

Volcanic  
Fields on  
Earth & Mars

Jacob  
Richardson

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Overview

Sills  
Vent Intensity  
Lava Flows

Arsia Mons  
Volcanic Field  
Methods  
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Implications  
Conclusions

# Modeling the Construction and Evolution of Distributed Volcanic Fields on Earth and Mars

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19 February 2016

# Acknowledgements

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## Some Collaborators

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James Wilson

Lis Gallant

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Jake Bleacher

Lori Glaze

## Funding Agencies

NASA Mars Data Analysis Program

NSF SSI

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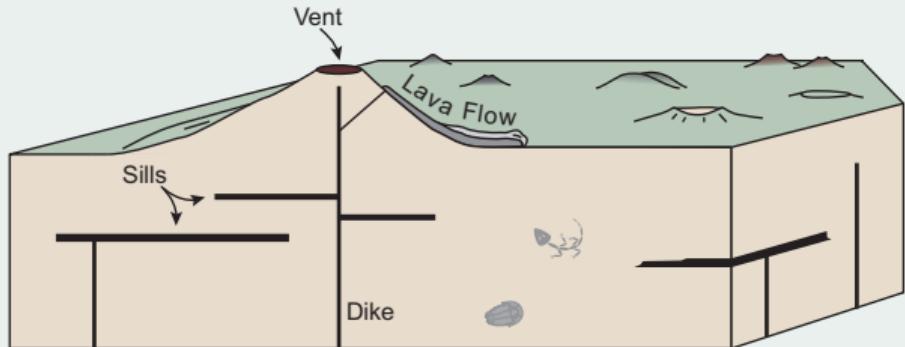
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## Distributed-style Volcanism

### Characteristics

- Clusters of volcanoes are formed, sometimes associated with large volcanoes
- New eruptions form new vents
- Eruptions are fed by small volume batches of magma
- Long periods of quiescence



# Outline of Talk

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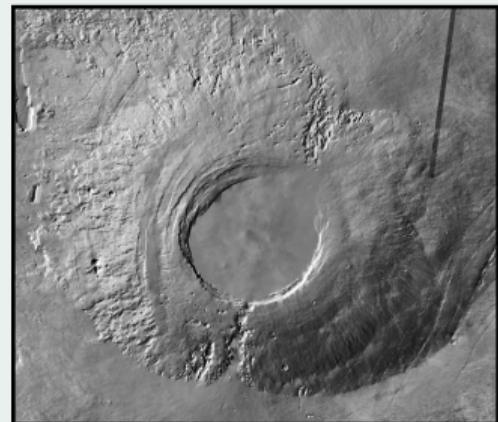
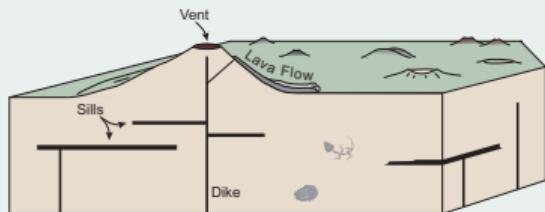
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- Volcanic fields, from the inside out
  - The role of sills in the formation of volcanic fields (Richardson et al., *Geology*, 2015)
  - The spatial organization of vents in volcanic fields (Richardson et al., *LPSC*, 2012)
  - Simulating lava flow emplacement  
(Kabanek et al., *Bull. Volc.*, 2015)
- Evolution of volcanism at Arsia Mons
  - Can its recent rate of volcanism be determined by studying a volcanic field with only satellite data?
- Conclusions



# The Igneous Plumbing System

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## San Rafael Volcanic Field, Utah

- Pliocene volcanic activity
- Now eroded to depth of ~1 km
- Sills and Dikes exposed



Chuck Connor with a Terrestrial Lidar (L. Connor)

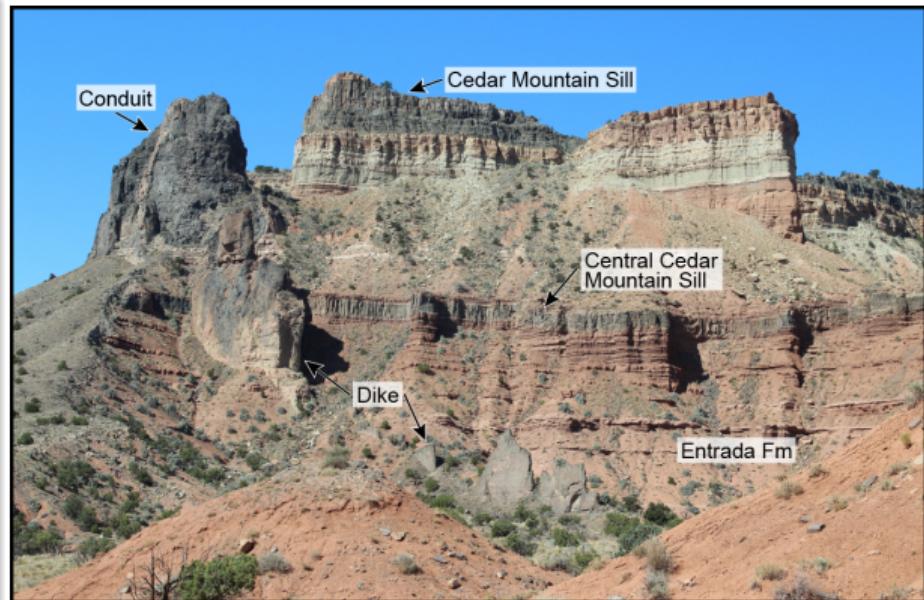


Photo Credit: Judy McIlrath

# The Igneous Plumbing System

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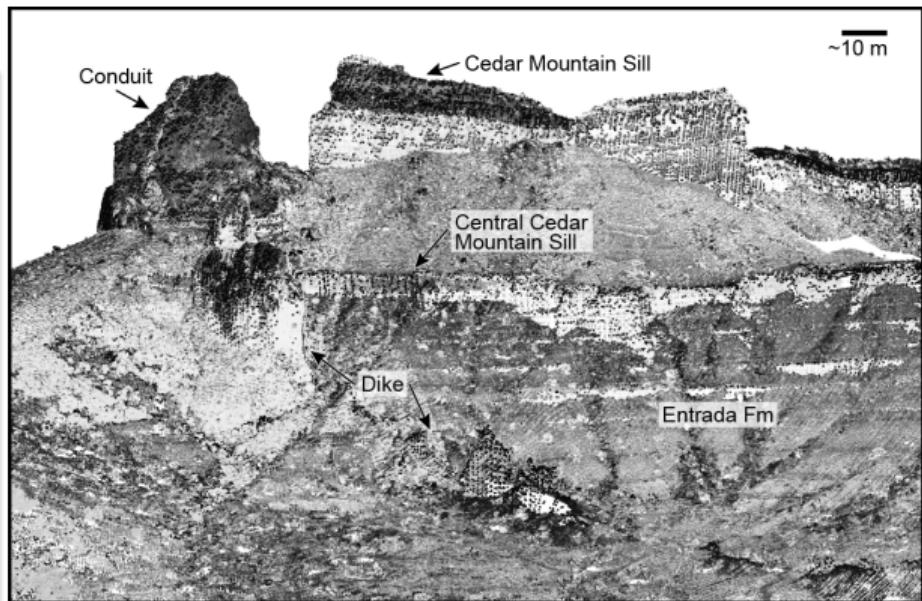
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## Results of lidar survey

- Sill volume comparable to volume thought to have erupted at surface
- Sills had ability to modulate eruption style by interacting with volcanic conduits
- Conduits deliver magma from depth to distributed volcanoes



*Richardson et al., Geology, 2015*

# Volcano organization in fields

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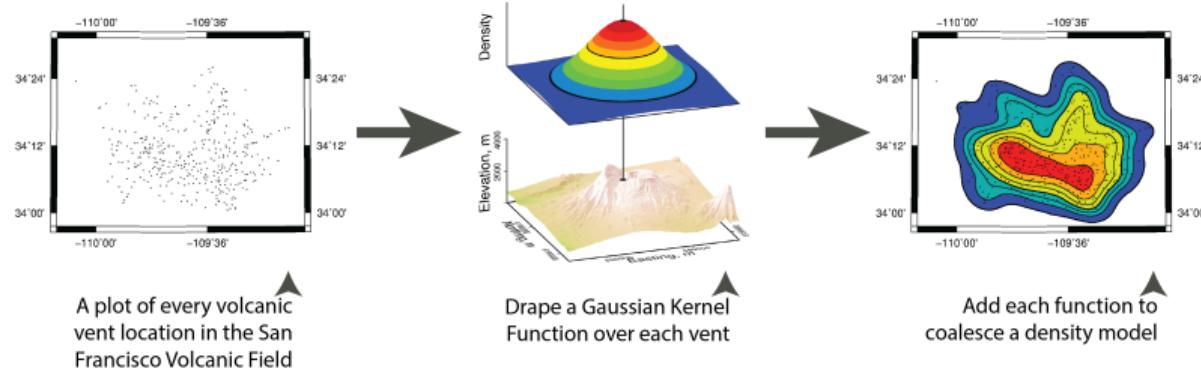
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The spatial organization of volcanoes is modeled as a density function



- Area of volcanic field defined as 95<sup>th</sup> percentile of density function

$$\text{Average vent intensity} = \frac{\# \text{ volcanic vents}}{\text{field area}}$$

- This model is applied to fields on Earth, Mars, and Venus

# Vent Spatial Intensity across the Solar System

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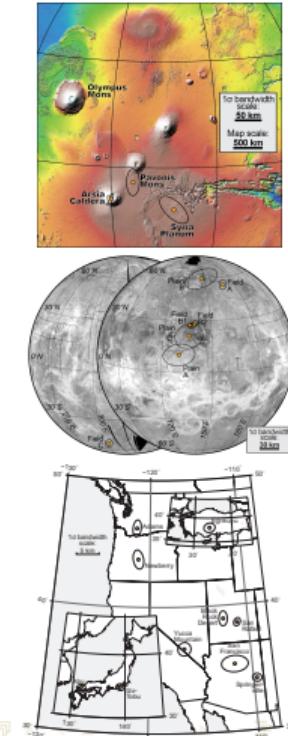
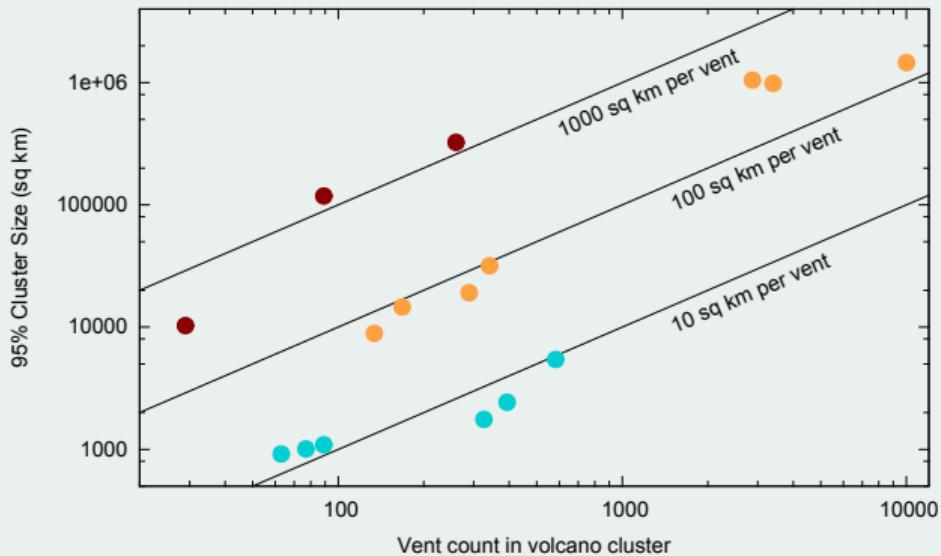
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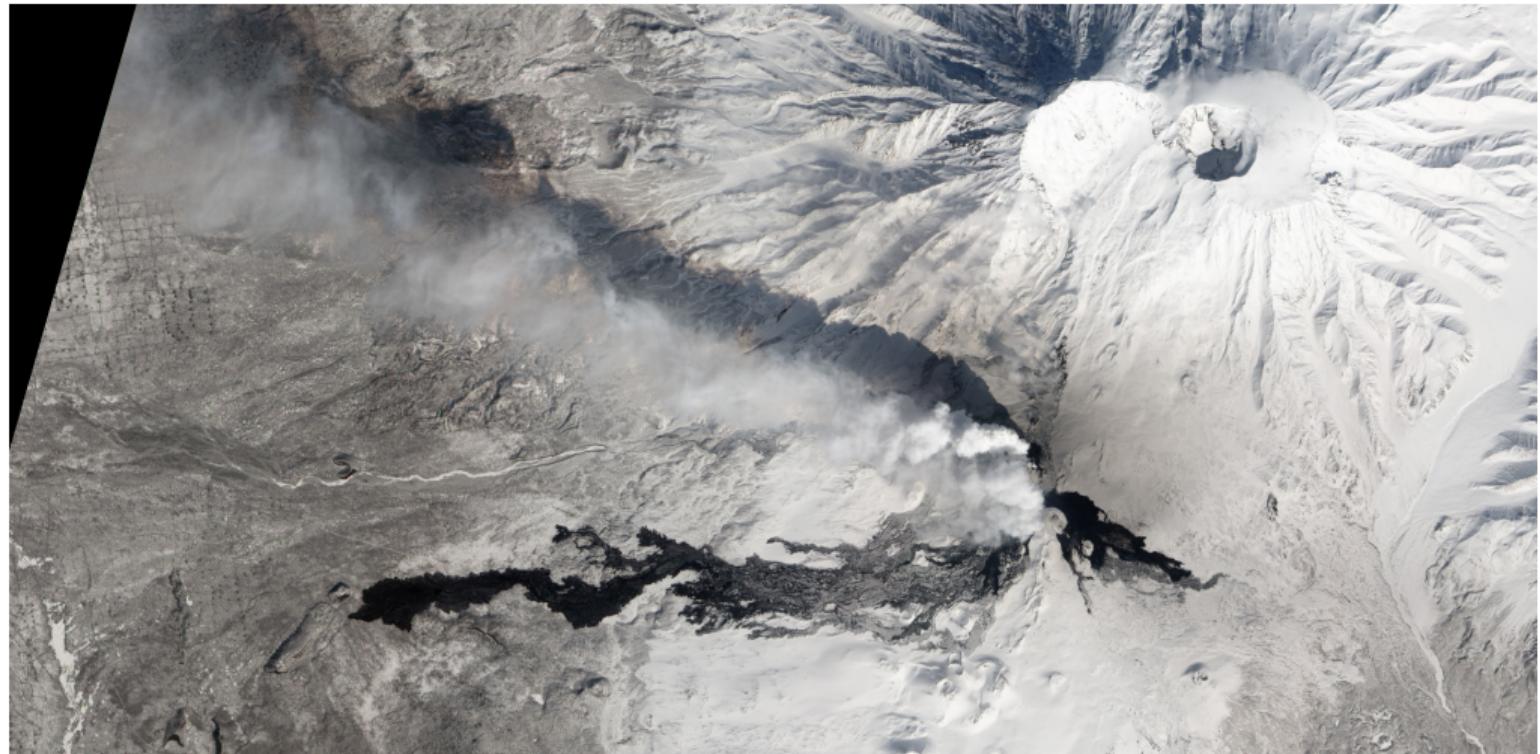
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## Average Vent Intensity, Colored by Planet



# The 2012-3 Tolbachik Lava Flow



*NASA Earth Observing-1 Mission, 1 February 2013*

# Lava Flows/Simulators

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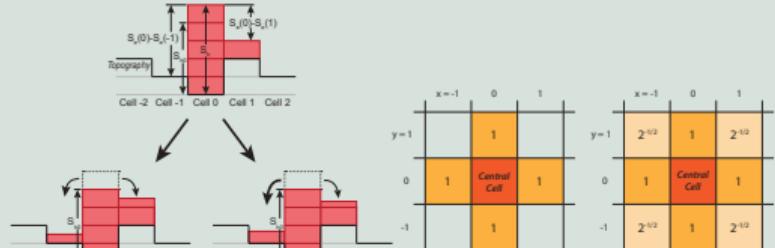
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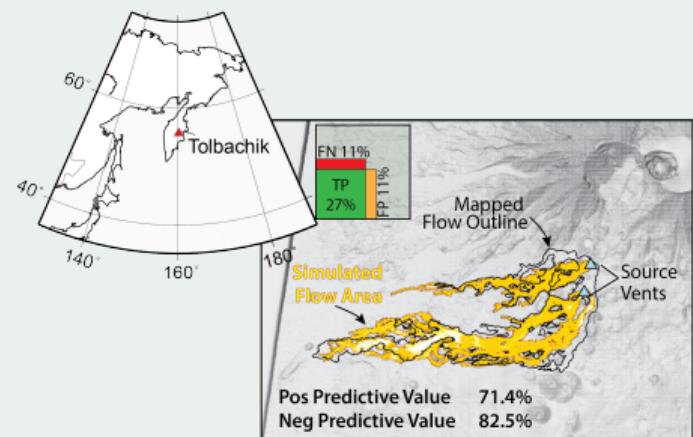
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- MOLASSES developed after Connor et al., *JAV*, 2012
- Spreads lava over a grid according to universal rules

## Optional Spreading Rules

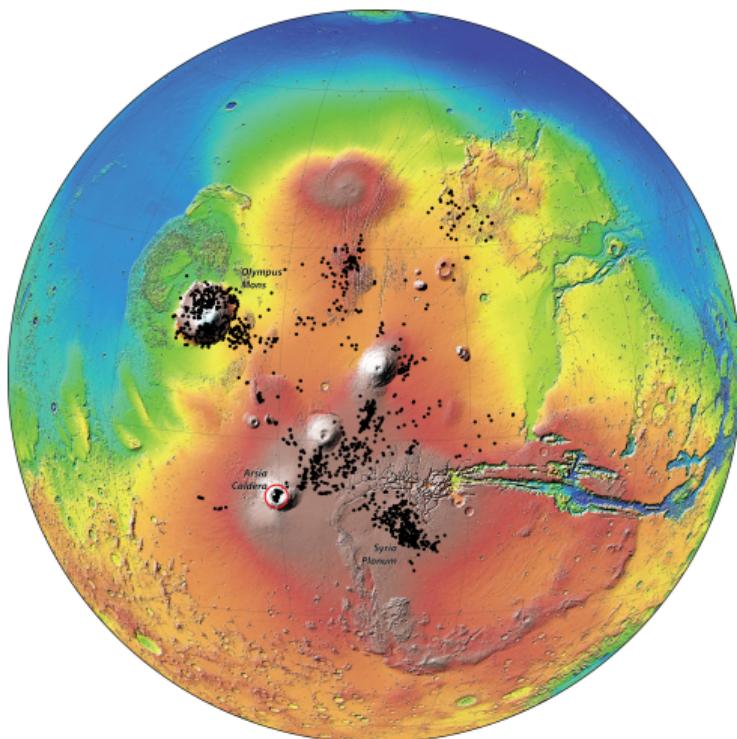


Using TanDEM-X satellite data, flow simulations match the 2012-3 Tolbachik flow between 70-85%.



Kubanek et al., *Bull. Volc.*, 2015

# Distributed Volcanism of the Tharsis Volcanic Province



## Tharsis Vent Catalog

- >1,000 small volcanic vents cataloged  
(Richardson et al., JVGR, 2013, Bleacher et al., JVGR, 2009)
- Groups of vents form isolated clusters

## Research Questions

- How does distributed-style volcanism occur over time and space in Tharsis?
- How do volcanic fields relate to the larger volcanoes on Mars?

# Arsia Mons Overview

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## Arsia Mons

- Large ( $1.5 \cdot 10^6 \text{ km}^3$ ) shield volcano with 110 km diameter caldera
- A cluster of volcanic vents lay in the caldera!

## Motivation

What are the recurrence rate of  
volcanism and delivery rate of  
magma to the surface?



# Arsia Mons Overview

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## Recurrence Rate and Magma Delivery Rate

$$\text{Recurrence Rate} = \frac{\text{Number of Events} - 1}{\text{Time elapsed}}$$

$$\text{Delivery Rate} = \frac{\text{Total Volume}}{\text{Number of Events}} \times \text{Recurrence Rate}$$

- Lavas from these vents can be mapped to estimate volume and timing of emplacement



# Mapping Volcanic Vents

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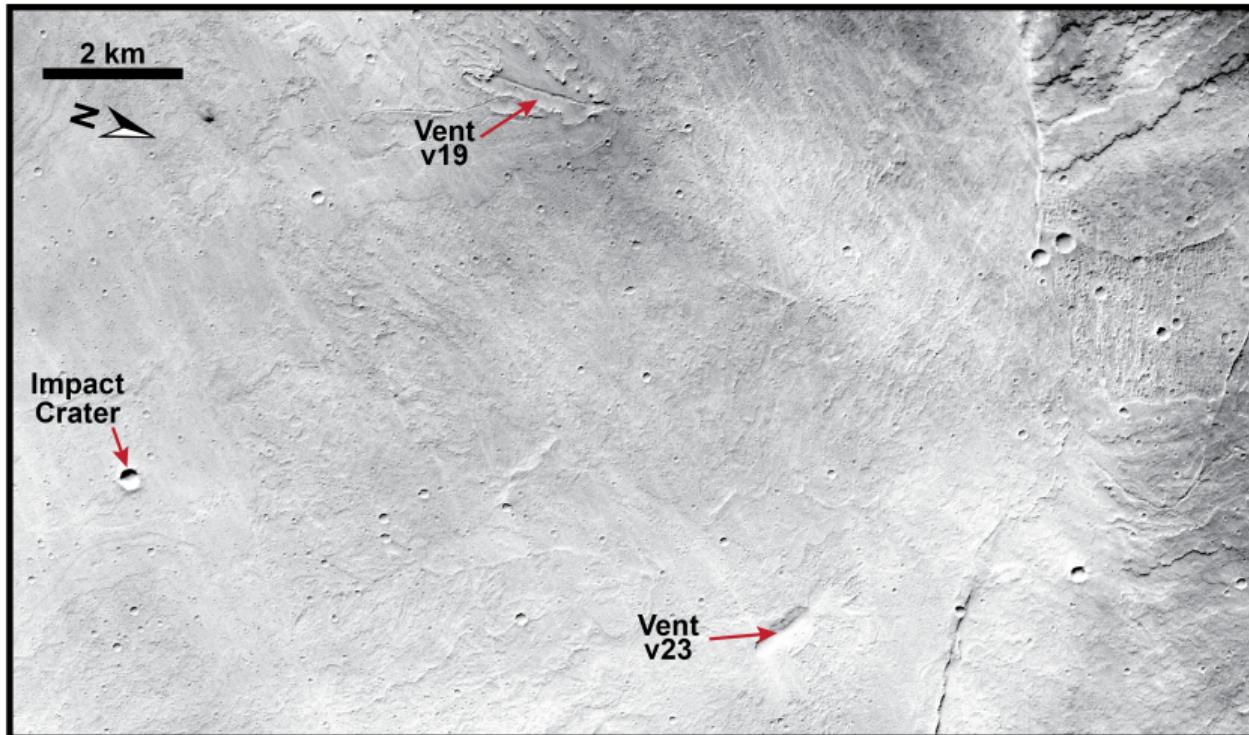
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CTX Image: G10\_022160\_1710\_XN\_09S120W (NASA/JPL-Caltech/MSSS)

# Mapping Lava Flows

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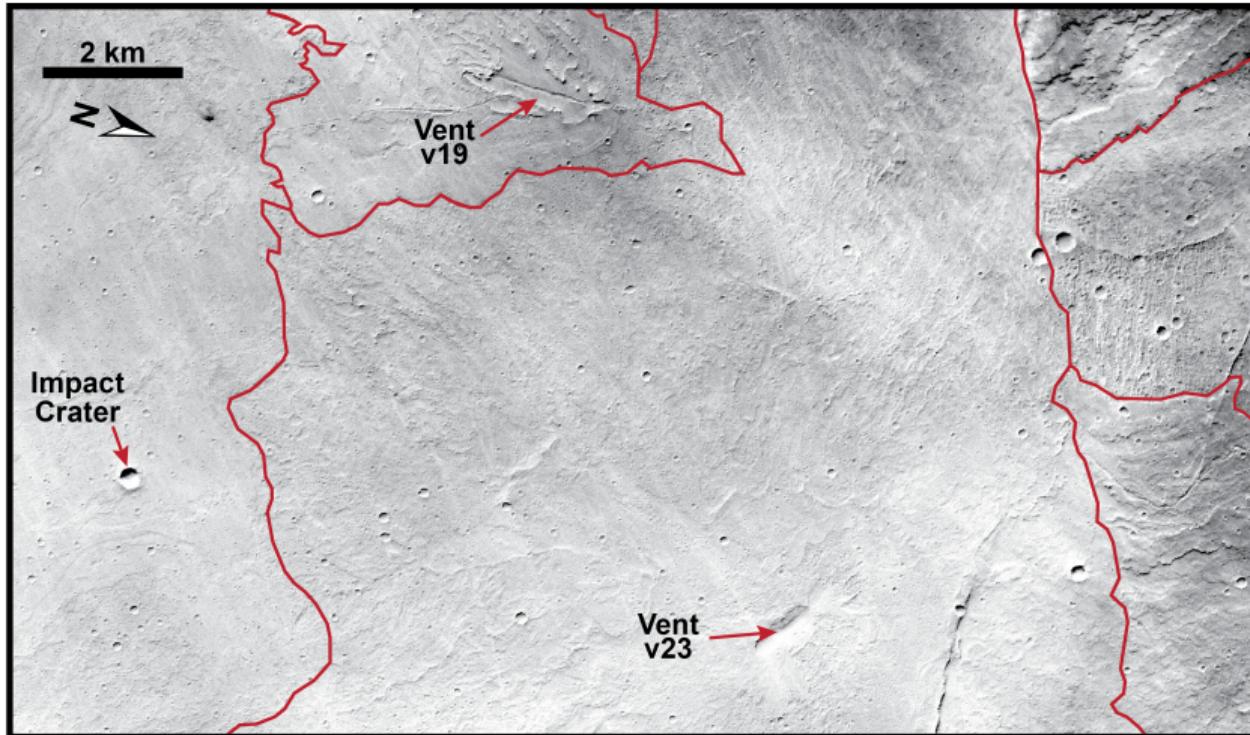
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# Lava Flow Map of Arsia Mons' Caldera

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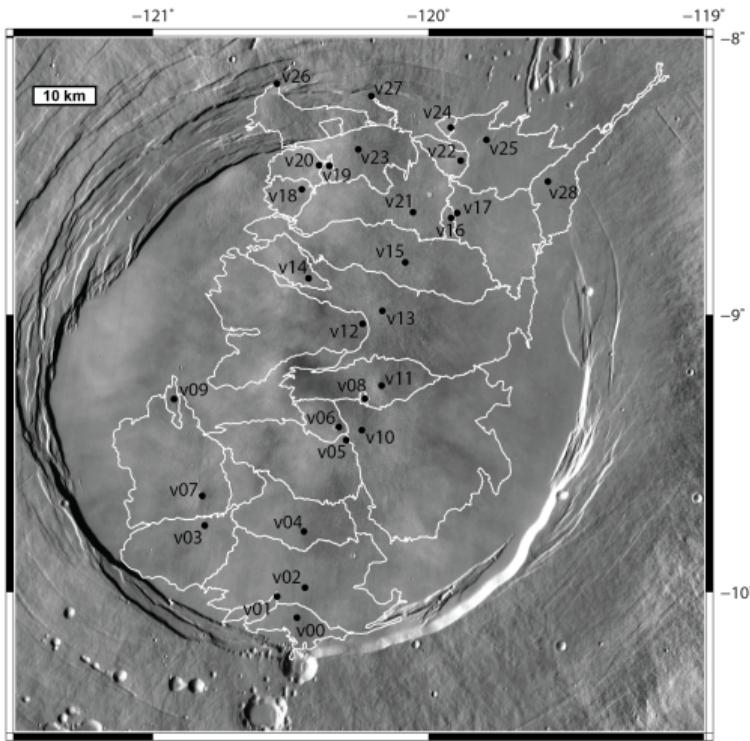
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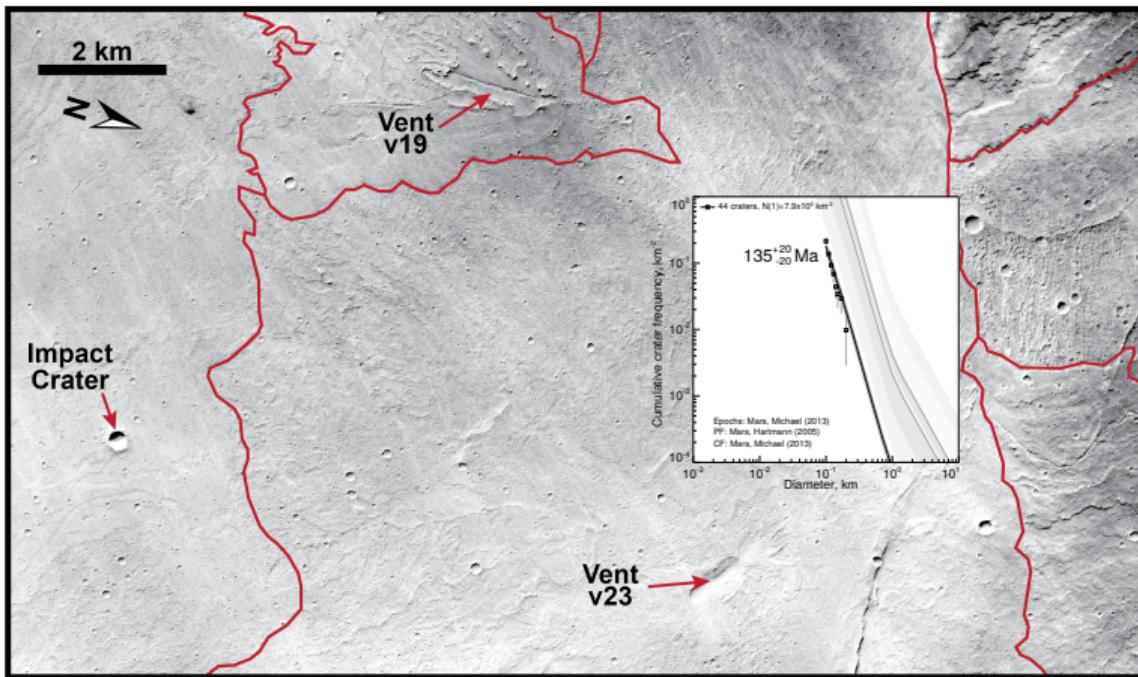
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## Mapping results

- 29 vents are cataloged, each with long lava flows
- Lava flow areas are 10s–100s km<sup>2</sup>
- Flow thicknesses assumed to be 10–80 m (Mouginis-Mark & Rowland, *Icarus*, 2008)
- From this, volumes estimates range from 10<sup>-2</sup>–70 km<sup>3</sup>

# Ages: Crater Counting



Impact craters on each flow are cataloged

More craters generally indicates older age

Ages and uncertainties modeled in *craterstats2* (Michael, *Icarus*, 2013)

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# Ages: Crater Counting

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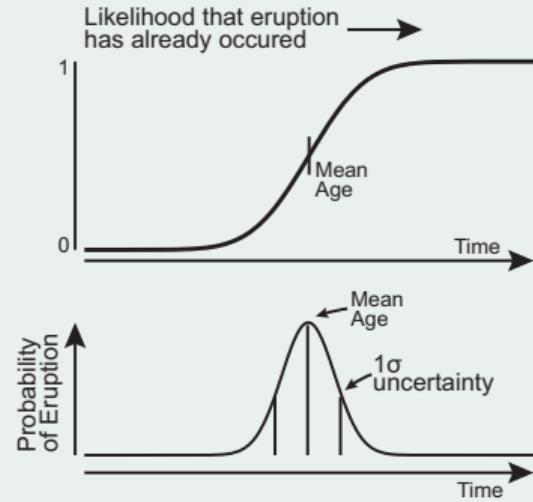
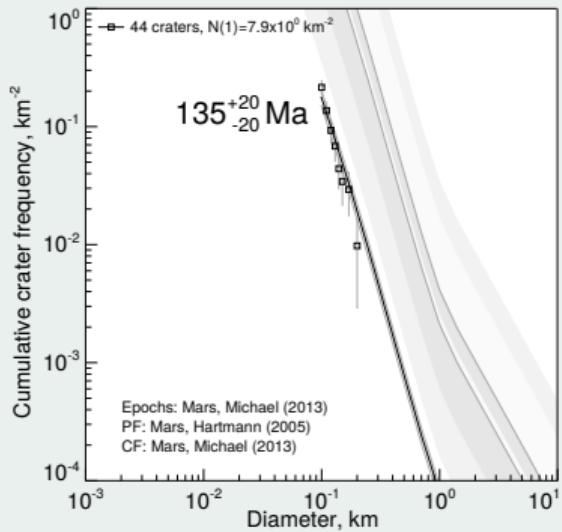
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Ages of flow emplacement are modeled as Normal Distributions

- Estimated age from *craterstats2* is used as the Mean Value
- Age Uncertainty is Standard Deviation



# Ages: Stratigraphy

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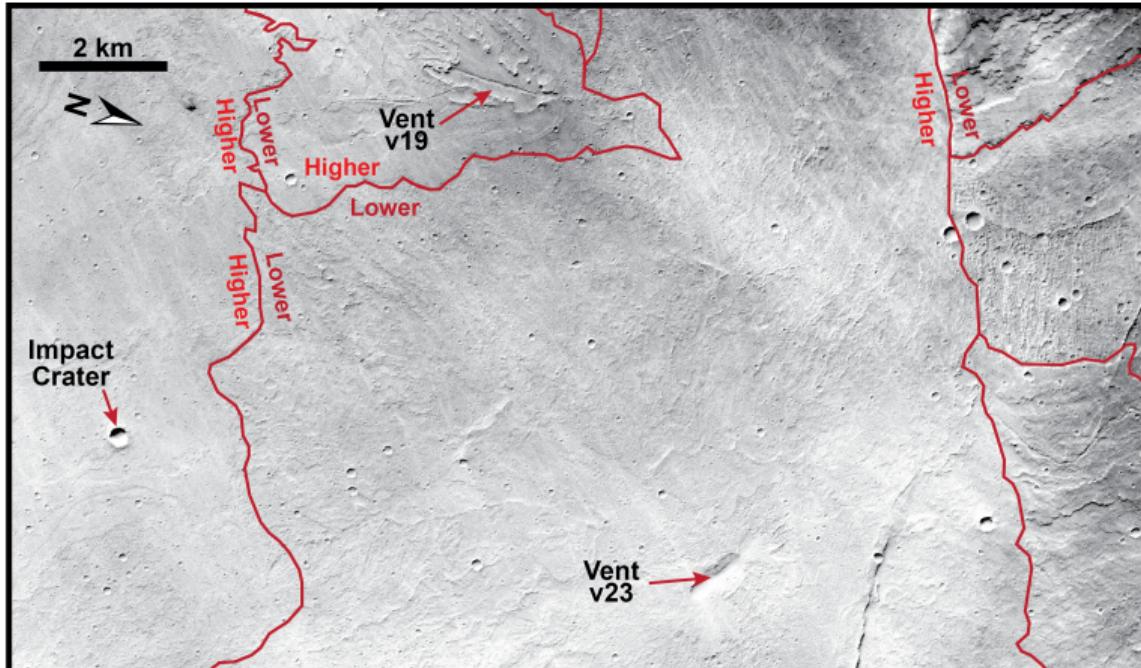
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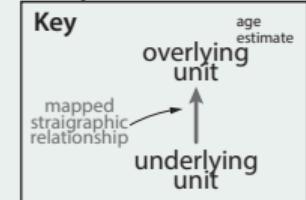


CTX Image: G10\_022160\_1710\_XN\_09S120W (NASA/JPL-Caltech/MSSS)

Stratigraphic  
relationships  
relatively date  
events.

Lava from v19  
overlies v23 lavas

*Graphical Form:*



# Combined Age Information

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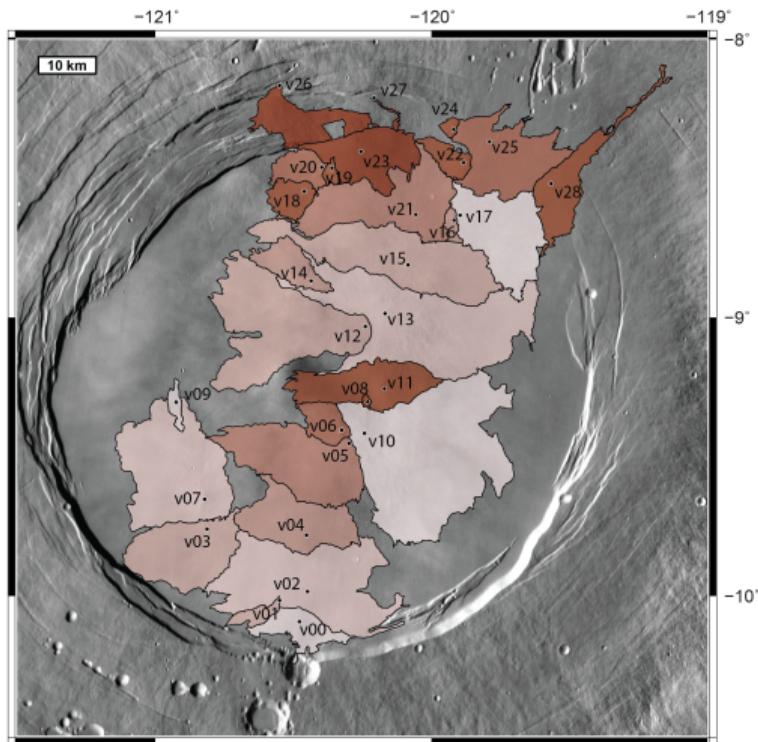
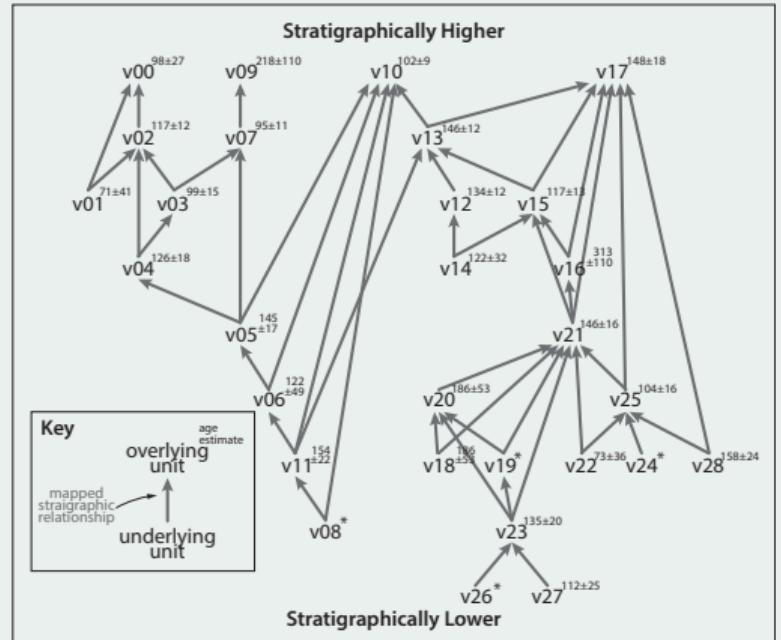
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## Stratigraphy “Web”



# Ages: Information Conflicts

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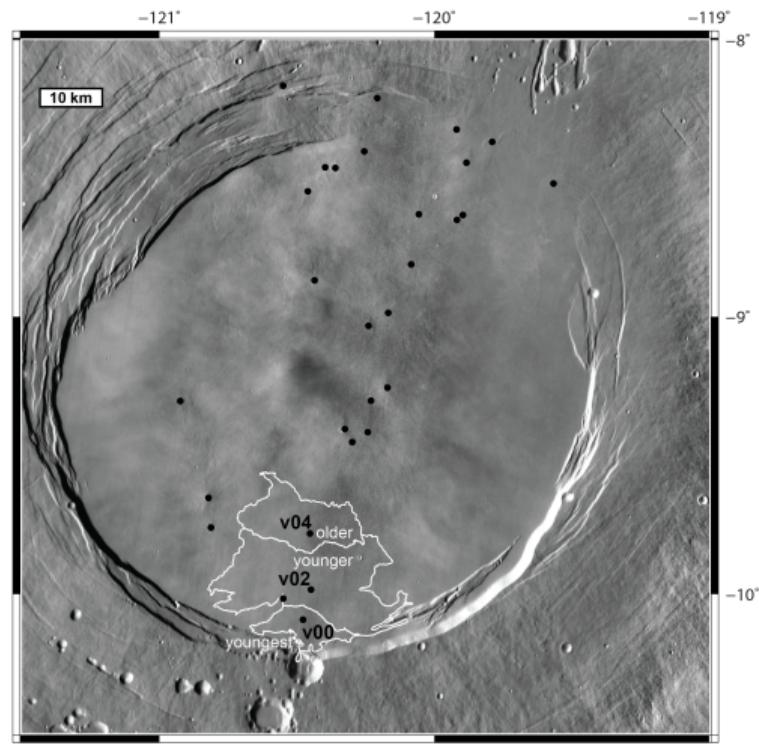
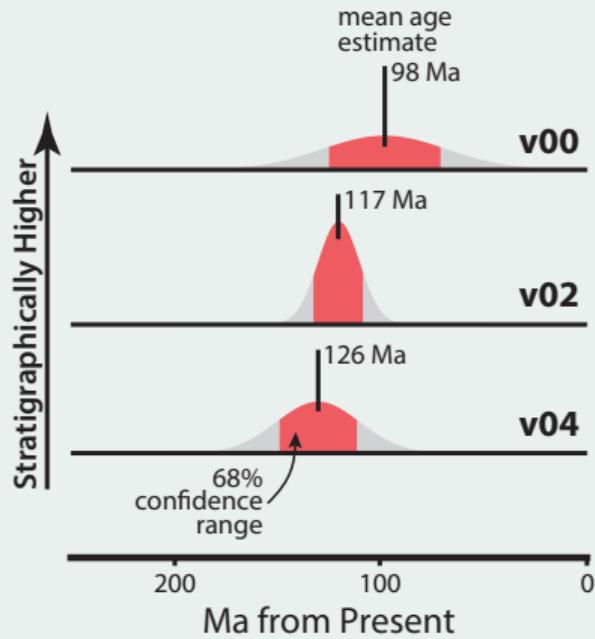
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Mean crater ages can agree stratigraphy...



# Ages: Information Conflicts

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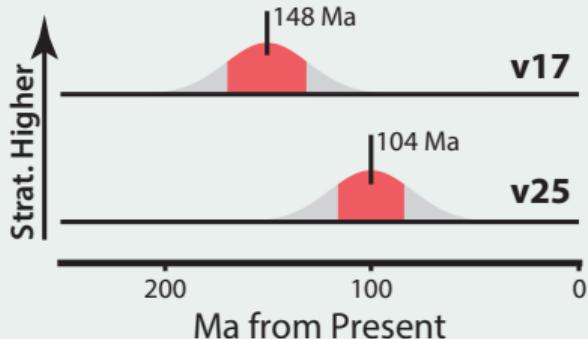
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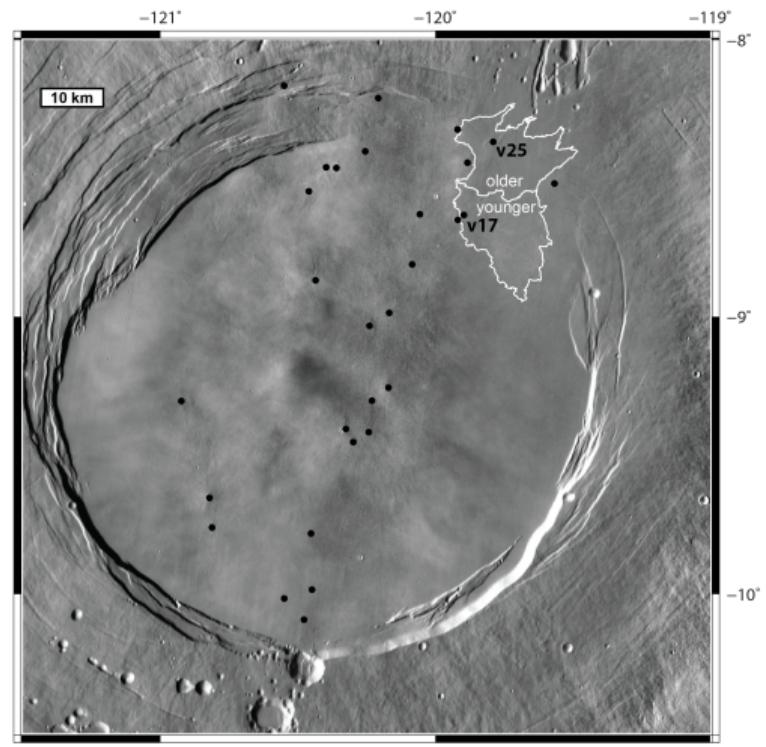
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...or mean age can disagree with strat.



But by probabilistically modeling age,  
possible ages can still be identified



# Volcanic Event Recurrence Rate Model (VERRM)

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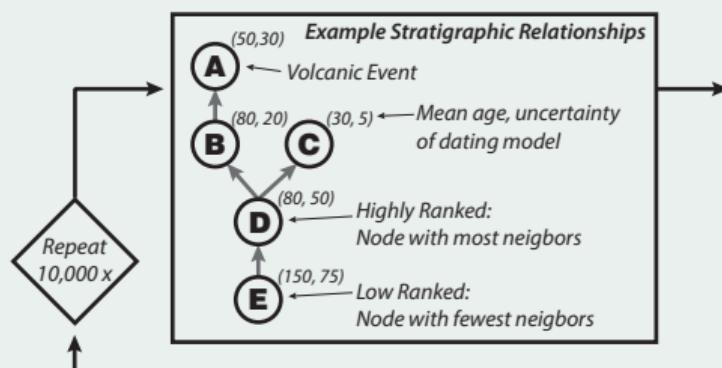
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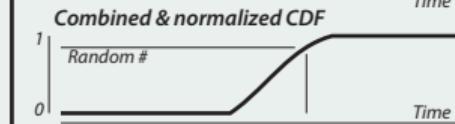
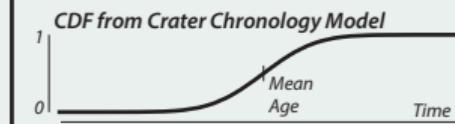
## Step 1: Find potential ages of all events in the field (Monte Carlo)

### Input Files

Age Model Database			Stratigraphic Relationship Database	
EventID	Mean_age	Uncertainty	Older	Younger
A	50	30	B	A
B	80	20	D	B
C	30	05	D	C
D	80	50	E	D
E	150	75		



For each vent:



Output

Sampled\_Age [A]  
Sampled\_Age [B]  
...  
Sampled\_Age [E]

# Volcanic Event Recurrence Rate Model (VERRM)

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## Step 2: Calculate Recurrence Rate of Volcanism

For each Monte Carlo simulation (i.e. each set of potential ages), model Recurrence Rate (RR) through time:

$$\text{RR}(t) = \frac{3}{T_{e-2} - T_{e+2}}$$

## Step 3: Calculate Magma Delivery Rate

Model Magma Delivery Rate (Flux) through time:

$$\text{Flux}(t) = \frac{\text{Volume}_e}{T_e - T_{e+1}}$$

# Results

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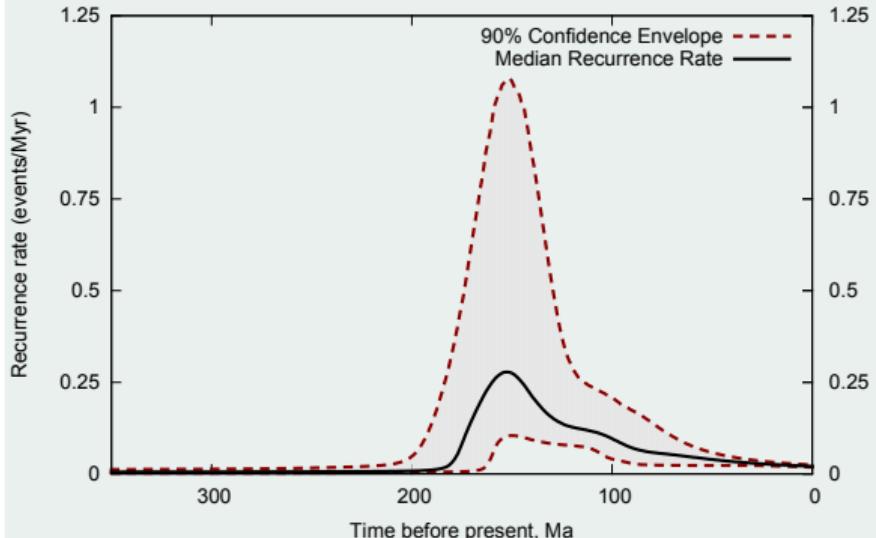
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## Recurrence Rate through time



- All 10,000 Recurrence Rate functions are combined
- Rate peaks at 150 Ma, producing 1 vent per 1-10 Myr (Median value:  $0.25 \text{ events Myr}^{-1}$ )
- Rate has decreased monotonically:  $\text{RR}(t = 0) \rightarrow 0$

# Volume Flux

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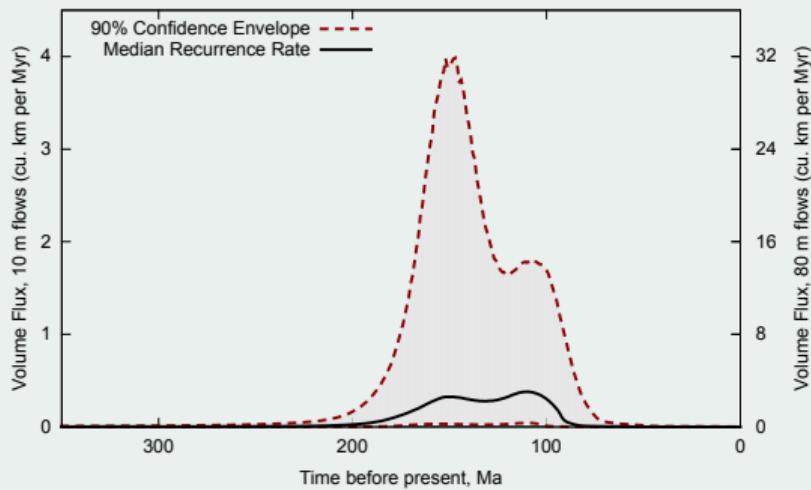
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## Magma Delivery Rate through time

- All 10,000 Magma Delivery Rate functions are combined
- Median rate plateaus at at 150 Ma ( $0.4\text{--}3 \text{ km}^3 \text{ Myr}^{-1}$ ), remains steady until 100 Ma before rapidly waning.
- Uncertainty in magma delivery rate is about 1 order of magnitude to either side of the median



# Tie-in with ashes and glaciers

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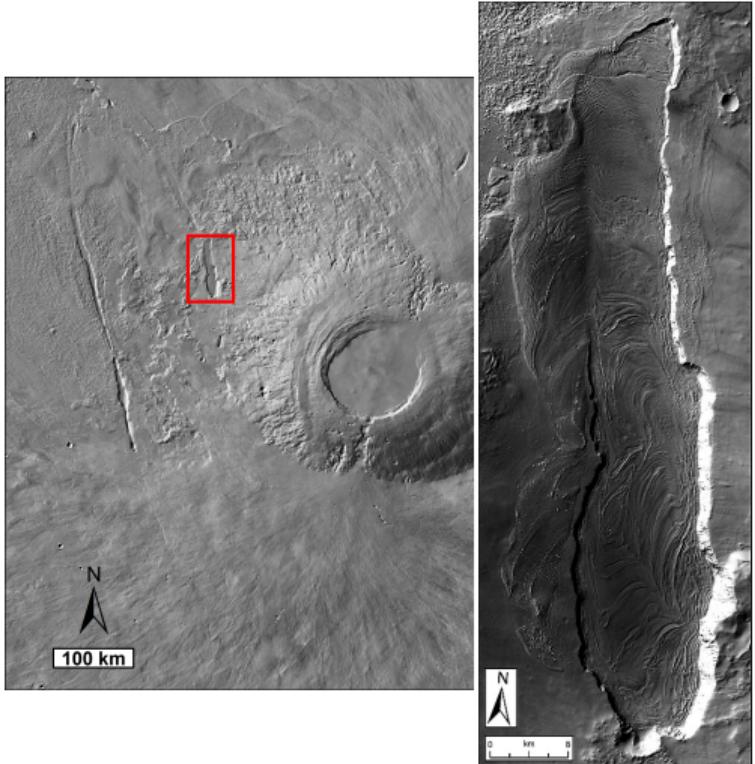
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- Extant glaciers are preserved on Western flank of Arsia
- Preserved for ~200 Ma by ashes (Kadish et al., *P&SS*, 2014)
- If ashes were sourced near-summit (Mouginis-Mark, *GRL*, 2002), our effusive volcanism might be predated by explosive activity

← from Shean et al., *JGR Planets*, 2007

# Model of waning volcanism of Arsia

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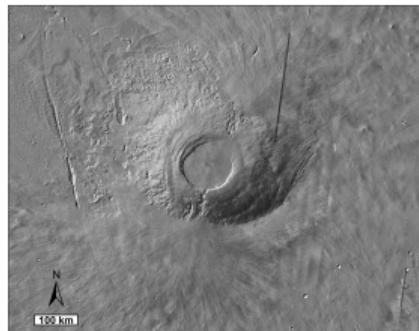
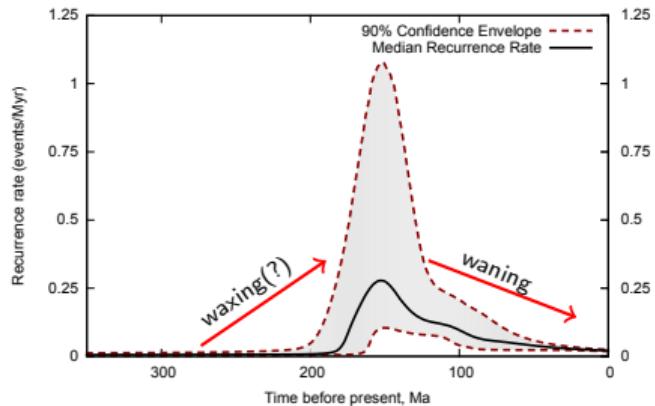
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- ① Large magma chamber fed edifice-building, sometimes explosive eruptions (Wilson et al., *JGR*, 2001)
- ② Ashes coated ice-rich deposits before 200 Ma
- ③ The chamber cooled from waning magma flux
- ④ Volcanism evolved from explosive to effusive as magma waned
- ⑤ Volcanism is now in hiatus ( $RR(t = 0) \rightarrow 0$ )

# Conclusions

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## Arsia Mons

- ① Late volcanism at Arsia Mons emplaced a volcanic field in its caldera
- ② Multiple dating methods used on lavas can be combined to estimate rate of volcanism, which peaked 150 million years ago
- ③ Volcanism waned and likely ceased 10-90 million years ago
- ④ This field might be related to a larger waning of volcanism at Arsia
- ⑤ Vents in this field are less concentrated than vents in terrestrial volcanic fields
- ⑥ Lava flows are an order of magnitude larger in volume than flows in most terrestrial fields

# Conclusions

## Overall Conclusions

- Volcanic fields have complex, voluminous roots
- Emplacement of lavas in these fields can be modeled
- Volcanic vent distribution in fields has a wide variation across the solar system
- These tools can be used to gain knowledge about volcanic fields on Mars with spaceborne instruments

