The geochemistry of primitive solar system bodies

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Galileo image of 243 Ida
Some goals for this hour

• A few important and/or representative materials and tools

• Physical processes and events recorded by geochemistry

• A schematic overview of geochemistry’s version of our creation myth

• The subject is gigantic and detailed; we will focus on first-order questions concerning ‘primitive’ objects
What do we imagine geochemistry might tell us of the histories of primitive solar system bodies?

• What?
  Recognizing primitive bodies for what they are
  Can we assign a given ‘primitive’ material to common groups or histories?

• When?
  Can we prove an object or its constituents formed in the first few million years?
  Can we rank/order an object within early solar system chronology?
  Can we recognize and date much later events?

• Where?
  Inside/outside the ‘snow line’?
  Adjacent to the sun?
  Prepare to be disappointed if you are hoping for something more subtle….

• How?
  Mixing of recognized early solar system components (CAI’s, chondrules, ice...)
  Water-rock reaction
  Metamorphism
  Metal/silicate differentiation
  Silicate partial melting
The family of environments in the early solar system

After Krot, 2009
Early temperature history of gas and dust in the disk

After Mousis et al., 2000
Early temperature history of planetesimals

Ghosh et al., 2006
• Intense heat and radiation in innermost disk, and vigorous, focused transport of particles
• Short lived radio-isotopes synthesized near sun
• CAI’s form near the sun
• Chondrules in denser inner disk
• Both strewn to snow line and beyond by X-wind
• Heating and short-lived radio-isotope production spatially heterogeneous
• Most of these processes happen simultaneously

Shu et al., 1997; Shang, 2007; Krot, 2009
Another end-member scenario — ‘anything-but-X-wind’

* A seeded solar system; dynamically mixed; shock-related melting

- Pre-solar nebula seeded with short lived radio-isotopes during or just before collapse
- Highly efficient dynamic mixing homogenizes many components
- CAI’s form first (likely near the sun)
- Chondrules form after (and repeatedly) in response to shock waves and other local effects
- Redistribution of CAI’s and chondrules through complex, somewhat ambiguous dynamics

Boss, 2011
Primitive meteorites look a lot like the sun in elemental abundances (minus the gas and all the hotness)

Two options
- They are fairly uniform condensates
- They are statistical samples of a wide variety of things
Chondrites

Chondrules
- Sub-micron silicate, oxide, sulfide, organics
- The petrographic ‘mortar’ of chondritic materials
- Lots seem processed; like ‘mini-chondrules’
- In volatile-rich bodies, altered to hydrous minerals and salts

Matrix
- Silicate melts (possibly multi stage)
- Moderately hot; more oxidizing
- Diverse in age and type

Refractory inclusions
- Gas/solid gas/liquid equilibria
- Very hot, reducing environment
- Relatively uniform in age and type

Grassland meteorite chondrules

Allende CAI’s surrounded by chondrules

Matrix-rich region of Allende
- Sub-micron silicate, oxide, sulfide, organics
- The petrographic ‘mortar’ of chondritic materials
- Lots seem processed; like ‘mini-chondrules’
- In volatile-rich bodies, altered to hydrous minerals and salts
The carbonaceous chondrites can be thought of as the shales of the early solar system.

A black shale
Details of refractory inclusions

Calcium-Aluminum Inclusions

*Highly refractory condensates*

Amoeboid Olivine Aggregates

*Somewhat cooler gas/solid reactions*

An = anorthite
Cor = corundum
Di = diopside
Fo = forsterite
Hib = hibonite
Mel = melilite
Met = metal
Pv = perovskite
Px = low-Ca pyroxene
Sp = spinel

Krot et al., 2009
Details of representative chondrules

Olivine rich

Pyroxene rich

Textural exotica

An = anorthite
Chr = chromite
Mes = mesostasis
Met = metal
Ol = olivine
Px = low-Ca pyroxene
Sf = sulfide
Sp = spinel

Krot et al., 2009
The temperature significance of CAI and Chondrule components

Davis and Richter, 2003; Krot et al., 2009
CAI’s are inclusions in (and thus predate) chondrules

An = anorthite
Cpx = high-Ca pyroxene
Grs = grossite
Hib = hibonite
Mel = melilite
Mes = mesostasis
Met = metal
Ol = olivine
Pv = perovskite
Px = low-Ca pyroxene
Sil = silica
Sp = spinel

I.e., condensation generally preceded igneous reprocessing

Krot et al., 2009
High precision Pb-Pb dating of CAI’s and Chondrules

I.e., condensation generally preceded igneous reprocessing, by ~1 Ma

Amelin et al., 2002; Connelly et al., 2008; Krot et al., 2009
It is sometimes assumed that chondrules preceded accretion of km-scale planetesimals. Seems clearly true in the case of parent bodies of chondrule-rich carbonaceous chondrites.

Ghosh, Weidenschilling and McSween, 2003
But some chondrules contain rocky precursors

Chondrules in a CV chondrite

Met = metal
Ol = olivine
Px = low-Ca pyroxene

These record recrystallization of igneous or metamorphic rock, likely under some significant pressure

Terrestrial dunnite
Thus at least some planetesimals existed before formation of at least some chondrules.
Short lived radionuclides

- For half-lives of millions of years or less, the show is long over in all early – solar system materials
- All you can measure is the inventory of daughter species accumulated in a sample
Short lived radionuclides

- That inventory can be a time-stamp for chemical differentiation
B and Be in Allende CAI’s

• $^{10}$Be generated by spallation
• Decays to $^{10}$Be, half life = 1.4 My
• Produces anomalies in $^{10}$B/$^{11}$B in materials with high Be/B

• Implies an irradiated environment at ~0.1 AU broadly resembling inner region of ‘X-wind’ model
• Similar processes may explain nuclides derived from $^{41}$Ca and $^{53}$Mn

McKeegan et al., 2000
$^{50}$Ti and $^{46}$Ti nucleosynthetic anomalies

*A related notion, but isotopes are stable tracers of nucleosynthesis*

- Ti is highly refractory and was condensed into the earliest solids in the solar system
- Its isotopic composition was not easily modified during secondary alteration processes.
- Two nuclides with different nucleosynthetic origins

$^{50}$Ti and $^{46}$Ti correlate $\rightarrow$ efficient mixing after nucleosynthesis

Unevenly distributed today $\rightarrow$ ‘unmixing’ by solar system processing

Trinquier et al., 2009; Zhang et al., 2012
$^{26}$Al as a chronometer and tracer

- Chronometer assumes $^{26}$Al (half life 0.7 Ma) was evenly distributed
- Date by measuring $^{26}$Mg accumulated in Al-rich minerals
- But, could be generated in solar system à la X-wind models
- Also happens to be an essential heat source for planetesimals

- Chronologies generally consistent and confirm high-precision Pb-Pb dating
- Seems unlikely this could be true unless $^{26}$Al was injected as a single ‘slug’ and then homogenized by very early dynamic mixing
Bulk primitive meteorites do not look like the sun in the isotopic composition of their most abundant element (O)

Clayton and Mayeda, 1993
Bulk primitive meteorites lie on a line connecting the sun and water in some primitive meteorites.

McKeegan et al., 2011
Self shielding: the (currently...) inevitable seeming origin of O isotope anomalies

\[ \text{CO} \rightarrow \text{O} + \text{C} \]
\[ \text{O} + \text{H} \rightarrow \text{H}_2\text{O} \]

Ice and dust grains

All isotopes

\( ^{17}\text{O} \text{ and } ^{18}\text{O only} \)
Scenarios for generating the solar-system’s $^{16}$O-poor water

1: Molecular cloud, prior to formation of disk
2: Light from sun, at inner edge of disk
3: Light from nearby star illuminates surface of disk; water-ice particles stir into disk
Ways in which the $^{16}$O-poor H$_2$O can imprint on solids

- Solar-composition solids
- High-temperature solid-gas exchange

*Note: animated slide*
Ways in which the $^{16}$O-poor H$_2$O can imprint on solids

Note: animated slide
The volatile-rich carbonaceous chondrites

Murchison; field of view ca. 2 cm
The volatile-rich carbonaceous chondrites

Murchison; field of view ca. 2 mm

Photomicrograph courtesy of A. Brearley
The volatile-rich carbonaceous chondrites
A conceptual model for the secondary origins of volatiles in asteroidal bodies

Initial aggregate of water ice, dust and coarse, anhydrous silicate and metal

Ice-poor body rich in hydrous silicates and mineralized veins

\[ H_2O \] evaporates or sublimes at surface of planitessimal and is lost to space

ice melts and product water reacts with solids
The seemingly plausible alternatives for the structure and evolution of volatile-rich planetesimals

I. Static water
   Small bodies
   Fast cooling < 20-50 km

II. Water exhalation

III. Convection
   Large bodies
   Prolonged cooling

After Young et al. 2003
Potential dynamical significance of recognizing convective water/rock reaction

Young et al., 2003
An expected range of thermal histories

Model of Travis and Schubert, 2005 and Young et al., 2003; data from Hutcheon, 1999; Brearley, 2000, 2001; Hoppe, 2004

$^{26}\text{Al}/^{27}\text{Al} \sim 5 \times 10^{-6}$

Surface $T \sim 170 \, \text{K}$
The carbonaceous chondrites come from the ‘goldilocks’ planetesimals

Big enough to stay cool by convection early; small enough to loose heat by radiation

Models from Young et al., 2003 and Travis and Schubert, 2005; T data from Guo, 2008.
The carbonaceous chondrites come from the ‘goldilocks’ planetesimals

*Big enough to stay cool by convection early; small enough to lose heat by radiation*
Quantitative models of asteroidal aqueous alteration

**Rock in a jar**

**Soup-to-nuts**

- fluid-dominated front
- reaction front
- rock-dominated front
- hot
- cold
- fluid flow
- CI chondrites
- CM chondrites
- CO, CV chondrites

Clayton and Mayeda, 1984; 1999

Young, 2000
Can we recognize fluid flow systems in the major element chemistry of chondritic materials?

- Elements subject to distinctive enrichments or depletions in fluid flow systems
There are clearly systematic ‘signals’ of water-rock reaction in the elemental abundances of chondrites

Browning et al., 1996
Can we connect simple visual observations to these sorts of geochemical and physical arguments?

Browning et al., 1996
What should we make of subtle differences in $^{16}\text{O}$ depletion between planetary-scale bodies?

- Presumably reflects weighted average H$_2$O/silicate ratio of ‘feeding zone’
- No really meaningful predictions (yet) of spatial/temporal gradients

Clayton and Mayeda, 1996
Dust-vapor hydration reactions I: thermodynamics

$P,T$ evolution of early nebula

Forsterite

Fe

Troilite (FeS)

$\text{Fe}^{2+}$ in silicates

Magnetite

Tremolite

Serpentine & Brucite

Water Ice

Fegley, 2000
Dust-vapor hydration reactions II: kinetics

Lifetime of solar nebula

Temperature (K)

log$_{10}$ lifetime (seconds)

Stable in early solar nebula
Meta stable in early solar nebula

Fe $\rightarrow$ FeS

Fe $\rightarrow$ magnetite

silicates $\rightarrow$ serpentine, talc, & brucite

Fegley, 2000

Lifetimes of 100 nm grains w/r to gas-phase reactions
Hydration associated with shock waves?

Ciesla et al., 2003
Igneous differentiation of asteroids

Ghosh et al., 2006
Hf-W isotope systematics as a chronometer for metal/silicate differentiation

- Chronometer assumes $^{182}$Hf (half life 8.9 Ma) and its daughter $^{182}$W were evenly distributed
- Date by measuring $^{182}$W accumulated in high and low Hf/W materials
- Generally dates metal/silicate separation

Corrected for cosmic ray W isotope production

- Confirms and generalizes petrographic observation that planetesimals differentiated while chondrule formation was still active
Element abundance signatures of silicate differentiation

Silicate melting/crystallization
Vapor/solid differentiation

Granular, cumulate Eucrite
Closing observations and questions

• Laboratory studies of meteorites can establish conditions and timing of
  – condensation
  – melting of dust
  – aqueous alteration
  – metal/silicate separation
  – silicate melting

• What of these do we want to know to address questions of general importance?

• Which things can we figure out remotely? With simple \textit{in situ} observations?

• Is there anything here we want to know so badly that we should invent new instruments or methods to do it?

• O isotopes present a special case; they seem to map a key process of spatially and temporally heterogeneous differentiation. But we don’t have any clear ideas about this all connects to planetesimal and larger scales.