Storage and Retention of Volatiles in Planetary Mantles (sort of)

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• What is the inventory of volatiles (H,C,N,S) in the bulk silicate Earth?
• How do these compare to potential cosmochemical sources?
• How does this constrain processes of volatile acquisition during accretion, differentiation, loss?
MANTLE

CORE

Exosphere
(=fluid envelopes, sediments, crust)
“Bulk Silicate Earth” (BSE)

MANTLE

Exosphere
(=fluid envelopes, sediments, crust)
**Hydrogen in the Exosphere**
*(Exosphere=everything above the Moho)*

*(Lecuyer et al. 1998)*

<table>
<thead>
<tr>
<th></th>
<th>Grams H$_2$O</th>
<th>Grams H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>$1.4 \times 10^{24}$</td>
<td>$1.56 \times 10^{23}$</td>
</tr>
<tr>
<td>Other</td>
<td>$2 \times 10^{23}$</td>
<td>$2.22 \times 10^{22}$</td>
</tr>
<tr>
<td>Total</td>
<td>$1.6 \times 10^{24}$</td>
<td>$1.78 \times 10^{23}$</td>
</tr>
<tr>
<td>Exosphere Carbon</td>
<td>Moles CO\textsubscript{2}</td>
<td>Grams C</td>
</tr>
<tr>
<td>--------------------------</td>
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</tr>
<tr>
<td>Sleep&amp;Zahnle ‘02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediments</td>
<td>(5.88 \times 10^{21})</td>
<td>(7.06 \times 10^{22})</td>
</tr>
<tr>
<td>Oceans</td>
<td>(3.31 \times 10^{18})</td>
<td>(3.97 \times 10^{19})</td>
</tr>
<tr>
<td>Oceanic Crust</td>
<td>(1.20 \times 10^{21})</td>
<td>(1.44 \times 10^{22})</td>
</tr>
<tr>
<td>Total</td>
<td>(7.08 \times 10^{21})</td>
<td>(8.50 \times 10^{22})</td>
</tr>
<tr>
<td>Hayes&amp;Waldbauer ‘06</td>
<td>(8.50 \times 10^{21})</td>
<td>(1.02 \times 10^{23})</td>
</tr>
<tr>
<td>Holser ‘89</td>
<td>(7.64 \times 10^{21})</td>
<td>(9.17 \times 10^{22})</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>(9.29\pm0.86 \times 10^{22})</td>
</tr>
</tbody>
</table>
"Bulk Silicate Earth" (BSE)

MANTLE

Exosphere

(=fluid envelopes, sediments, crust)
Schematic Features of Water Storage (and hydrous melting) the Mantle

Hirschmann, 2006
Hydrous mantle transition zone indicated by ringwoodite included within diamond

Shirey, 2013
- **Upper mantle**
- **Volcanic trail**
- **Hot spot**
- **Oceanic ridge**
- **Mantle plume**
- **Core**

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Mid-Ocean Ridge Quenched Pillow Glass

Easter Microplate
Kingsley et al. 2002

Mid-ocean ridge basalt glasses

Olivine-hosted Melt Inclusions (in MORB or OIB)
[McDonough & Sun, 1995, minus Continental Crust]
CO$_2$/Ba of undegassed basalts

- N.Arch H'wii D08
- EMORB MG15
- EMORB S16
- MORB R15
- petit spot OH13
- popping rx C08
- MORB OHMI MG15
- OIB R15
- Lv17 EqAtl. MORB
- Lky Strk MORB W15
- UDM MG15

105±15

enriched mantle

depleted mantle

CO$_2$/Ba vs. Nb/Ba
Enstatite chondrite

Carbonaceous chondrite

Bergin et al. 2015
PNAS
The Bulk Silicate Earth Abundances of Major Volatiles Are FRACTIONATED compared to chondritic abundances.
Consider a magma ocean: It produces (at least) 3 reservoirs—silicate, core, and atmosphere.
Hirschmann, 2016

Chief Reservoirs in a Largely Molten Planet

- Atmosphere
- Mantle
- Core
- Ocean

Metal/Silicate Partition Coefficient $D_{\text{met/sil}}$

Solubility Constant ($S$) ppm/MPa

- Carbon
- Sulfur
- Nitrogen
- Water ($H_2O$)
- Hydrogen ($H_2$)
Partial Mantle/Core Equilibration

(mass metal/mass mantle=0.1)

Hirschmann, 2016
Siderophile Tendency (Preference for the core)

$C \gg S$

$D_s$ (metal/silicate) (Boujibar et al. 2014)

$D_c$ (metal/silicate) (Chi et al. 2014)

Li et al. 2016
BSE/Late Veneer (Cl)

1.0

0.1

magma

ocean remnant

parent body processing or late loss of low T atm.
C/S ratio has echoes of the “Late Veneer”.

Righter, 2003

Terrestrial depletions

Cl chondrites

one bar partition coefficients

slightly siderophile
moderately siderophile
highly siderophile

Increasing siderophile behavior ->
Summary

• The BSE budgets of C and H are well-constrained by ratios to refractory lithophile elements (Ba, Ce)
• BSE volatiles are low, but there are plenty of loss mechanisms (to core, to space)
• BSE volatiles are fractionated relative to chondrites. Either volatiles were delivered by differentiated bodies or there were selective loss mechanisms during differentiation. Probably both.