Magmatic Evolution 1: Initial Differentiation of the Moon

Chapter Leads: Amy Gaffney[1], Paul Warren[2]

Writing Team: Lars Borg[1], Kerri Donaldson Hanna[3], David Draper[4], Nick Dygert[5], Lindy Elkins-Tanton[6], Katie Joy[7], Tabb Prissel[8], Jenny Rapp, Edgar Steenstra[9], Wim van Westrenen[9]

1: Lawrence Livermore National Laboratory
2: University of California, Los Angeles
3: University of Oxford
4: NASA – Johnson Space Center
5: The University of Texas at Austin
6: Arizona State University
7: The University of Manchester
8: Rutgers University
9: VU University Amsterdam

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Magmatic Evolution 1 - Themes

- What rocks and magma sources were produced during lunar differentiation?
- When did the Moon differentiate?

Was there a magma ocean?

- Was it global?
- Was it local?
- Was there more than one magma ocean-like event?
- (What was the role of serial magmatism in *large-scale differentiation*?)

Introduction and the case for a Magma Ocean

- Brief history of the Magma Ocean as a concept
- Observations supporting the existence of a very plagioclase-rich global crust
- Challenges in forming a global plagioclase-rich crust without a magma ocean
- Other geochemical arguments: mare basalt Eu anomalies, urKREEP, etc…
- Ferroan anorthosites: leading candidates for remnants of magma ocean flotation crust
- Concluding caveat: the Magma Ocean is a *hypothesis*, continues to be tested

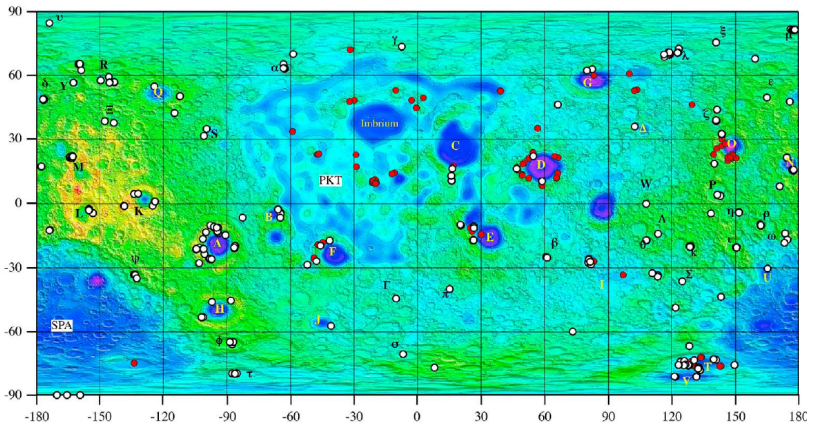
New observations of primordial(?) differentiation products

Meteorites provide samples of rock types not found in Apollo/Luna collections. Are any of these primordial differentiation products? Are meteorites further evidence for an extremely plagioclase-rich global crust?

- Proposed (but very small) Mg-anorthosite: ALHA 81005, NWA 2996
- Proposed (but very small) PAN fragments: Dho 489

Remote observations reveal the global distribution of rock types

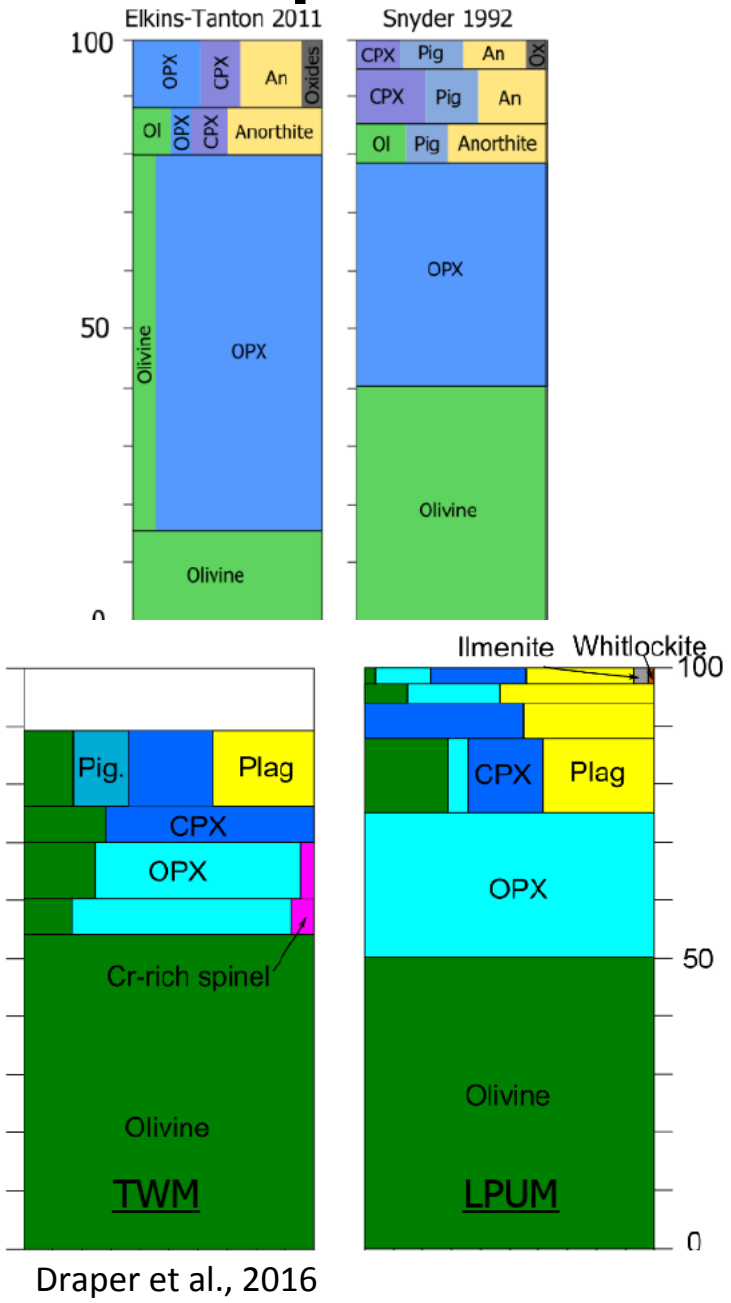
- Anorthosite
- Low-Ca pyroxene, olivine
- Th distribution
- Magnesian central farside highlands



Yamamoto et al. (2012)

What rocks and magma sources were produced during lunar differentiation?

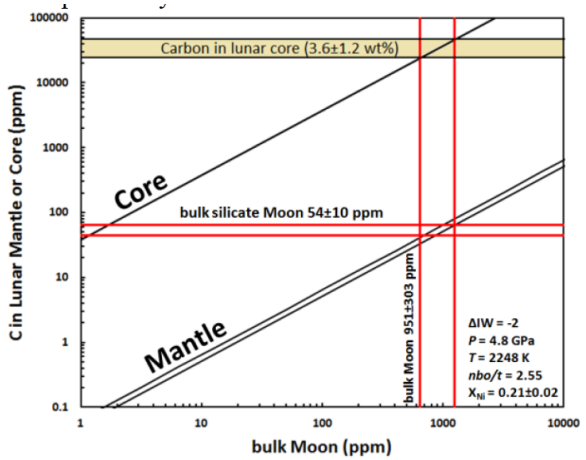
- Experiments constrain the range of possible materials that may be produced during magma ocean crystallization
  - Recent experiments explore: bulk composition (major elements, water), crystallization mode (equilibrium, fractional, hybrid, role of intercumulus liquid)
  - Results of recent experiments constrain: crystallization sequence/mineralogy, major/trace element compositions (urKREEP), density, thickness…



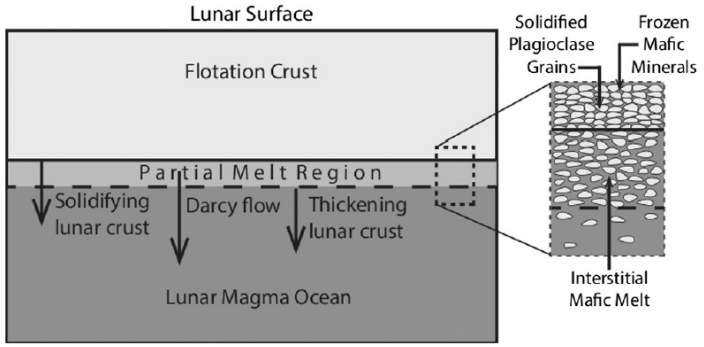
Draper et al., 2016

Constraints on differentiation processes from geochemical and geophysical models

- Depth of magma ocean: experimental constraints, Giant Impact models, seismic experiments, core formation models
- Solidification processes and duration: thermodynamic constraints
- Bulk composition: water, mineral assemblages
- Depth/thickness of differentiation products: Anorthosite lid, high-Mg suite, mafic cumulates, core
- Cumulate overturn: density profiles, viscosity structure, overturn-related melting, speed of overturn
- Size and composition of core



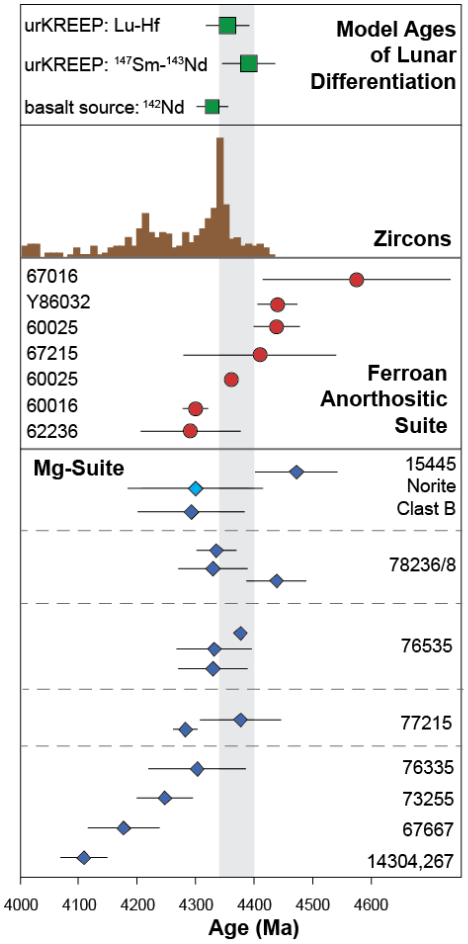
Steenstra & van Westrenen, 2016



Piskorz & Stevenson (2014)

When did the Moon differentiate?

- Magma source regions are formed during differentiation; magmas derived from these sources are used to constrain formation ages of the sources
  - Hf-W short-lived system: maximum age
  - urKREEP, mare basalt source model ages
- Ages of rocks and minerals
  - Rocks that (may have) formed during differentiation: anorthosites
  - Rocks and minerals that (probably) formed after differentiation: Mg-suite, zircons
- Do ages always, precisely, reflect the time of igneous crystallization?



Summary and Synthesis of Outstanding Questions

- How are the different anorthosite types related?
- How have the anorthosites been modified since they formed?
- Do model differentiation ages represent primordial differentiation or a secondary magmatic event?
- The after-effects of lunar differentiation are seen in essentially all subsequent stages of lunar evolution, even if the Magma Ocean turns out to be an exaggeration