Take home messages

- Two types of gullies identified on Vesta: curvilinear and linear
- Curvilinear gullies formed by transient flow of liquid water
- Sourced in subsurface ice-bearing deposits
- First morphological evidence to suggest that Vesta is not as dry as previously thought
2 types of gullies identified on Vesta

- Two types of gullies: different morphologies & network geometries
- 48 craters containing linear type gullies
- 11 craters containing curvilinear type gullies
- Gullies in craters that are relatively young, e.g. Marcia ~60-150 Ma (Williams et al. 2013)
Linear gullies example: Fonteia crater
Linear gullies in Fonteia: detailed map

- Originate in alcoves below spurs
- Linear, straight channels
- Parallel channels
- Rarely intersect
- Low length to width ratio
- Sometimes end in lobate deposits
- Bounded by levees
Analogous to lunar gullies

Kumar et al. (2013)

Fan

Channel

Alcove

Direction of flow

0  50  100 Meters

0  0.5  1 Kilometers
Curvilinear gullies example: Cornelia crater

Note pitted terrain
Curvilinear gullies in Cornelia: detailed map

Legend
- Talus
- Slumped material
- Pitted terrain
- Lobate deposits

Curvilinear gully
Curvilinear gully feeding lobate deposits

0 1 2 3 4 km

N
Curvilinear gullies in Cornelia: detailed map

- Originate below cliff base/ V-shaped alcoves
- Curvilinear, sinuous channels
- Dendritic to subparallel networks
- Frequently intersect
- High length to width ratio
- Some end in superposing lobate deposits
Analogous to terrestrial and martian gullies

Malin & Edgett (2000)
Linear & curvilinear gullies have different morphologies.

### Length to width ratio of gullies in Vestan craters

<table>
<thead>
<tr>
<th>Crater</th>
<th>Arruntia</th>
<th>Cornelia</th>
<th>Fabia</th>
<th>Rubria</th>
<th>Antonia</th>
<th>Canuleia</th>
<th>Fonteia</th>
<th>Severina</th>
<th>Sextilia</th>
<th>40S30E</th>
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<tr>
<td>Linear gullies</td>
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<tr>
<td>Curvilinear gullies</td>
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</table>
• Impact melt has been ruled out for both gully types

• Morphologies & network geometries of linear gullies consistent with dry granular flow

• Morphologies & network geometries of curvilinear gullies resemble those formed by flow of liquid water
Evidence for volatiles & water on Vesta

- Pitted terrain: formed by impact-induced degassing of volatile material (Denevi et al. 2012)
  - associated with curvilinear gullies

NASA/JPL-Caltech/UCLA/MPS/DFLR/IDA/JHUAPL 1 km
Evidence for volatiles & water on Vesta

- From meteorites:
  - quartz & other mineral veins => aqueous alteration
    (Treiman et al. 2004, Warren et al. 2013)
  - high OH apatites => water in magmas (Sarafian et al. 2012)
  - carbonaceous chondrite clasts (e.g. Herrin et al. 2011)

- From Dawn data:
  - dark material is carbonaceous chondrite (Reddy et al. 2012)
  - areas of OH (De Sanctis et al. 2012)
  - areas high in H (Prettyman et al. 2012)
Formation mechanism of curvilinear gullies

(a) Incoming ice-rich body

(b) Pre-existing regolith deposits

(c) Transient reservoir

(d) Transient surface water flow

Evaporation contributes to pitted terrain formation

Drained ice-bearing layer

Formation of pitted terrain

Talus and landslide deposits

Transient water released by impact-induced heating
Conclusions & implications

• Curvilinear gullies formed by transient flow of liquid water, sourced in subsurface ice-bearing deposits

• First morphological evidence to suggest that Vesta is not as dry as previously thought

• Vesta is a diverse, heterogeneous and complex mini-world with planetary-style processes

• Should not be surprised by possible presence of water on other asteroids
Thank you!

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Thank you!

Dawn team at Goldstone Deep Space Network, January 2011
1. Average radius: 262 km (Russell et al. 2012)

2. Differentiated: iron core, olivine mantle & basaltic crust
   Russell et al. (2012) & Ermakov (in prep.)


4. Little impact melt is anticipated or observed (Williams et al. 2013)

5. Dark material is exogenous (carbonaceous chondrite) & bright material is endogenous (freshly exposed) (Reddy et al. 2012, McCord et al. 2012)
### Linear & curvilinear gullies have different morphologies

<table>
<thead>
<tr>
<th>Curvilinear gullies</th>
<th>Linear gullies</th>
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<tbody>
<tr>
<td>Originate below base of cliffs/ in V-shaped alcoves</td>
<td>Originate in alcoves below spurs</td>
</tr>
<tr>
<td>Curvilinear, sinuous channels</td>
<td>Linear, straight channels</td>
</tr>
<tr>
<td>Subparallel to dendritic networks</td>
<td>Parallel networks</td>
</tr>
<tr>
<td>Frequently intersect</td>
<td>Rarely intersect</td>
</tr>
<tr>
<td>High length to width ratio</td>
<td>Low length to width ratio</td>
</tr>
<tr>
<td>Sometimes end in smaller lobate deposits, covered by pitted terrain</td>
<td>Sometimes end in larger lobate deposits &amp; bounded by levees</td>
</tr>
</tbody>
</table>
### Morphologies consistent with sapping

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Typical for curvilinear gullies?</th>
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</thead>
<tbody>
<tr>
<td>1. Constant channel width</td>
<td>Yes: 50±10 m</td>
</tr>
<tr>
<td>2. Dendritic network geometry</td>
<td>Yes</td>
</tr>
<tr>
<td>3. Long main valleys &amp; short, stubby tributaries</td>
<td>Yes</td>
</tr>
<tr>
<td>4. High tributary junction angles</td>
<td>Yes</td>
</tr>
<tr>
<td>5. Sapping below permeable layer</td>
<td>Yes</td>
</tr>
<tr>
<td>6. Plots of characteristics of sapping channels on Earth</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- Groundwater/ aquifer origin has been suggested for some Martian gullies (e.g. Malin & Edgett 2000, Heldmann et al. 2007)
Forming the curvilinear gullies

- Morphologies of curvilinear gullies are consistent with groundwater sapping => probable formation mechanism

Cross section view of one side of crater:
Curvilinear gullies formed by sapping

Adapted from Luo (2000)
Formation mechanism of curvilinear gullies

- Pressure-temperature diagram for $\text{H}_2\text{O}$

\[ \sim 145 \text{ K} \]
Formation mechanism of curvilinear gullies

- Water is stable as a gas on Vesta’s surface, however,
- Water will not all instantaneously evaporate
- Top layers will evaporate while sub-layers are protected and can flow [experiments soon!]
- Evaporation takes at least ~97 hrs
- Gullies can be carved in ≥22 minutes