Last Week – Impact cratering

• Why and how do impacts happen?
  – Impact velocity, comets vs. asteroids

• Crater morphology
  – Simple, complex, peak-ring, multi-ring

• Cratering and ejecta mechanics
  – Contact, compression, excavation, relaxation

• Scaling of crater dimensions
  – Strength vs. gravity, melting

• Cratered landscapes
  – Saturation, modification, secondaries, chronology

• Planetary Effects
This Week – Mass Movements

• What are the processes by which down-slope movement occurs?
• What surface record of these processes exist?
• What do the observations tell us about surface properties?

• Creep
• Landslides
• Gravity currents
Downhill creep

• Downhill creep can occur in several ways
  – Expansion/contraction cycles (why?) e.g. freeze/thaw
  – Rainfall
  – Small impacts

• The rate of creep is (often) proportional to the slope

\[ \frac{\partial z}{\partial t} = - \frac{\partial}{\partial x} \frac{S}{x} \quad S = -K \frac{\partial z}{\partial x} \]

\( S \) is the flux \((m^2s^{-1})\)
\( K \) is the diffusivity \((m^2s^{-1})\)

Putting this together, we get:

\[ \frac{\partial}{\partial t} z = K \frac{\partial^2 z}{\partial x^2} \]

What is this?
Diffusion

• So we can model downhill creep as a *diffusive* process
• The diffusivity $K$ tells us how rapid creep is and how old a landscape might be (e.g. scarp softening)
• Diffusion creates *convex-upwards* topography (opposite to river profiles)

\[
\frac{\partial z}{\partial t} = K \frac{\partial^2 z}{\partial x^2}
\]

From initial and final profile shape we can infer the product $Kt$ – Why? How?

Lunar $K \sim 0.005 \text{ m}^2/\text{kyr}$ (crater degradation)
Western US $K \sim 1 \text{ m}^2/\text{kyr}$

Atacama Desert, Chile (Perron and Dietrich, 2006)  
Columbia Hills, Mars  
North Massif, the Moon
What controls $\kappa$?

- A larger $\kappa$ means more rapid slope degradation
- We can use the relationship $\kappa \sin \alpha \approx uh$ where $u$ is a downslope speed and $h$ is active layer thickness
  - E.g. if the active layer is a viscous flow (see Week 4), then

$$\kappa \approx \frac{\rho gh^3}{\eta}$$

- Gophers can be an important source of diffusivity!
Application: Lunar Rilles

Images courtesy Caleb Fassett

AS15-85-11398/AS15-85-11399
Photo Credit: Jim Irwin
Application: Lunar Rilles

Issue:
Unlike with craters, don’t have constraint on form of initial topo or age
Application: Lunar Rilles

Rectangular initial profile:
\(~90^\circ\) interior slopes…

Final $\kappa t \sim 18300$ m²
If $\kappa \sim 0.005$ m²/Kyr then $t \sim 3.5$ Gyr
Infill $\sim 40$ m

Triangular initial profile:
\(30^\circ\) interior slopes…

Final $\kappa t \sim 14500$ m²
If $\kappa \sim 0.005$ m²/Kyr then $t \sim 2.5$ Gyr
Infill $\sim 60$ m
Landslides

Resistance to sliding:

\[ \sigma_s = c + (\sigma_n - p) \tan \phi \]

- \( c \) is the cohesion (Pa)
- \( \sigma_n \) is the normal stress (=\( \rho gh \cos \theta \))
- \( p \) is the fluid pressure
- \( \phi \) is the angle of friction

For a cohesionless material, \( \phi \) is the angle of repose. Why?

Why do landslides frequently happen during/after heavy rain?
Angle of repose

- Angle of repose is *independent* of gravity
The ratio $H/L$ is an indication of the friction coefficient during landslide formation – why?

Friction coefficient is smaller for large slides, and smaller for Earth than Mars and Callisto. The reason for these differences is not understood.

Moore et al. 1999
Long-runout landslides

• A mystery!
• Only occur for large slides (>10^6 m^3)

• Probably not gas-supported
• Perhaps “acoustic fluidization”? 
Landslide Examples

McGovern et al. 2004

Oahu
Mars
Kilauea
Callisto
Io

Hawaiian landslide major hazard is *tsunamis* – evidence in Pacific NW?
Cliff Failure

Average vertical stress \( \sigma_v = \rho gh/2 \)

Normal stress \( \sigma_n = \sigma_v \cos^2 \theta \)

Shear stress \( \sigma_s = \sigma_v \cos \theta \sin \theta \)

\[ \sigma_s = c + (\sigma_n - p) \tan \phi \]

Put it all together and . . .

\[ h_{\text{crit}} = \frac{2c}{\rho g} \tan \left( 45^\circ + \frac{\phi}{2} \right) \]

Does this make sense?

Comet Wild 2 has vertical cliffs \( \sim 100 \text{m high} \)

\( \rho \sim 0.7 \text{ g/cc (say), } g \sim 0.5 \text{ mm s}^{-2} \)

What is the implied cohesive strength?
Thermal expansion plays a role

Rockfalls happen at particular times of day
A spectrum of flows
Density Currents

- Fluid-supported (air or water)
- Can travel at 100’s m/s
- Thin deposits, no levees
Granular Flows on Mars

Impact-triggered dust avalanche on Mars
Debris Flows / Mud Flows

Marcus landslide, AZ

- Pronounced levees
- Thicker deposits, large boulders
- Travel 10’s m/s

300m
Summary

• Downhill creep is diffusive: \[ \frac{\partial z}{\partial t} = K \frac{\partial^2 z}{\partial x^2} \]

• Resistance to sliding depends on pore pressure: \[ \sigma_s = c + (\sigma_n - p) \tan \phi \]

• Angle of repose is independent of gravity

• Effective friction coefficient of long-runout landslides is very low
Backup/deleted slides follow
Grain to Grain frictional contact

Wet Sand

Angle of Repose

Water Saturated Sand

Water completely surrounds all grains and eliminates all grain to grain contact.