Francis Birch (1952)



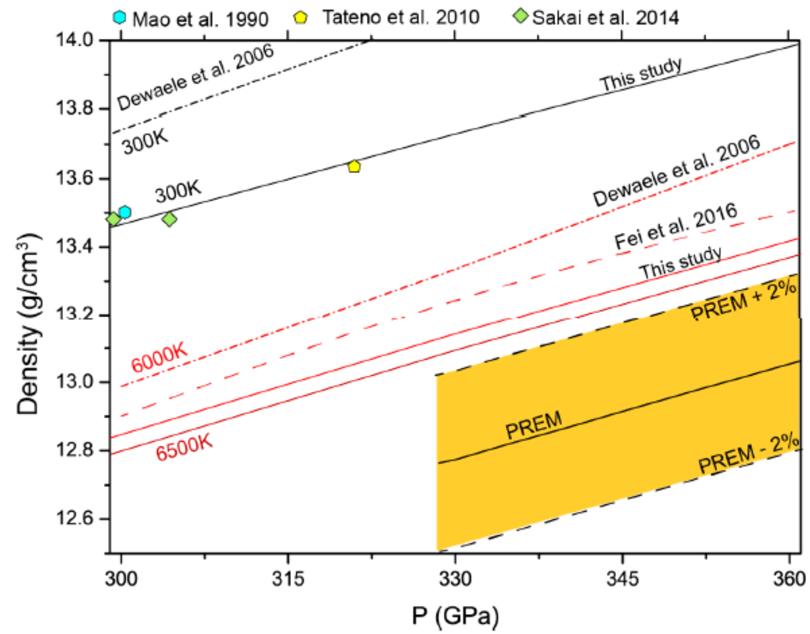
after Uchida *et al.* (2001)

Liquid outer core :
Density deficit of 7.5%



Kuwayama et al, Phys. Rev. Lett., 2020

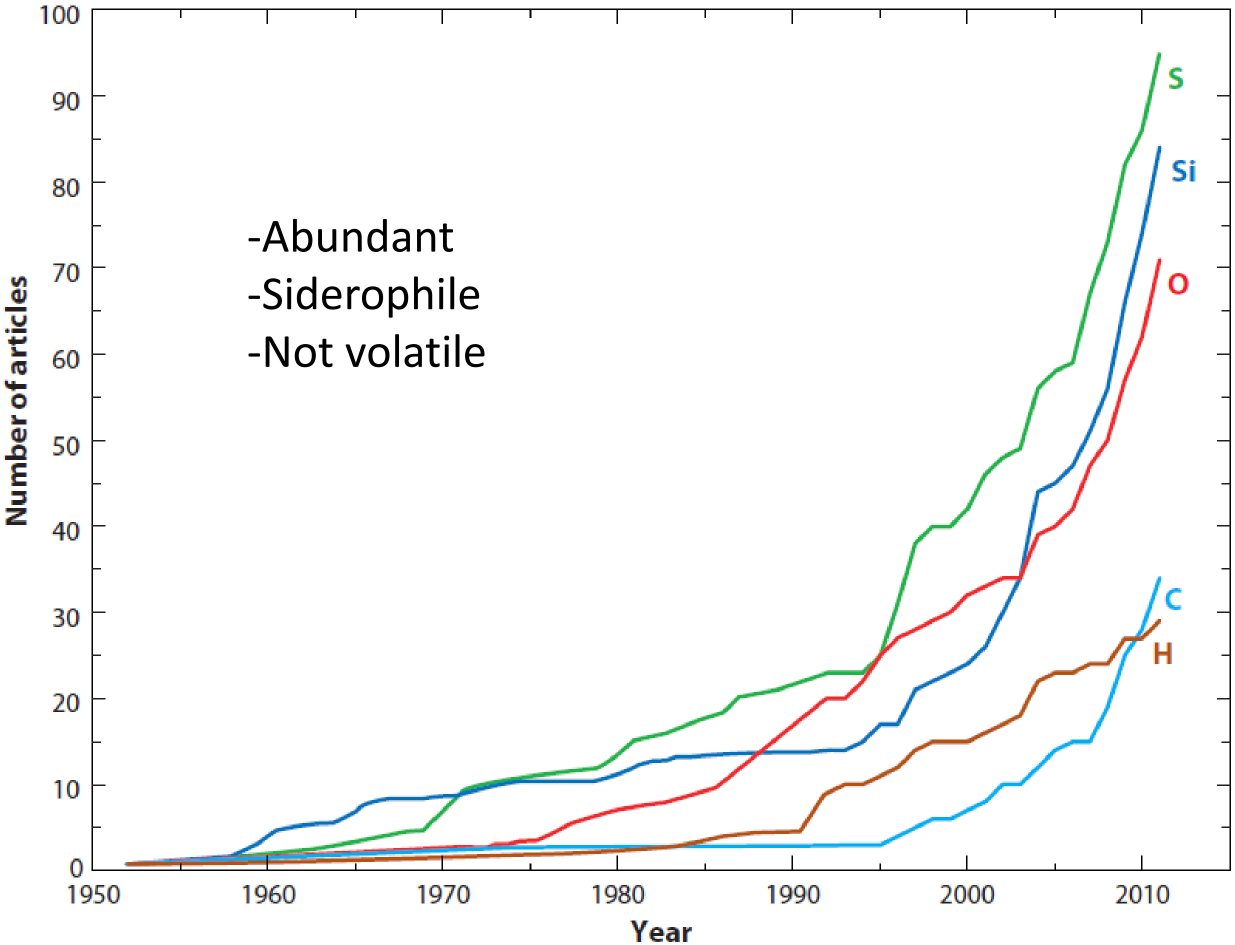
Solid inner core:
Density deficit of 3%



Miozzi et al, Minerals, 2020

Light elements preferentially partition in the liquid

Light elements alloyed with iron



-Abundant
-Siderophile
-Not volatile

Hirose et al, 2013

Birch's law

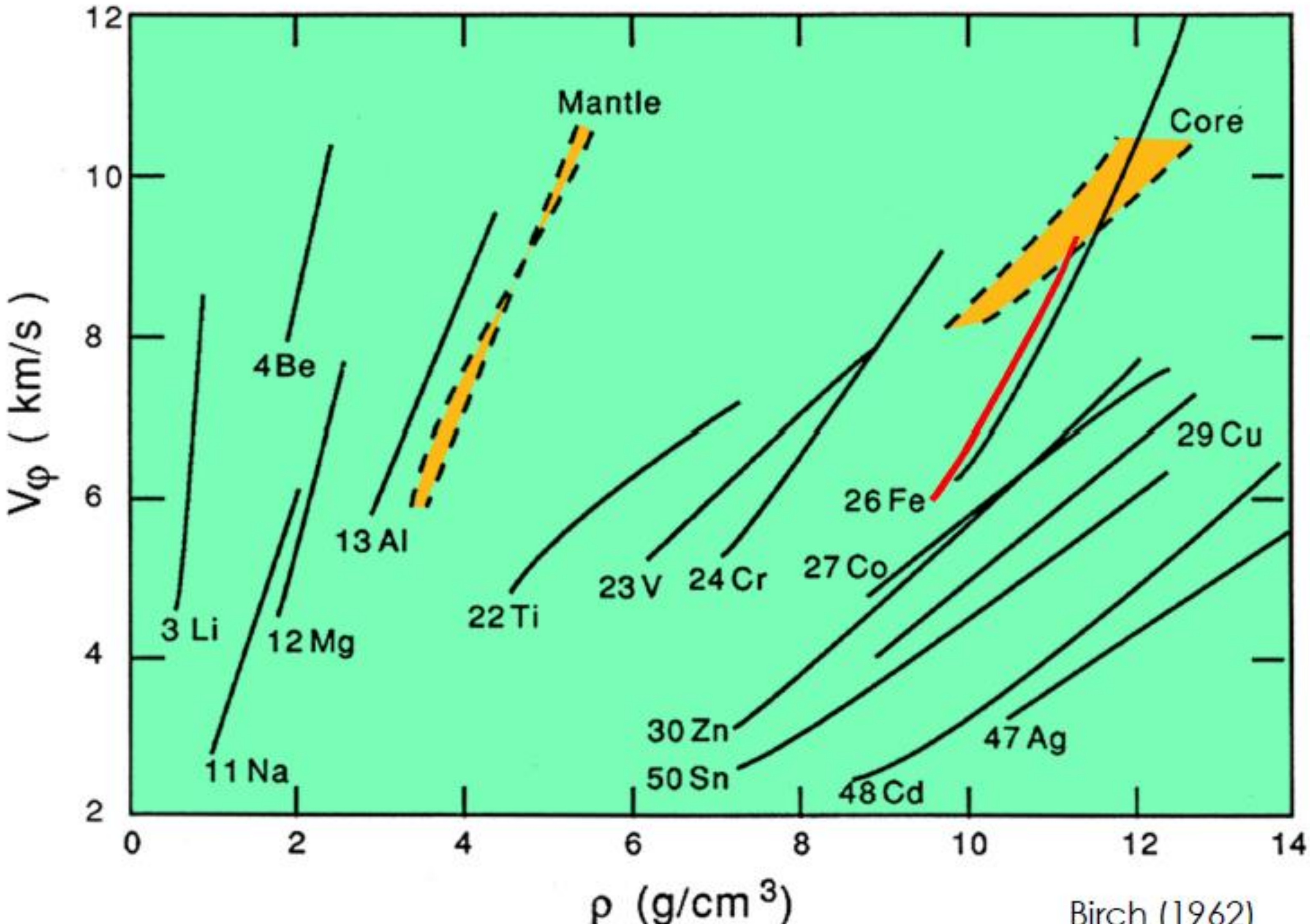
$$V = a(\overline{m}) + b\rho$$

Relation between density,
velocity and mean atomic number

Birch's Law: Why Is It So Good?

DAE H. CHUNG

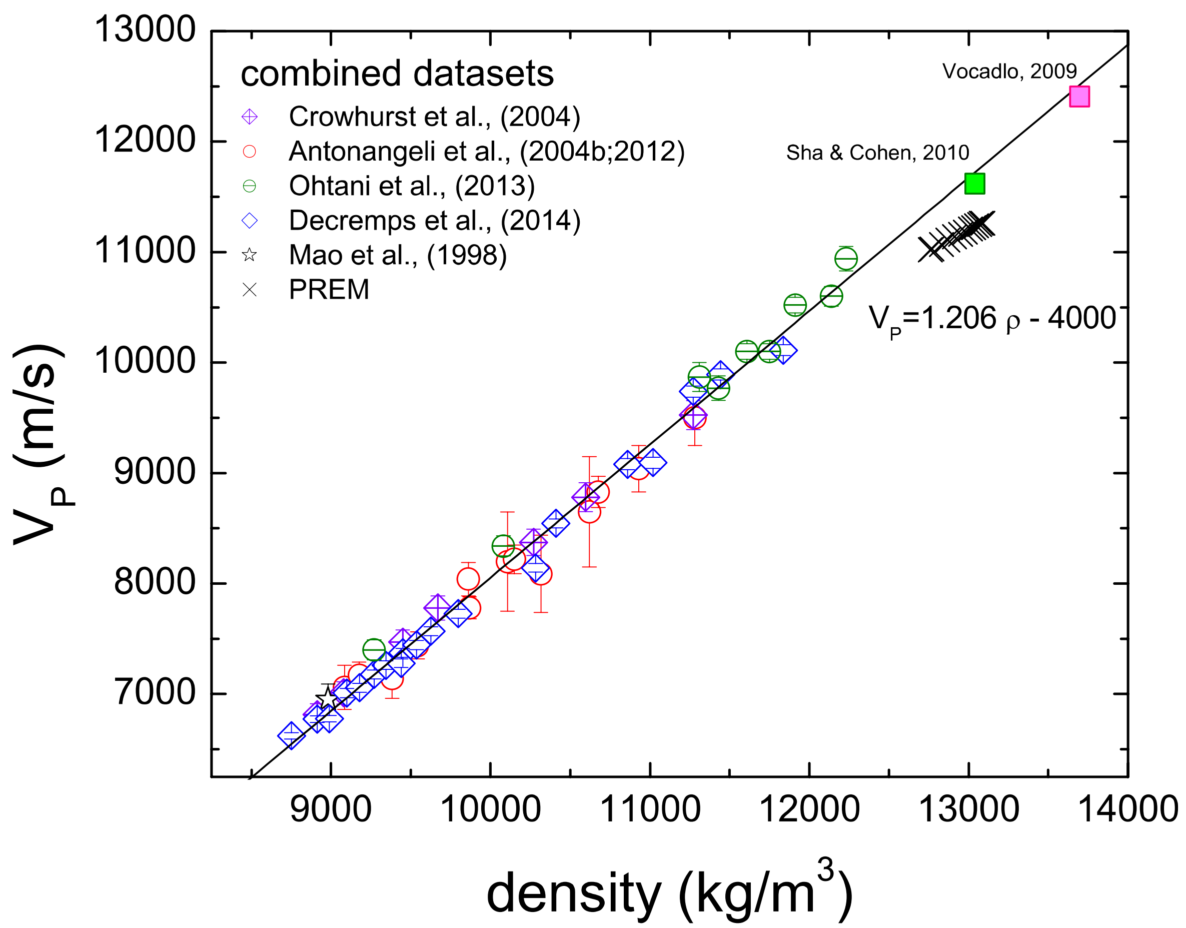
SCIENCE, VOL. 177   21 JULY 1972

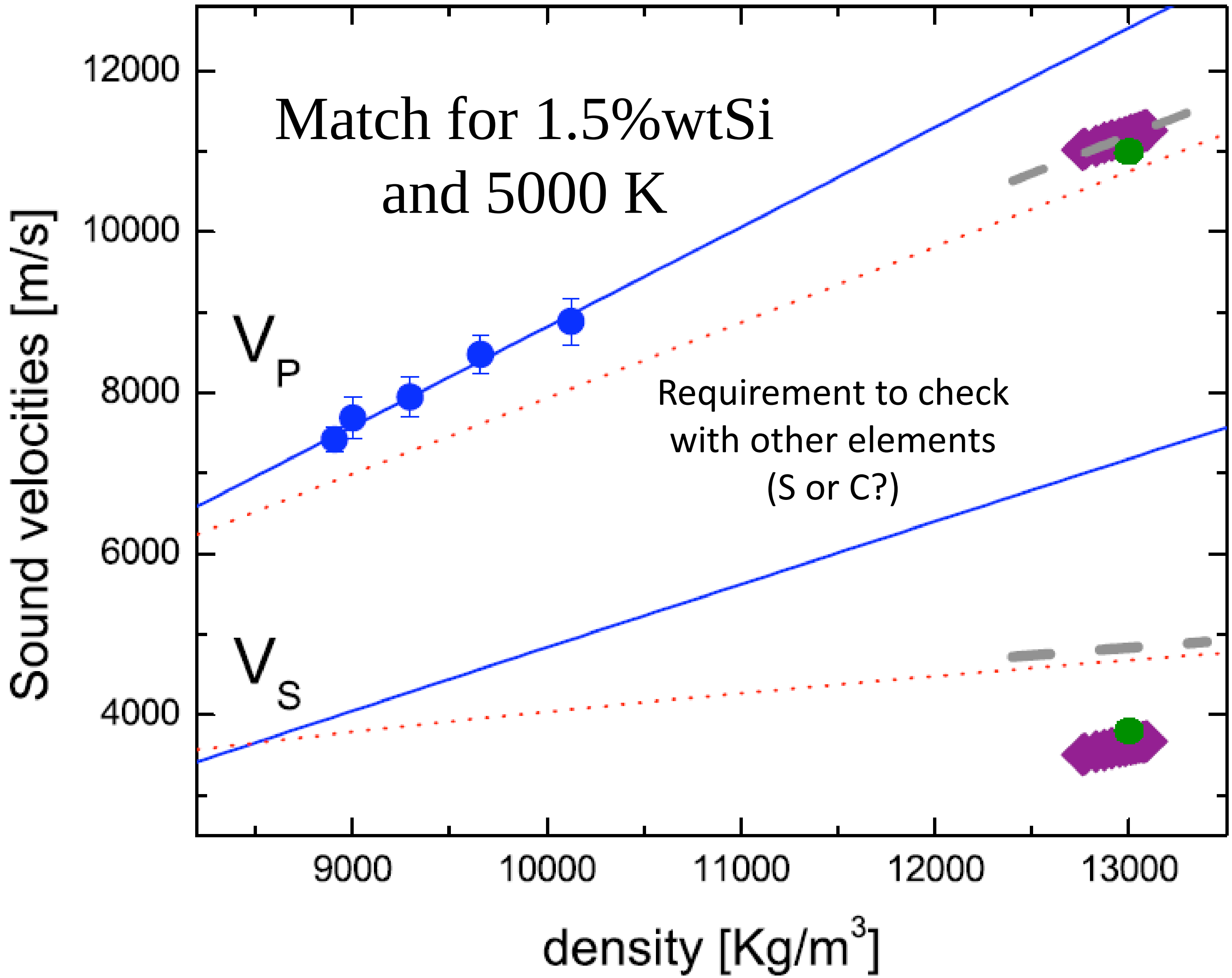


Mantle
Core
3 Li
4 Be
11 Na
12 Mg
13 Al
22 Ti
23 V
24 Cr
26 Fe
27 Co
29 Cu
30 Zn
47 Ag
48 Cd
50 Sn
Vφ (km/s)
ρ (g/cm 3)
0
2
4
6
8
10
12
14

Birch (1962)

Birch law in Pure Fe at 300 K





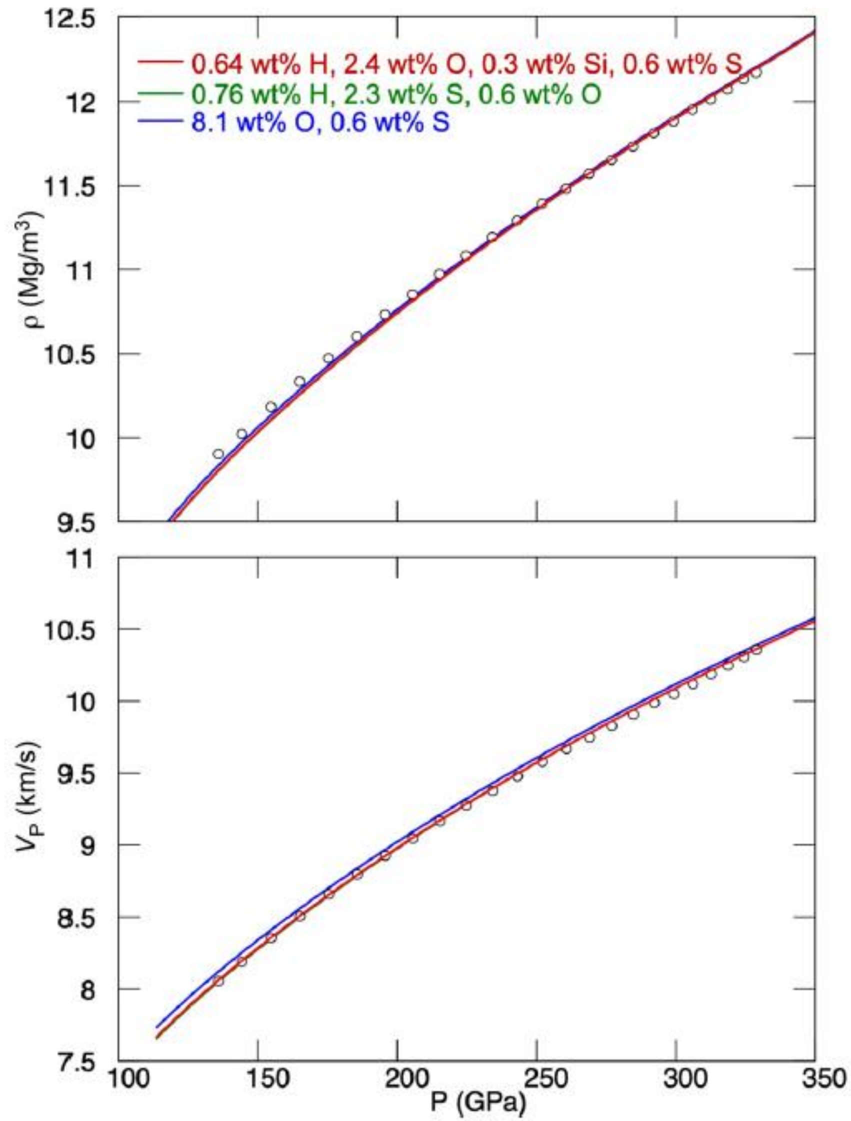
Match for 1.5%wtSi
and 5000 K
Requirement to check
with other elements
(S or C?)
V_P
V_S
Sound velocities [m/s]
density [Kg/m^3]
12000
10000
8000
6000
4000
9000
10000
11000
12000
13000

Chemical compositions of the outer core examined by first principles calculations

Koichiro Umemoto [a,*], Kei Hirose [a,b]

[a] Earth-Life Science Institute, Tokyo Institute of Technology, Meguro, Tokyo 150-8550, Japan
[b] Department of Earth and Planetary Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan

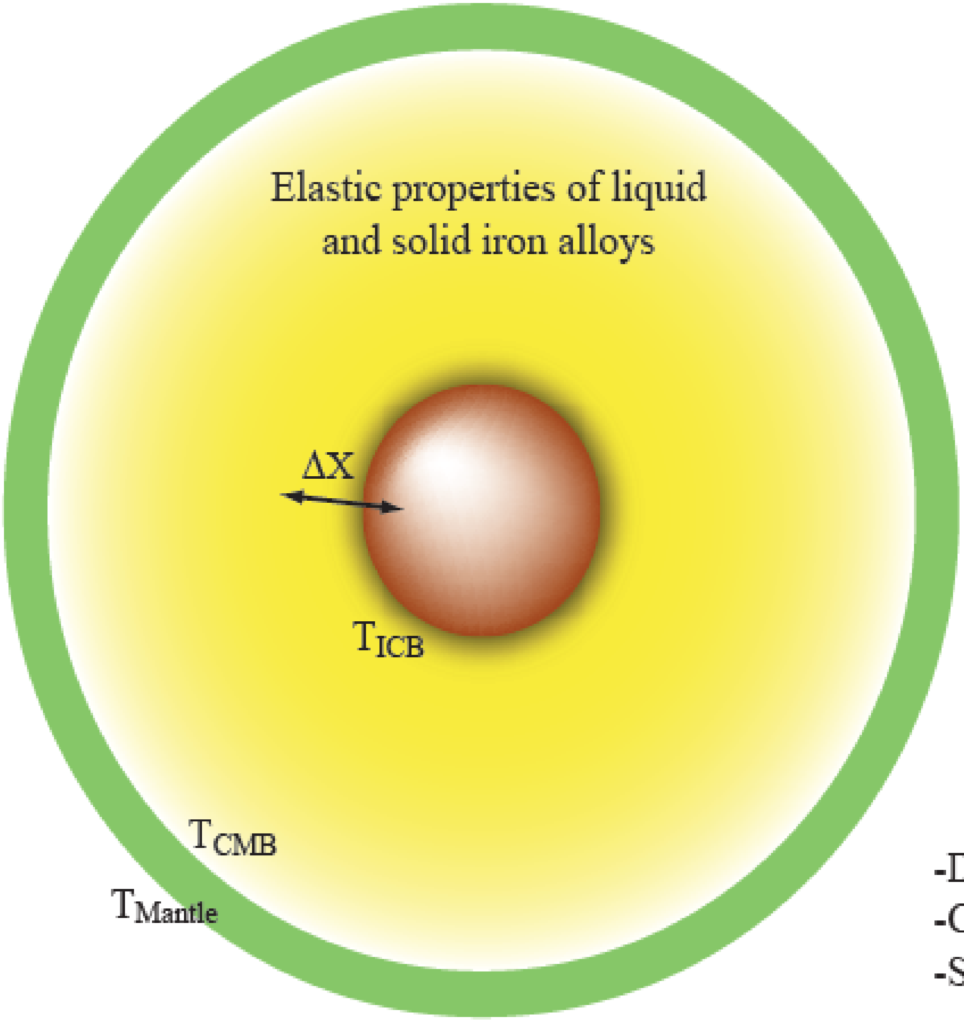
Earth and Planetary Science Letters 531 (2020) 116009



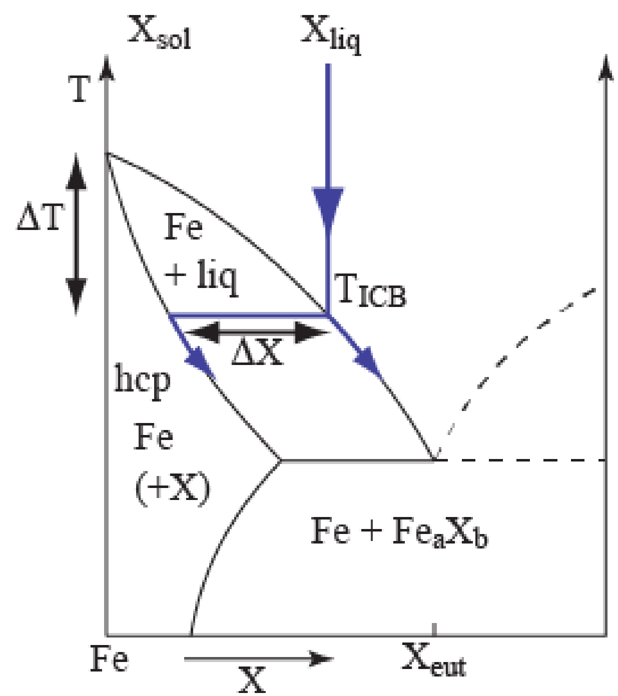
Calculations of density and sound velocity give O as major light element in the Earth's core (or hydrogen)
Silicon seems not compatible.
Sulfur a bit compatible.

Only density and velocity, in a multi-component system, cannot help to discriminate!

Properties of the Earth's core

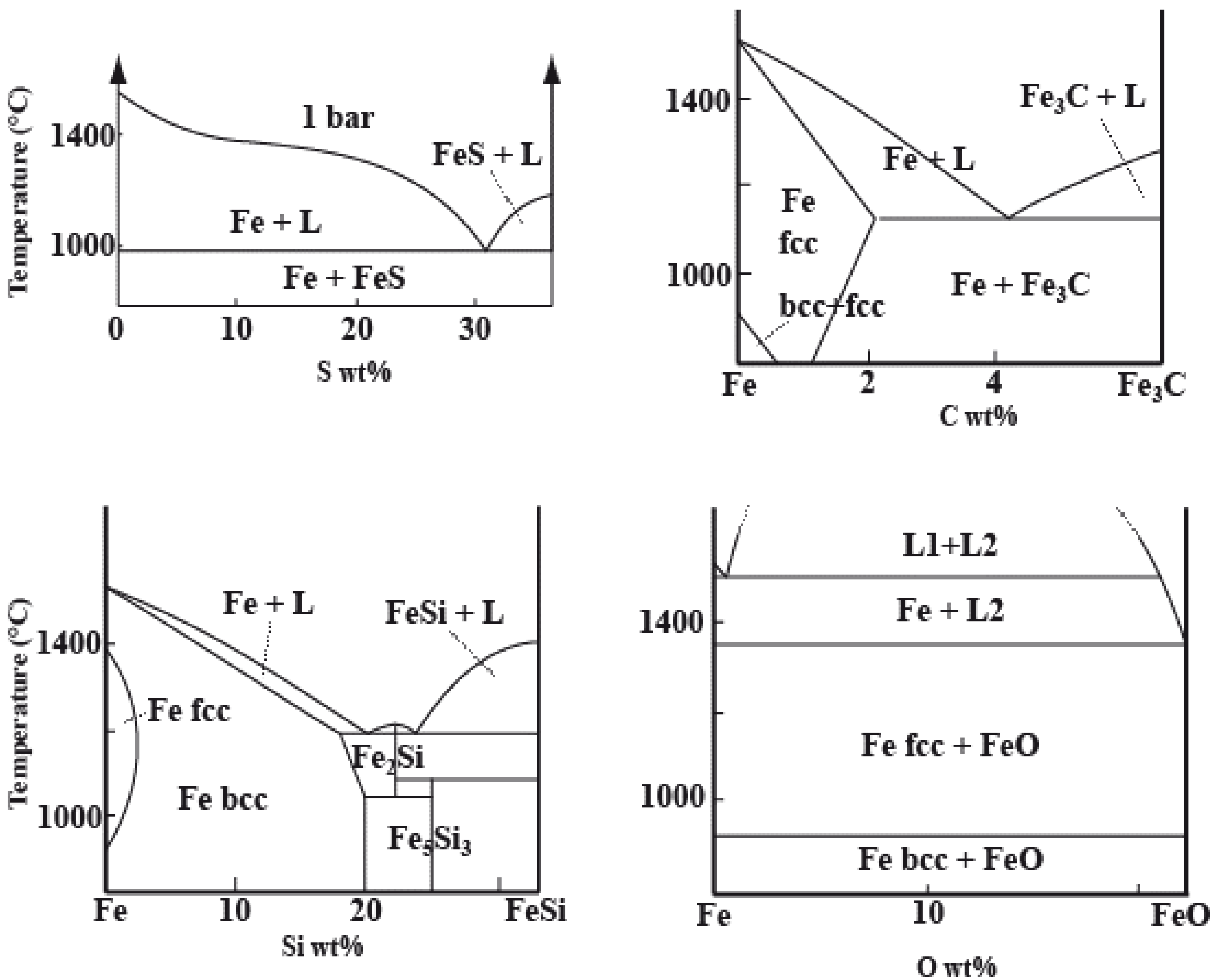


Phase diagrams under high pressure

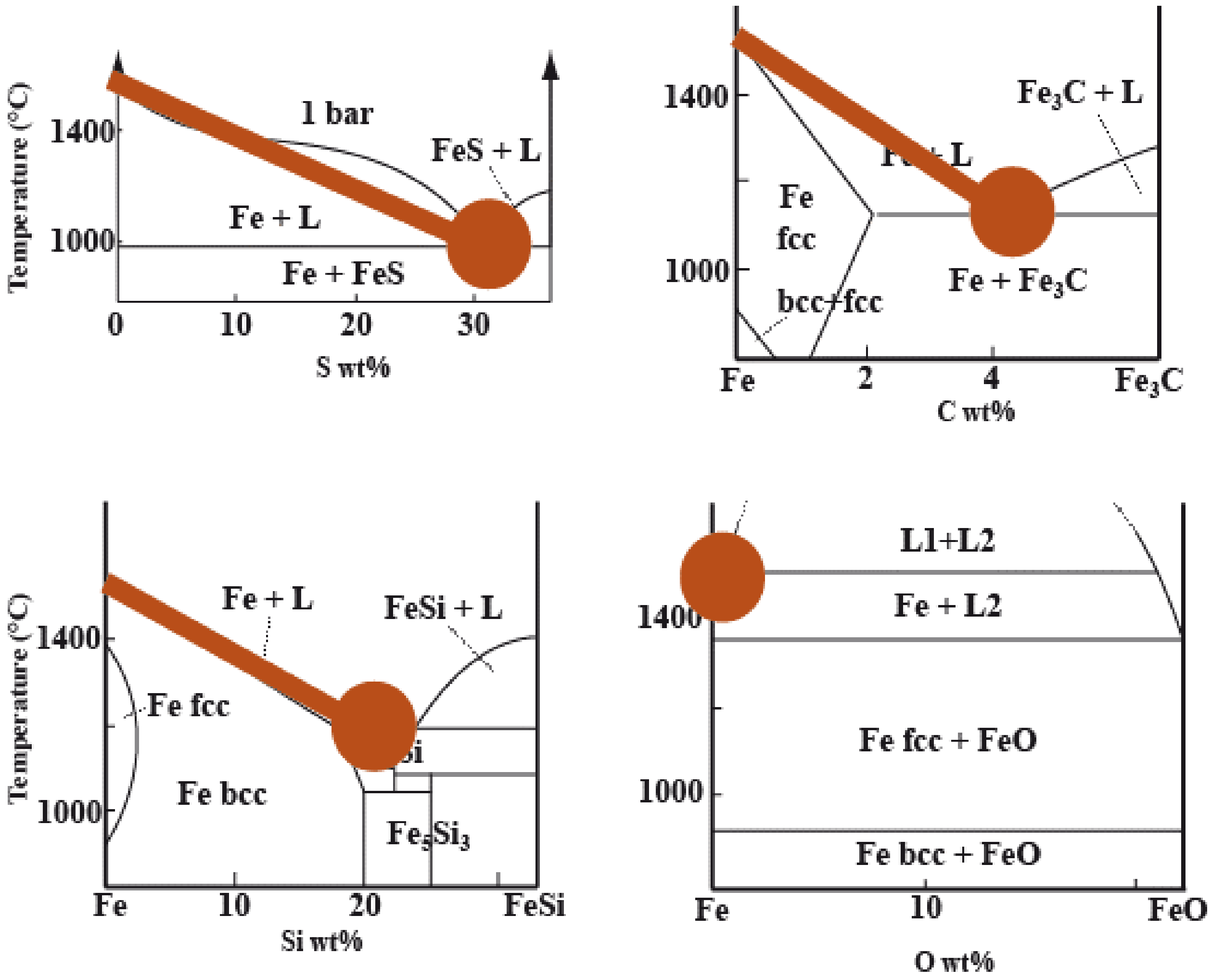


-Density jump at Inner Core Boundary
-Crystallisation of denser Fe
-Solid silicates at the Core-Mantle Boundary

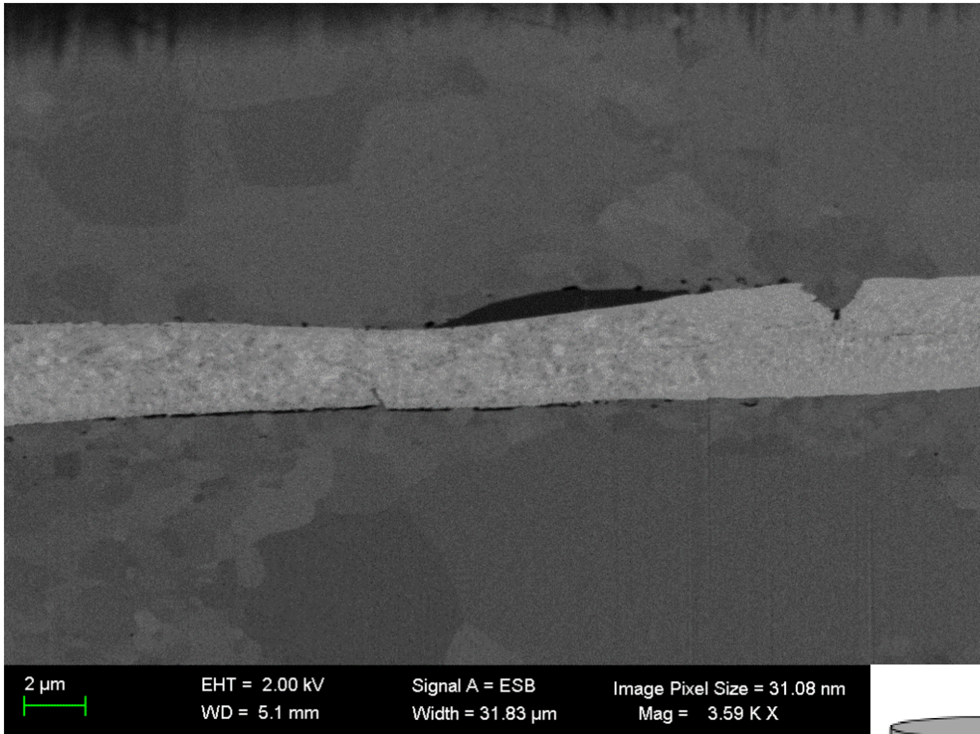
Eutectic point position with pressure

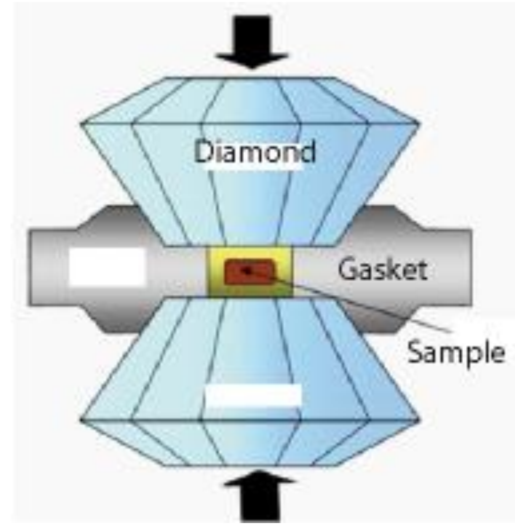


Eutectic point position with pressure

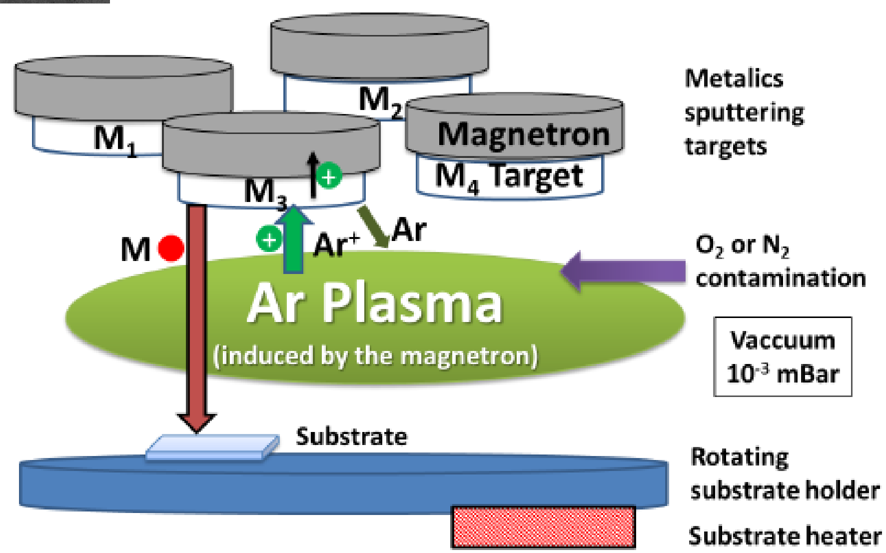


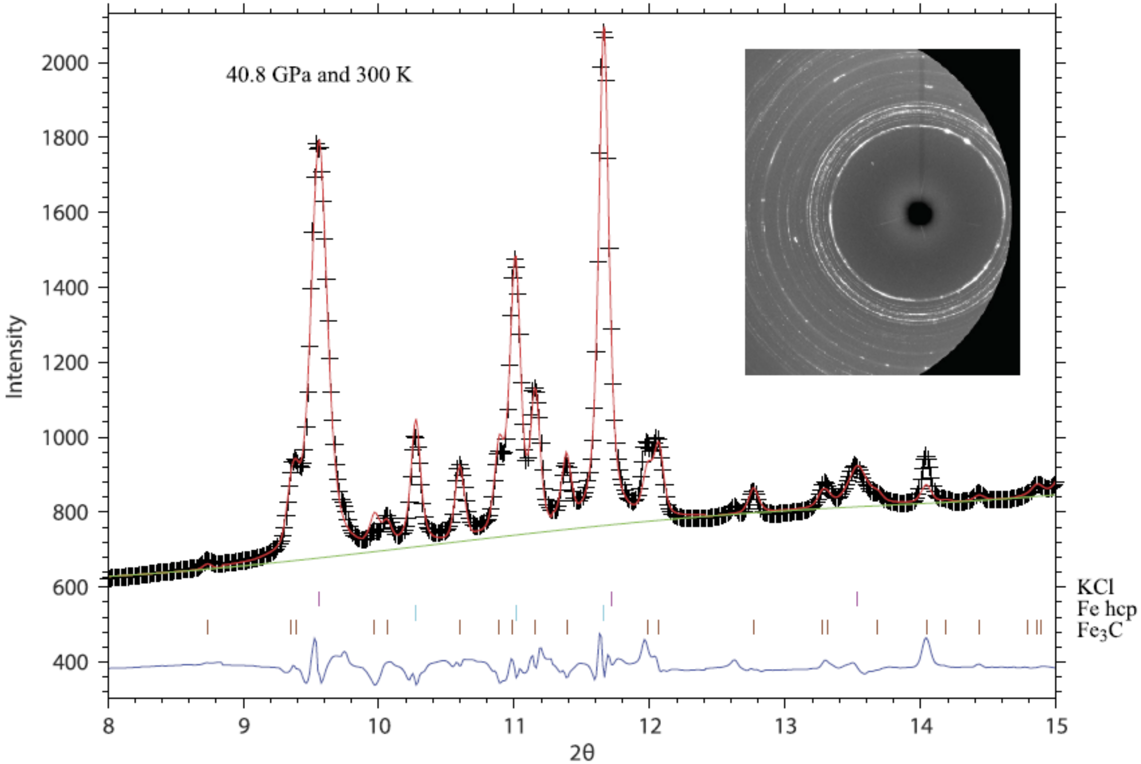
Starting materials for High Pressure experiments



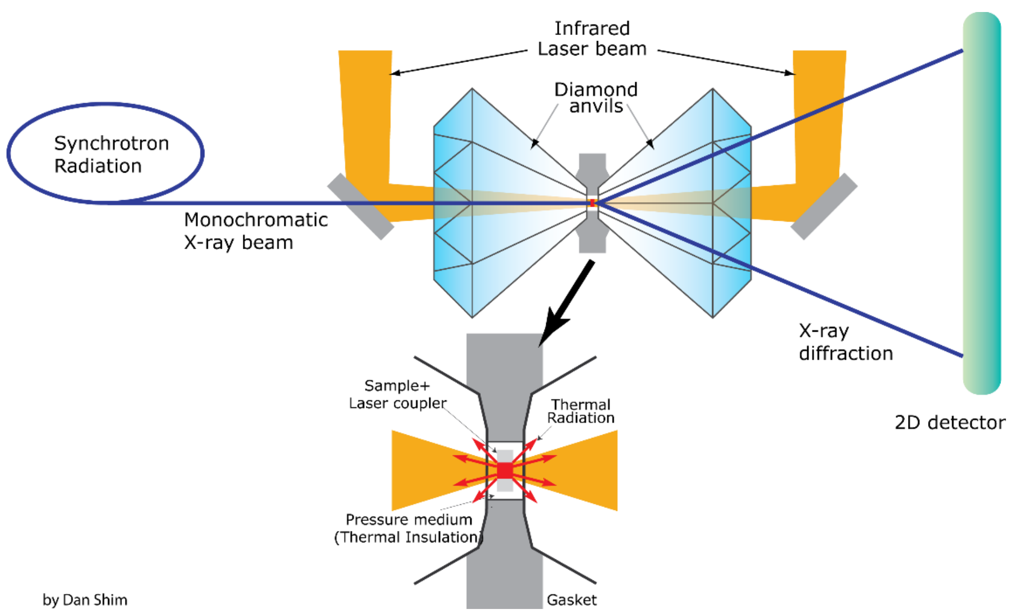


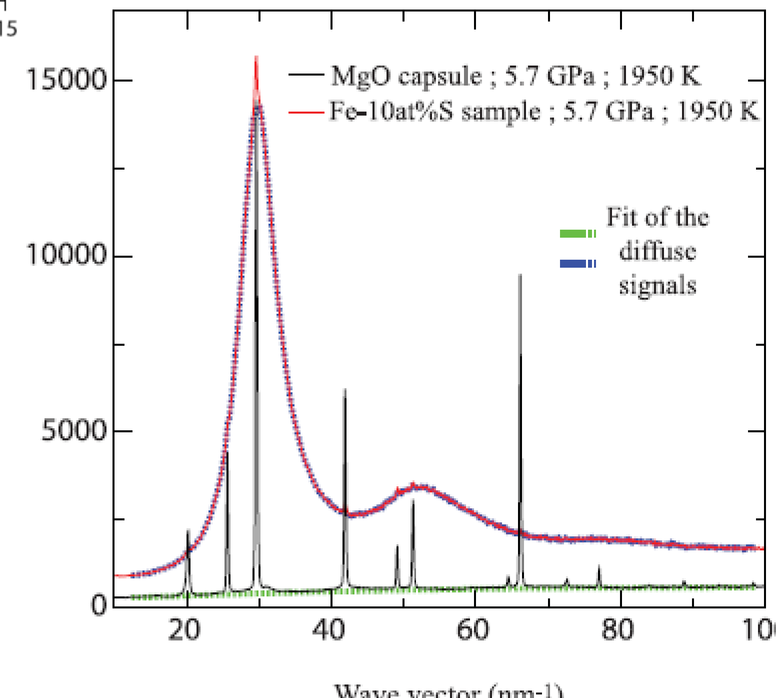
Preparation of samples homogeneous at ~10 nm scale using the Plasma-Vapor Deposition technique

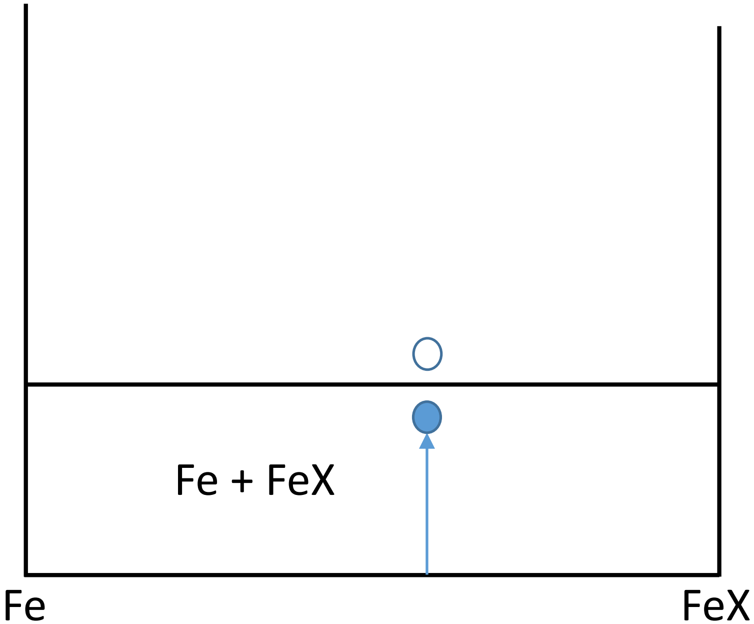


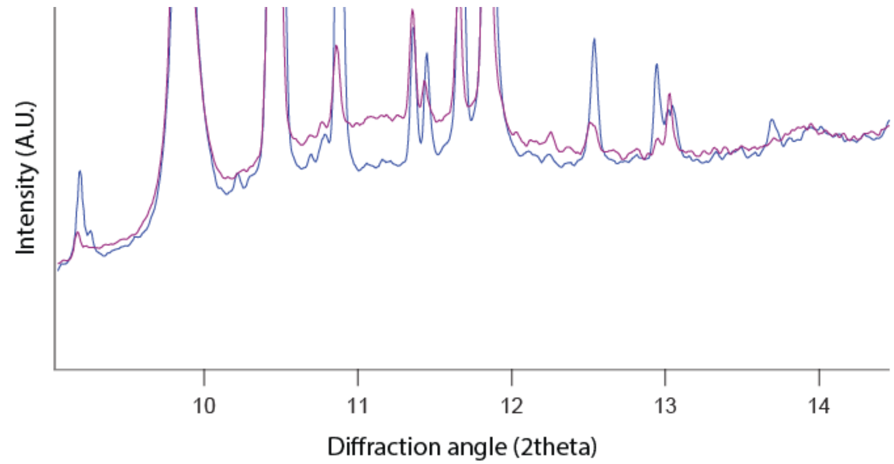


Probing iron alloys by *in situ* X-ray Diffraction under extreme conditions

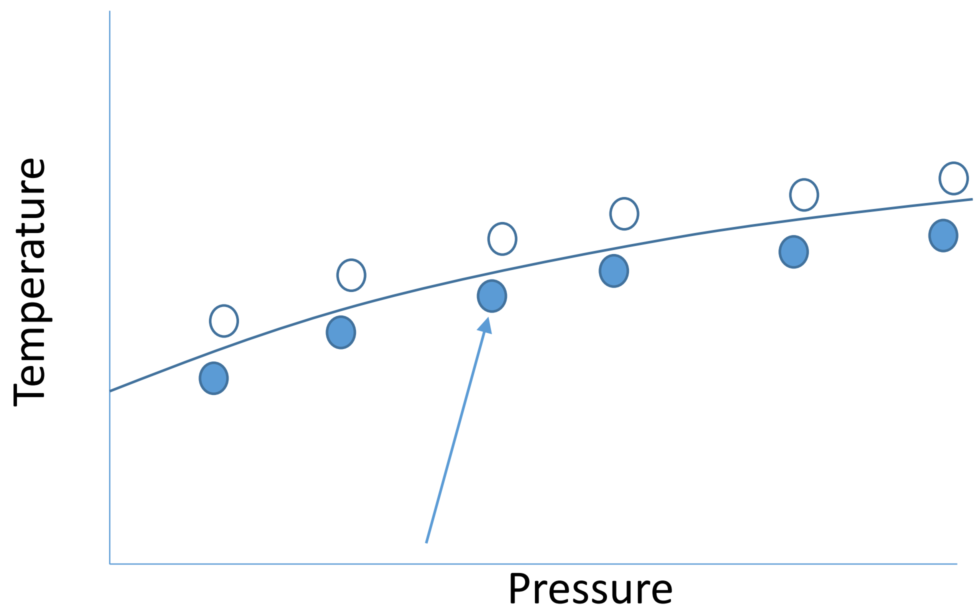






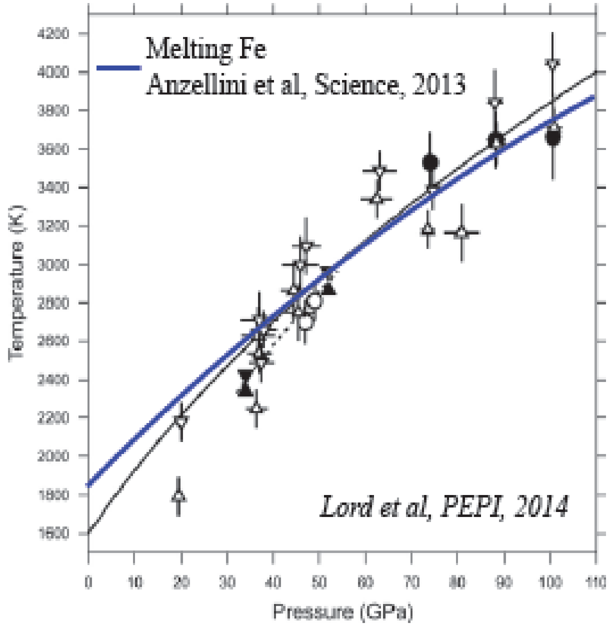


Melting temperature

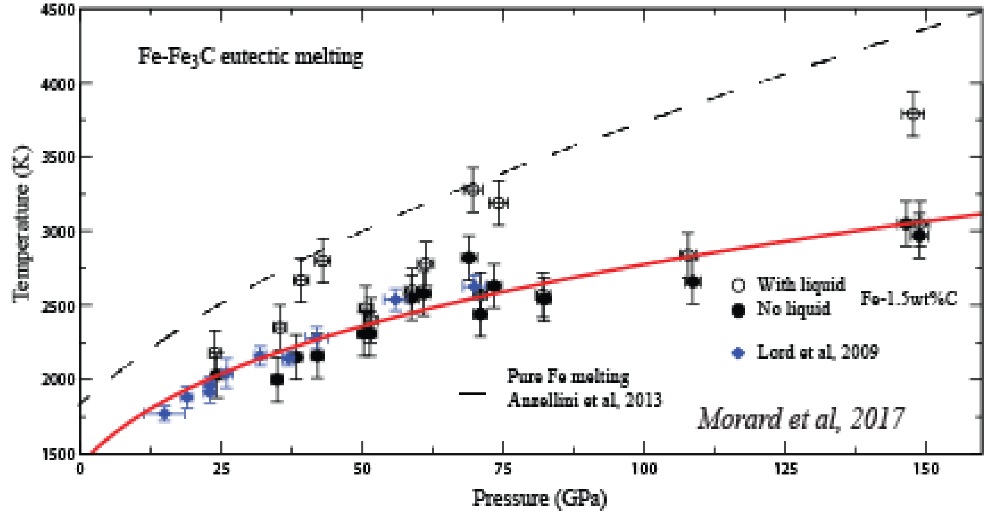


Excellent agreement in the literature for melting of iron alloys

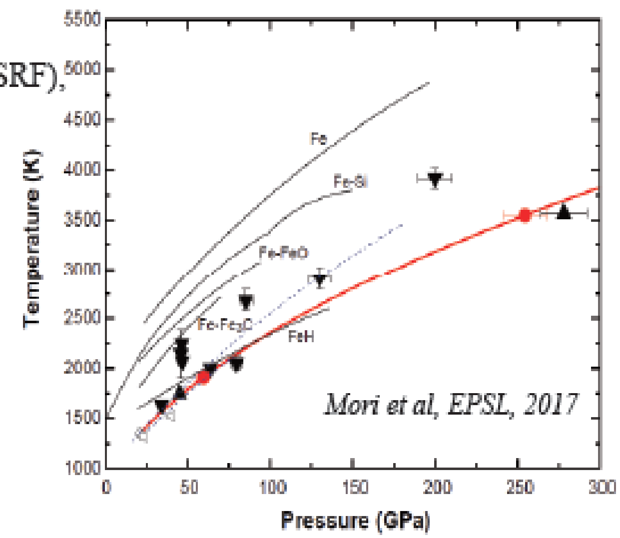
Fe-10wt%Si : XRD (APS, ESRF), laser power vs temperature



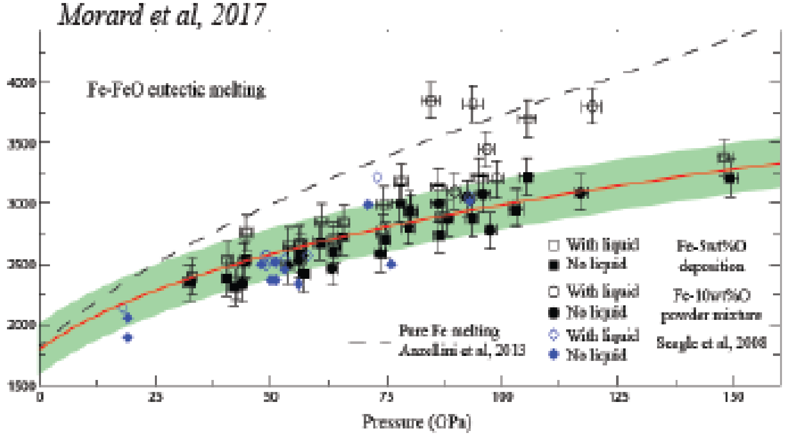
Fe-C system : XRD (APS, ESRF); laser power vs temperature



Fe-S system :
XRD (APS, Spring8, ESRF),
recovered sample

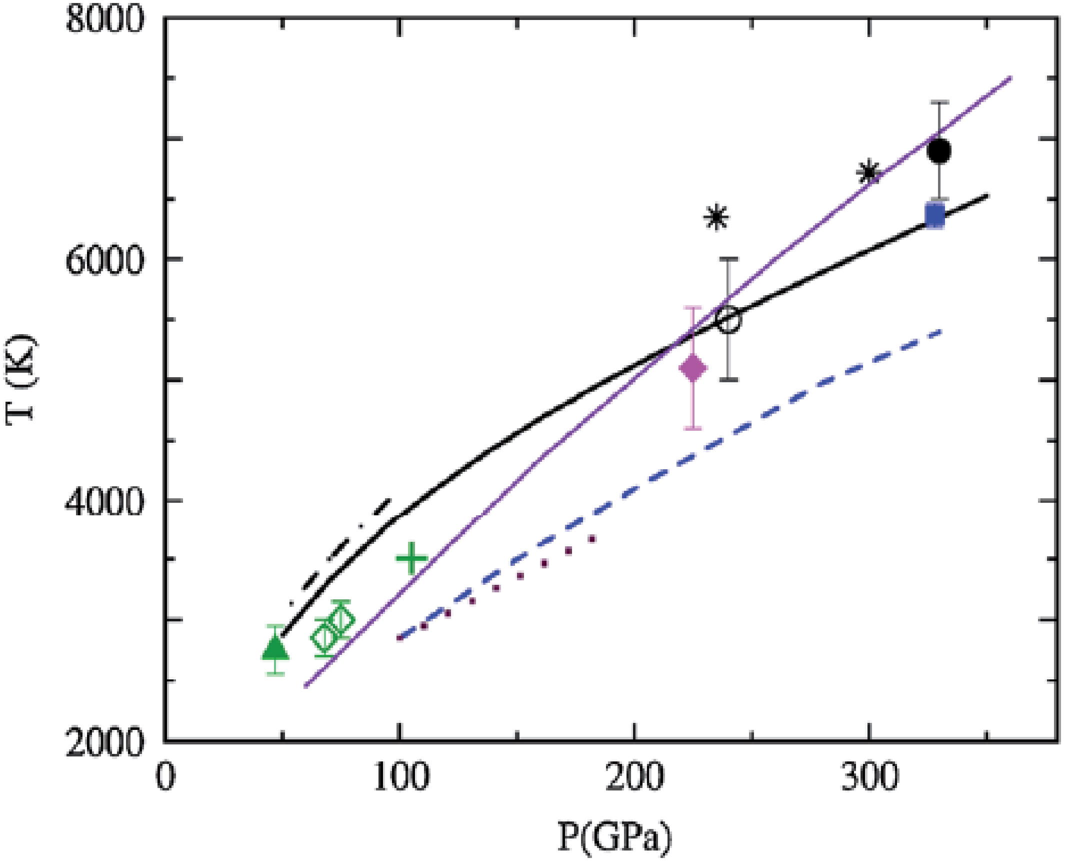


Morard et al, 2017



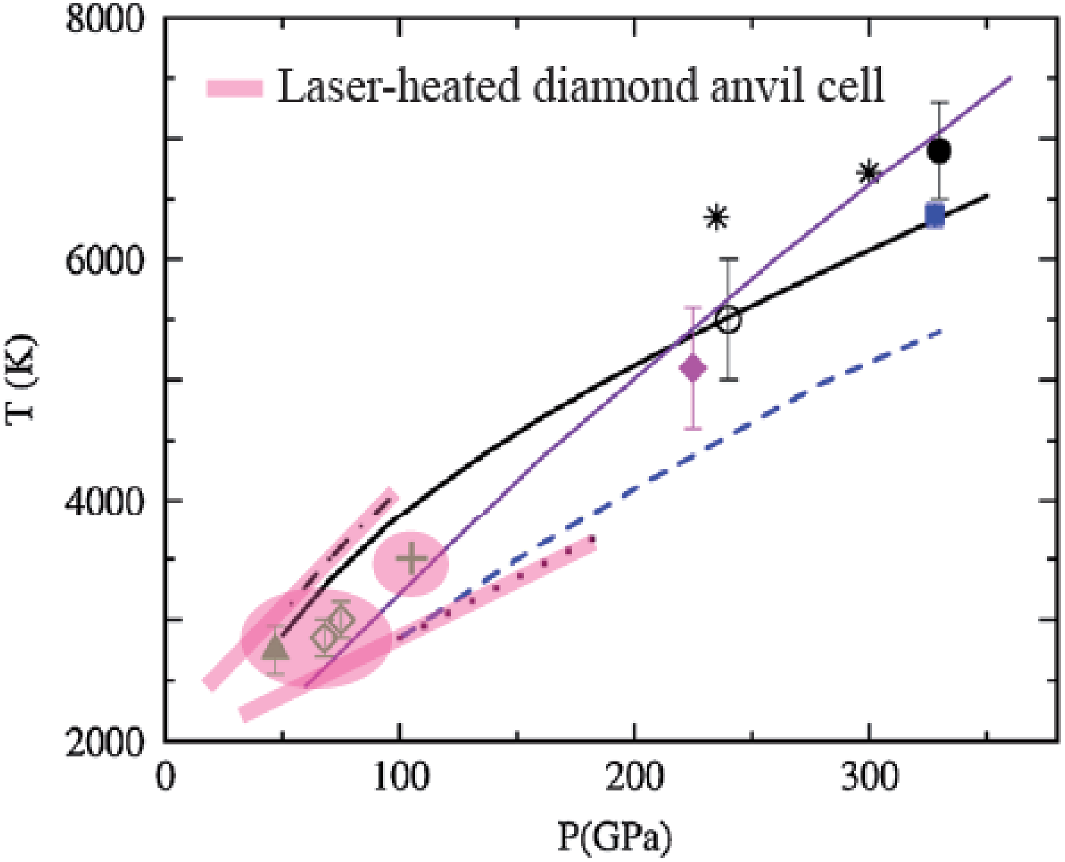
Fe-O system :
XRD (APS, ESRF),
recovered sample

Excellent disagreement in the literature for melting of pure Fe



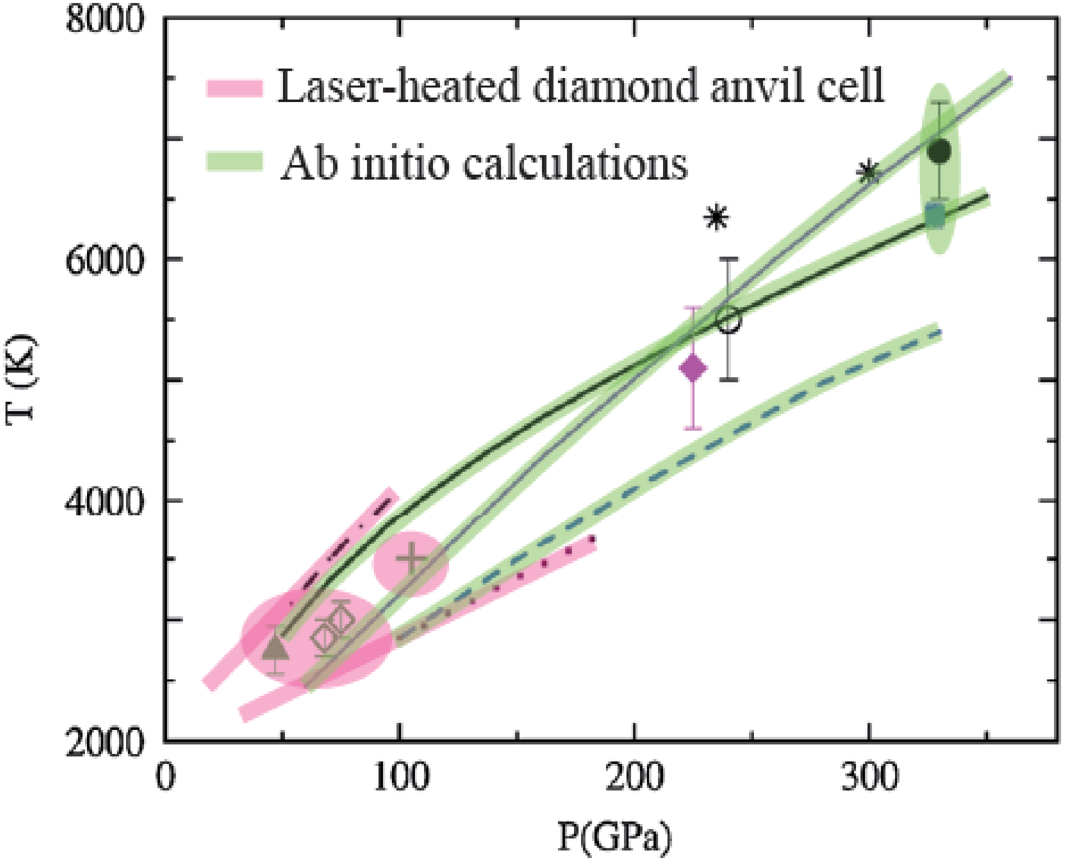
From Sola et al, 2009

Excellent disagreement in the literature for melting of pure Fe



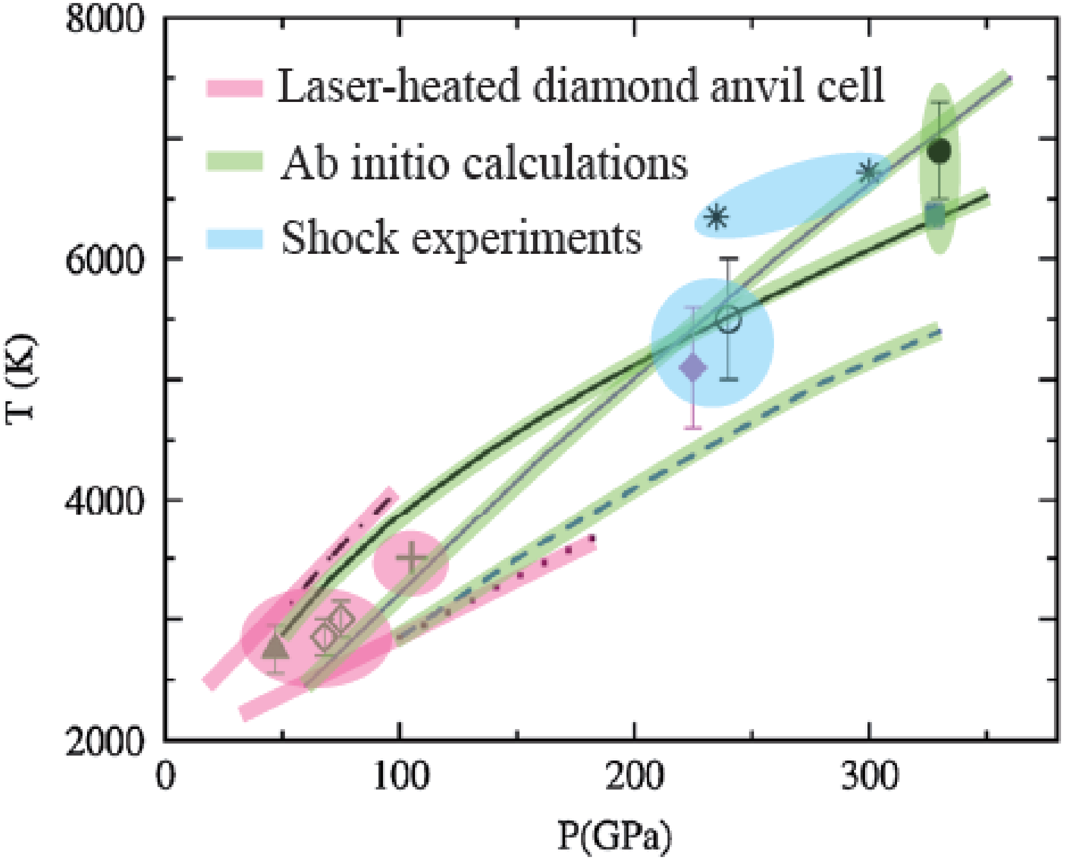
From Sola et al, 2009

Excellent disagreement in the literature for melting of pure Fe



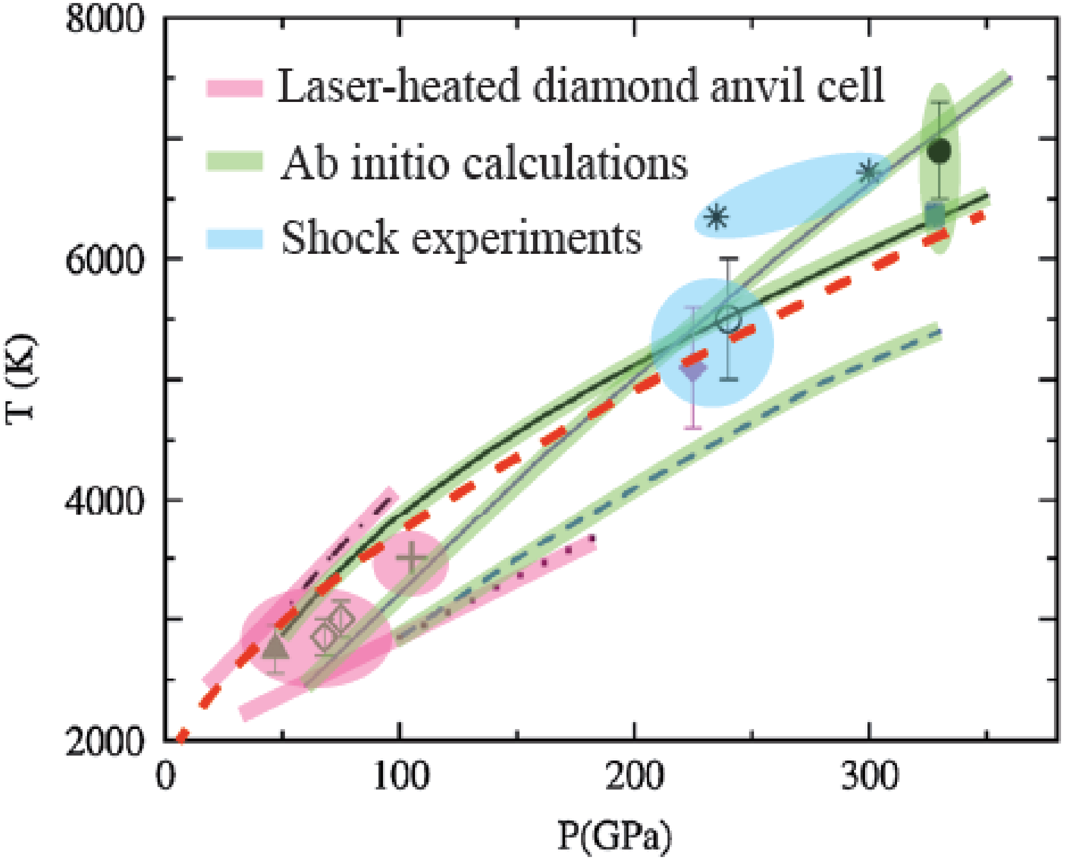
From Sola et al, 2009

Excellent disagreement in the literature for melting of pure Fe



From Sola et al, 2009

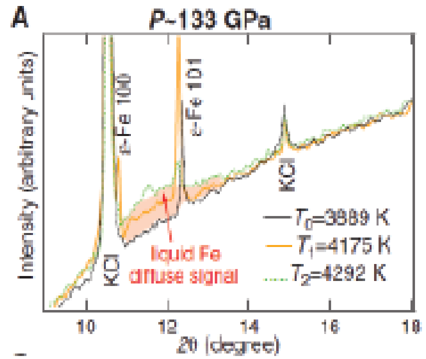
Excellent disagreement in the literature for melting of pure Fe



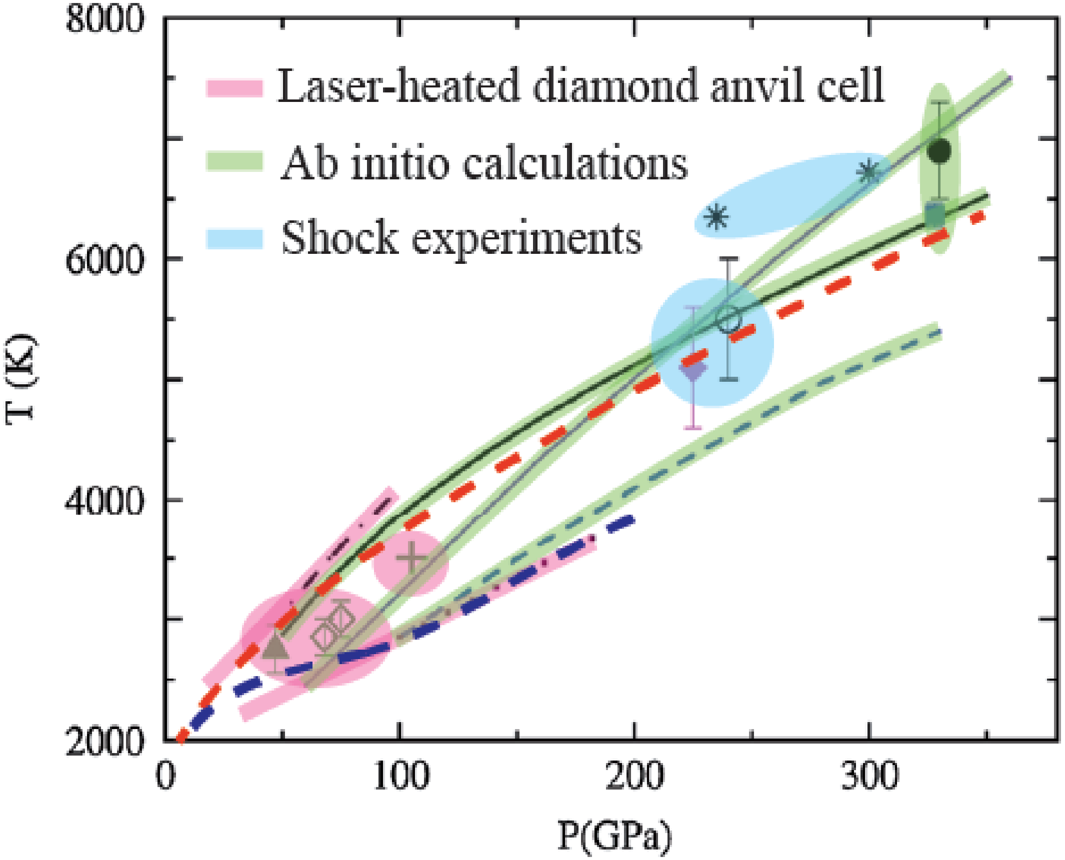
From Sola et al, 2009

Anzellini et al, Science, 2013

Melting by XRD under high pressure

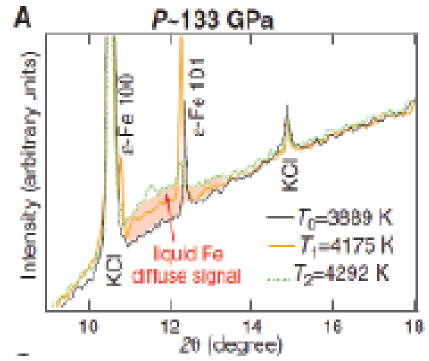


Excellent disagreement in the literature for melting of pure Fe



From Sola et al, 2009

Anzellini et al, Science, 2013
Melting by XRD under high pressure



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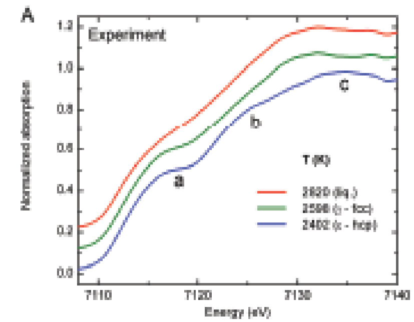
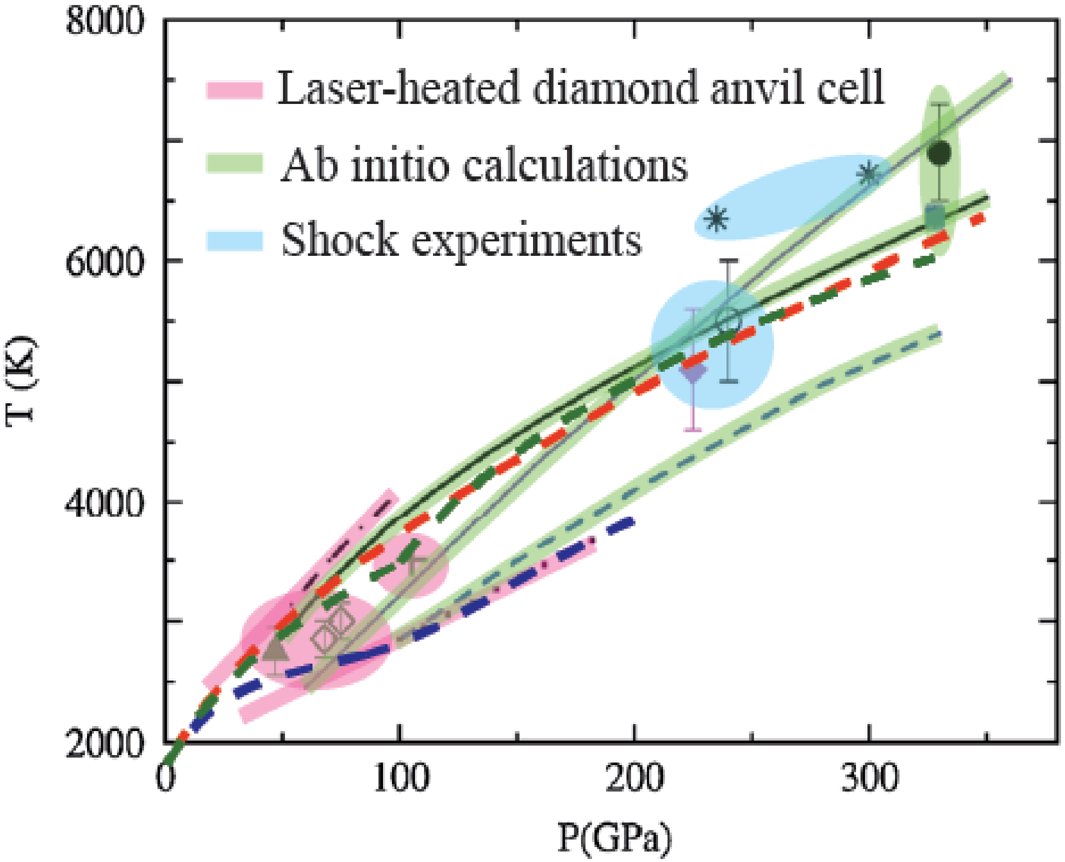
Aquilanti et al, PNAS, 2015
Melting by XANES under high pressure

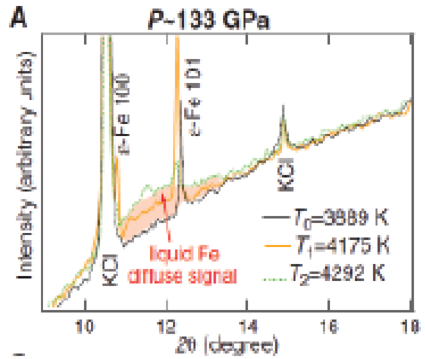


Excellent disagreement in the literature for melting of pure Fe



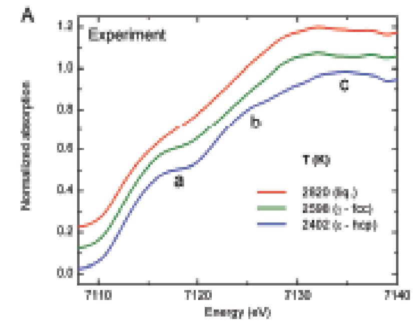
From Sola et al, 2009

Anzellini et al, Science, 2013
Melting by XRD under high pressure



≠

Aquilanti et al, PNAS, 2015
Melting by XANES under high pressure



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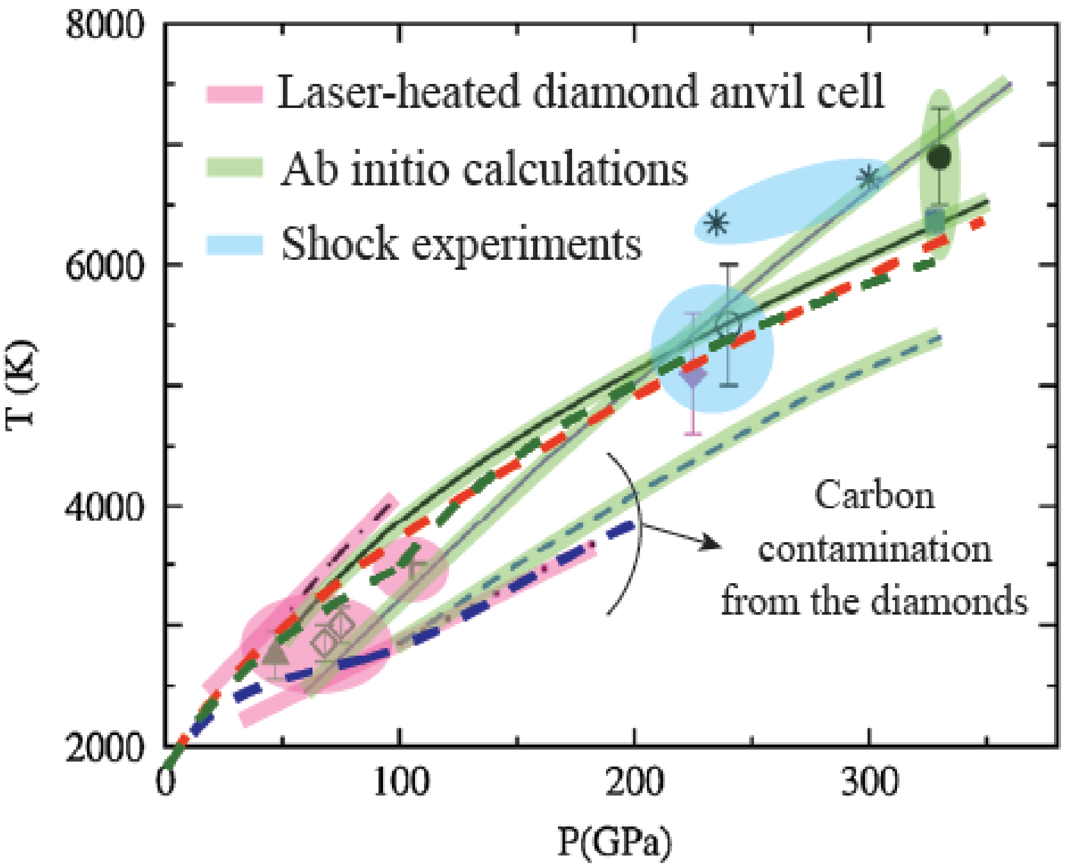
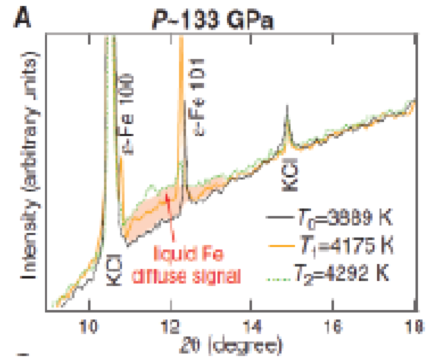
Morard et al, GRL, 2018
Melting by XANES under high pressure

Excellent disagreement in the literature for melting of pure Fe



From Sola et al, 2009

Anzellini et al,
Science, 2013
Melting by XRD
under high pressure



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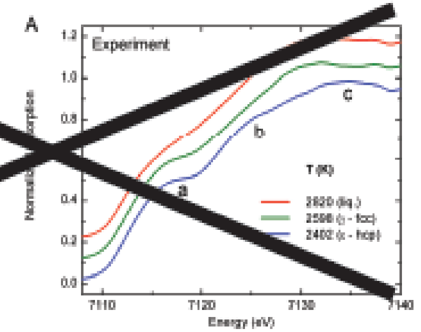
~~Aquilanti et al,~~
~~PNAS, 2015~~
~~Melting by XANES~~
~~under high pressure~~



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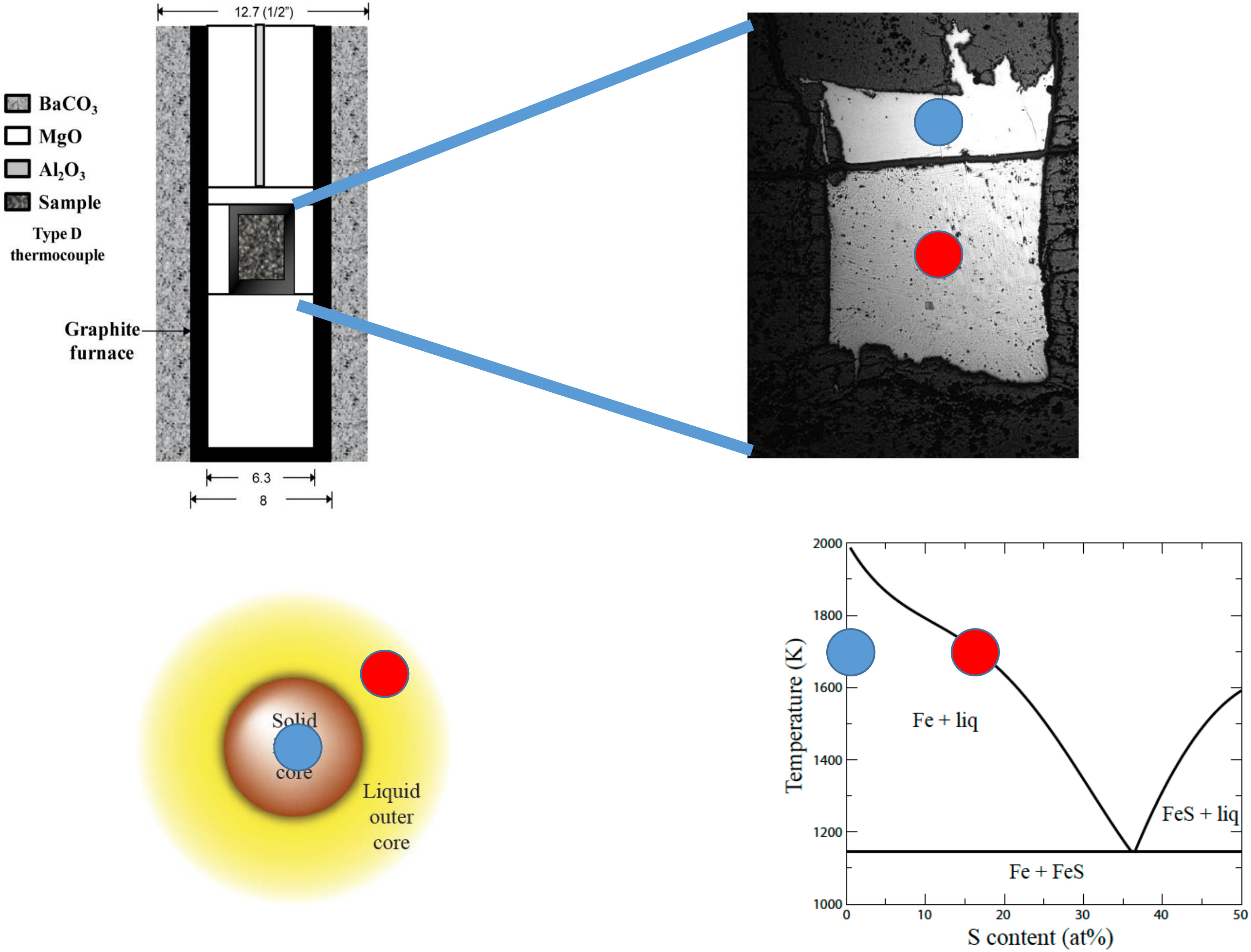
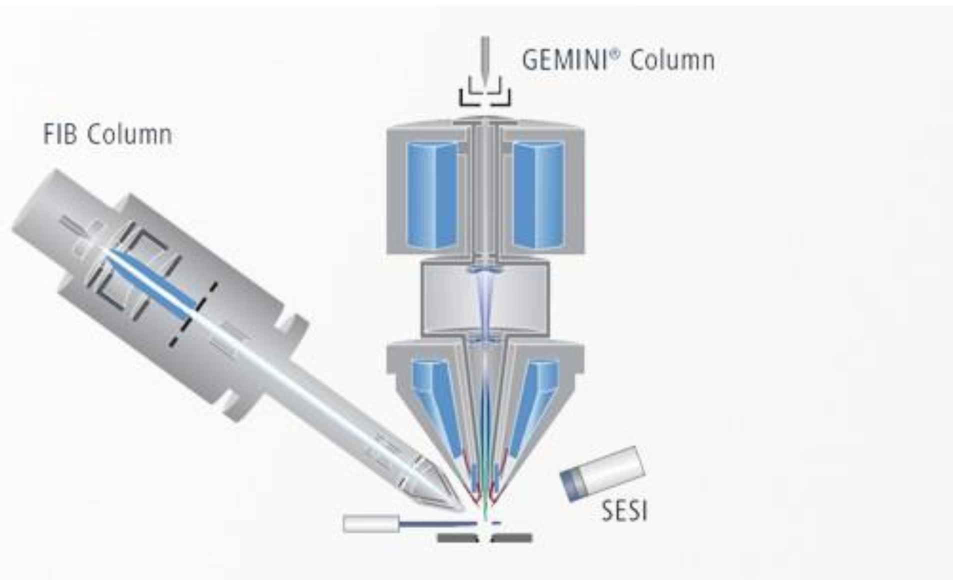
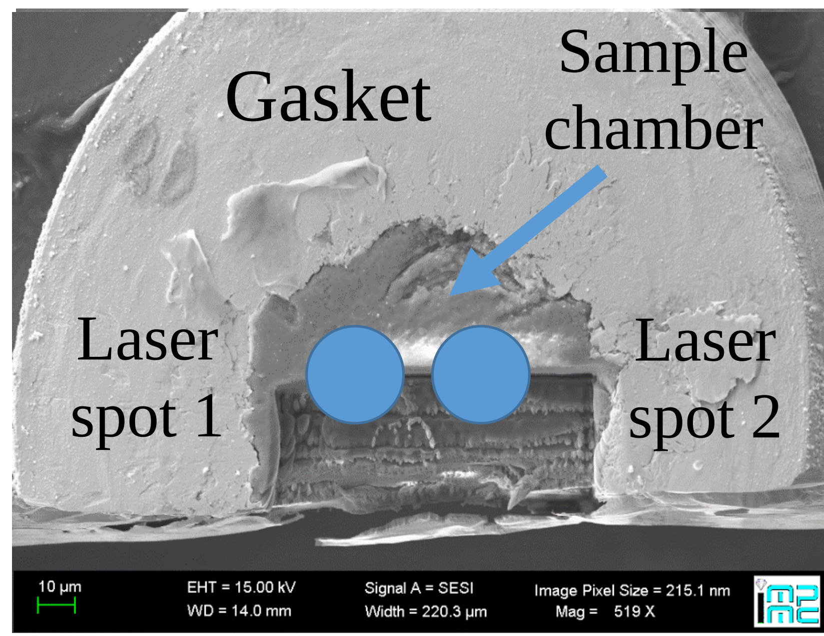
Morard et al,
GRL, 2018
Melting by XANES
under high pressure



after Buono & Walker, GCA 2011

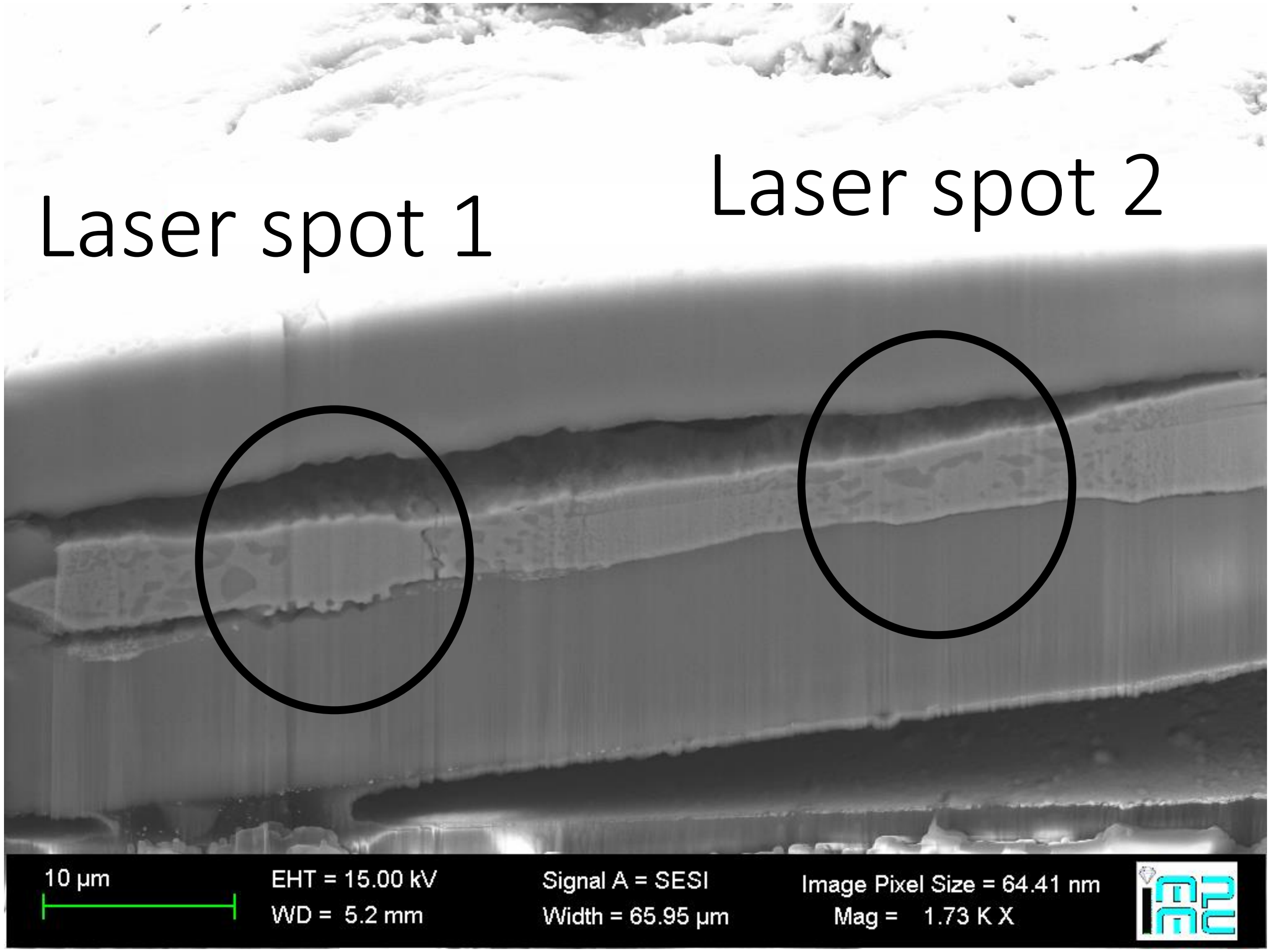
Analysis of post-experiment samples



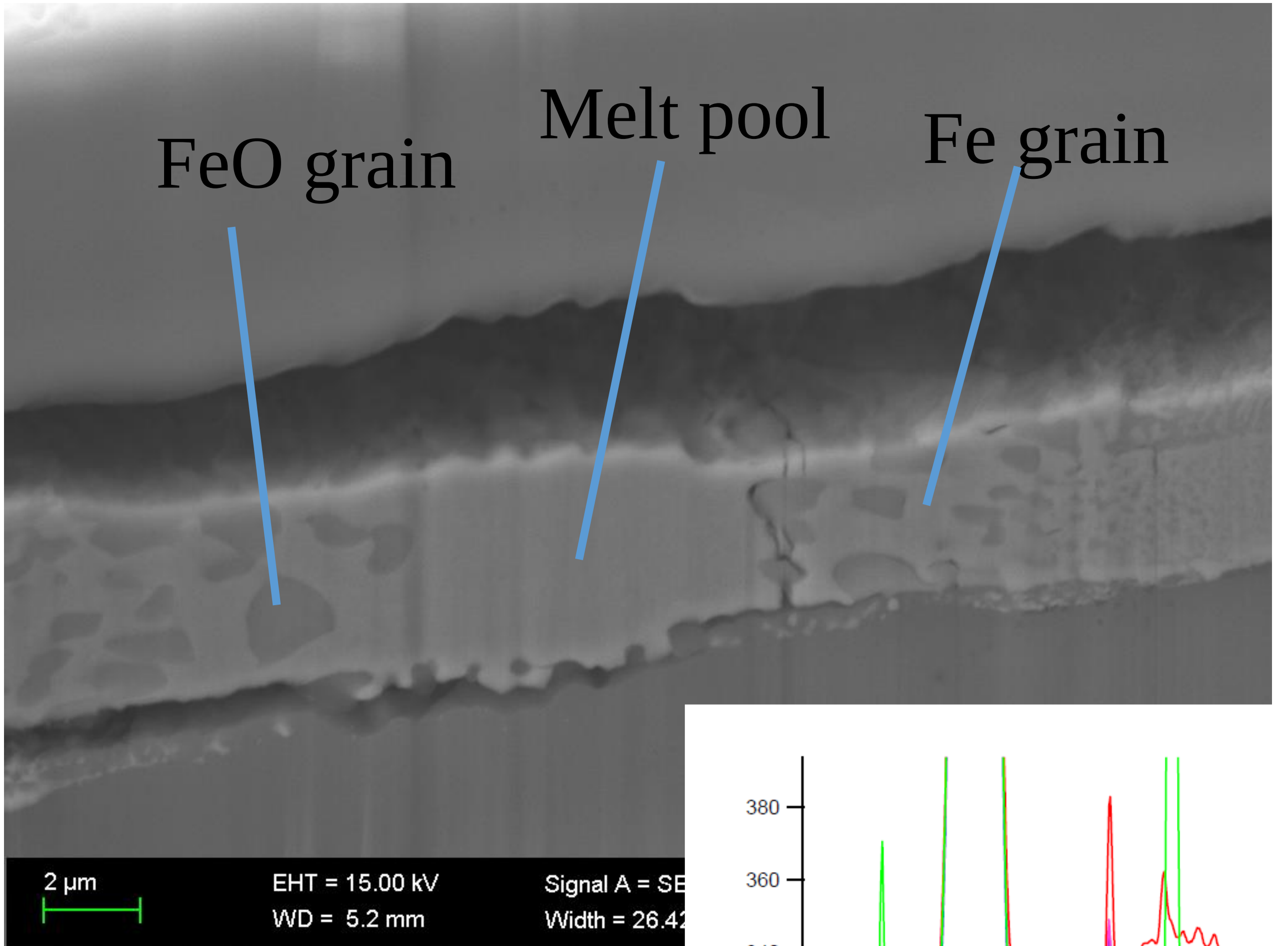


Sample recovered after laser heating experiment at 41 GPa

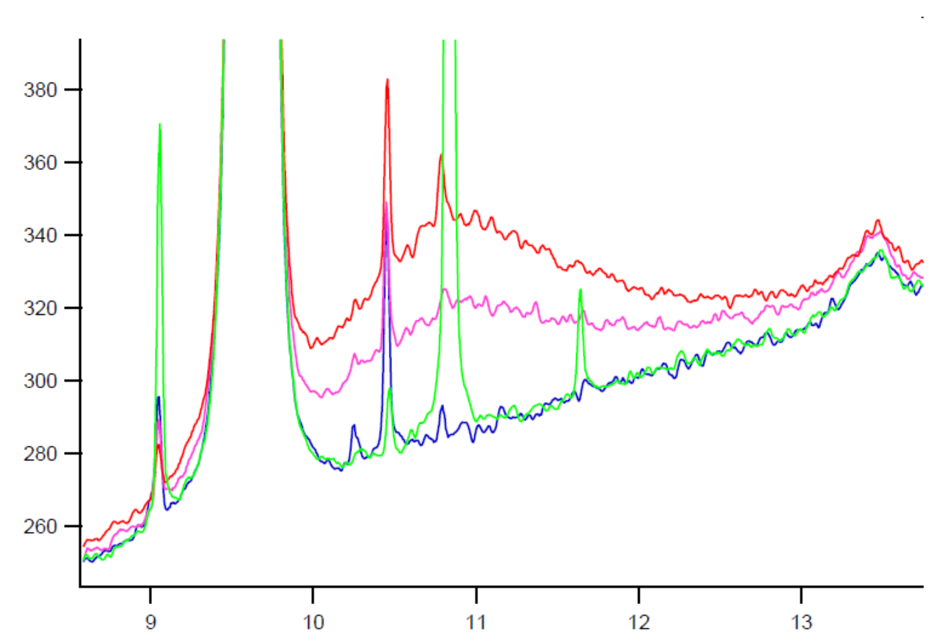
Confirmation from analysis of sample texture after laser heating



Laser spot 1

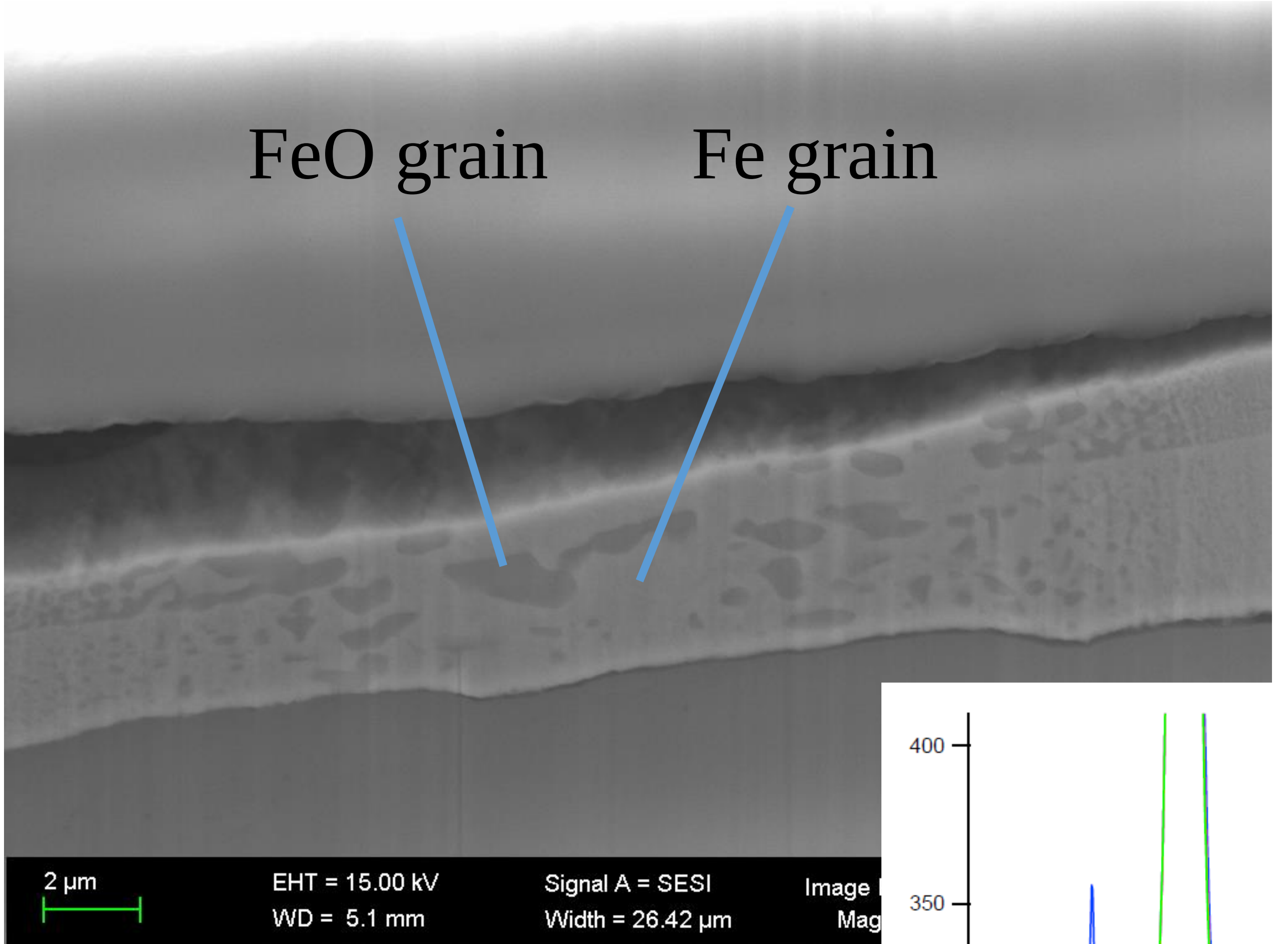


Above melting temperature

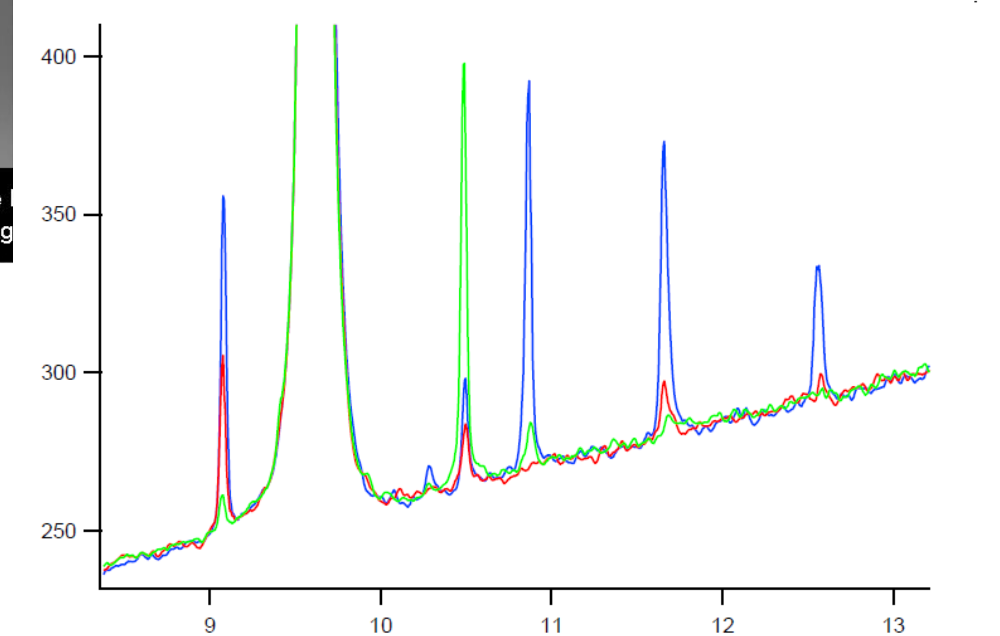


2110 K
2310 K
2390 K
2550 K

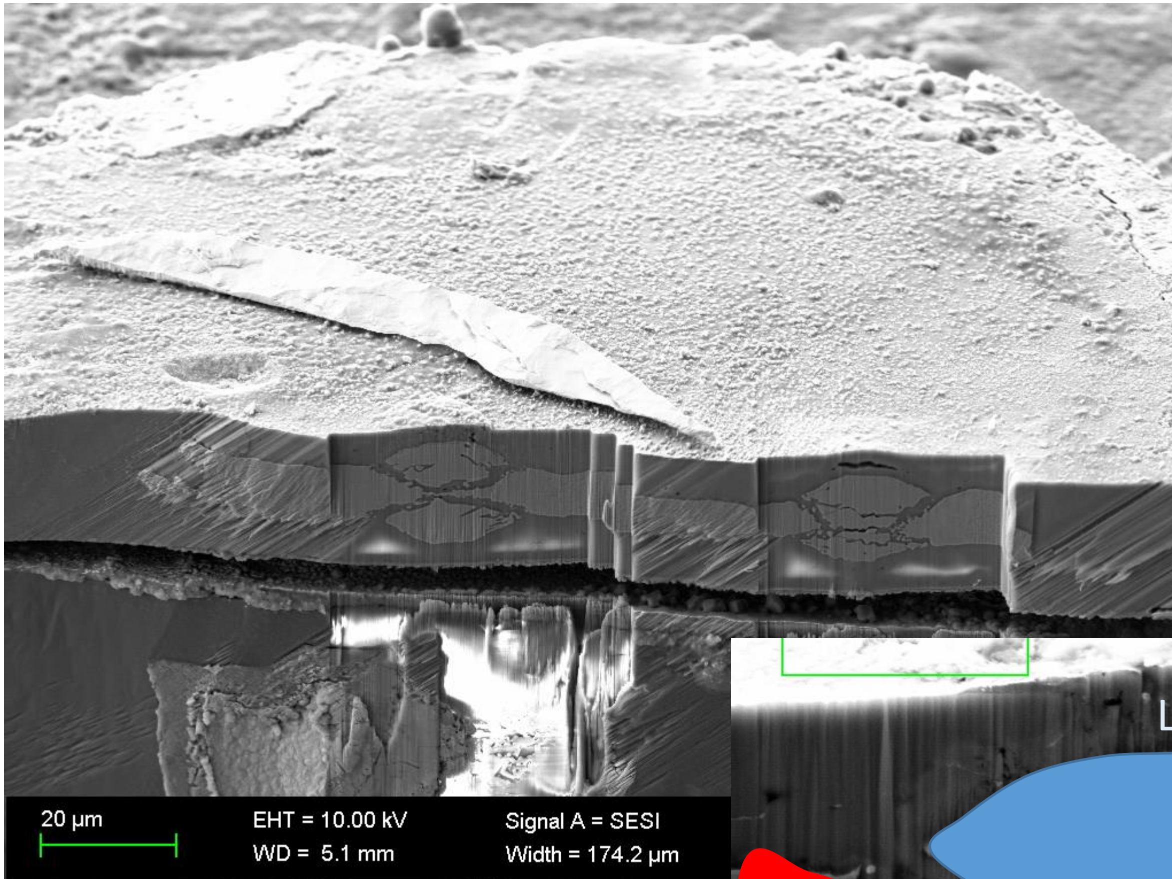
Laser spot 2

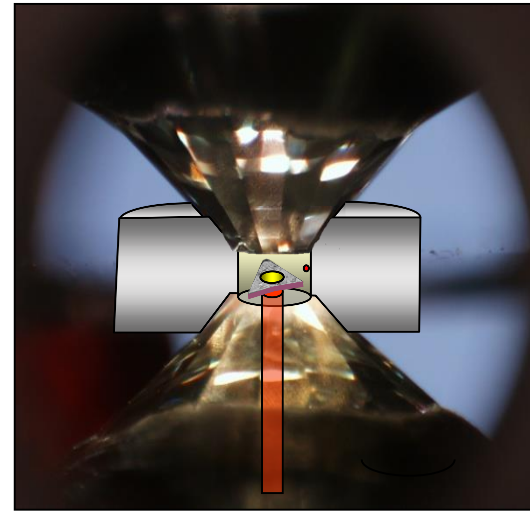


Below melting temperature

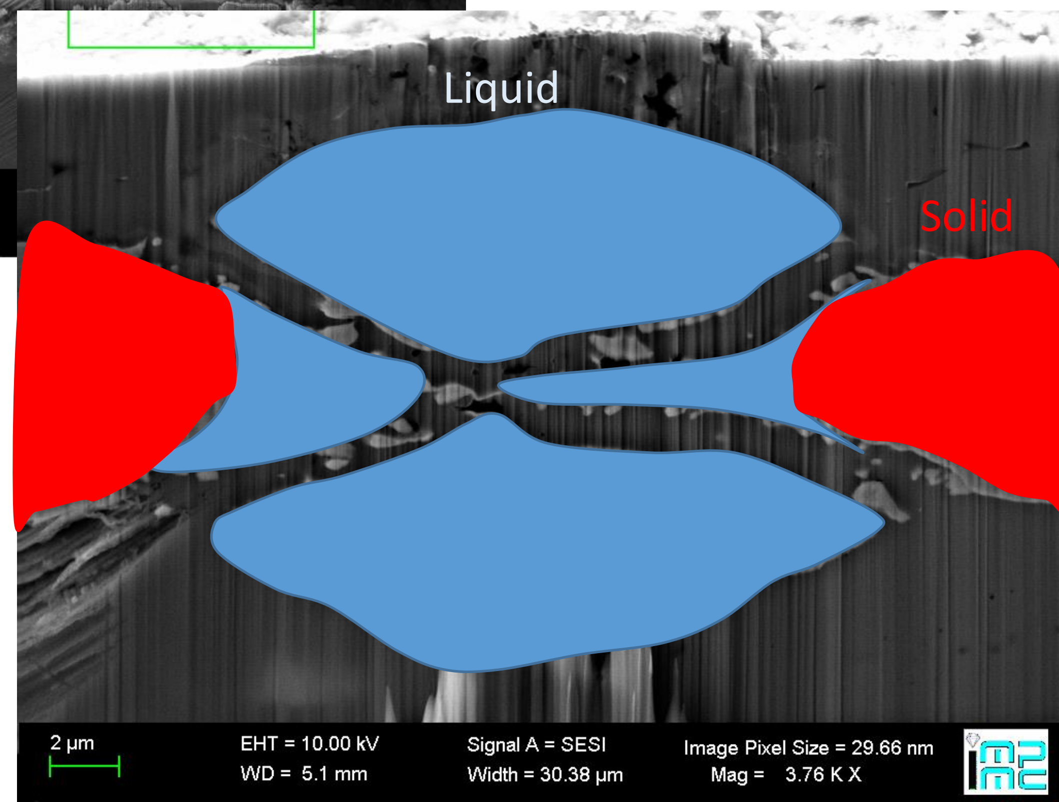


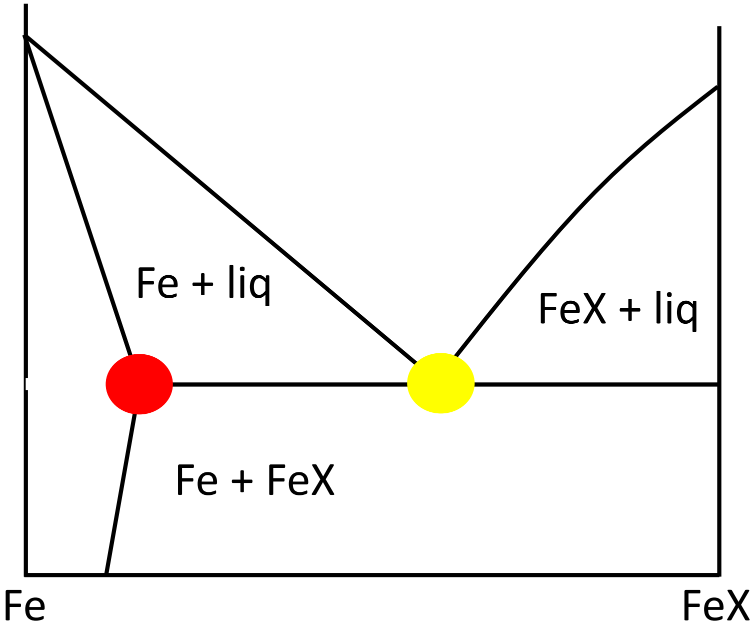
2070 K
2150 K
2170 K

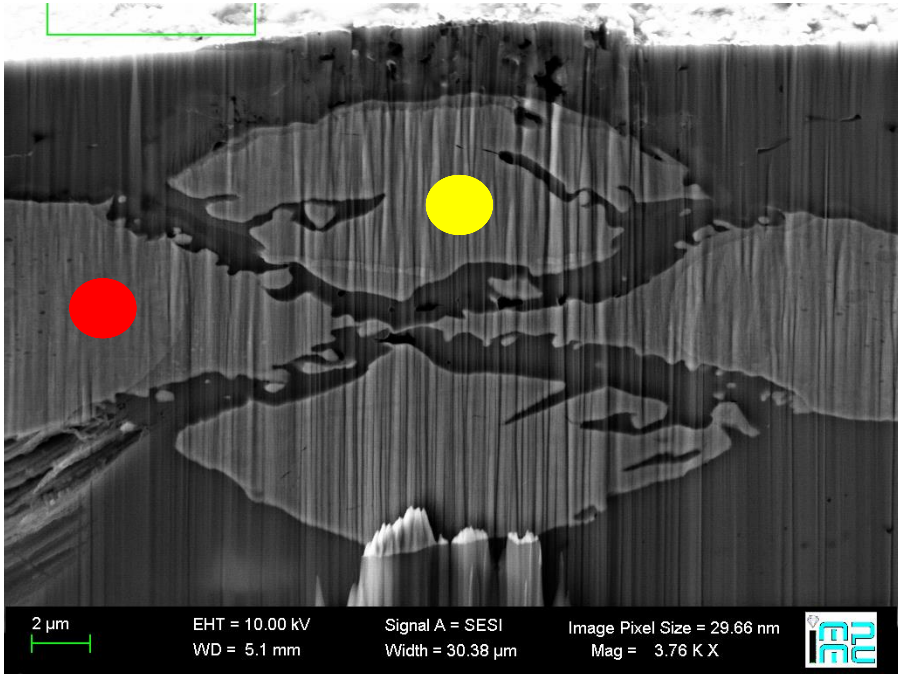




Creating a planetary core experimentally



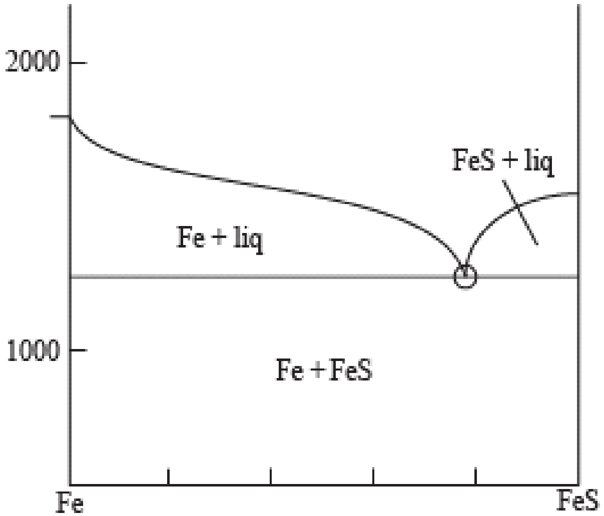


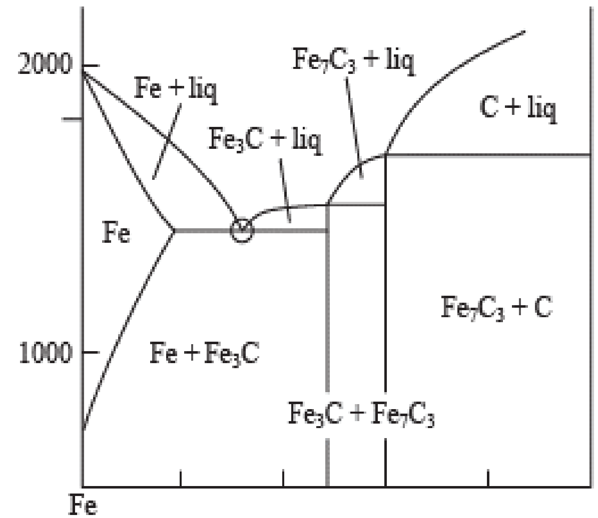


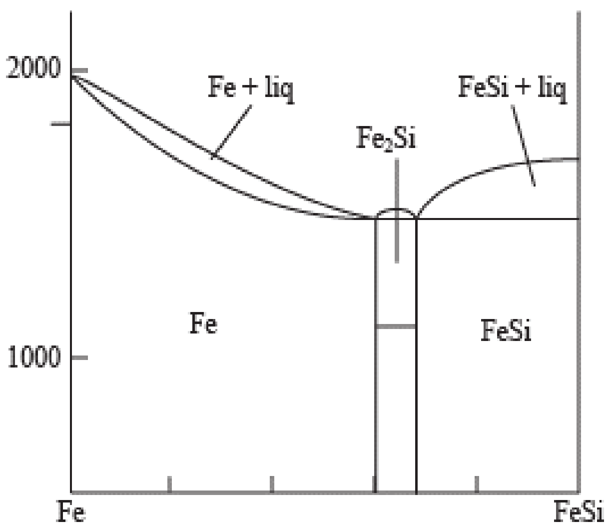
Determination of the phase diagram under high pressure

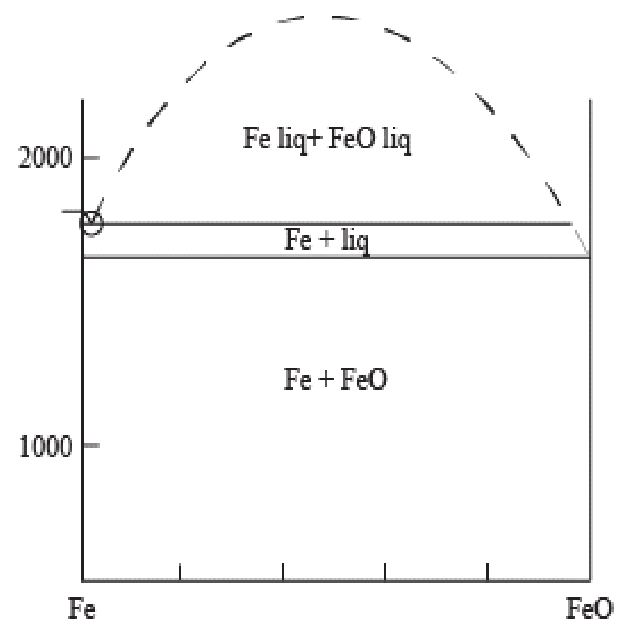
- Fe-FeS system :
- [*Fei et al.*, 2000; *Li et al.*, 2001; *Campbell et al.*, 2007; *Stewart et al.*, 2007; *Buono and Walker*, 2011; *Morard et al.*, 2011; *Kamada et al.*, 2012; *Ozawa et al.*, 2013; *Mori et al.*, 2016]
- Fe-FeSi System :
- [*Kuwayama and Hirose*, 2004; *Morard et al.*, 2011; *Fischer et al.*, 2012, 2013; *Morard et al.*, 2014; *Tateno et al.*, 2015; *Ozawa et al.*, 2016]
- Fe-Fe_3C system:
- [*Chabot et al.*, 2008; *Lord et al.*, 2009; *Nakajima et al.*, 2009; *Fei and Brosh*, 2014; *Liu et al.*, 2016; *Morard et al.*, 2017]
- Fe-FeO system:
- [*Ringwood and Hibberson*, 1990; *Alfe et al.*, 2000; *Tsuno et al.*, 2007; *Seagle et al.*, 2008; *Tsuno and Ohtani*, 2009; *Morard et al.*, 2017]

Ambient pressure

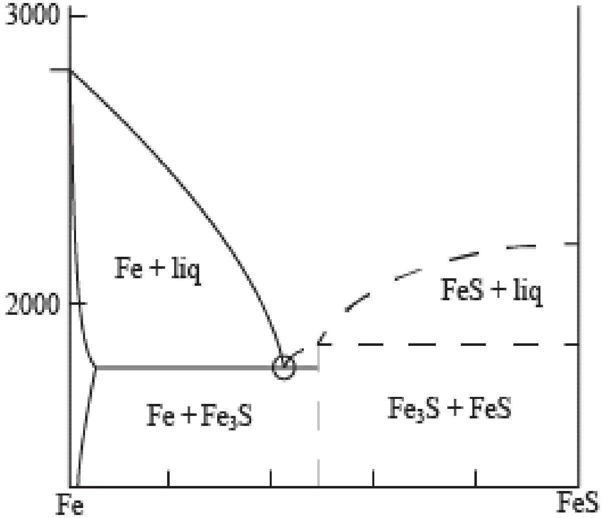


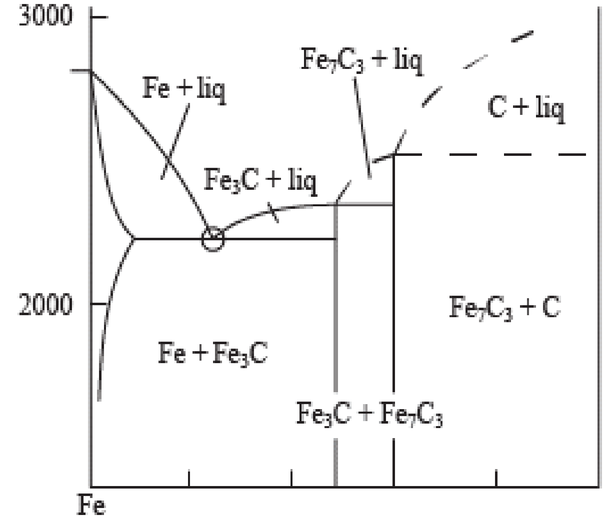


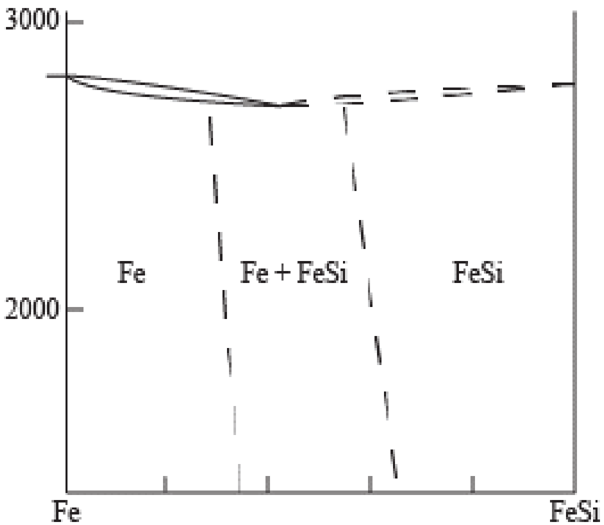


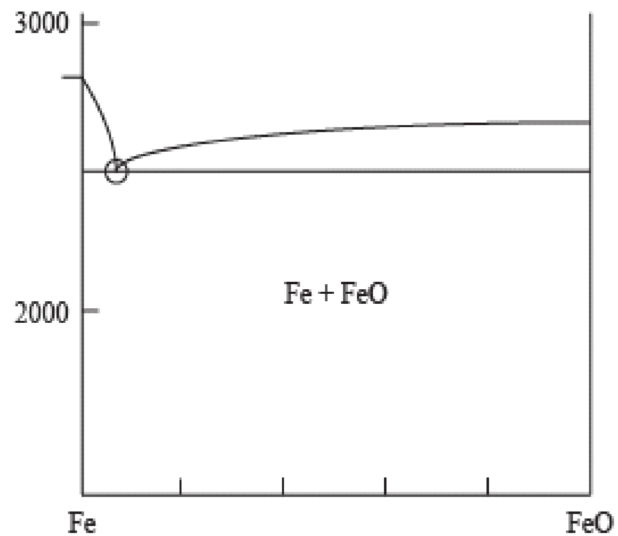


P=40 GPa

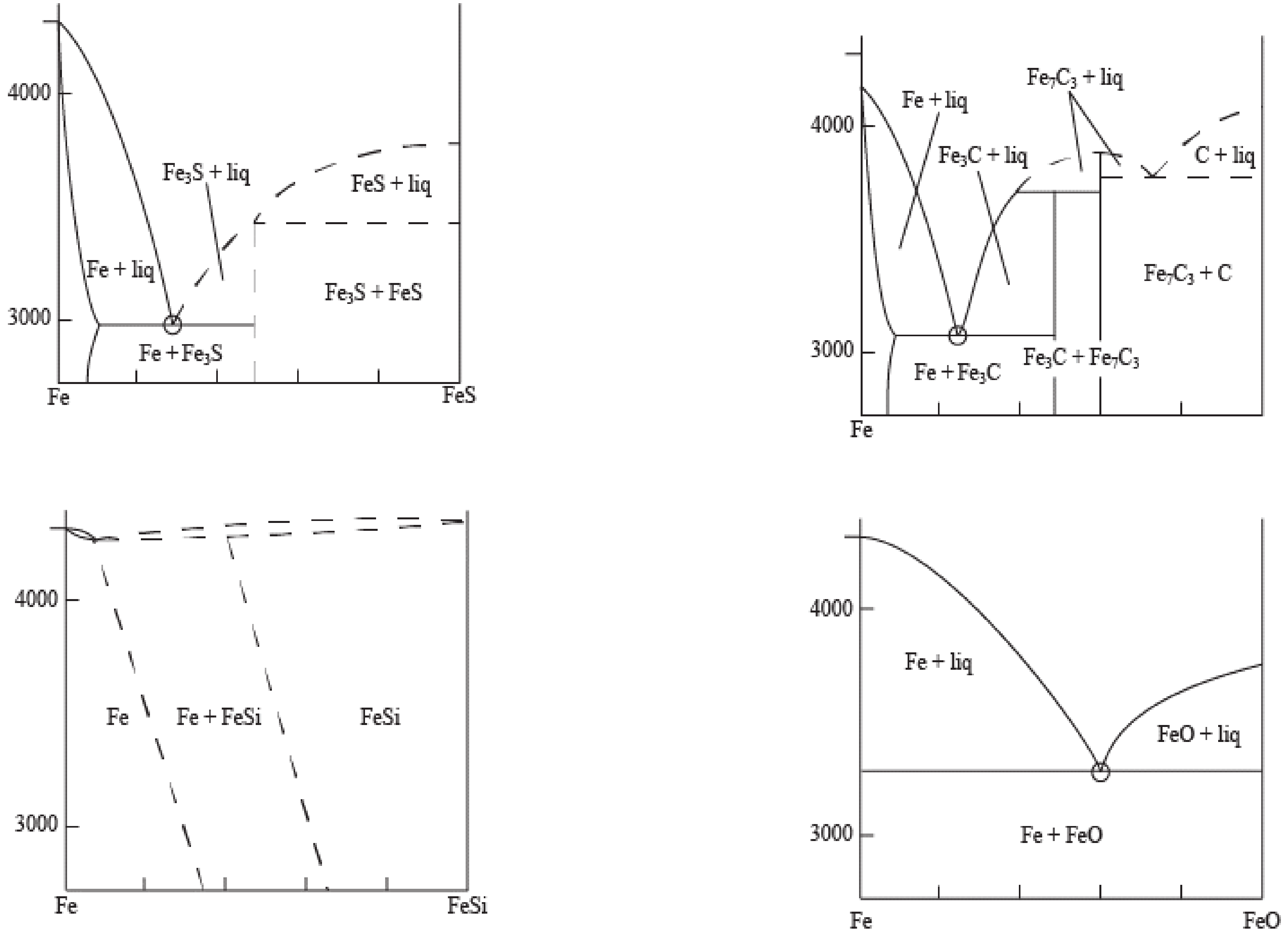

3000
2000
Fe + liq
FeS + liq
Fe + Fe_3S
Fe_3S + FeS
Fe
FeS


3000
2000
Fe + liq
Fe_7C_3 + liq
C + liq
Fe_3C + liq
Fe_7C_3 + C
Fe + Fe_3C
Fe_3C + Fe_7C_3
Fe

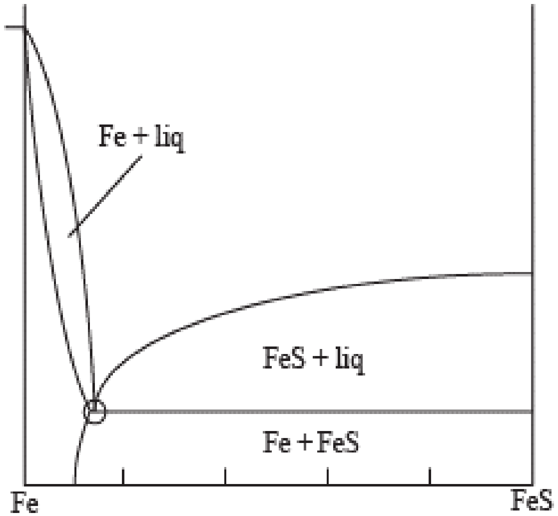

3000
2000
Fe
Fe + FeSi
FeSi
Fe
FeSi


3000
2000
Fe + FeO
Fe
FeO

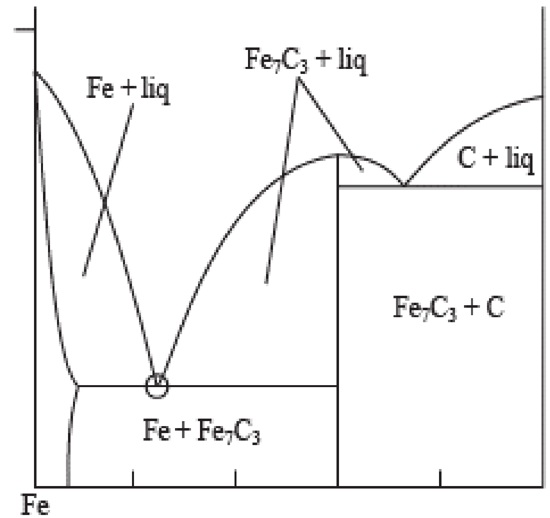
P=136 GPa


4000
3000
Fe3S + liq
FeS + liq
Fe + liq
Fe3S + FeS
Fe + Fe3S
Fe
FeS
Fe + liq
Fe7C3 + liq
4000
Fe3C + liq
C + liq
Fe7C3 + C
3000
Fe + Fe3C
Fe3C + Fe7C3
Fe
4000
3000
Fe
Fe + FeSi
FeSi
Fe
FeSi
4000
Fe + liq
FeO + liq
3000
Fe + FeO
Fe
FeO

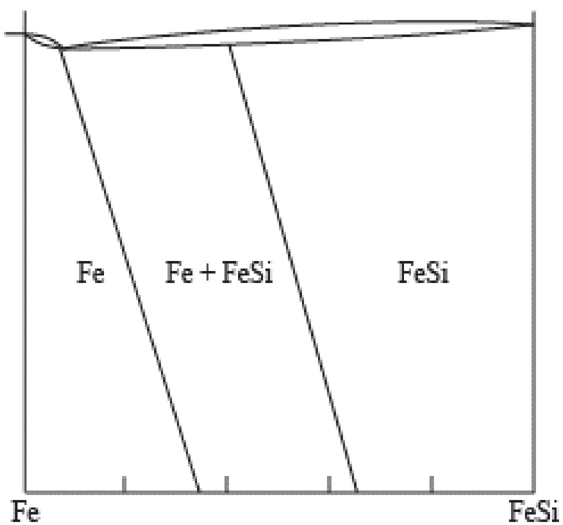
P=330 GPa



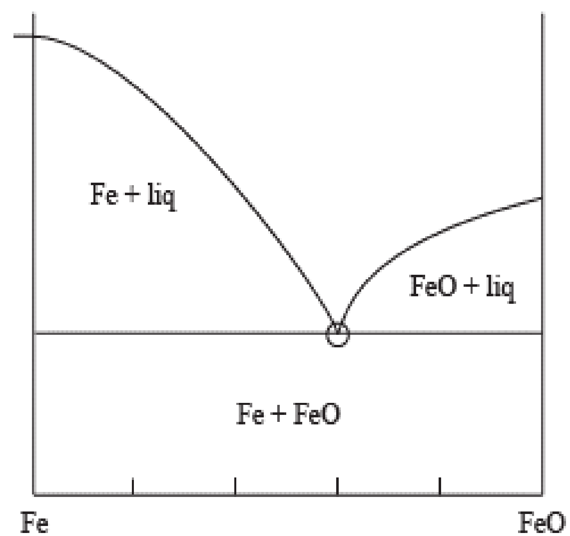
Fe + liq
FeS + liq
Fe + FeS
Fe
FeS



Fe + liq
Fe_7C_3 + liq
C + liq
Fe_7C_3 + C
Fe + Fe_7C_3
Fe

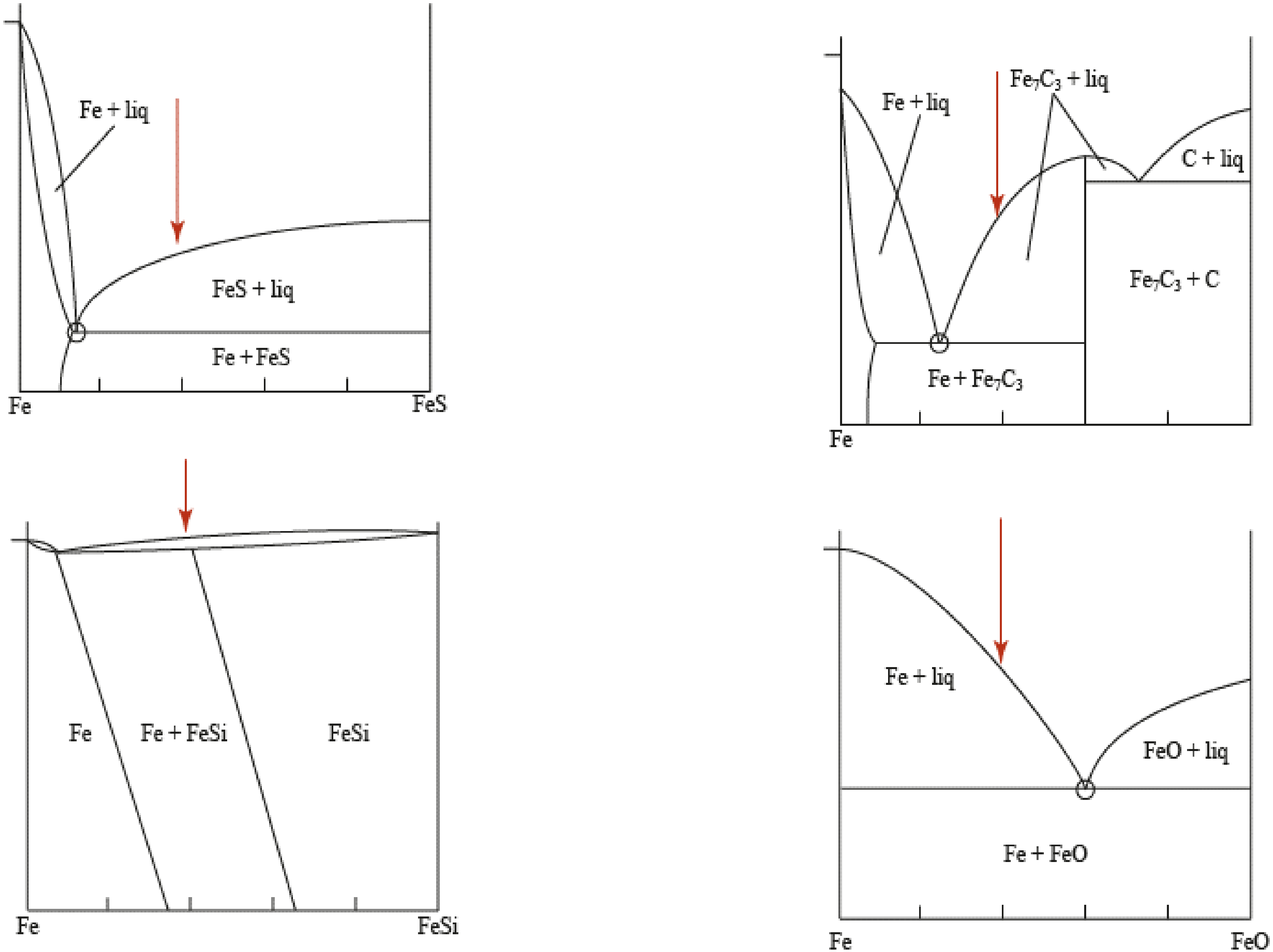


Fe
Fe + FeSi
FeSi
Fe
FeSi

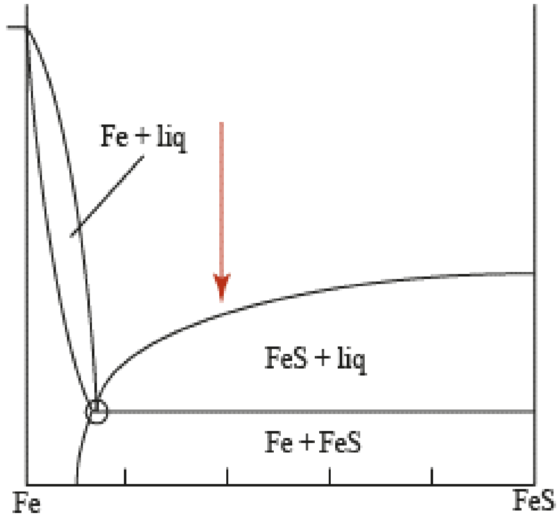


Fe + liq
FeO + liq
Fe + FeO
Fe
FeO

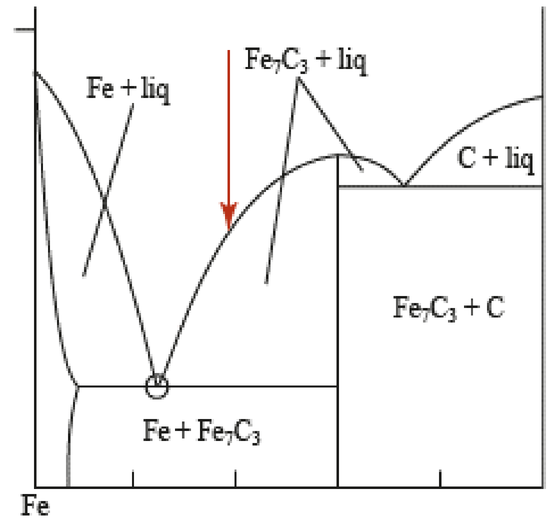
P=330 GPa

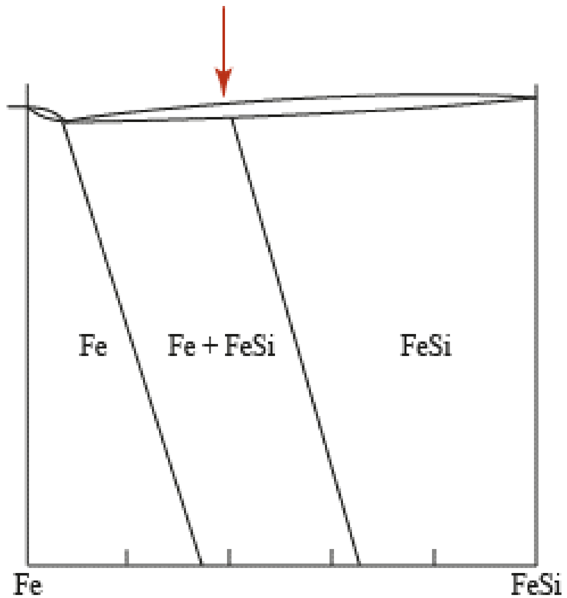

Fe + liq
FeS + liq
Fe + FeS
Fe
FeS
Fe₇C₃ + liq
Fe + liq
C + liq
Fe₇C₃ + C
Fe + Fe₇C₃
Fe
Fe
Fe + FeSi
FeSi
Fe
FeSi
Fe + liq
FeO + liq
Fe + FeO
Fe
FeO

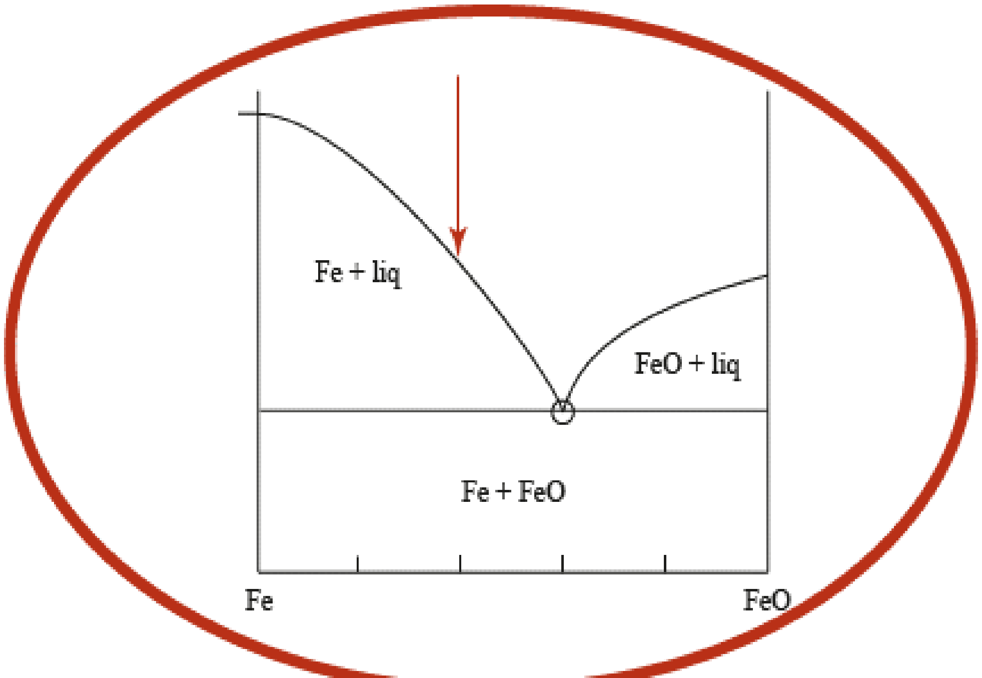
P=330 GPa



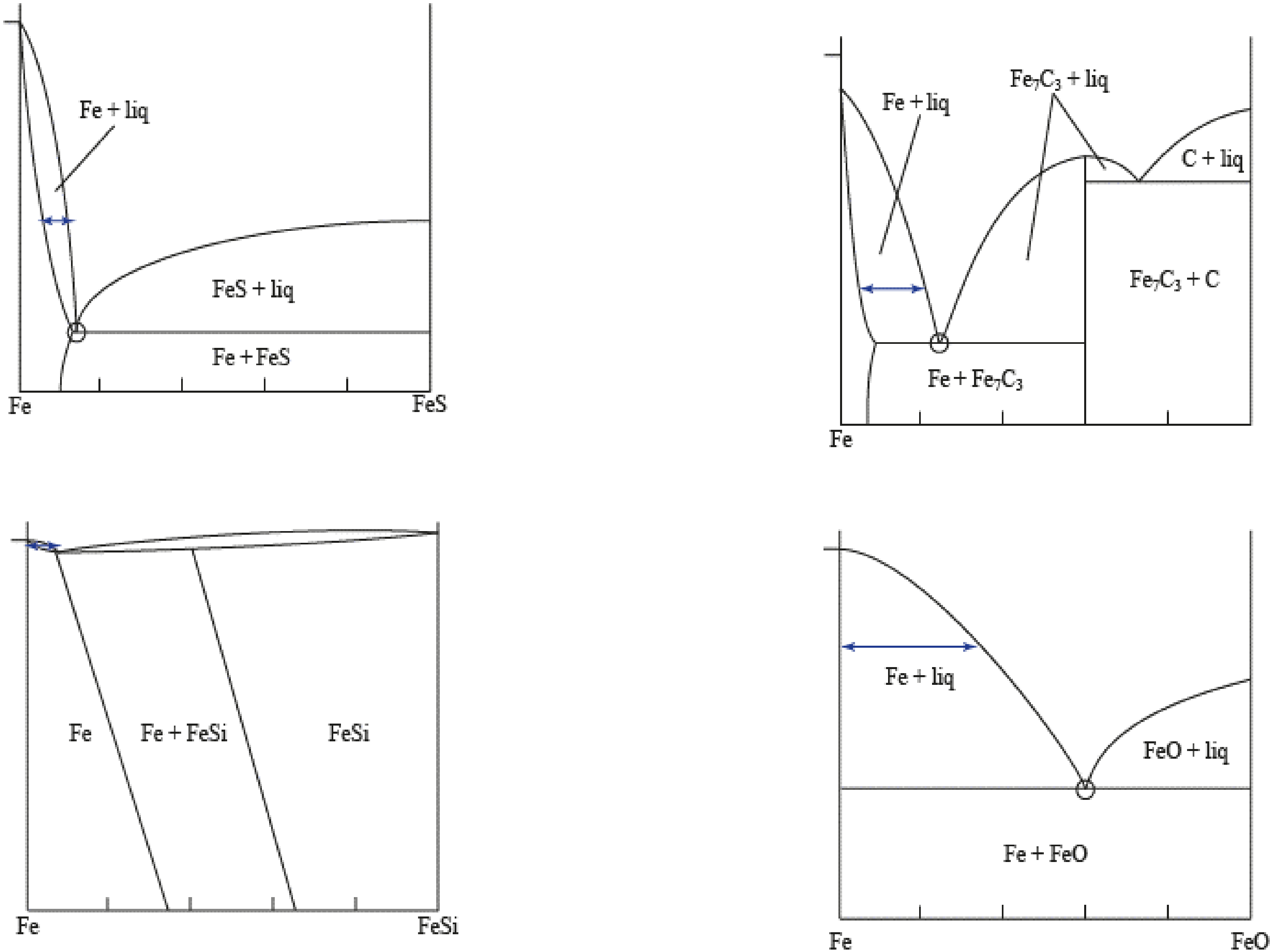
To have a Fe inner core, Oxygen is required



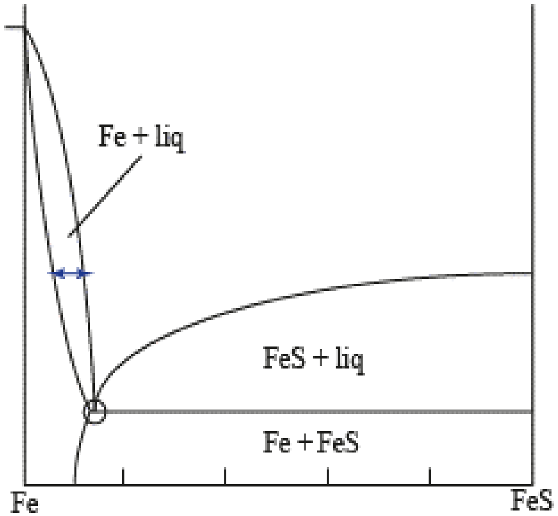




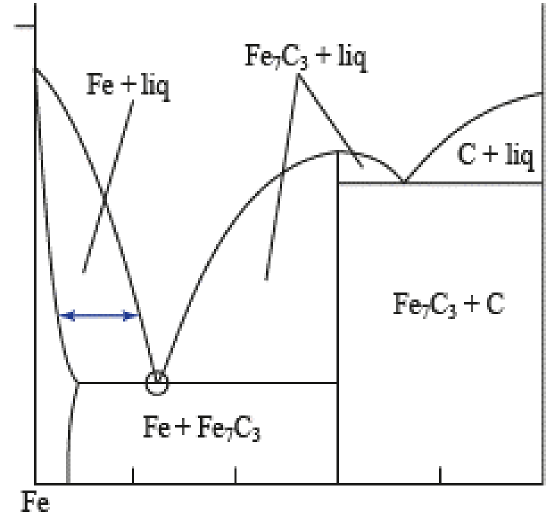
P=330 GPa

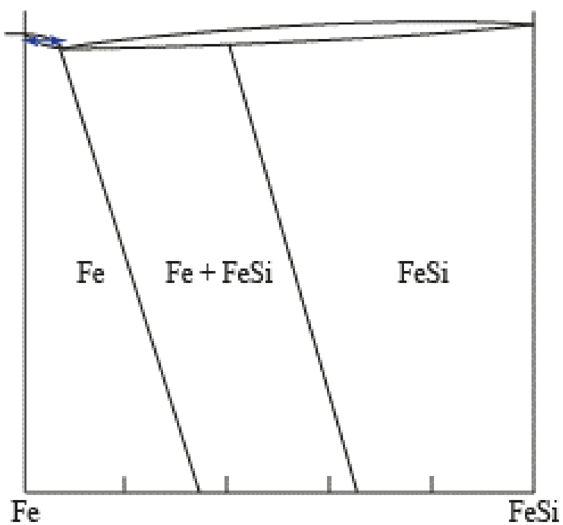

Fe + liq
FeS + liq
Fe + FeS
Fe
FeS
Fe_7C_3 + liq
Fe + liq
C + liq
Fe_7C_3 + C
Fe + Fe_7C_3
Fe
Fe
Fe + FeSi
FeSi
Fe
FeSi
Fe + liq
FeO + liq
Fe + FeO
Fe
FeO

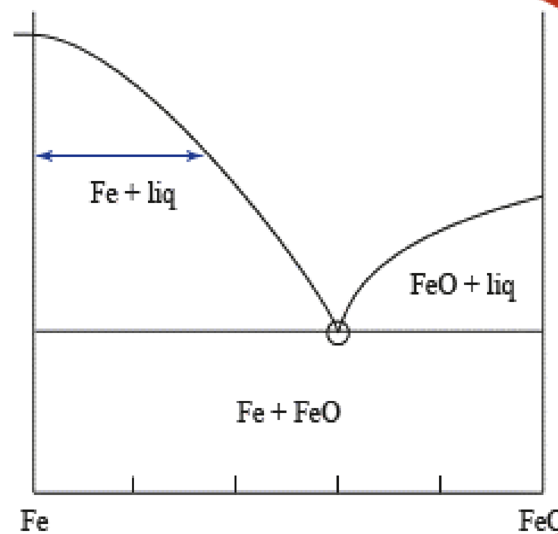
P=330 GPa



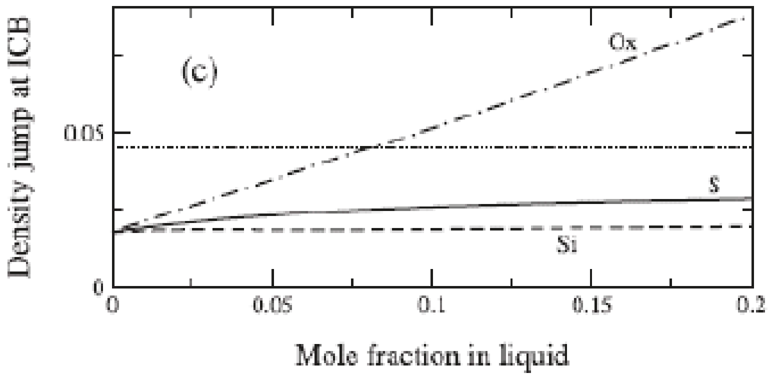
To account for the density difference between inner and outer core, Oxygen is required





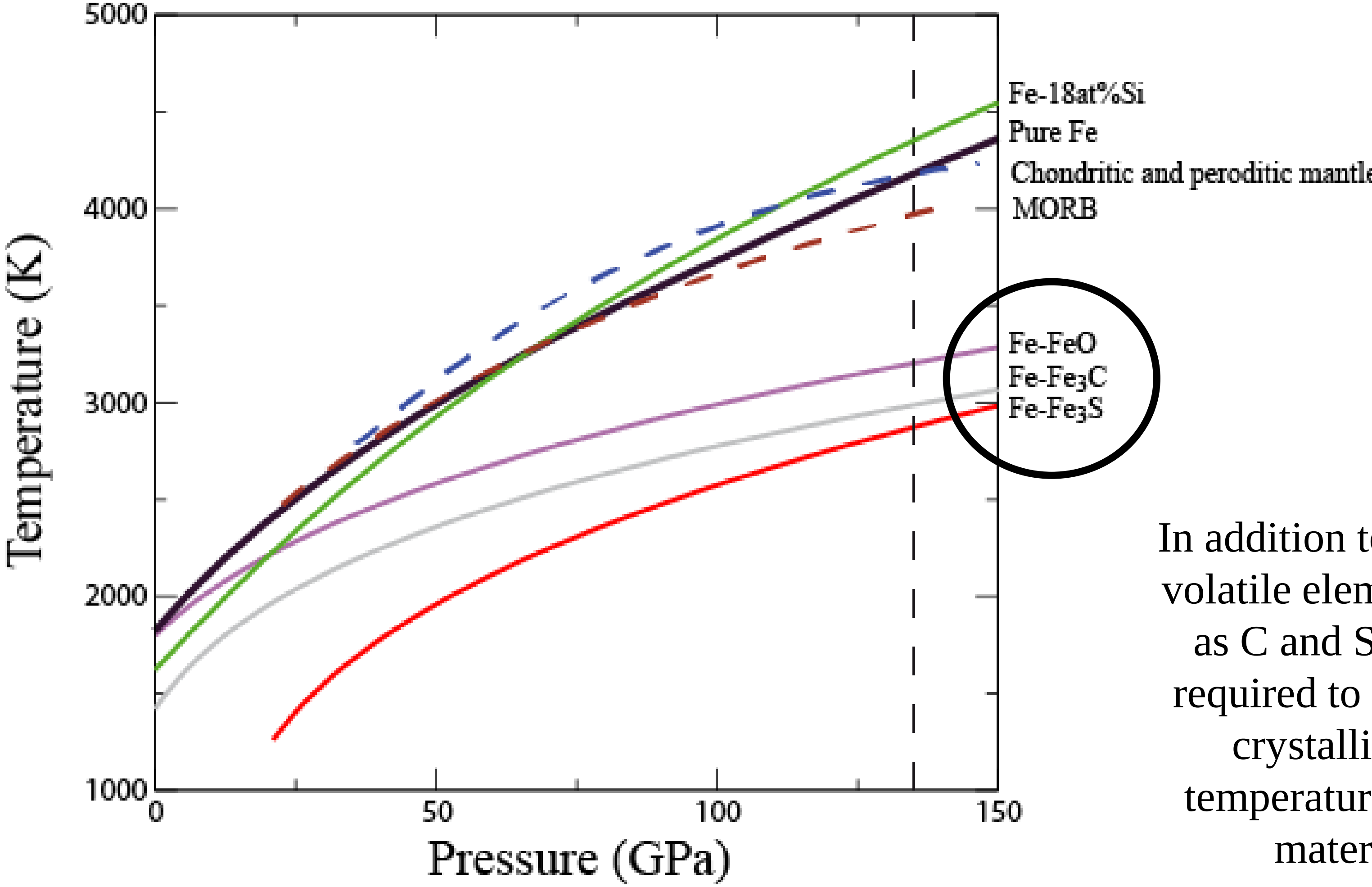


Phase diagrams of iron alloys under Earth's core conditions



Alfè et al, EPSL, 2002

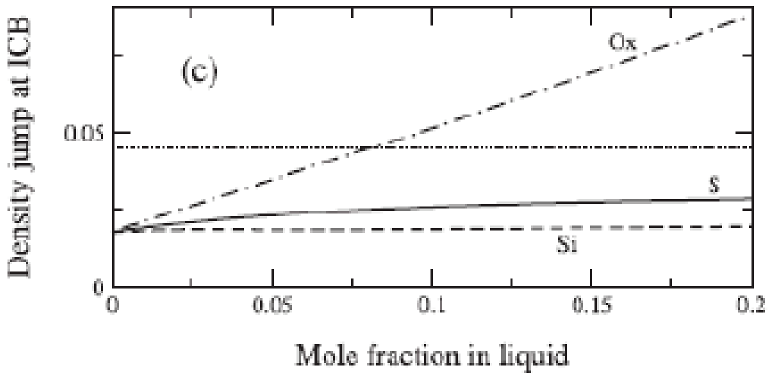
Oxygen is required to explain the liquid/solid density difference in the Earth's core



In addition to Oxygen, volatile elements such as C and S may be required to lower the crystallisation temperature of core materials

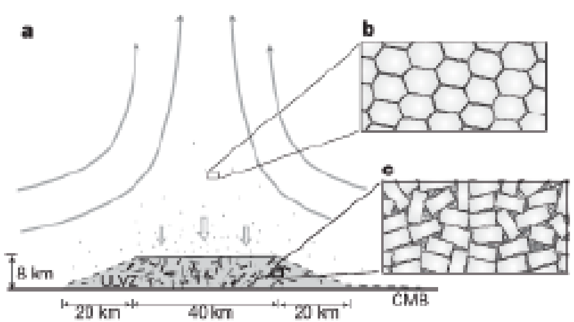
Morard et al, Earth Planetary Science Letters, 2017

Phase diagrams of iron alloys under Earth's core conditions



Alfè et al, EPSL, 2002

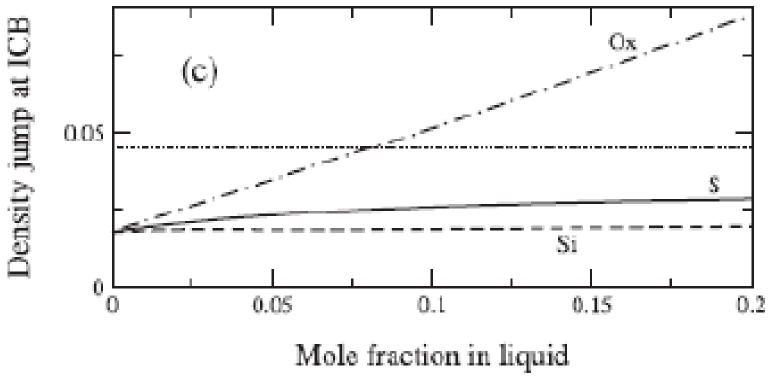
Oxygen is required to explain the liquid/solid density difference in the Earth's core



Rost et al, Nature, 2005

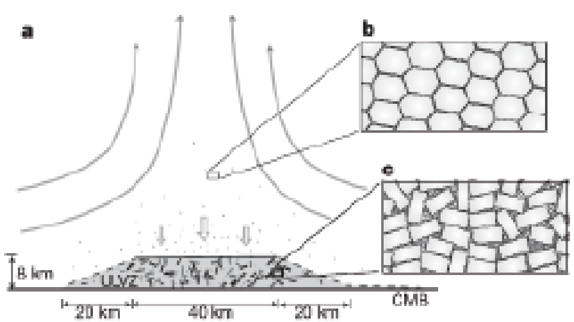
As melting is not ubiquitous at the CMB, volatiles are required in the core to lower the crystallisation temperature of the Earth's liquid outer core

Phase diagrams of iron alloys under Earth's core conditions



Alfè et al, EPSL, 2002

Oxygen is required to explain the liquid/solid density difference in the Earth's core



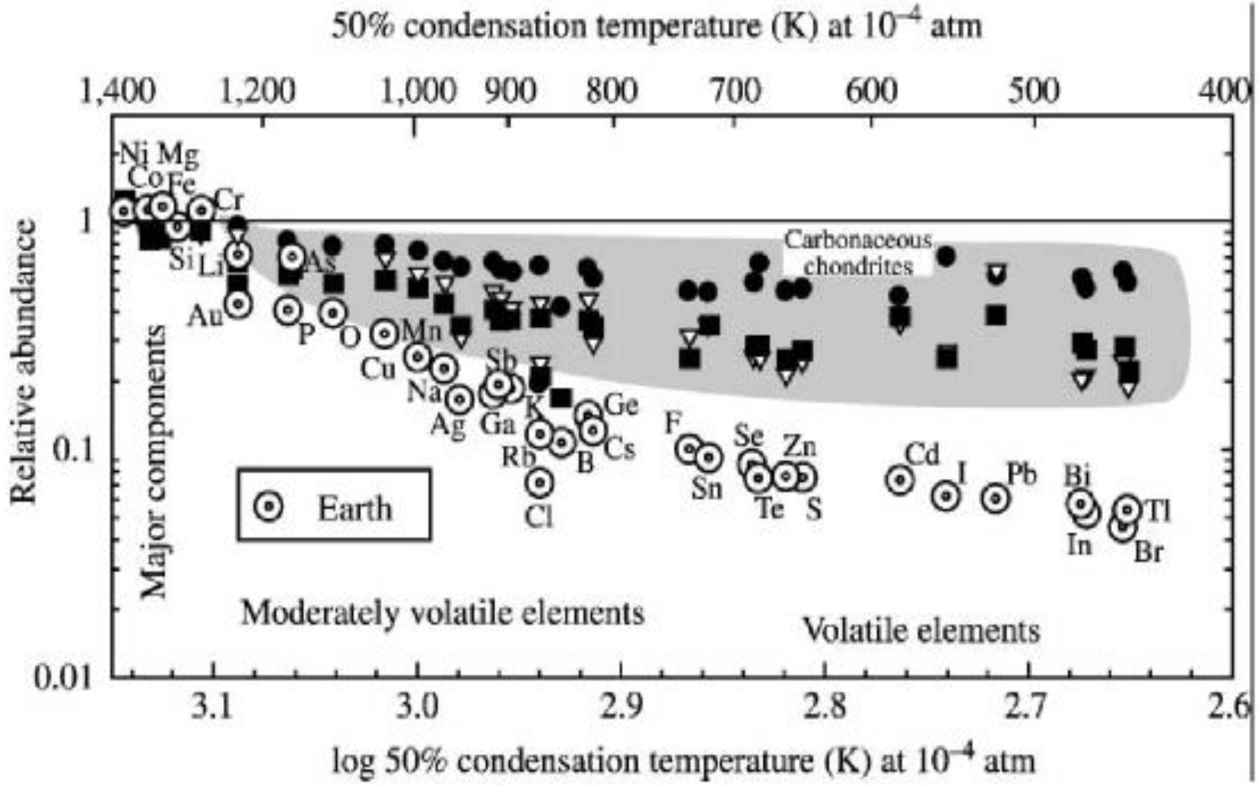
Rost et al, Nature, 2005

As melting is not ubiquitous at the CMB, volatiles are required in the core to lower the crystallisation temperature of the Earth's liquid outer core

Let's add geochemical constraints !!!

Problem for geochemists : how to put S in the Earth's core?

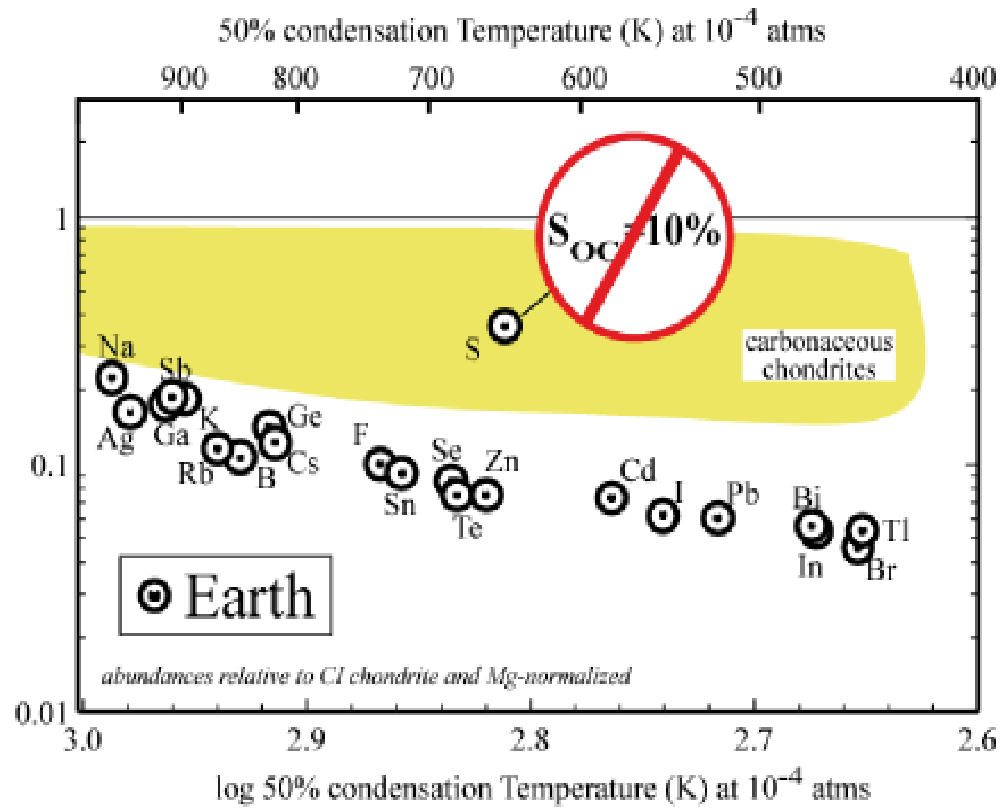
The Earth is depleted in some volatiles elements such as sulfur...



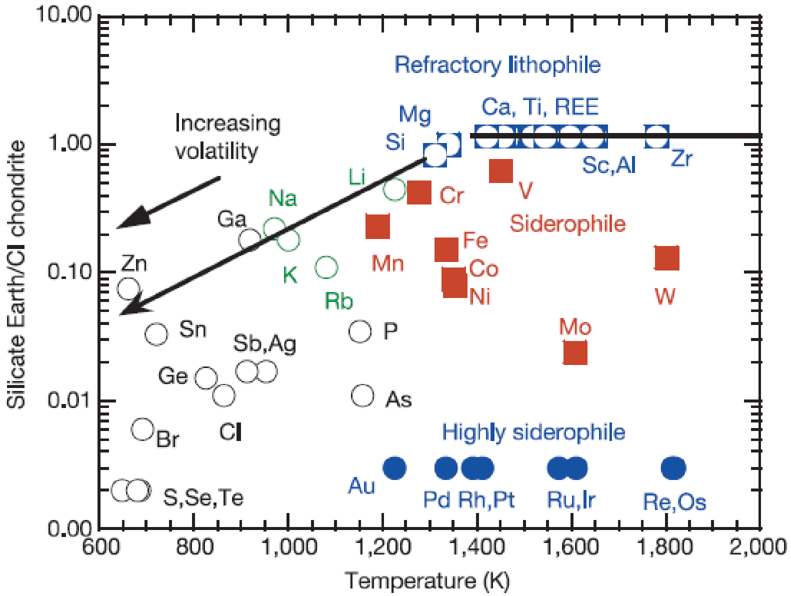
Problem for geochemists : how to put S in the Earth's core?

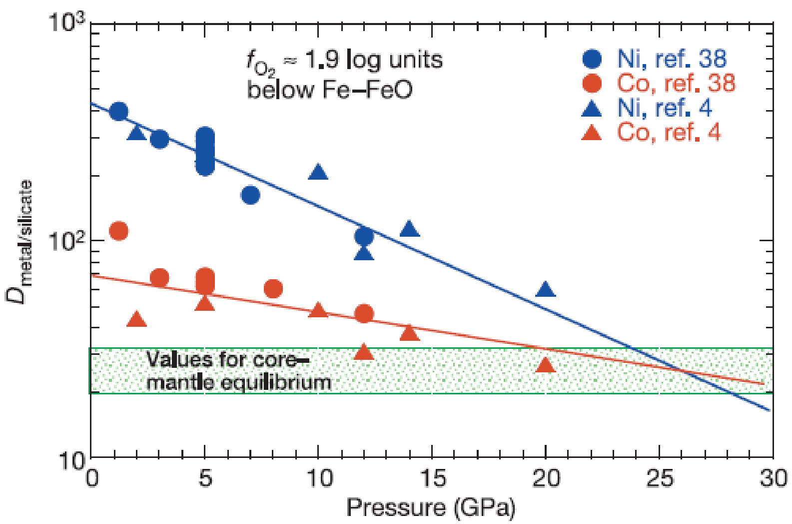
The Earth is depleted in some volatiles elements such as sulfur...

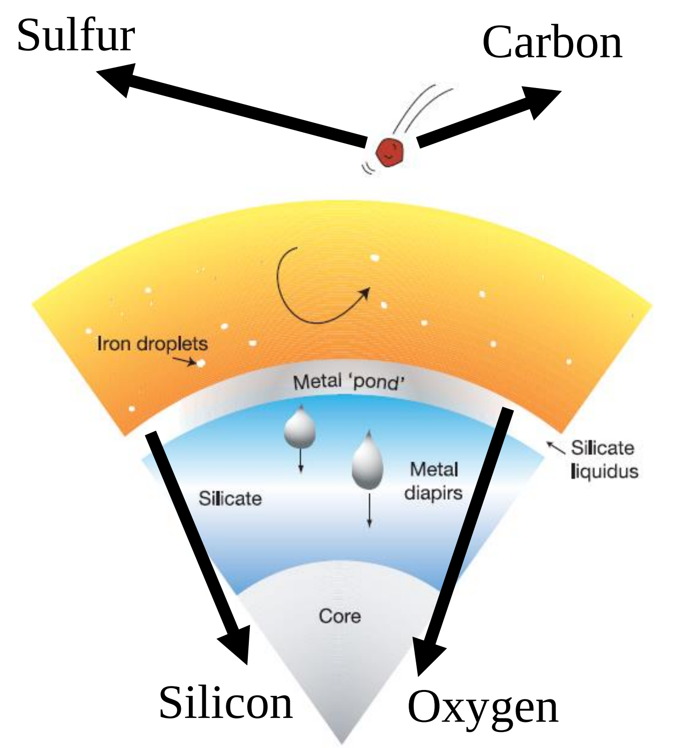
Only ~2% sulfur in the outer core



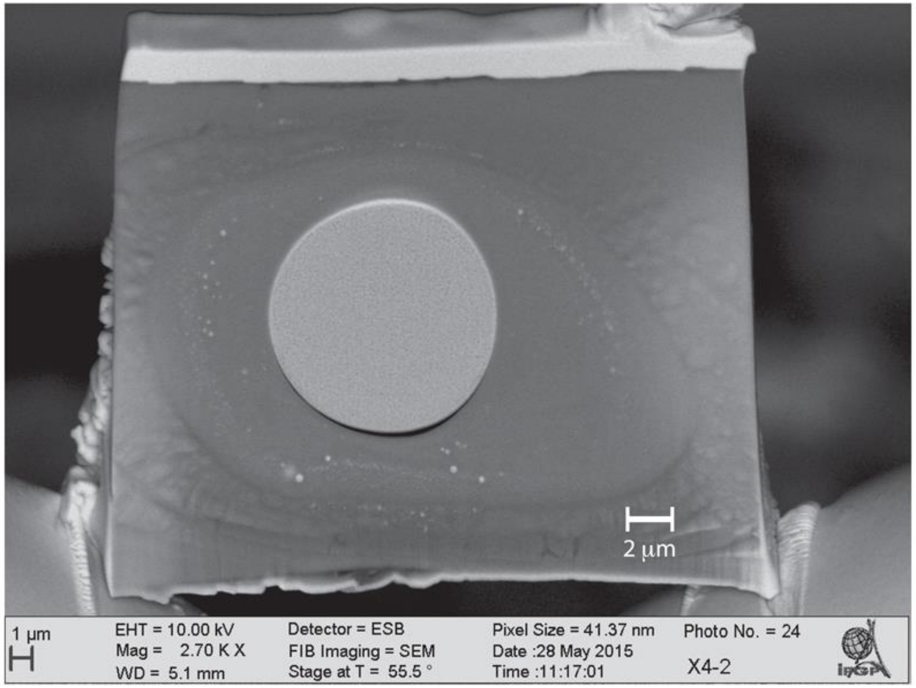
The magma ocean scenario

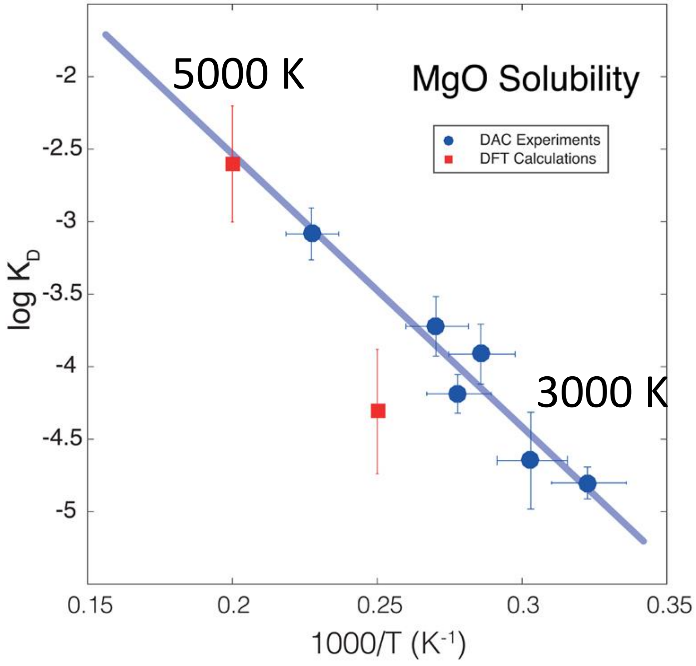






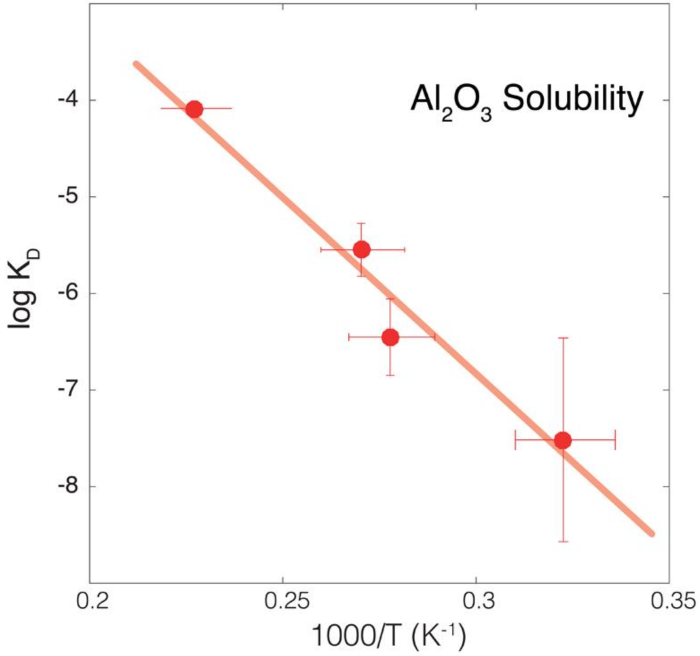
Wood et al, Nature, 2006





Magma ocean reproduced experimentally

Merge into one phase at very high temperature?

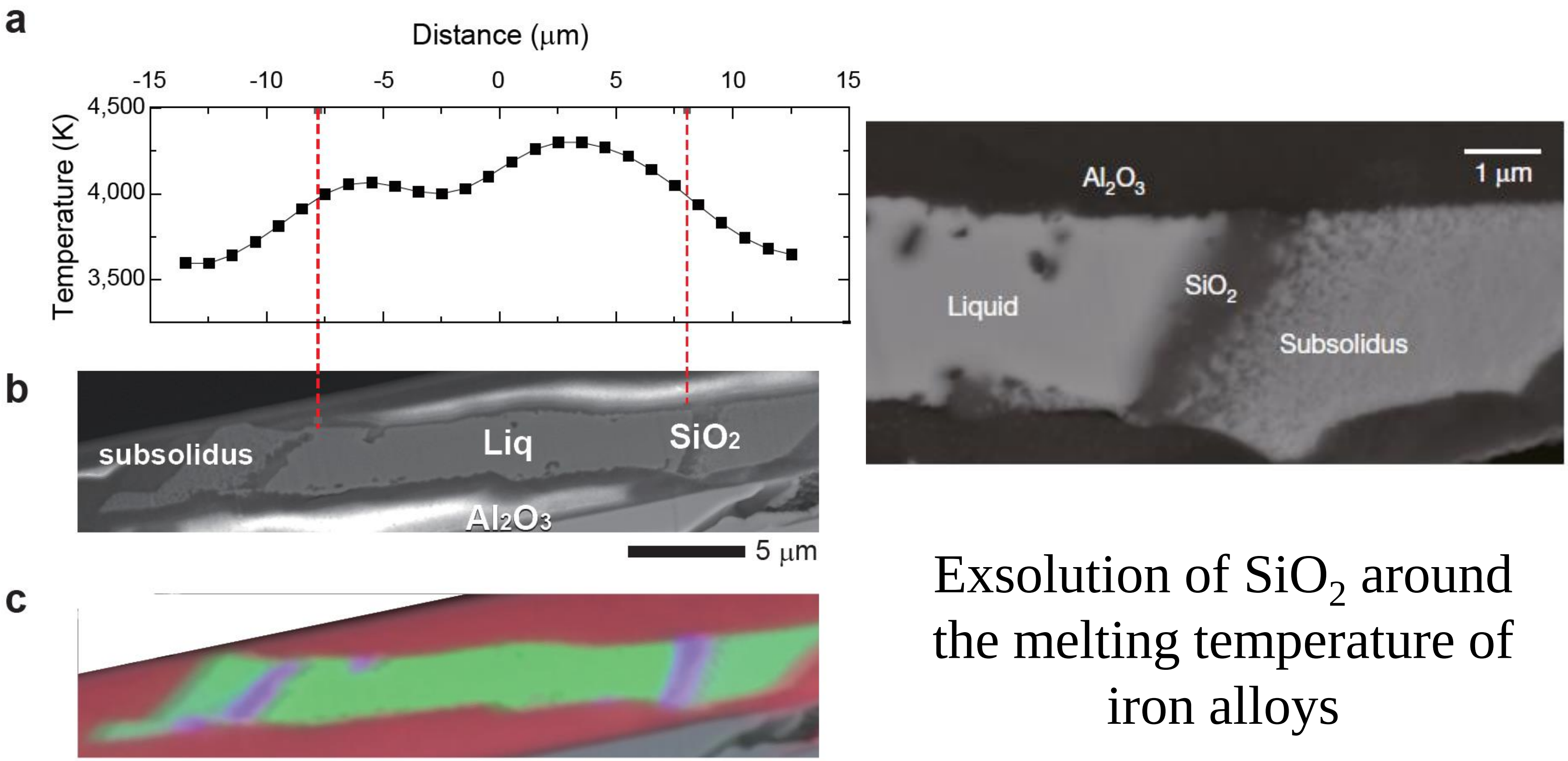


Badro, Siebert and Nimmo, Nature, 2016

Crystallization of silicon dioxide and compositional evolution of the Earth's core

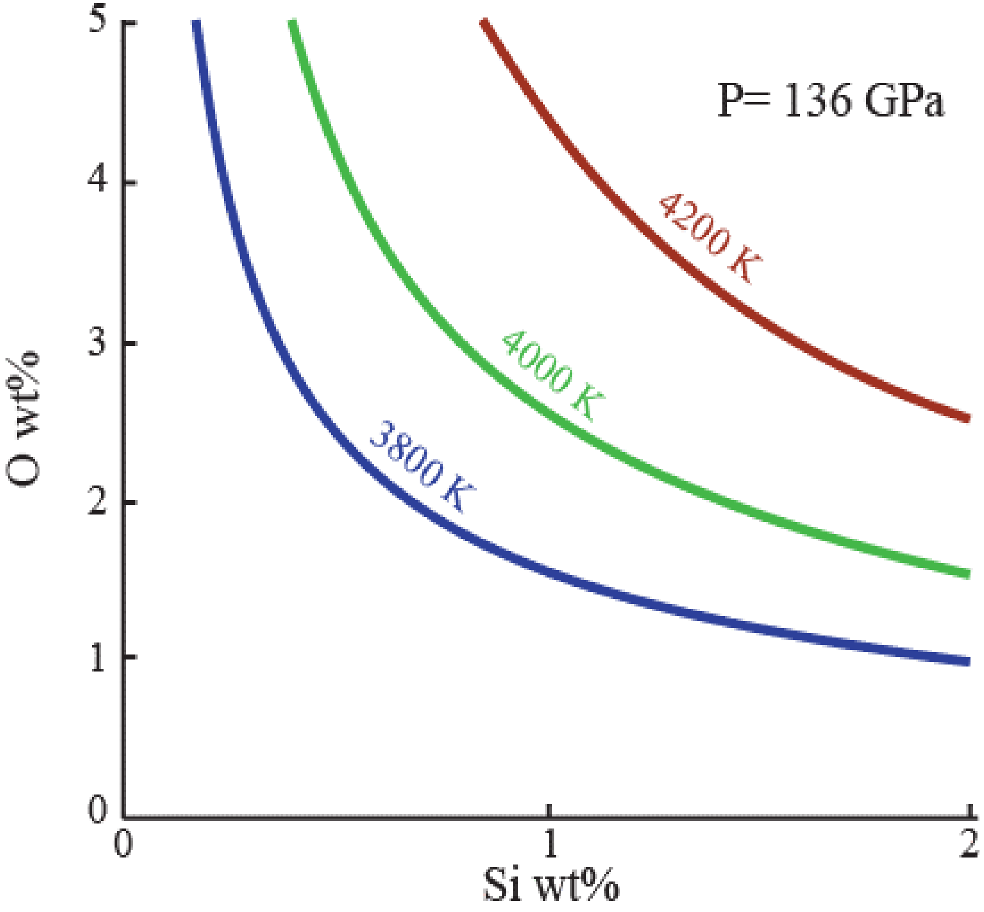
Kei Hirose[1], Guillaume Morard[2], Ryosuke Sinmyo[1], Koichio Umemoto[1], John Hernlund[1], George Helffrich[1] & Stéphane Labrosse[3]

Nature, March 2017



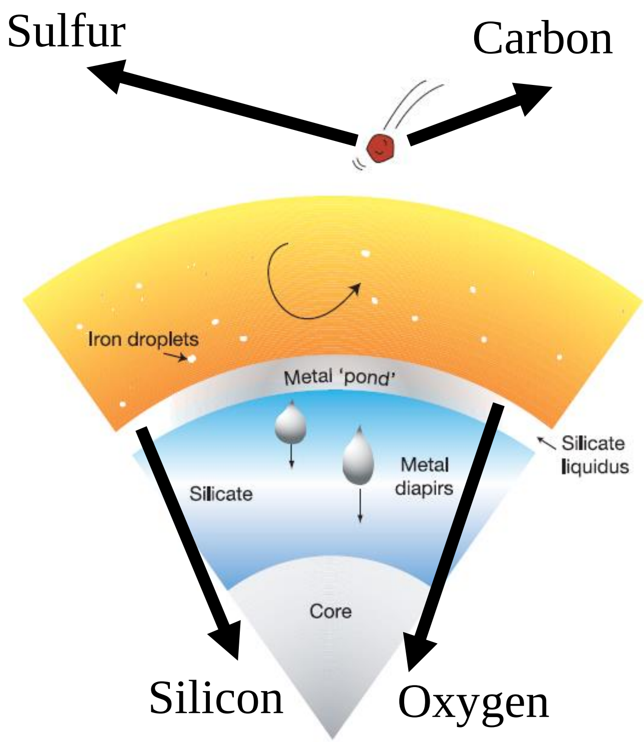
Exsolution of SiO_2 around the melting temperature of iron alloys

SiO2 crystallization constrains the Earth's core composition



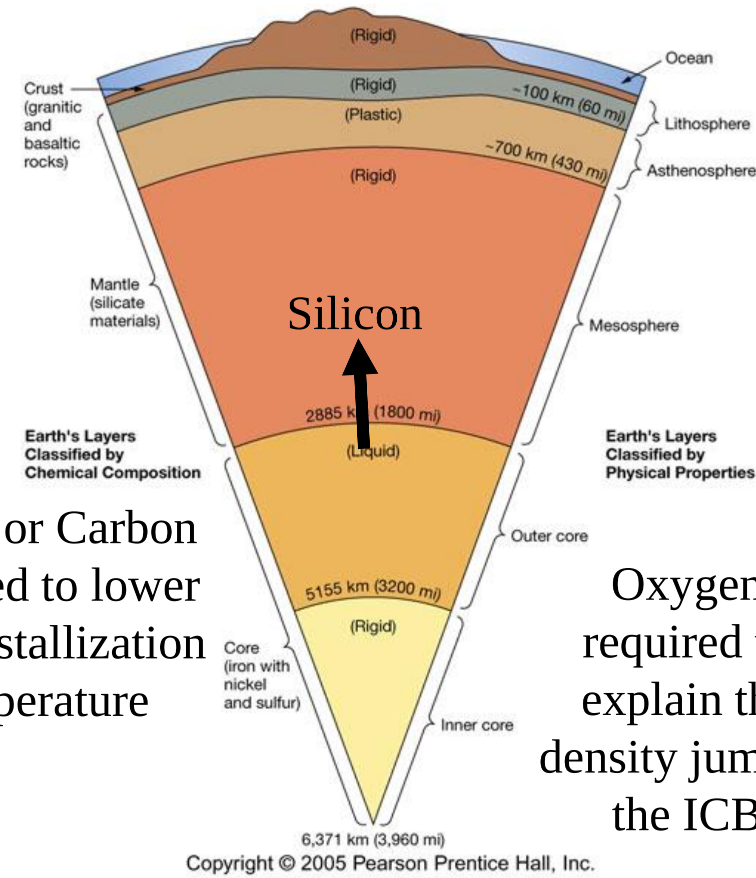
Either Oxygen or Silicon in the Earth's core

Early Earth



Present day Earth

Sulfur or Carbon required to lower the crystallization temperature



Oxygen required to explain the density jump at the ICB

Origin of Earth's Water: Chondritic Inheritance Plus Nebular Ingassing and Storage of Hydrogen in the Core

Jun Wu[1,2], Steven J. Desch[1], Laura Schaefer[1], Linda T. Elkins-Tanton[1], Kaveh Pahlevan[1], and Peter R. Buseck[1,2]

[1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [2]School of Molecular Sciences, Arizona State University, Tempe, AZ, USA

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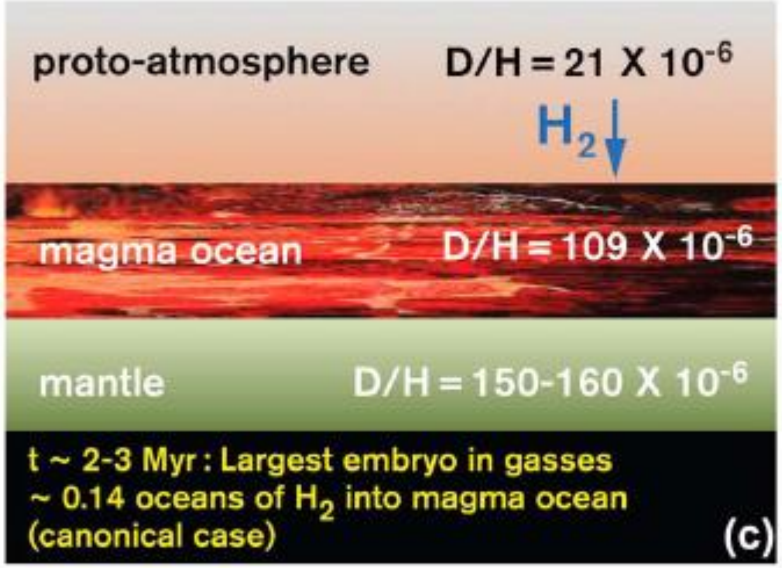
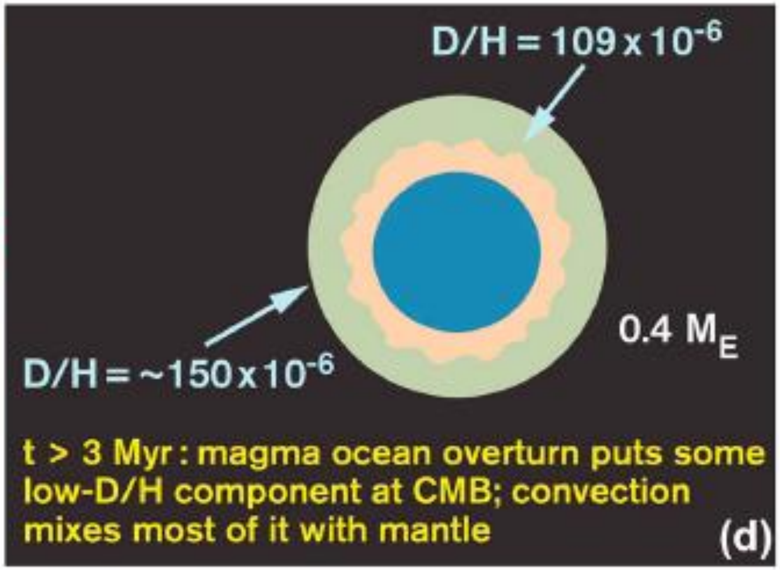
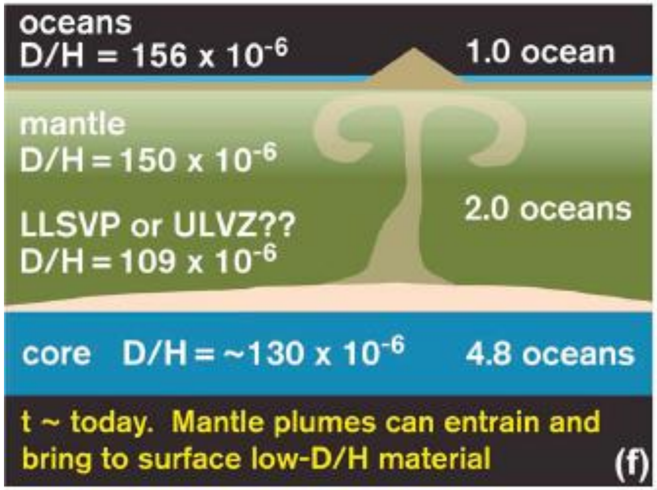
Journal of Geophysical Research: Planets







A lot of Hydrogen in the core?

Light elements in the Earth's core
Take home messages

- Strongly related with the scenario of core formation (inherited from the Earth's differentiation)

- Volatile elements not favored by geochemistry (but a bit required to lower melting temperature of core materials)
- Oxygen seems to be favored for the outer core (fit for density, velocity, density jump at ICB)
- Other element required for inner core : Si? Or S ?

- Not much data for H, mainly due to experimental problems. Incorporated during magma ocean?