The magma ocean era:
volatiles, silicates, and magma oceans during the first 100 Ma of an Earth-sized rocky planet’s lifespan

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Why care?  **Water and carbon**

More happened in the first 100 Ma of Earth-sized rocky planet evolution than in all subsequent planetary history! Establishment of the major reservoirs, partitioning of water and carbon between {Fe-metal core, silicate mantle+crust, low-density envelope, and escape-to-space.}
Take-home: 10 facts about the first 100 Ma of an Earth-sized rocky planet’s lifespan

#1: MAGMA OCEANS FORM ON EARTH-SIZED ROCKY PLANETS
#2: MAGMA OCEANS CAN PERMIT VOLATILE EQUILIBRATION BETWEEN SILICATE LAYER AND LOW-DENSITY ENVELOPE
#3: PLANET INITIAL AMOUNTS OF CO2, H2O AND H2 ARE POORLY CONSTRAINED
#4: WELL-STIRRED MAGMA OCEANS CAN PROTECT VOLATILES FROM GIANT IMPACTS, BUT NOT FROM XUV-DRIVEN HYDRODYNAMIC ESCAPE
#5: CARBON ♥ FE-METAL; WATER DOES NOT
#6: MAGMA OCEAN LIFETIME RANGES FROM $10^3$ yr - $\infty$, DEPENDING ON THE SUPPLY OF CO2, H2O, AND H2, AS WELL AS DISTANCE FROM STAR
#7: MAGMA OCEANS START CRYSTALLIZING AT >100 KM DEPTH
#8: MAGMA OCEAN LIQUID $\rightarrow$ SOLID TRANSITION AT LIQUID:CRYSTAL RATIO ~1:1
#9: GREAT MAJORITY OF VOLATILES ARE DRIVEN TO THE SURFACE DURING CRYSTALLIZATION. SOME ARE TRAPPED IN THE CRYSTALS.
#10: CHEMISTRY OF FIRST LIQUID WATER OCEAN DEPENDS ON RELATIVE TIMESCALES OF FIRST-CRUST EXTRUSION, WATER VAPOR CONDENSATION, AND C DELIVERY.
Sources of information: zircons, elemental+isotopic compositions, theory, chronology showing rapid formation, Lunar data, high-pressure experiments, observations of exoplanetary systems. Future: Io observations?

DAC = Diamond Anvil Cell

Dispersing debris after a large impact in an exoplanetary system
Meng et al. 2014 Science

4.4 Ga zircon
Harrison AREPS 2009

Io: the only rocky-world magma ocean for light-years in any direction
Khurunna et al. Science 2011

Lunar Highlands: scum of a magma ocean
Definition of a magma ocean

**ASTROPHYSICS/PLANET FORMATION LITERATURE**

- "envelope"/"atmosphere" (gas accreted from nebula, mostly H2)
- core (assembled from solids)

**PLANETARY GEOSCIENCE LITERATURE**

- supercritical volatile-rich layer (can be H2-dominated OR H2O-dominated)
- silicate magma ocean
- Fe-metal core

- atmosphere
- liquid water ocean
- silicate mantle
- Fe-metal core

**METAL**

- everything other than H and He

**VOLATILES**

- H, He, Ne, Ar ...
- "astrophysical ices"

- Fe in in Fe⁰ oxidation state

**Habitability Literature**

- H2O + C species

**Cosmochemistry Literature**

- as above + Na, K, "MVEs"
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FULLY LIQUID MAGMA OCEAN

CRYSTALLIZING MAGMA OCEANS
Magma oceans form on Earth-sized rocky planets + smaller bodies

Magma oceans if $^{26}$Al conc. is high (<3 Myr in Solar System)

"10 km – Vesta sized"

"Moon- to Mars-sized"

"Earth-sized"

“Deliver accretional energy ($10^8$ J/kg) fast relative to re-radiation timescale. ($C_p \sim 10^3$ J/kg for metal, silicates)"

Ghanbarzadeh, Hesse et al. PNAS 2017
Magma oceans form on Earth-sized rocky planets

Robin Canup
Two types of **permanent magma oceans on exoplanets:**

**Too close to star:** magma planets
Intrinsic abundance: <0.5% of stars


**Too much gas:** “mini-Neptunes”
Intrinsic abundance: >30% of stars

“Too much tidal heating” rarely allows permanent magma oceans for exoplanets (see Kislyakova et al. Nature Astronomy 2017 for an exception). However, tides can cause temporary magma oceans on rocky planet during tidal circularization.

If gas arrives late: top-down metal-silicate differentiation → mass concentrates at planet center → GPE release → magma ocean
Magma oceans can permit volatile equilibration between silicate layer and low-density envelope

Magma ocean phase: rapidly churning magma directly underneath volatile-rich envelope → chemical equilibrium between dissolved volatiles in the magma layer, and exsolved volatiles in the envelope. force balance for flow: buoyancy vs. Coriolis & inertia

Contrast with today’s Earth: Oxygenated atmosphere over relatively reduced, sluggishly -overturning, solid silicate mantle → not in chemical equilibrium. Force balance for flow: buoyancy vs. viscous forces

Liquid magma (no crystals) is as runny as liquid water

$u_0 \approx 0.6 \left( \frac{\gamma \alpha l F}{\rho c_p} \right)^{1/3}$ ~10 m/s

Solomatov, in Treatise on Geophysics, 2015

Dingwell 2004 EPSL
Solubilities are high enough that most volatiles (H2O, CO2, ...) are scrubbed from the low-density envelope.

Henry’s Law: activity in the melt is proportional to partial pressure at the silicate-volatile interface. On an Earth-sized rocky planet, silicate column mass is $O(10^{10})$ kg/m$^2$
#3: The starting bulk fraction of CO2, H2O and H2 is unknown

The CO2, H2O (etc ...) volatile content of rocky planets in the habitable zone is set by inherently stochastic processes. The H2 abundance on rock-dominated planets is set by processes that we are only just beginning to understand (e.g., papers by Eve Lee & Eugene Chiang).

Figure from Kite & Ford arXiv 2018
see also Raymond et al. 2004, 2007 Ciesla et al. 2015, and many others

Figure 16. Example output from our model showing stages in planet growth. Color scale shows H2O fraction ($f_W$). Red rings mark planets that initially have habitable surface water. Green rings mark habitable-zone planets with initially frozen surfaces. Disk size shows planet mass. Planets migrate inwards for the first few Myr of the simulation subject to parameterized, imposed migration torques.
#4: Well-stirred magma oceans can protect volatiles from giant-impact erosion, but not XUV-driven hydrodynamic escape

*These 2 processes are the most powerful volatile loss processes – all others are relatively wimpy (Zahnle & Catling ApJ 2017)*

Ocean removal by giant impacts (n.b.: Ocean vaporization is not enough for ocean removal)

Simulations suggest that the Moon-forming impact was marginally able to remove any pre-existing Earth ocean

\[ Q_s \sim v_e^2 \text{ for oligarchic impact} \]

\[ v_e = \sqrt{\frac{2GM}{r}} \]

escape velocity

Lock et al. LPSC 2014
See Schlichting ApJ 2015 for an argument that planetesimal impacts, not giant impacts, are the most erosive

Volatile dissolved in the melt are protected from giant impacts
Atmospheric escape by hydrodynamic escape can be understood in terms of the Jeans parameter: $\lambda_{esc} = \frac{GMm}{kT(R + z)}$

**Jeans parameter:**

$\lambda_{esc}$

(= “escape parameter”)

> 10: stable atmosphere, hydrostatic, Jeans escape (usually slow)

$< \sim 2$: hydrodynamic escape (often fast)

Lewis & Prinn, “Planets and their atmospheres,” p.108

Relative to today’s Sun, the Sun around the time of the Moon-forming impact had lower bolometric luminosity, but much higher EUV + soft X-ray luminosity $\rightarrow$ increases $T_{\text{exobase}}$ $\rightarrow$ lowers Jeans parameter.
See Dasgupta, 2013, Reviews in Mineralogy & Geochemistry, for an elegant discussion.
#6: Will the ocean ever crystallize? Magma ocean lifetime ranges from $10^3$ yr to $>>10^{10}$ yr, depending on the greenhouse effect of volatiles (CO$_2$, H$_2$O, and H$_2$).

Volatile released on impact

**Figure 6.14** The surface pressure and temperature for a model of impact degassing during accretion of the Earth. In this model, degassing exceeds escape to space when the growing planet reaches roughly 0.5 of an Earth radius. At that point, the atmosphere is opaque to the thermal infrared in a “runaway greenhouse” state and the surface melts. The steam atmosphere eventually collapses when the planet nearly reaches the current Earth radius. (Adapted from Zahnle et al. (1988) Reproduced with permission from Elsevier. Copyright 1988.)

Catling & Kasting 2017, “Atmospheric evolution on inhabited & lifeless worlds,” ch. 6
Volatile Blanket (Mainly H2O) Extends Magma Ocean Lifetime Through Greenhouse Effect

Zahnle 2007 Space Science Reviews
A long-lived magma ocean on Venus may have caused desiccation by XUV-driven hydrodynamic escape during the magma ocean phase, explaining Venus’ high D/H but without any habitable epoch.

Figure 3 | Water partitioning between steam atmosphere and planetary interior. The amount of water depends on the rate of loss and the duration of the MO period. a, Planet at 1 AU (type I). Most of the primordial water remains and contributes to the steam atmosphere at the time of complete solidification. b, Planet at 0.7 AU (type II). The final total mass of water is less than $0.1M_{\text{EO}}$. 

Hamano et al. Nature 2013
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#7: Magma oceans start crystallizing at $>100$ km depth

Solomatov (2000)
Magma oceans start crystallizing at depth, not at the surface, because the adiabat (profile to which a rapidly convecting system will adjust) is steeper than the solidus (melting curve) on a T-vs-Z diagram.

\[
\text{Adiabat: } \left( \frac{\partial T}{\partial r} \right)_S = \frac{T \alpha g}{C_P}
\]

Elkins-Tanton (2012)
Figure 9  Crystallization of the magma ocean: (a) The lower part of the magma ocean is below liquidus (dotted line), convection is controlled by melt viscosity, and the temperature (heavy solid line) is adiabatic; (b) high-viscosity, gravitationally unstable region with the maximum packing crystal fraction forms near the bottom of the magma ocean ($\phi = \phi_m$ curve is shown with a dashed line); (c) cooling beyond $\phi = \phi_m$ proceeds via solid-state convection, which is still fast at this stage. The temperature in the high-viscosity region below solidus (solid line) can be superadiabatic; (d) $\phi > \phi_m$ everywhere and the rate of cooling and crystallization of the remaining melt are controlled by solid-state convection and melt percolation. The gray and black crystals schematically illustrate different mineral phases.
#8: Magma ocean liquid → solid transition occurs at xtl:liquid ratio ~1:1

Ten-or-more-order-of-magnitude increase in viscosity
Needles “solidify” at lower xtl:liquid ratio than spheres

Walsh & Saar J. Volcanology Geothermal Res. 2008:

Zahnle et al. 2015 arxiv
#9: Great majority of volatiles are driven to the surface during crystallization. Some are trapped in the crystals.

Liquid magma and H2O are ~fully miscible, but
Solid upper-mantle rock stores ~100 ppm H2O

Chemistry of the first liquid water ocean depends on the relative timescales of first-crust extrusion, vapor condensation, and C delivery.

Kite & Ford arxiv 2018:
My personal feelings about field direction

• Study of the magma ocean era has great potential!
• Under-invested in.
• Under-exploited: Simple integrative theory
  (e.g. Lindy Elkins-Tanton, Kevin Zahnle, Norm Sleep),
  molecular dynamics, theory for transport processes
  (e.g. Pascale Garaud)
• Frontiers: Fluid dynamics, new techniques
  (e.g. Gregor Golabek, Hidenori Genda, Jenny Suckale …)
  Spacecraft mission to Io?
• Lamppost/keys syndrome – Earth mantle geochemistry and Earth
  mantle seismology have both hit diminishing returns – Earth deep-
  interior work is approaching diminishing returns
• >10 GPa lab experiments have reached diminishing returns; very
difficult to do lab experiments at 5000K & 5 GPa which is the relevant
range for mini-Neptune volatile-silicate interfaces → need for
molecular dynamics simulation
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Zahnle et al. 2007 Space Science Reviews
Sleep & Zahnle 2001 JGR-Planets
Bonus slides
Dwarf planet Ceres is a possible example of whole-planet migration.
Magma oceans form on Earth-sized rocky planets & under extreme circumstances may grade into “synestias”
Recent development:
Rocky-planet destruction by hydrodynamic escape

N.B. This does not apply to planets near the habitable zone (due to low vapor pressures)

Main-sequence stars orbited by planets that are currently being destroyed: KIC 12557548, KOI-2700, K2-22.


Notice the minimum in gas temperature

Destruction of Mercury-mass planet:
Within protoplanetary disks, the habitable zone is in a region that theory suggests should be dry.

- Scattering of impactors

MB = Main Belt (2-3.5 AU)
TNO = TransNeptunian Object

von Dishoeck et al. in Protostars & Planets VI, 2014
What crystallizes? The simple story

Elkins-Tanton (2012)