What makes a planet (unin)habitable?
Runaway greenhouse, moist greenhouse
Course outline

Foundations (1-2 weeks)
- Earth history
- HZ concept, atmospheric science essentials
- Post-Hadean Earth system

Principles – how are habitable planets initiated and sustained? (4-5 weeks)
- Volatile supply, volatile escape
- Inner edge and outer edge of the habitable zone
- Long-term climate evolution

Specifics (2.5 weeks)
- Hyperthermals on Earth
- Early Mars
- Oceans within ice-covered moons
- Exoplanetary systems e.g. TRAPPIST-1 system
Logistics/Today

• Homework 3 is due tomorrow in my mailbox, 1st floor Hinds
• Homework 4 will be issued Saturday, due next Friday
• **Hinds 176**, 3:35p-4:30p, Tue May 14 for make-up lecture
• Presentation
• Earth-climate stabilization: looking under the hood of the carbonate-silicate feedback
  – The carbonate-silicate feedback hypothesis
  – Testing the hypothesis
  – Refining the hypothesis
What controls the weathering rate?

- Water supply (to flush away dissolved products)
- CO₂ concentration (acidity; thermodynamics)
- Temperature (➔ kinetics)
- Reactive surface area (uplift/tectonics/erosion)
Refining the carbonate-silicate weathering feedback hypothesis: shift from direct T to indirect hydrologic control

What accounts for the lab-vs.-field discrepancy in weathering rates?
What is the role of flushing?

\[ \frac{dc}{dz} = \frac{R_d}{q} \left(1 - \frac{c}{c_{eq}}\right) \]

Maher EPSL 2010
It takes time for the soil water to reach equilibrium with the soil.

$$c(x) = c_0 \exp \left( \frac{-R_n \phi x \tau}{qc_{eq}} \right) + c_{eq} \left( 1 - \exp \left( \frac{-R_n \phi x \tau}{qc_{eq}} \right) \right)$$

$\tau$ is a constant

Advection-reaction equation (heterogenous, irreversible reactions)

$c [\mu mol/L]$ = concentration of a dissolving solute

$R_n [\mu mol/L/yr]$ = net dissolution rate (affected by availability of fresh minerals)

$q [m/yr]$ = flow rate

Damkohler number:

$$Da = \frac{R_n l \phi}{qc_{eq}} = \frac{t_f}{T_{eq}}$$

$$t_f = l \phi / q [yr]$$

$$T_{eq} = c_{eq} / R_n [yr]$$

$Da \to 0$, $c(x) \to 0$

$Da \to \infty$, $c(x) \to c_{eq}$

$$c(t_f) = c_0 \exp \left( \frac{-t_f \tau}{T_{eq}} \right) + c_{eq} \left( 1 - \exp \left( \frac{-t_f \tau}{T_{eq}} \right) \right)$$

Need to integrate over the hillslope (with different travel times)
**Damkohler number** (widely used)  

\[ Da = \frac{R n l \phi}{q c_{eq}} = \frac{t_f}{T_{eq}} \]

multiply by \( q \)

**“Damkohler Coefficient”** (used only by Maher & Chamberlin 2014)

\[ Dw[m / yr] = \frac{L \phi}{T_{eq}} \]

**Integration**

\[ C = \frac{C_0}{1 + \tau Dw / q} + C_{eq} \frac{\tau Dw / q}{1 + \tau Dw / q} \]

integration over an exponential distribution of travel times not shown (see Maher & Chamberlin 2014, supplementary equations S6-S8)
Main controls on solute flux: travel-time of fluid and age of soil

Central California marine terrace chronosequence

young soil, more reactive
old soil, less reactive
Symbols: output from a reaction-transport model
Curves: analytic fit
Soil production rate approximately balances erosion rate (and, less precisely, rock uplift rate).


Mountain soil thicknesses are usually $<\sim O(1)$ m.
\[ Dw(\text{m/year}) = \frac{L\phi}{T_{eq}} = \frac{L\phi R_{n,\text{max}} f_w}{C_{eq}} \]
Note: effect of orographic precipitation

(local relief: 10 km window)

Montgomery & Brandon
EPSL 2002: negative feedback on mountain height
Where’s the **direct** effect of temperature? A: It’s small.

**Fig. S7:** Temperature sensitivity of weathering reactions. The primary mineral dissolution reactions and CO$_2$ dissociation reactions are show in solid lines, while the net reactions are shown in light stippled lines. The starred reaction in bold represents a simplified version of the one of the net reaction considered in the RTM simulation. Thermodynamic data is from ref. (92).
Where’s the effect of temperature?

(B) Increases in $k_{\text{eff}}$ by a factor of 2, 5 and 10 (see legend) corresponding to temperature increases of 15 to 30°C and 15 to 40°C and 15 to 75°C, respectively. Because $k_{\text{eff}}$ appears in both the $R_n$ term and the $f_w$ term (i.e., in the numerator and the denominator of $D_w$) the effects of temperature are minimal at small $D_w$, but increase with increasing $D_w$ as the numerator becomes larger. (C) and (D) Sensitivity analysis is shown in
$Dw(\text{m/year}) = \frac{L\phi}{T_{eq}} = \frac{L\phi R_{n,\text{max}} f_w}{C_{eq}}$

$f_w = \text{fraction of fresh minerals}$

Maher & Chamberlain Science 2014: 
**Earth’s thermostat is mediated by wetting of mountain belts in response to global warming**
Mountain belts also release $\text{CO}_2$ (via metamorphic decarbonation and by oxidation of C in uplifted shale, coal)

Evans et al., G$^3$, 2008

Bickle, Terra Nova, 1996
Tests for the carbonate-silicate weathering feedback hypothesis:

- Seek present-day gradients weathering corresponding to present-day gradients in temperature between watersheds.
- Seek evidence for weathering increases during geologically-sudden warm events.
- (Because of the Faint Young Sun) look for evidence of higher pCO2 in the distant geologic past.
Q: When CO$_2$ goes up, does temperature go up?

A: Sudden rises in CO$_2$ are accompanied by temperature rises; longer-term changes in temperature may have other controls, e.g. albedo.

Retallack, Phil. Trans., 2002

Before 1 Mya, temperature records are more reliable than pCO$_2$ records.
River input

- Composition of upper continental crust (UCC) ~ composition of shales ~ composition of river sediments.

- [Seawater] >> [UCC]: S, Cl, F, B, Mg, Na, K
- [Seawater] << [UCC]: Pb, Al, Si, Fe
How river input (discharge x concentration) is measured

Acoustic Doppler profiling (discharge)

Stream gages (discharge)

Sampling for chemistry (concentrations)
Concentration-discharge relationships show dilution trend at large discharge.

This trend is also observed for the seasonal cycle of runoff in individual rivers. Therefore, constructing an annual-average budget requires many concentration measurements.

**Figure 6** Holland’s (1978) plot of total dissolved solids vs. runoff for the world’s rivers. Solid curve shows general trend; solid line shows dilution trend.
Some support for T and runoff control on weathering, but much scatter

\[ F_{\text{CO}_2} = k \cdot \text{Run} \cdot \exp \left( \frac{-E_a}{R} \cdot \left( \frac{1}{T} - \frac{1}{T_0} \right) \right) \]

Data: 99 small granitic catchments

Oliva et al. 2003

Kinetically-limited watersheds vs. supply-limited watersheds

Transport-limited, High weathering intensity (plains)

“supply” limited

Earth’s ability to recover from a hyper-thermal resides in the mountains

Kinetically-limited, low weathering intensity (steep mountains)
Putting it all together: combined effect of rainfall, temperature, and erosion rate on dissolved flux

West et al. 2005 EPSL
Testing the carbonate-silicate weathering feedback using present-day temperature gradients: Rivers and streams in Antarctica

Nezat et al. GSA Bulletin 2001

| TABLE 1. LENGTHS, DISCHARGES, AND CALCULATED $\text{H}_2\text{SiO}_4$ AND $\text{HCO}_3^-$ DENUDATION RATES FOR TAYLOR VALLEY STREAMS |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Length* (km)    | Discharge (m$^3$) | $\text{H}_2\text{SiO}_4$ (µM) | $\text{H}_2\text{SiO}_4$ denudation$^\dagger$ (10$^3$ mol·km$^{-2}$·yr$^{-1}$) | Discharge (m$^3$) | $\text{H}_2\text{SiO}_4$ (µM) | $\text{H}_2\text{SiO}_4$ denudation$^\dagger$ (10$^3$ mol·km$^{-2}$·yr$^{-1}$) |
| Fryxell Basin   |                 |                   |                    |                 |                   |                    |
| Canada Stream   | 1.5             | 41 710            | 27.8              | 4 m stream width| 146              | 24                | 75 350           | 30.6            | 298              | 0.20            | 2520             |
| Lost Seal Stream| 2.2             | 20 630            | 46.5              | 24 m stream width| 93               | 16                | 56 480           | 34.0            | 175              | 0.49            | 3140             |

| TABLE 2. CHEMICAL DENUDATION RATES CALCULATED FROM STREAM $\text{H}_2\text{SiO}_4$ AND $\text{HCO}_3^-$ FLUXES |
|-----------------|-----------------|-----------------|
| River           | $\text{H}_2\text{SiO}_4$ (10$^3$ mol·km$^{-2}$·yr$^{-1}$) | $\text{HCO}_3^-$ (10$^3$ mol·km$^{-2}$·yr$^{-1}$) | Source |
| World average   | 64              | 300             | Hu et al. (1982) |
| Tisa (Eastern Europe)* | 90              | 640             | Lyons et al. (1992) |
| Mekong (Southeast Asia)$^\dagger$ | 100             | 680             | Hu et al. (1982) |
| Amazon (South America)$^\ddagger$ | 130             | 300             | Hu et al. (1982) |
| Cahaba (Alabama, USA)* | 55              | 736             | Lyons et al. (1998) |
| Alabama (Alabama, USA) | 51              | No data         | Lyons et al. (1998) |
Paleocene-Eocene Thermal Maximum
A hyperthermal 55 Mya

Adequate spatial coverage

Time resolution limited to > 1 Kyr by bioturbation

Though brief relative to the ~100 Kyr timescale of the weathering feedback, the CO₂ release that triggered the PETM was much more prolonged than anthropogenic CO₂ release.
Sustained temperature rise:
expect – increased weathering; intensified hydrologic cycle;
CO2 drawdown on ~100 Kyr timescale

Time interval estimated using cyclostratigraphy and helium-3 accumulation
Osmium-isotope systematics

Oceanic Os Inputs

Continental Run-off

“Continental Crustal” Weathering

Ultramafic Weathring

Extraterrestrial Input

Seawater $^{187}\text{Os}/^{188}\text{Os} =$ flux weighted average of inputs

Seafloor hydrothermal Input

Red arrows low $^{187}\text{Os}/^{188}\text{Os}$ about 0.13

Green arrow high $^{187}\text{Os}/^{188}\text{Os}$ - today about 1.4

Q: Where does the “rest” of the Os go?
A: into clastic sediments (suspended load), and then sedim. basins (e.g. deltas) for long-term storage
Example of Os-isotope response to a hyperthermal (0.18 Ga, non-PETM) event. Cohen et al. Geology 2004, “Osmium isotope evidence for the regulation of atmospheric CO$_2$ by continental weathering.”

Evidence for increased chemical weathering at the PETM. Dickson et al., P$^3$, 2015

Other potential proxies for weathering intensity include $^7$Li and $^{40}$K.
Evidence for increased chemical weathering at the PETM

Dickson et al., P³, 2015

$mbsf$ = meters below sea floor
Return to the Paleocene-Eocene Thermal Maximum (55 Mya): consistent with Maher & Chamberlin?

PETM: geologically-rapid injection of isotopically light C $\rightarrow$ global warming. How did Earth’s climate recover?

Bowen & Zachos,
Nature Geoscience 2010
Predictions of M&C 2014 for the PETM:

• Extent of weathering should increase (clay mineralogy reflecting deeper weathering)
• Rainfall should increase (at least in mountainous zones relevant to weathering).
There is a global kaolinite spike at the PETM

Kaolinite = clay formed from thorough intense leaching of parent rock; associated with humid climates

Gibson et al. Sedimentary Geology 2000

Also found on Mars (Carter et al. Icarus 2015)
The age of the kaolinite is uncertain

John et al. Geology 2012

Massive increase in physical erosion (stripping of previously-leached laterites)
John et al. Paleoceanography 2008
Figure 9. Summary of the carbon isotope results obtained in this and other studies and conceptual cross section from the continent to the deep sea. Data from left to right are for Tumey Gulch (continental slope, California), Lodo Gulch (outer shelf, California), Wilson Lake (inner shelf, New Jersey), Bass River (inner to outer shelf, New Jersey), and various deep-sea records (ODP Sites 1051, 690, and 1263).
Evidence for hydrological change in mountainous regions

Fluvial response to abrupt global warming at the Palaeocene/Eocene boundary

Brady Z. Foreman¹, Paul L. Heller¹ & Mark T. Clementz¹

Figure 1 | Generalized geologic map showing major Laramide structures and associated basins. The Uinta and Piceance Creek basins were separate during the Palaeocene and the earliest Eocene epochs, and Cenozoic volcanic fields substantially post-date the deposition of the Wasatch formation.
- floral indications of initial drying followed by return to wetter conditions


Pyrenees: Schmitz & Pujalte, Geology 2007
Severe data-model mismatch when only temperature-dependent silicate weathering is considered

Bowen 2013
Is the carbonate-silicate weathering feedback enough to explain the data?

Dashed lines: without organic matter feedbacks
Solid lines: with organic-matter feedbacks

Bowen 2013
Key points from the required reading

• Transport limitation vs. kinetic limitation
• Conceptual understanding of hillslope- and watershed-scale weathering, controls on fluxes, relative timescales
Key points – a look under the hood of the carbonate-silicate feedback hypothesis

• Main fluxes and reservoirs in the long-term carbon cycle: what is the evidence for a negative feedback?
• Testable elements of the carbonate-silicate weathering hypothesis: how well do they hold up to testing?
• Evidence from past shocks to the Earth system and present-day weathering bearing on the carbonate-silicate weathering hypothesis.
  - Testing hydrologic control on silicate weathering rates as an explanation for recovery from the PETM
  - Alternative, organic-carbon explanations
• Possible explanations for the lab-vs.-field discrepancy in weathering rates: the role of flushing.
Backup slides
A new proxy for weathering: $^7$Li

\[
\delta^7\text{Li} (\%o) = \left\{ \left( \frac{^{7}\text{Li}/^{6}\text{Li}}{^{7}\text{Li}/^{6}\text{Li}} \right)_{\text{Sample}} \right\} - 1 \right\} \times 1000
\]

Seawater
[Li] = 26 \, \mu M
\delta^7\text{Li}_{SW} = 31\%o
\tau \approx 1.2 \, \text{Ma}

Lithium cycle is mostly in silicate rocks and aluminosilicate clays; none in carbonates.
High weathering intensity: Low riverine $^7$Li concentrations.
Low weathering intensity (e.g. mountains): High riverine $^7$Li concentrations.
0.9% increase

Dissolved Li 50 Ma → suspended Li today?

(Other interpretations possible).

Ocean Drilling Program
Evidence for increased chemical weathering at the PETM

Dickson et al., P3, 2015

SVALBARD

$^{187}\text{Os}/^{188}\text{Os}_{(i)}$

0.3 0.4 0.5 0.6 0.7 0.8

Depth (mbsf)

515 520 525 530 535 540 545

$\delta^{13}\text{C}_{\text{org}}$

mbsf = meters below sea floor
Seasonal and interannual variability

Gislason et al. 2009

Icelandic watersheds showing a large, recent temperature increase (natural experiment)
Testing the prediction of a pole-to-equator increases in weathering rates

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Runoff, mm yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;30</td>
</tr>
<tr>
<td>&lt;4</td>
<td></td>
</tr>
<tr>
<td>tundra and taiga, (0.75)</td>
<td>wet taiga, 1.6</td>
</tr>
<tr>
<td>4-15</td>
<td></td>
</tr>
<tr>
<td>semi-arid temperate, (0.6)</td>
<td>temperate, 1.4</td>
</tr>
<tr>
<td>15-25</td>
<td></td>
</tr>
<tr>
<td>arid, 0.25</td>
<td></td>
</tr>
<tr>
<td>&gt;20</td>
<td></td>
</tr>
<tr>
<td>mixed tropical, 2.35</td>
<td></td>
</tr>
</tbody>
</table>

Weathering rates are expressed in $10^6$ gm km⁻² yr⁻¹ of dissolved SiO₂. Parentheses signify poorly determined values.
DeConto et al., Nature 2012: polar permafrost as a carbon capacitor
Large-scale organic carbon burial offshore in deltas today

Sequestration of petrogenic C moderates C release from eroding coal, org.-rich shale
Sequestration of biospheric C draws down CO2 from atmosphere/ocean.

Galy et al. Nature 2007
Galy et al. Nature 2015*

* Optional reading this week

Figure 2 | Relationship between biospheric POC yield ($Y_{\text{bios}}$) and suspended sediment yield. Data obtained by subtracting measured petrogenic OC fluxes from riverine POC fluxes (black dots) and those obtained using petrogenic OC fluxes inferred from the relationship shown in Fig. 1 (grey dots) plot on the same trend. The regression line is $Y_{\text{bios}} = 0.081 Y_{\text{sed}}^{0.56}$, $r^2 = 0.78; P < 0.001$. 
Survival chances of terrestrial organic matter are slight unless deposition is fast (usually only for the deltas of rivers draining fast-eroding mountain belts).

Because re-oxidation of organic matter (both terrestrial and marine) is usually efficient, oil and coal are rare in the rock record.
Snowball Earth catastrophe can be modeled using a 1D (latitudinal) Energy Balance Model (EBM)

\[ \frac{Q}{4} S(x)[1 - \alpha(x)] = A + BT(x) + \nabla \cdot \mathbf{F}, \]

\[ x = \sin(\text{latitude}) \]

\[ x_s = \text{ice line latitude} \]

\[ x = \sin(\text{latitude}) \]

Suppose

\[ \alpha = 0.6, \ T < T_s \]

\[ \alpha = 0.3, \ T > T_s \]

normalized latitudinal distribution of insolation (depends on obliquity)

Budyko 1969: \[ \nabla \cdot \mathbf{F} = C(T - \overline{T}). \]

North 1975: \[ \nabla \cdot \mathbf{F} = -D \frac{d}{dx}(1 - x^2) \frac{dT}{dx}. \]

Following Roe & Baker 2010 (optional reading, pdf on website)
Snowball Earth catastrophe can be modeled using a 1D (latitudinal) Energy Balance Model (EBM)

\[
\frac{Q}{4} S(x_s)(1 - \alpha_s) - C(T_s - \bar{T}) = A + BT_s,
\]

(absorbed shortwave \quad \text{flux divergence})

\[
\frac{Q}{4} (1 - \alpha_s) S(x_s) + \frac{Q C}{4 B} (1 - \alpha_p) = \text{constant}.
\]

Due to spherical geometry for a rapidly-rotating planet:
- At lower latitudes,
  - local insolation (negative feedback) increases more slowly with decreasing latitude
  - local divergence of the heat flux (+ve feedback) leads to more cooling with decreasing latitude

Following Roe & Baker 2010 (optional reading, pdf on website)

but see Abbot et al. 2011 for a proposed low-latitude stable-ice-line glacial state
Fig. 2. Change in surface temperature ($\Delta T = T_s - 285^\circ K$) and carbon dioxide partial pressure ($P$) as functions of change in effective temperature ($\Delta T_e = T_e - 253^\circ K$) for several values of the volcanic and metamorphic source of $CO_2$. Present day values are designated $P_0$ and $V_0$. The broken line shows the surface temperature variation for constant $CO_2$ pressure.
CO$_2$ versus time for the last 0.5 Gyr
Gastornis in earliest Eocene forest

Major radiation of mammals at the PETM (e.g., horses double in size)
Testing the silicate-weathering feedback hypothesis with hyperthermals

Cui et al. Nature Geoscience 2011
No evidence for T or runoff control on physical erosion from $^{10}\text{Be}$ data

$^{10}\text{Be}$: spallation product of $^{16}\text{O}$, 1 Myr half-life, formed by neutron bombardment <~1 m from Earth surface (Neutrons are cosmic-ray secondaries)

von Blanckenburg EPSL 2006