EART163 Planetary Surfaces

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Last week – “Water”

- Subsurface water – percolation, sapping
  \[ v_d = \frac{k}{\eta} \frac{dP}{dx} \quad \kappa_{hyd} = \frac{k}{\phi \eta} \Delta P \]

- Surface flow
  - Water discharge rates
  - Sediment transport – initiation, mechanisms, rates
    \[ u^* = \sqrt{gh \sin \alpha} \quad u^*_{crit} = \left( \frac{\rho_s - \rho_f}{\rho_f} \right)^{1/2} (gd)^{1/2} \theta^{1/2} \]

- Channels – braided vs. meandering

- Fluvial landscapes
This Week – Ice & Sublimation

- Ice rheology
- Glaciers & ice sheets
- Ice in the subsurface
- Sublimation
Glaciers

- Ice accumulates in high regions (lapse rate)
- Flows downhill once sufficiently thick (velocity strongly depends on $h$)
- Loss by melting and/or sublimation at low elevations
Non-Newtonian Flow

- Ice is *non-Newtonian* – strain rate depends on \((stress)^n\)
- This alters the flow behaviour

\[
\dot{\varepsilon} = \frac{\partial u}{\partial z} = A \sigma^n
\]

\[
u(z) = u_{\text{max}} \left(1 - \left[1 - \frac{z}{h}\right]^{n+1}\right)
\]

\[
u_{\text{max}} = A\left(\rho gh \sin \alpha\right)^n \frac{h}{n + 1}
\]

- Newtonian \((n=1; \text{parabolic})\)
- Non-Newtonian \((n>1)\)

Vertical distance \(z\)

Velocity \(u\)

Axisymmetric, flat flow

Replace \(\alpha\) with \(h/r\)

2D, downslope flow
Ice rheologies

\[ \dot{\varepsilon} = A \sigma^n \exp\left( \frac{Q}{RT_{ref}} - \frac{Q}{RT} \right) \]

<table>
<thead>
<tr>
<th></th>
<th>( T_{ref} (K) )</th>
<th>( A ) (MPa(^{-n}) s(^{-1}))</th>
<th>( n )</th>
<th>( Q ) (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water ice</td>
<td>270</td>
<td>10^{-6}</td>
<td>1.8</td>
<td>50</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>170</td>
<td>1.5x10^{-6}</td>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>N(_2)</td>
<td>50</td>
<td>2x10^{-2}</td>
<td>2.2</td>
<td>5</td>
</tr>
</tbody>
</table>

- All three are non-Newtonian \((n>1)\)
- At the same temperature, the viscosity order is \(N_2 << CO_2 << H_2O\)
- In reality, rheology also depends on grain size, silicate fraction etc. etc.
Rock Glaciers

- Rare on Earth
- Rock particles increase viscosity
- Common(?) on Mars
- On Mars, ice may have sublimed away – see later
Nitrogen Glaciers on Pluto
Cold vs Warm-based glaciers

- On Earth, the base of a glacier can be either above the freezing point (“warm”) or below it (“cold”)
- Cold-based glaciers have \( \sim \)zero velocity at the base
- Warm-based glaciers have non-zero basal velocities (liquid water and/or soft sediments lubricate the base)
- Warm-based glaciers can undergo “surges” when the basal conditions change (e.g. water is rerouted)

![Diagram](attachment:diagram.png)

- Ice-sheets (e.g. Antarctica) are subject to feed-backs e.g. more melting -> more lubrication -> faster flow -> more ice loss etc. . .
- The ocean can also play a role in this case (seawater infiltration)
Glacial erosion happens mainly via embedded rocks. Rate of erosion depends on overburden pressure ($\rho gh$). But if the overburden pressure exceeds ~3MPa, the erosion shuts off – because the rocks get pushed upwards into the ice (the ice yield strength is exceeded). This explains why glaciation produces U-shaped valleys (why?)
Glacial Deposition

- Glaciers leave a variety of deposits as they retreat
- Analogues to some of these deposits have been identified on Mars
Glaciation on Mars

Lobate debris aprons (LDAs)
Ice sheet profiles (static)

Net force = $\rho gh^2/2$

Net resistance = $Y_B L$

$$h = \sqrt{\frac{2Y_B L}{\rho g}}$$
Martian polar caps

- Water ice below CO$_2$
- Polar troughs – wind?
- Radar sounding
Are the Martian caps CO$_2$ ice?

Martian ice cap, 160 K

$h= 2$ km, $r=300$ km, $g=3.7$ ms$^{-2}$, $\rho=1.5$ g/cc

At 160K, $A=0.4 \times 10^{-6}$ MPa$^{-n}$ s$^{-1}$

$\rho gh=11.8$ MPa, $u_{\text{max}}=0.05$ m/yr

Flow timescale $\sim r/u_{\text{max}} \sim 6$ Myr

$u_{\text{max}} = A \left( \rho gh \frac{h}{r} \right)^n \frac{h}{n+1}$

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$h= 1$ km, $r=50$ km

$u_{\text{max}}=0.1$ m/yr

Flow timescale $\sim 0.5$ Myr

Seems very short!

Doesn’t seem completely implausible, but what about the canyons?
Radar Sounding

- Propagation speed identifies material (water ice)
- Layering suggests climate cycles (e.g., Milankovitch)
- But we don’t have good absolute ages

Milankovitch cycle image? Mars single seismometer? Ocean tsu
Ice wedges & Polygons

- Formed by melting-freezing cycles
- Near-surface features – annual thermal wave penetrates a depth $\sim (\kappa t)^{1/2}$
- *Scale* of polygons not well understood
Mars Polygons

Patches of ice just below the surface, revealed by Phoenix thrusters.
Ice exposed at the surface

*Mars Express* image
70.5° North, 35 km across

HiRise image
~70° North, 50 m across
Neutron Spectrometer

- Cosmic rays produce neutrons
- Neutrons can be detected from orbit
- Hydrogen is a good absorber of neutrons
- A lack of neutrons implies near-surface (<2m deep) hydrogen
- This is assumed to be water ice
Sublimation

- In equilibrium, a solid (or liquid) will have a finite vapour pressure above it.
- At this vapour pressure the upwards and downwards molecule fluxes are equal.
- The downwards flux \( \sim \rho_g v_{rms} \)

If the vapour is removed, the upwards flux will exceed the downwards flux and sublimation will result.

The rate of solid removal \( dh/dt \) is given by:

\[
\frac{dh}{dt} = \frac{P_{vap}}{\rho_s} \sqrt{\left( \frac{\mu}{2\pi RT} \right)}
\]

\( \alpha \)
Energy limitations

- Vapour pressure is strongly temperature-dependent
- So sublimation depends on temperature
- Sublimation also takes energy (because conversion to vapour requires latent heat $L$)

*Maximum* sublimation rate is limited by available power per unit area $F$: \[ \frac{dh}{dt_{\text{max}}} = \frac{F}{\rho_s L} \]

- Sublimation rate also decreases if the pressure above the solid surface is non-zero
Example Vapour Pressure Curve

\[ \ln P_{vap} = -\frac{4.8 \times 10^4}{RT} + 26.6 \]  

(pressure in Pa, T in K)
Where does sublimation happen?
Sublimation of Water Ice

\[
\frac{dh}{dt} = \frac{P_{vap}}{\rho} \sqrt{\frac{\mu}{2\pi RT}}
\]

\[
\ln P_{vap} = -\frac{4.8 \times 10^4}{RT} + 26.6
\]

- Applications:
  - Galilean satellites
  - Ceres
  - Mars

<table>
<thead>
<tr>
<th>Temp (K)</th>
<th>$P_{vap}$ (Pa)</th>
<th>$\frac{dh}{dt}$ (m/s)</th>
<th>$t$ (1 km loss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>$4 \times 10^{-10}$</td>
<td>$7 \times 10^{-16}$</td>
<td>45 Gyr</td>
</tr>
<tr>
<td>150</td>
<td>$6 \times 10^{-6}$</td>
<td>$1 \times 10^{-11}$</td>
<td>3 Myr</td>
</tr>
<tr>
<td>180</td>
<td>$4 \times 10^{-3}$</td>
<td>$6 \times 10^{-9}$</td>
<td>5 kyr</td>
</tr>
<tr>
<td>220</td>
<td>1</td>
<td>$1 \times 10^{-6}$</td>
<td>30 yr</td>
</tr>
</tbody>
</table>

Phoenix landing site

Occator crater, Ceres
Sublimation Features (?)

“Spires” on Callisto

“Bladed terrain” on Pluto (spacing ~5km)

“Penitentes” on Earth
“Swiss cheese terrain”, Mars

~1m per year recession

Martian polar winter

100m scalebar (appx)
“Spiders” on Mars?

“Spiders” are typically ~200m across.

Similar process on Triton?
Lag deposits

- Albedo-sublimation feedbacks occur.
- Sublimation shuts off once a thick enough lag deposit is produced (few metres).
- Relevant to Mars and bodies in the outer solar system.

Spencer (1987)
Iapetus

- Extreme albedo contrasts
- Albedo-sublimation feedbacks
- Combination of dust deposition and volatile trapping

Spencer & Denk (2010)
Summary – Ice & Sublimation

• Ice rheology
  – Non-Newtonian
  \[ \dot{\varepsilon} = \frac{\partial u}{\partial z} = A\sigma^n \]

• Glaciers & ice sheets
  – Cold-based vs. warm-based
  – Erosional & depositional features

• Ice in the subsurface
  – Polygons, ice wedges, thermal wave, neutron data

• Sublimation
  – Albedo-lag feedbacks
  \[ \frac{dh}{dt} = \frac{P_{vap}}{\rho}\sqrt{\frac{\mu}{2\pi RT}} \]
Next Steps

• This Thursday (26th) – research lecture #1
• Next Tuesday (31st) – research lecture #2
• Next Thursday (2nd) – recap/revision

• Final – Monday (6th) 8am-11am
flow

\[ h \]

\[ z \]

\[ \alpha \]