Surface Geology & Geologic Processes on Primitive Bodies

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Outline

• Diagnostic potential of geologic processes for understanding origin & evolution of primitive bodies
  • Impact Cratering
  • Erosion/Gradation
  • Tectonism
  • Volcanism

• Interspersed with examples from primitive bodies:
  • Main Belt & Near Earth Asteroids
  • Comet Nuclei
  • Planetary Satellites (some not so primitive though...)

• Some thoughts about future observations
Vesta is about 560 km wide
Ceres, the largest asteroid

Vesta, the 3rd largest asteroid

Ceres, the largest asteroid
• Where does “geology” begin to be expressed?

• At large enough sizes, objects can preserve impact craters without being completely destroyed

• Above a threshold size, self-gravity leads to a spherical shape because of internal heating/relaxation. Differentiation? Gradational processes?

• Larger sizes, more internal heating: Volcanism? Tectonism? Gradation?

• Note: Somewhere in here is where some people define “planet”...
Planetary Surface Processes

Four major *geologic* processes:
- Impact Cratering
- Volcanism
- Tectonism
- Erosion (also called “Gradation”)

The combination of these processes, working over a variety of timescales, is responsible for producing what we see on solar system surfaces today with spacecraft and telescopes.
Impact Craters:
Common geologic landforms on all spatial scales

Lunar maria are huge impact basins that were flooded by lava. Only a few small craters appear on the maria.

Lunar highlands are ancient and heavily cratered.

a. Many craters are bowl-shaped.
b. Impacts into icy ground may form muddy ejecta.
c. Ancient Martian rains apparently eroded this crater.
d. Opportunity sol 433 Navcam image of a ~20 cm diameter impact crater
Key Morphologic Parameters

- **Crater diameter**
- **Crater depth** (relative to surroundings...)
- **Floor** diameter (if there is a “floor”)
- Degree and type of **failure** of the inner walls
- Radial **range of the ejecta** (including possible impact melt)

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**Fig. 7.1** Variables and parameters important in impact crater scaling relations. These quantities are divided into three groups: Projectile variables are density $\rho_p$, diameter $L$, mass $m$, impact velocity $v_i$, kinetic energy $W$, and angle of impact $\theta$. Transient crater descriptors are apparent diameter $D_{at}$, radius $R_a = D_{at}/2$, distance from the crater’s center $r$, crater depth $H_{at}$, crater volume $V$ and ejecta blanket thickness $\delta$. Target variables are density $\rho_t$, yield strength $Y$, porosity $\phi$, and the acceleration of gravity $g$. Not all of these quantities are independent, but the different forms are used where convenient in this chapter.

Melosh (1989)
All craters "simple" for bodies smaller than a few hundred km...

Lunar Craters

“Simple” Depth/Diam. $\approx 1/5$

“Complex”

“Transition”

Transition $\approx g^{-1}$

Melosh (1989)
Ages of Planetary Surfaces

**Relative ages** often determined by impact crater number density [craters/km$^2$]

If these two images are of the same-sized regions on the same planet, which area is likely older?

Why?

What assumptions are required?
Relative Age Dating from Impact Craters: “Crater Retention Age”

Example/Idealized Surface

Hartmann (1977)

Actual/Absolute Dates
Soderblom et al. (1974)
3 populations of craters:
1. "Fresher" (young) craters < 1 km diameter
2. Degraded craters < 6 km
3. Degraded craters > 10 km
→ Change in early large impactor flux/environment?

2 populations of craters:
1. "Fresher" (young) craters < 1 km diameter
2. Degraded larger craters
→ Role of last major impact?

Sullivan et al. (2002)
Impacts can also reveal stratigraphy...

Vesta
HAMO Cycle 1,
F2_372565839, 70 m/pixel

bright rayed crater

Courtesy of David Williams (ASU)
Impacts can also reveal stratigraphy...

Vesta
HAMO Cycle 1,
F2_370834998, 70 m/pixel

Dark-Rayed Crater

Courtesy of David Williams (ASU)
Volcanism

Volcanism is the melting of materials within a planet and the transport or eruption of these materials onto a planetary surface.

On the terrestrial planets, the molten material, or magma, is silicate rock. For some outer planet asteroids, satellites, and dwarf planets, the magma could be water ice or molten sulfur.
Io's silicate volcanism

Icy satellite volcanic resurfacing?
Enceladus "Volcanic" Plumes...

- Satellite is only 500 km diameter, yet internally active!
- Subsurface liquid water? Newest astrobiology “hotspot” in the solar system...
Small Dark Flow

Brighter flow (mass movement or impact melt?)

Landslide deposit or impact melt

Courtesy of David Williams (ASU)
Tectonism is the deformation of the surface and interior of a planet, driven by either internal (volcanic, tidal, etc.) or external (impact) forces.

Tectonic processes produce faults, fractures, and folds with morphologies dependent upon the style of local deformation as well as the physical properties/conditions of the surface materials.
Equatorial ridge is ~20 km wide and up to ~20 km tall...
Structural features on Eros

Ridges, Grooves, and Fractures
Tidally-forced tectonism?

Thomas et al. (2002)

Robinson & Proctor (2002)
Phobos

Ridges, Grooves, and Fractures
Impact-forced tectonism?
Vesta

Concentric and radial grooves related to large basins

NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission
Tectonic features related to
(1) impact disruption
(2) differentiation (?)
(3) volcanic processes (?)

Color-coded heights (additional hill-shading)
heights above ellipsoid (289/280/229 km)
-22.28 km 19.10 km

NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission

Vesta

Courtesy of David Williams (ASU)
Erosion or gradation is the wearing down of high places and the filling in of low places on a planetary surface.

For airless bodies, these erosional and depositional processes are driven by gravity.

The primary means of moving materials by gradation on airless bodies is via "mass wasting", or the downslope movement of surface materials.

On airless bodies, gradational processes can produce landslides, talus cones, slope streaks, and sediment "ponds"
Mass Movement on Vesta

Darker, Lobate units: Mass movement flows or Impact melt flows

HAMO
Cycle 1, F2_370968622, 70 m/pixel

Courtesy of David Williams (ASU)
Bright Lobate Unit: Ejecta or Impact Melt?

HAMO Cycle 1, F2_370836647, F2_370836978, F2_370837307, 70 m/pixel

Landslide Deposit

Vesta

Courtesy of David Williams (ASU)
Sedimentary "ponds" on Eros

Robinson & Proctor (2002)

NASA/JHU-APL/Cornell/NEAR Mission
Phoebe
200 km diam.
Captured KBO?
Helene
43x38x26 km
Other Clues about Process and Properties from Geologic Observations

Imaging and topographic/shape data enable estimates of primitive body volume. Combined with mass estimates from spacecraft tracking gives an estimate of density.

Imaging and tracking of asteroid satellites is another way to determine mass and estimate density.

Mass and density combined with compositional data can enable an estimate of porosity.

Topographic/shape information combined with gravity mapping data (from orbital campaigns) enables an estimate of the locations and magnitudes of crustal density anomalies.

Considerable confusion about the geology of comet nuclei.
Density & Porosity

Most asteroids are rocky, many are very porous
253 Mathilde
66x48x46 km
C Type

How can such a small object survive such an intense pounding?

Porous *rubble pile* nature of many asteroids absorbs impact shock
Hyperion

Porosity gone wild?
25143 Itokawa
535x294x209 meters
S Type, density = 1.9 g/cm³

Where are the impact craters?

Is Itokawa a rubble pile?

JAXA/Hayabusa Mission
Topography from stereo imaging (left) can be removed from gravity signature to reveal crustal density anomalies (right)
Comets:
Increasing the sample imaged by spacecraft

Halley: 1985
Borrelly: 2001
Wild-2: 2004
Tempel-1: 2005, 2011
Hartley-2: 2010
Comet Tempel-1

Deep layers wrap around, roughly parallel to “top” facet.

Regional differences in erosion and a wide variety of topographic forms

Why is the boundary between regions parallel to the layers? Draping? Regional erosion?

Many puzzles!
Geology of Tempel 1

Physical character:
mean density of $0.4 \pm 0.2 \, \text{g cm}^{-3}$

Geologic units
layer structures: deep/shallow?
“smooth” deposits and flows
relation between types of layers
(photometric variations?)

Processes
venting, pitting, and deposition
scarp retreat
 cratering
regional variations
relation to jet structures

Is this a pristine object? Puzzles...
Wild-2:

- Rugged surface
- Circular depressions
- What are they?
- Craters?
- Sublimation pits?
The darker area with close round depressions is the part of Tempel 1 that most closely resembles Wild-2.
The Future?

- Rosetta mission at 67P/Churyumov–Gerasimenko
- First close-up look at Ceres with Dawn -- will this be our first close-up look at a KBO?
- New Horizons first close-up look at Pluto/Charon
- OSIRIS-REx mission to 1999 RQ₃₆ (C-type)
- New Discovery, New Frontiers, ESA opportunities...

- Expectation is that increased sampling will result in increased diversity of surface geologic processes, and probably increased puzzles...
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<thead>
<tr>
<th>Crosscutting Themes</th>
<th>Priority Questions</th>
<th>Key Bodies to Study</th>
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<tbody>
<tr>
<td>Building new worlds</td>
<td>1. What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated?</td>
<td>Comets, Asteroids, Trojans, Kuiper belt objects (see Chapter 4)</td>
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<td>2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?</td>
<td>Enceladus, Europa, Io, Ganymede, Jupiter, Saturn, Uranus, Neptune, Kuiper belt objects, Titan, rings (see Chapters 4, 7, and 8)</td>
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<td>3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?</td>
<td>Mars, the Moon, Trojans, Venus, asteroids, comets (see Chapters 4, 5, and 6)</td>
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<td>Planetary habitats</td>
<td>4. What were the primordial sources of organic matter, and where does organic synthesis continue today?</td>
<td>Comets, asteroids, Trojans, Kuiper belt objects, Enceladus, Europa, Mars, Titan (see Chapters 4, 5, 6, and 8)</td>
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<td>5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?</td>
<td>Mars and Venus (see Chapters 5 and 6)</td>
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<td>6. Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?</td>
<td>Enceladus, Europa, Mars, Titan (see Chapters 6 and 8)</td>
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<td>Workings of solar systems</td>
<td>7. How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?</td>
<td>Jupiter, Neptune, Saturn, Uranus (see Chapter 7)</td>
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<td>8. What solar system bodies endanger Earth’s biosphere, and what mechanisms shield it?</td>
<td>Near-Earth objects, the Moon, comets, Jupiter (see Chapters 4, 5, and 7)</td>
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<td>9. Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?</td>
<td>Mars, Jupiter, Neptune, Saturn, Titan, Uranus, Venus (see Chapters 5, 6, and 8)</td>
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<td>10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?</td>
<td>All solar system destinations. (see Chapters 4, 5, 6, 7, and 8)</td>
</tr>
</tbody>
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Summary

• Geologic and geophysical observations of primitive (or "semi-primitive") bodies enable assessment of the role of impact, tectonic, erosional, and volcanic processes in their origin and evolution

• Some geologic observations, like density, porosity, and the spatial variations in impact crater size frequency distribution and degradation state, could provide constraints on formation models and surface/interior evolutionary pathways

• What surprises await among the giant unsampled populations of KBOs, Centaurs, and Trojans?