



OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

A first look at Bennu and Ryugu for signatures of formation in the arrangements of its surface features



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The OSIRIS-REx and Hayabusa2 Teams



This Study's Relevance

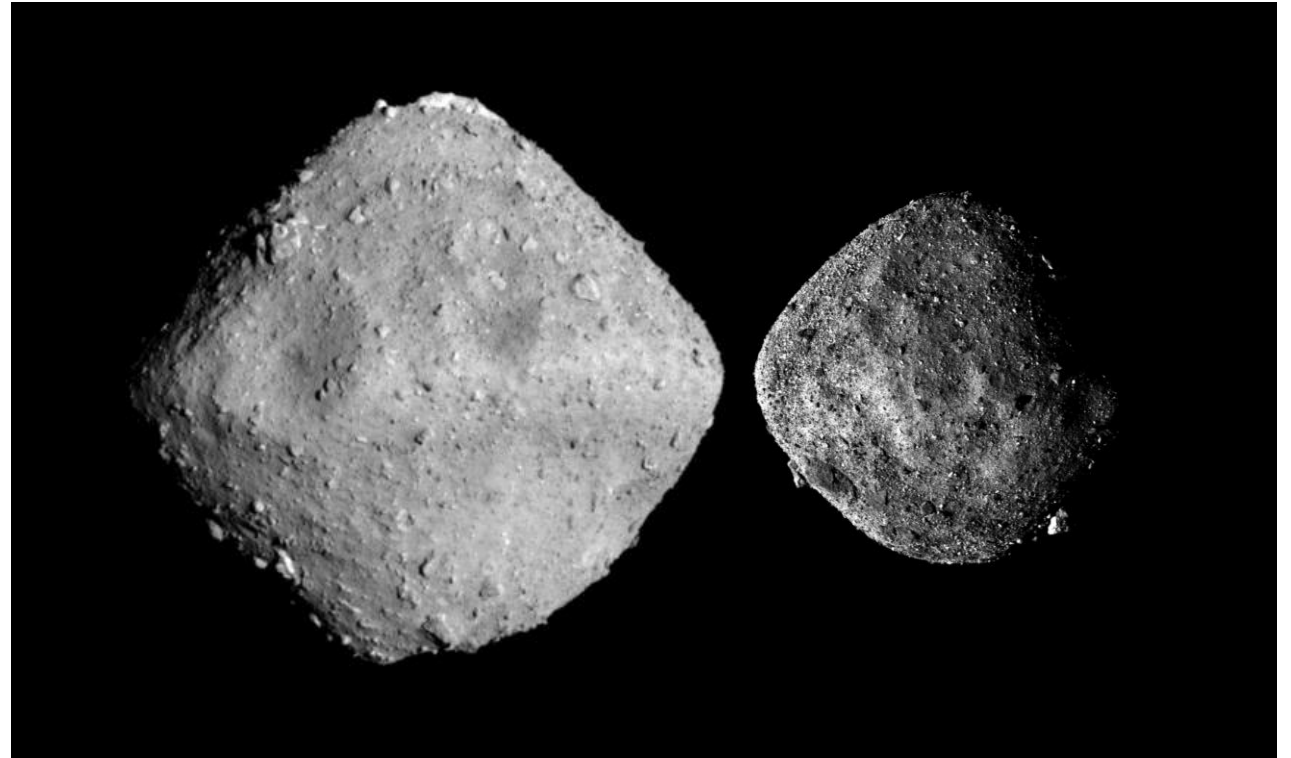
Part of an OSIRIS-REx Participating Scientist Program investigation into the behavior and evolution of regolith populations/shape attributes on small bodies.

Stephen R. Schwartz
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Alice Quillen

Erik Asphaug
Hideaki Miyamoto
Martin Jutzi

- Regolith generation
 - impacts, grinding, thermal effects, ...
- Movements: loss to space or subsurface
 - lofting caused by impacts, solar radiation pressure/electrostatic effects, influence of seismic energy, ...

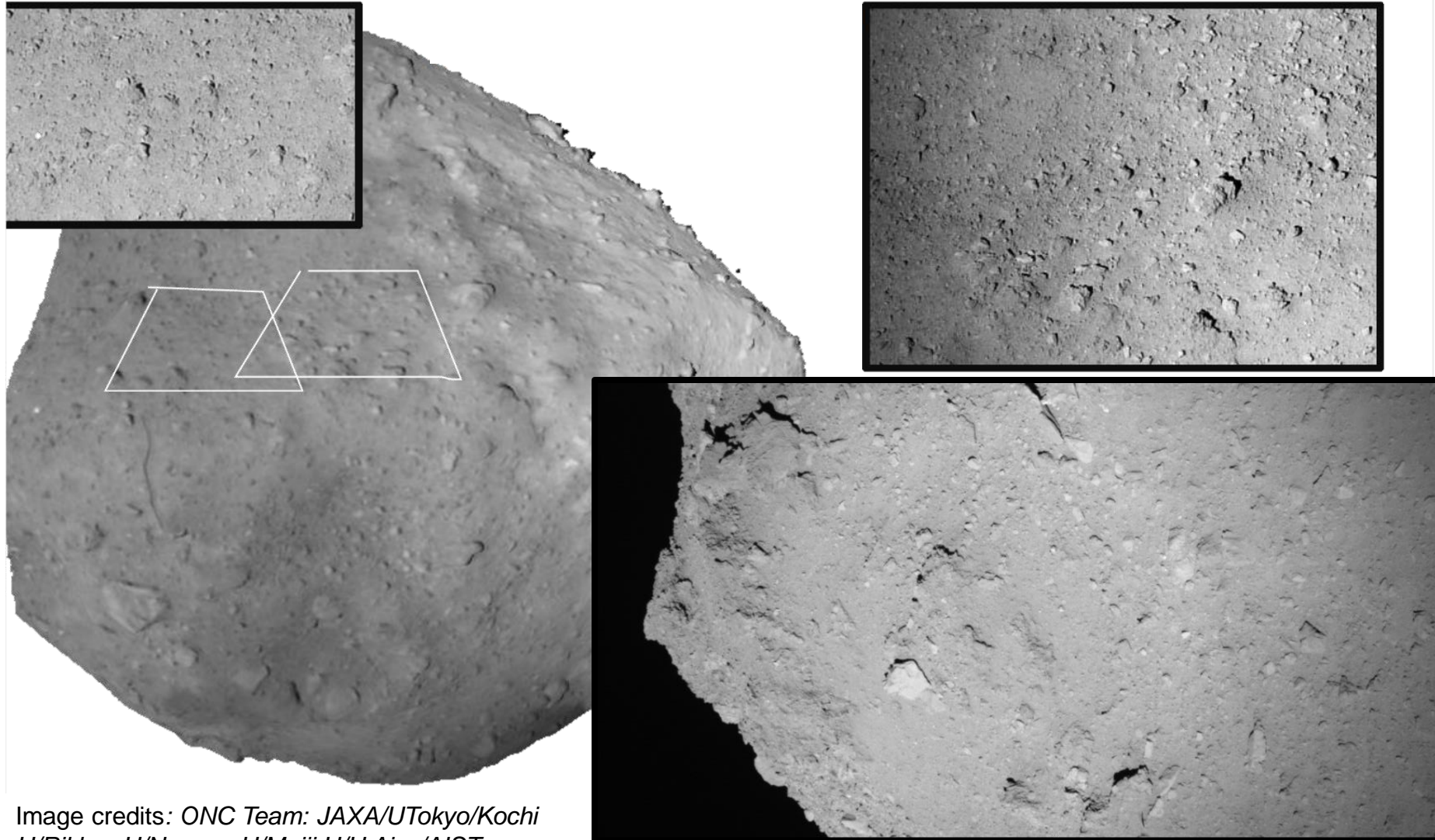
Study is also a part of science investigation within the ONC instrument team on Hayabusa2.



Ryugu image, photographed at 12:50 p.m. (JST), June 26, 2018. *Credit: ONC Team: JAXA/UTokyo/Kochi U/Rikkyo U/Nagoya U/Meiji U/U Aizu/AIST.*
Bennu image, mosaic of photographs taken December 2, 2018. *Credit: IPWG Team: NASA/U. Arizona/LPL.*



Ryugu



- **Some lineaments come from boulder alignments.**
- **Many of these are aligned to local gravitational slope.**

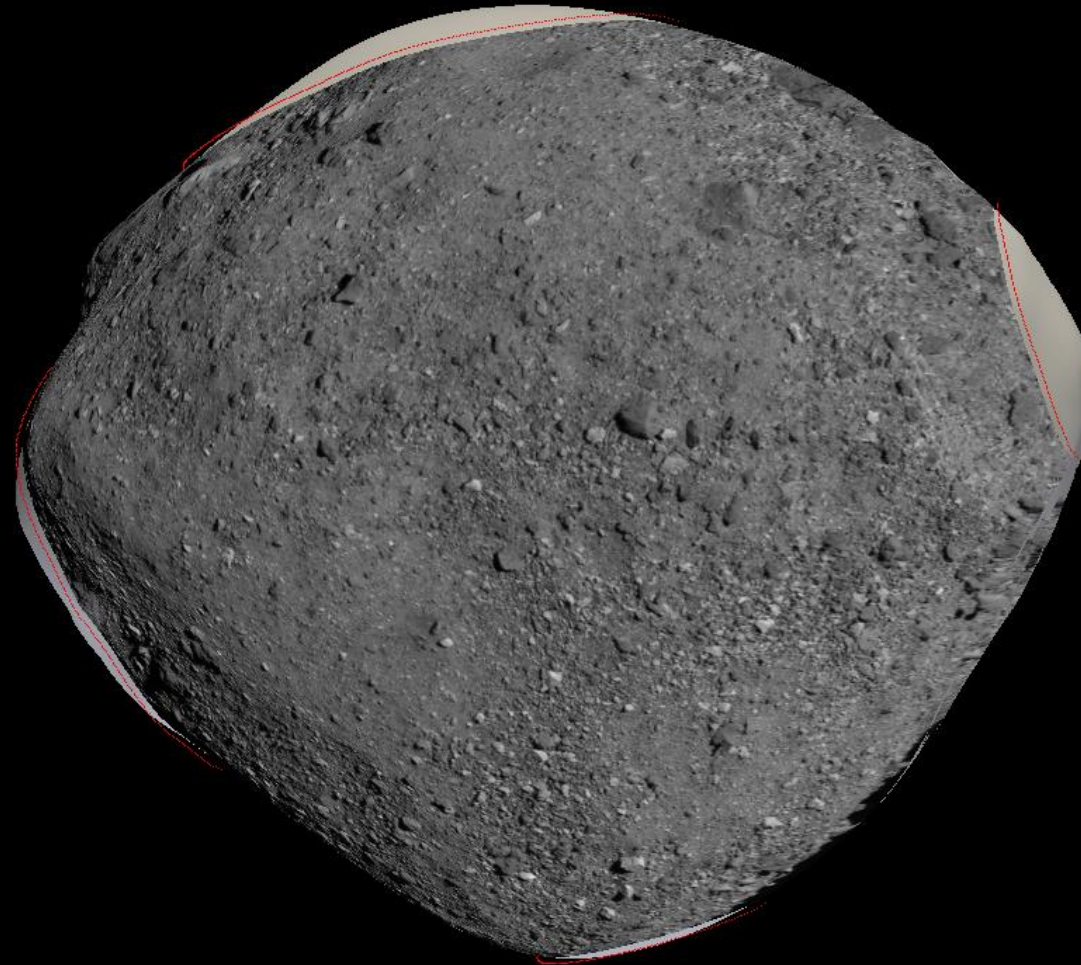


*Slides and analyses c/o
Hideaki Miyamoto and
Hayabusa2 ONC Team*

Image credits: ONC Team: JAXA/UTokyo/Kochi
U/Rikkyo U/Nagoya U/Meiji U/U Aizu/AIST.



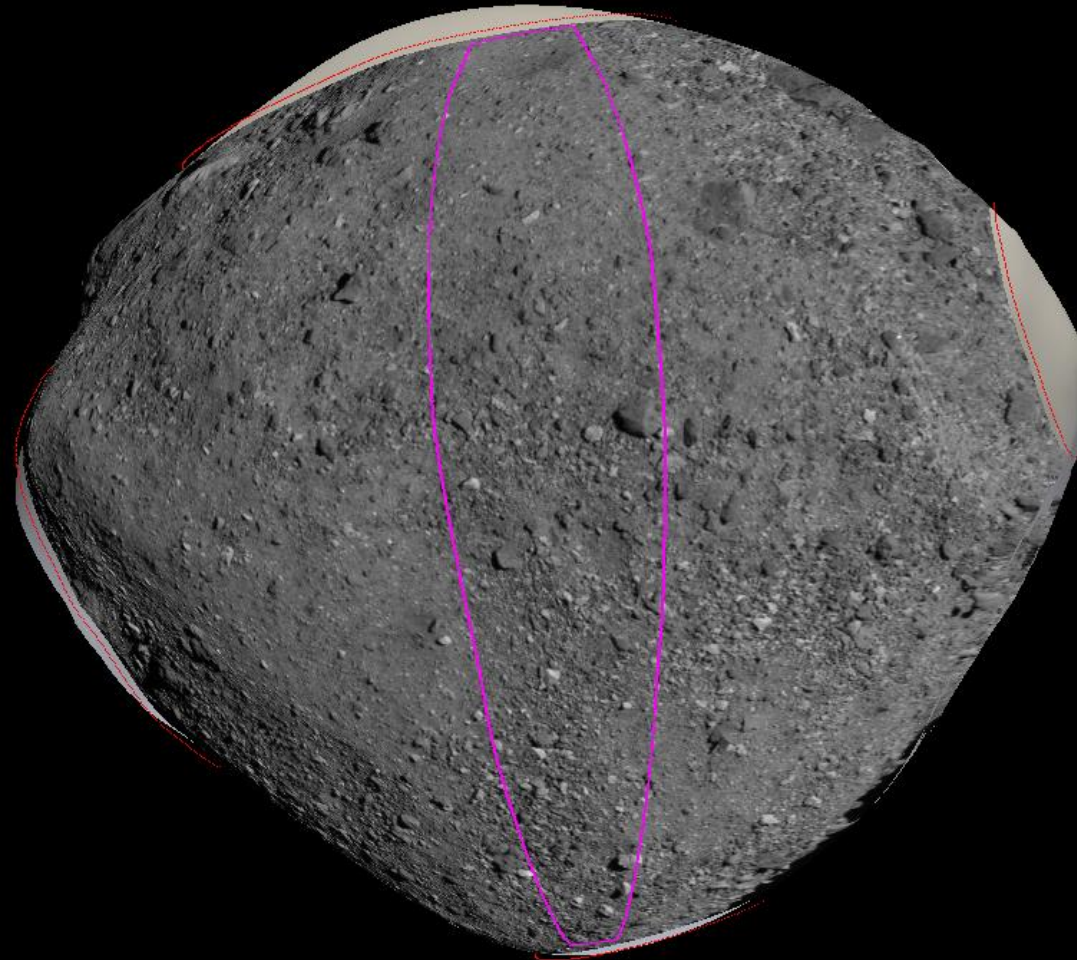
Boulder Orientations on Bennu



Dec. 1 OCAMS PolyCam image (IPWG) projected onto Bennu shape model (ALTWG) using the Small Bodies Mapping Tool (SBMT) developed at the Johns Hopkins University Applied Physics Laboratory.



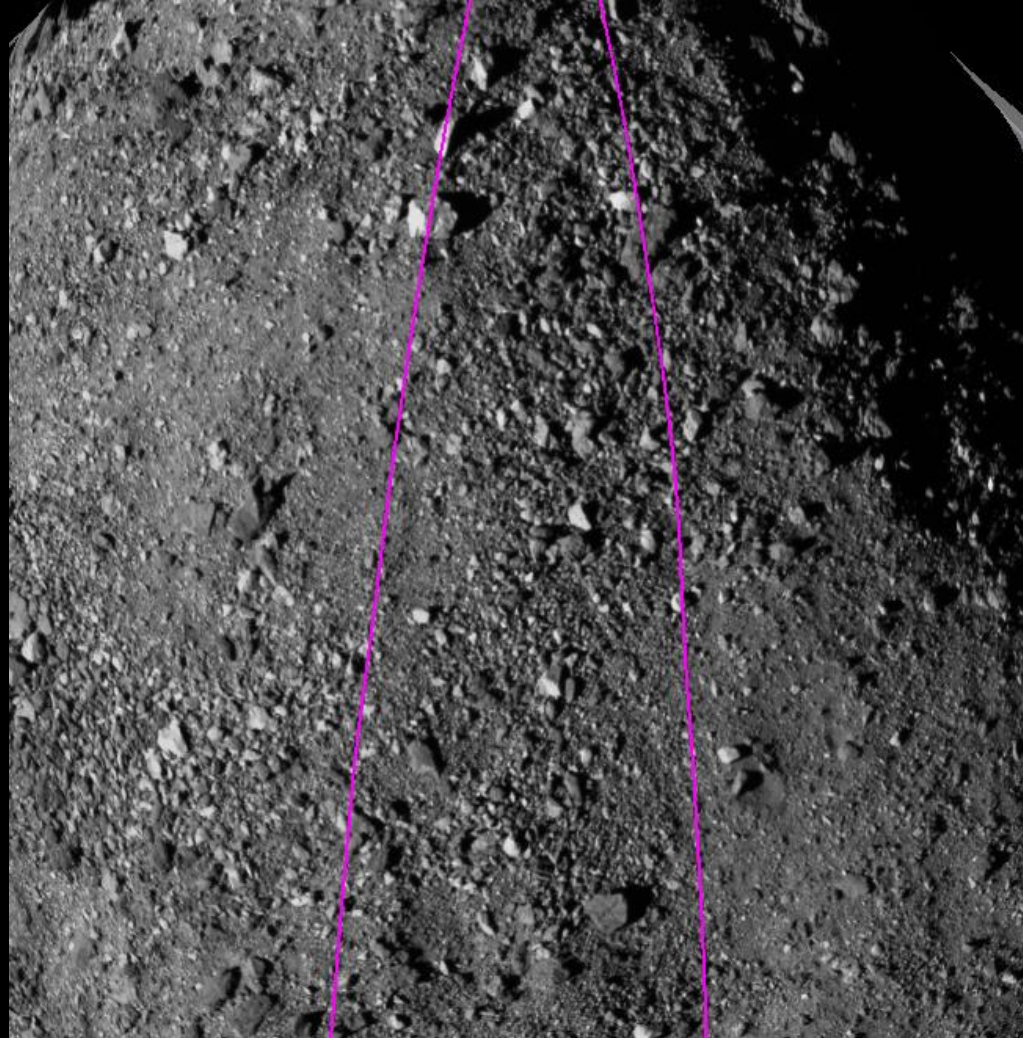
Boulder Orientations on Bennu



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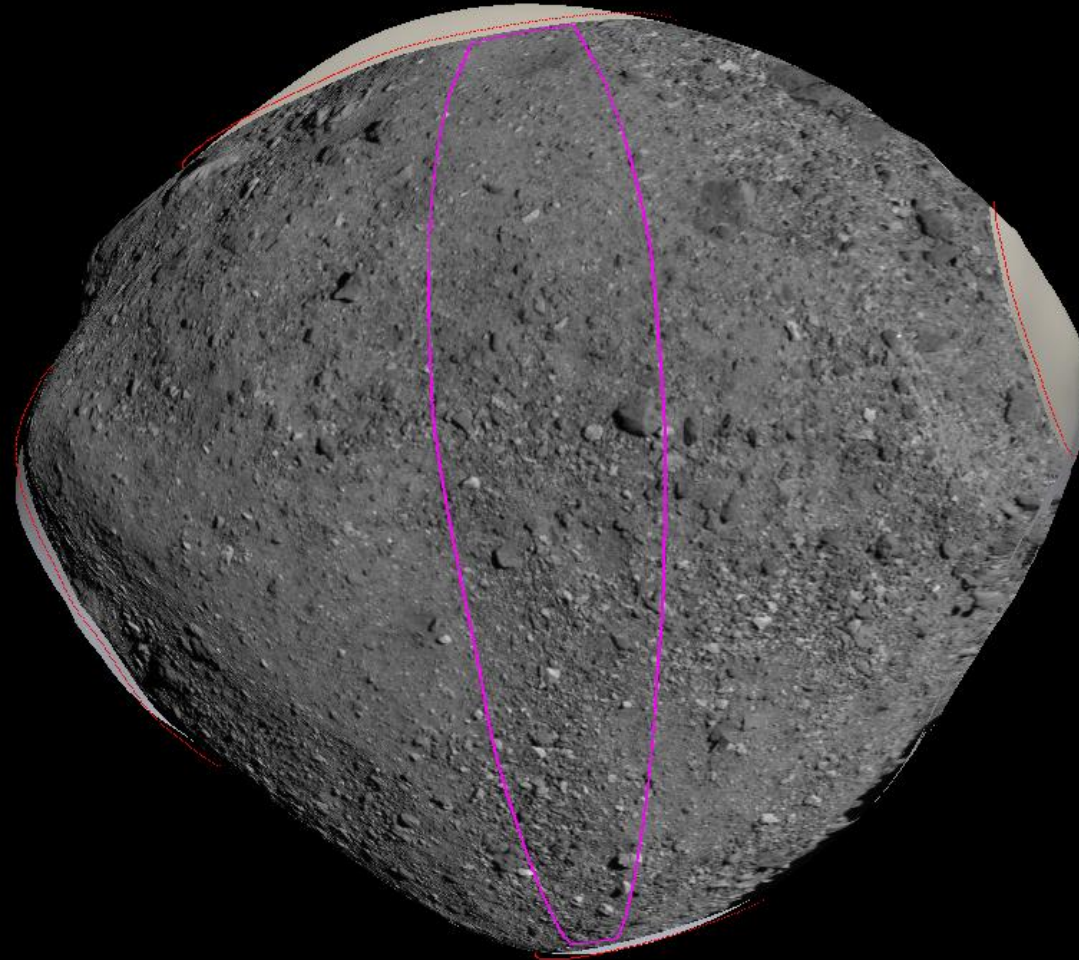
Boulder Orientations on Bennu



Dec. 2 OCAMS PolyCam image (IPWG) projected onto Bennu shape model (ALTWG).

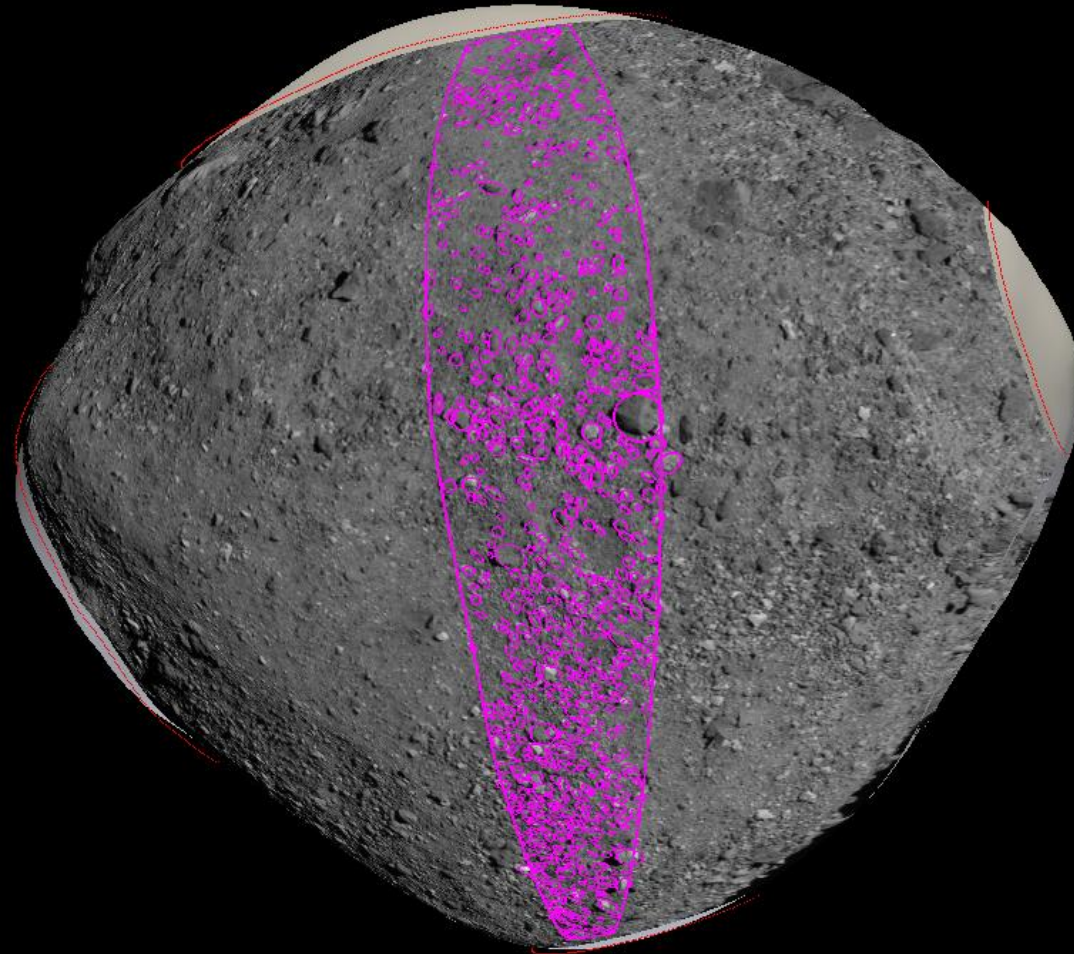


Boulder Orientations on Bennu



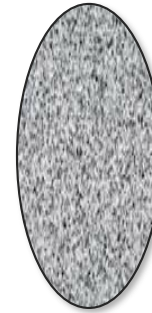
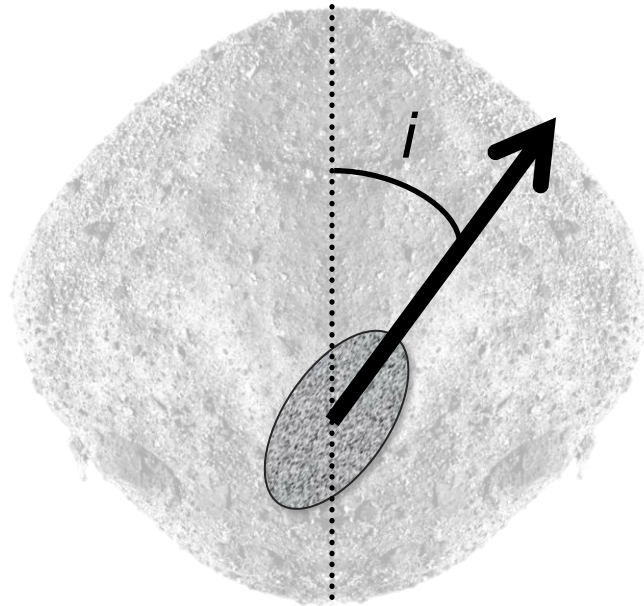


Boulder Orientations on Bennu

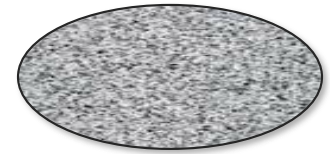




Orientation w.r.t. Longitudinal Lines



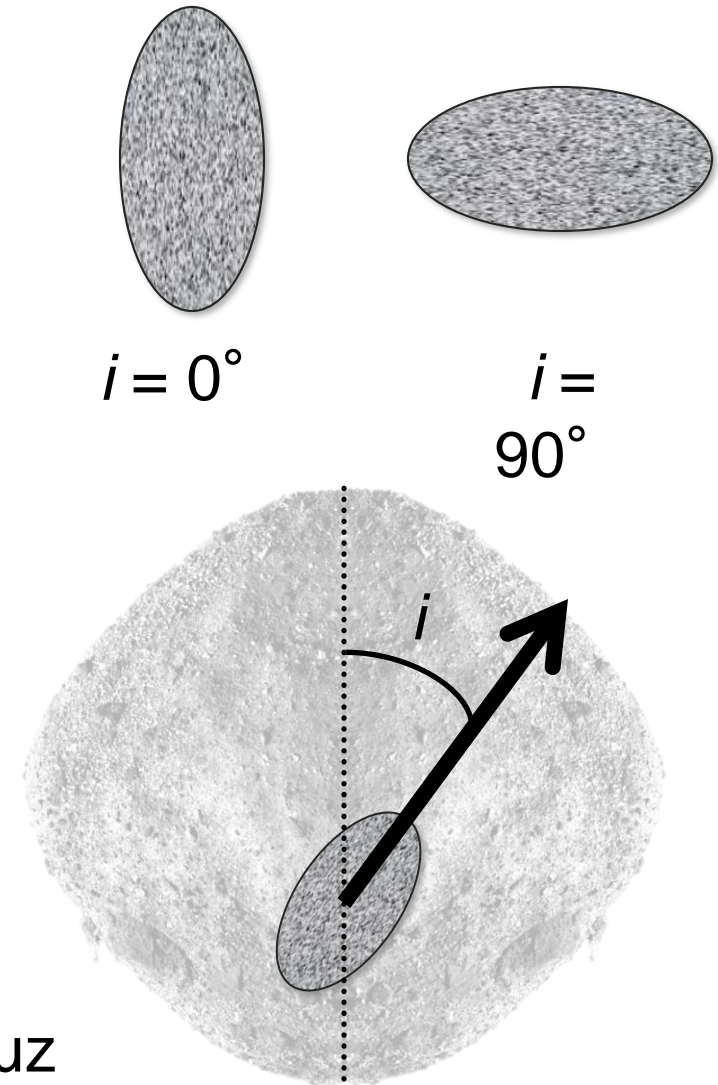
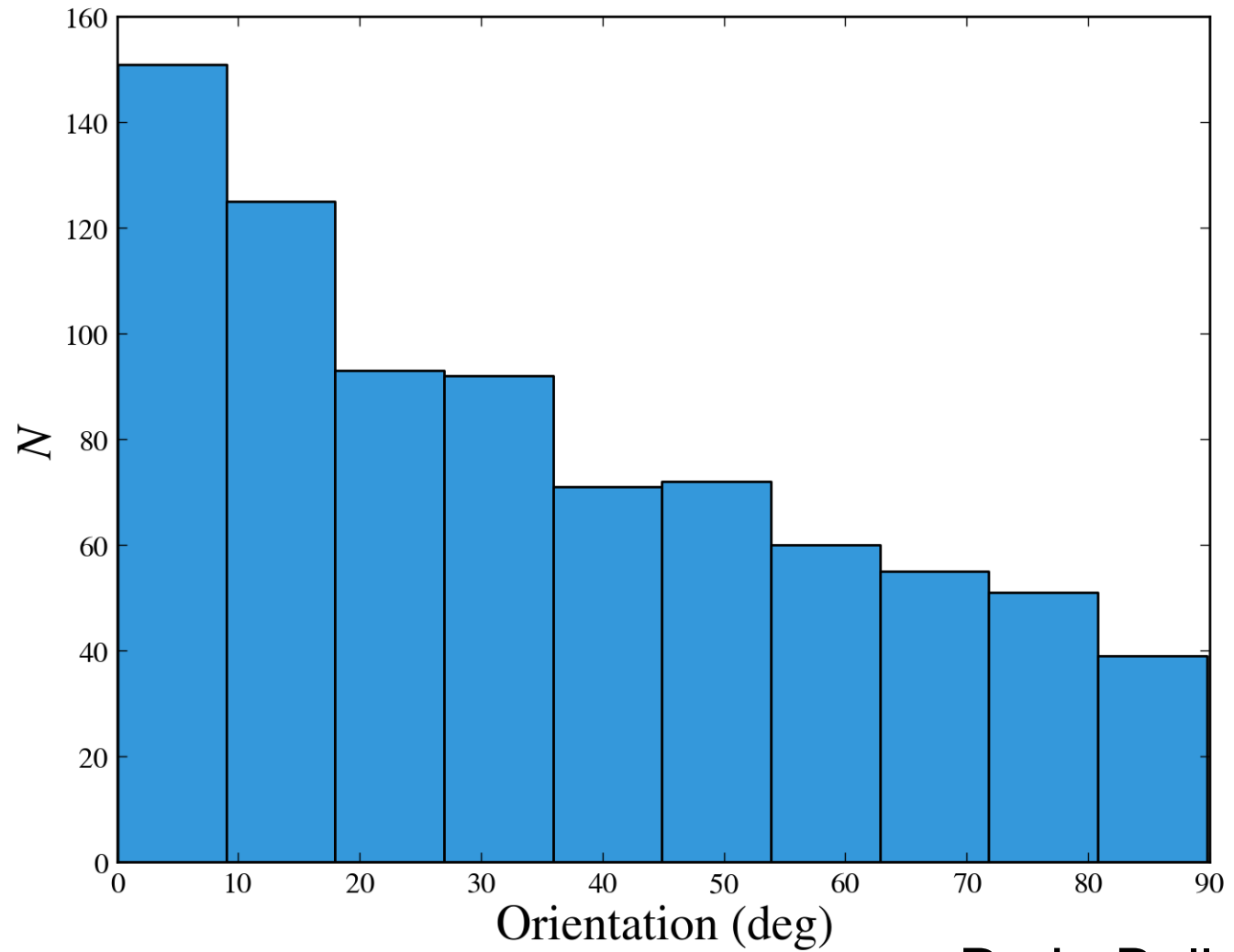
$i = 0^\circ$



$i = 90^\circ$



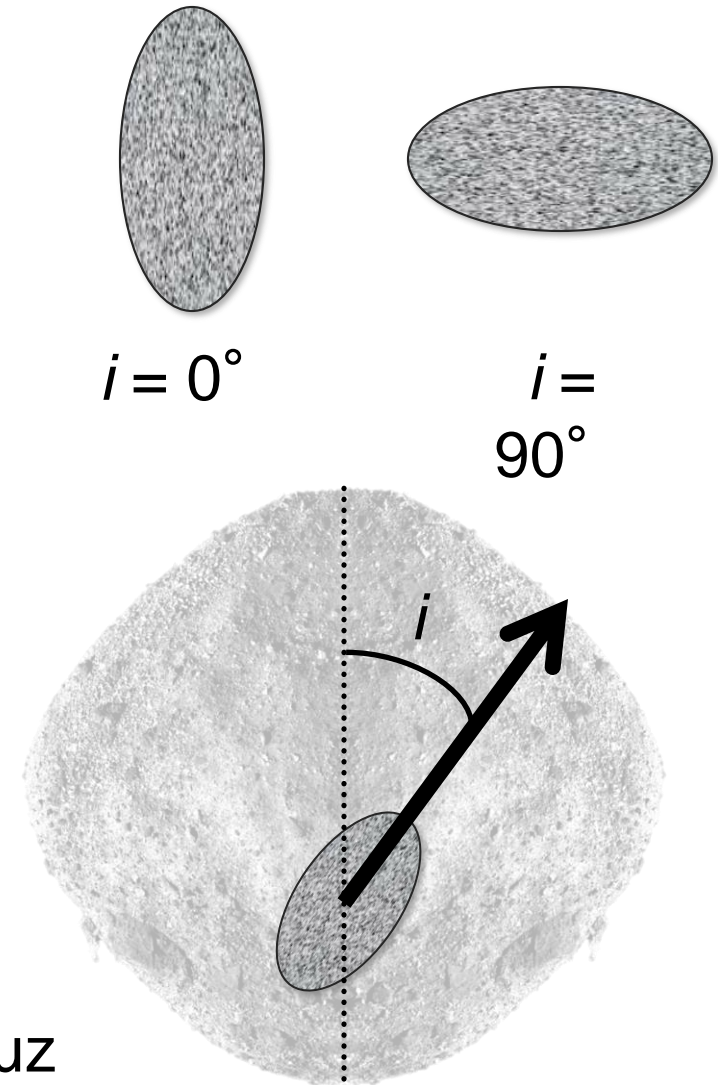
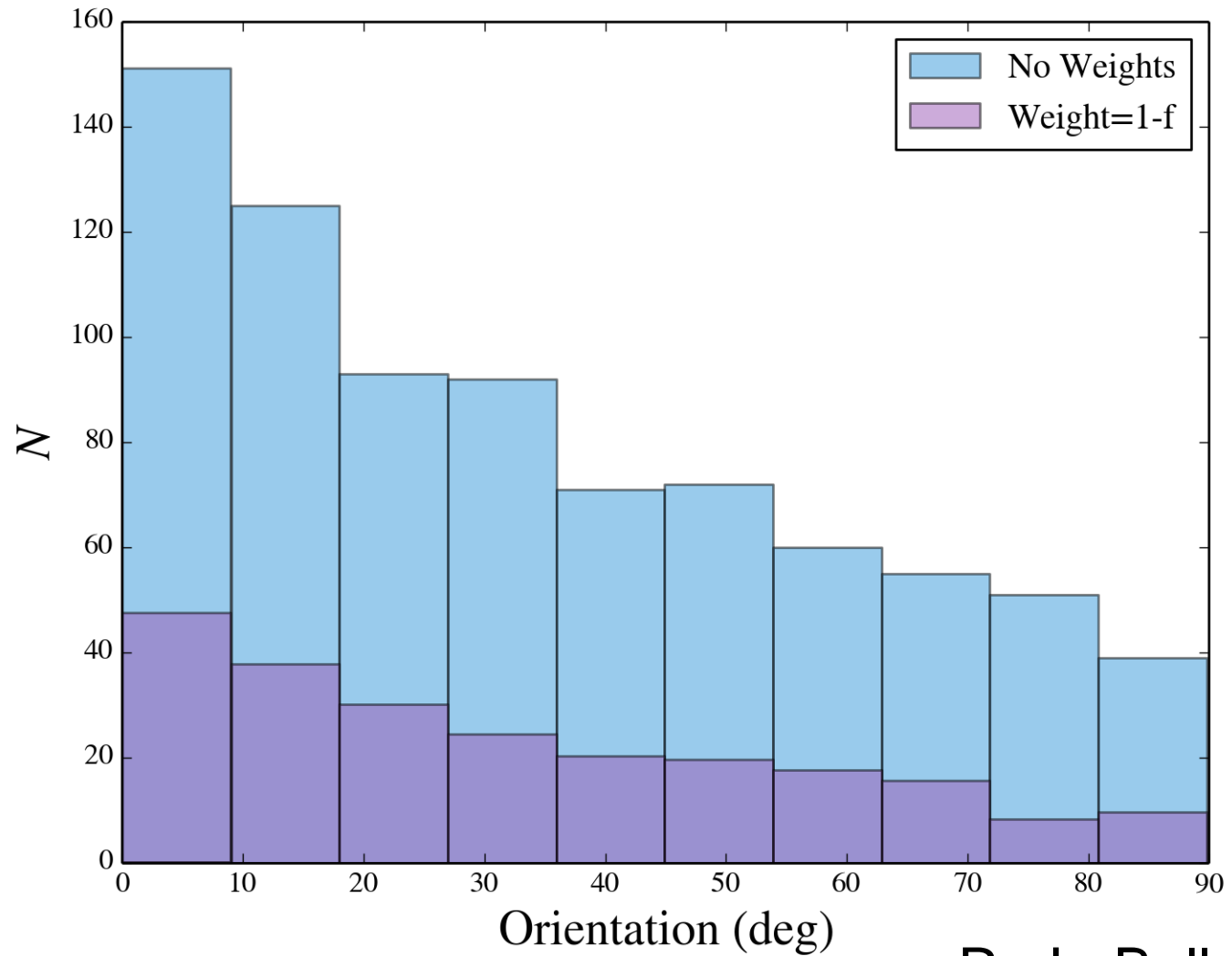
Orientation w.r.t. Longitudinal Lines



R.-L. Ballouz



Orientation w.r.t. Longitudinal Lines



R.-L. Ballouz



Shape Model with Image Mosaic and Slope (colors) Overlay

See Radio
Science Talk
Next Session:
P22A-05
11:00 am
(Scheeres et al.)

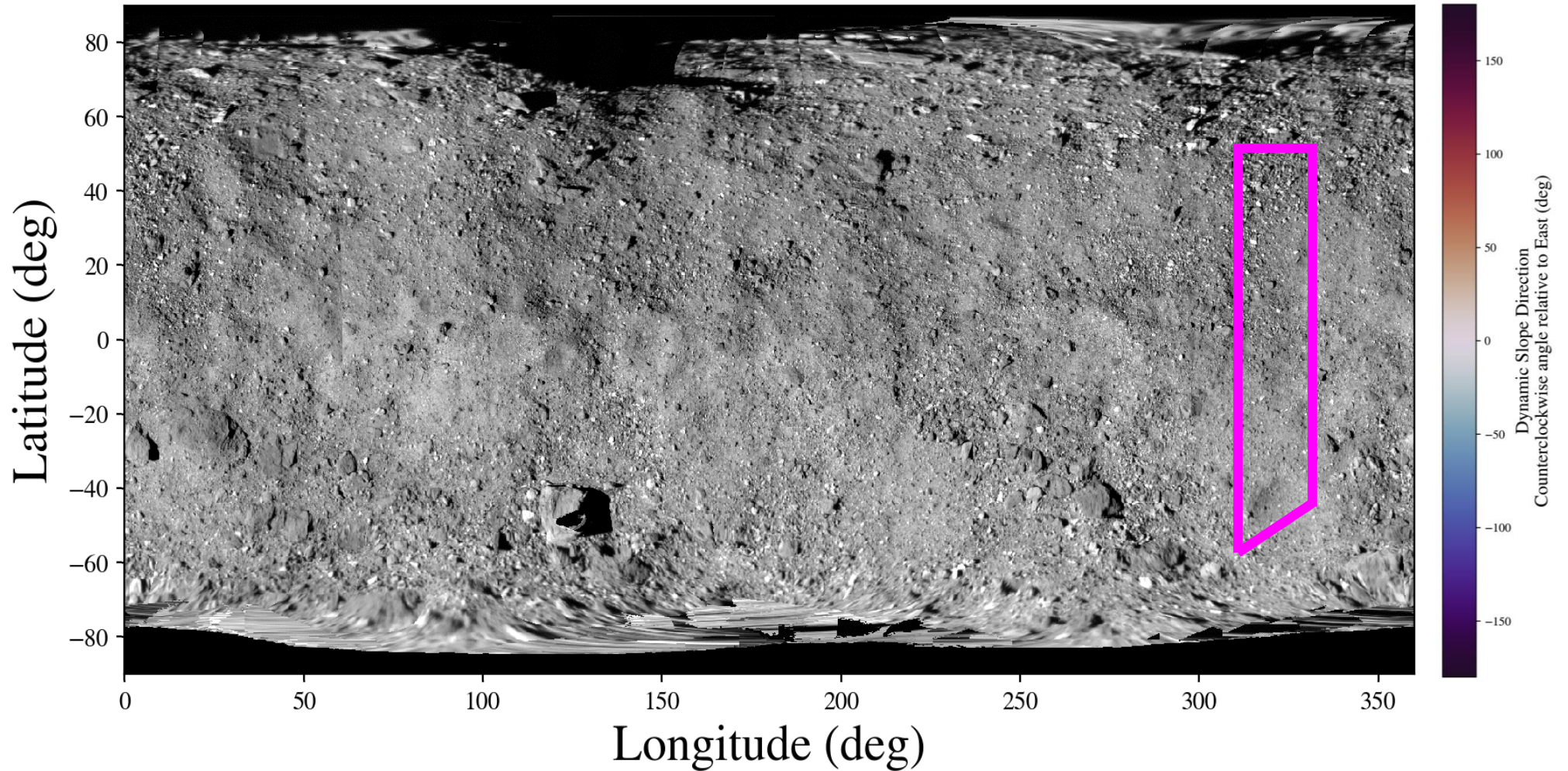


Image Credit OSIRIS-REx Science Teams: Image Processing, Radio Science, Altimetry, Regolith Development.



Shape Model with Image Mosaic and Slope (contours) Overlay

See Radio
Science Talk
Next Session:
P22A-05
11:00 am
(Scheeres et al.)

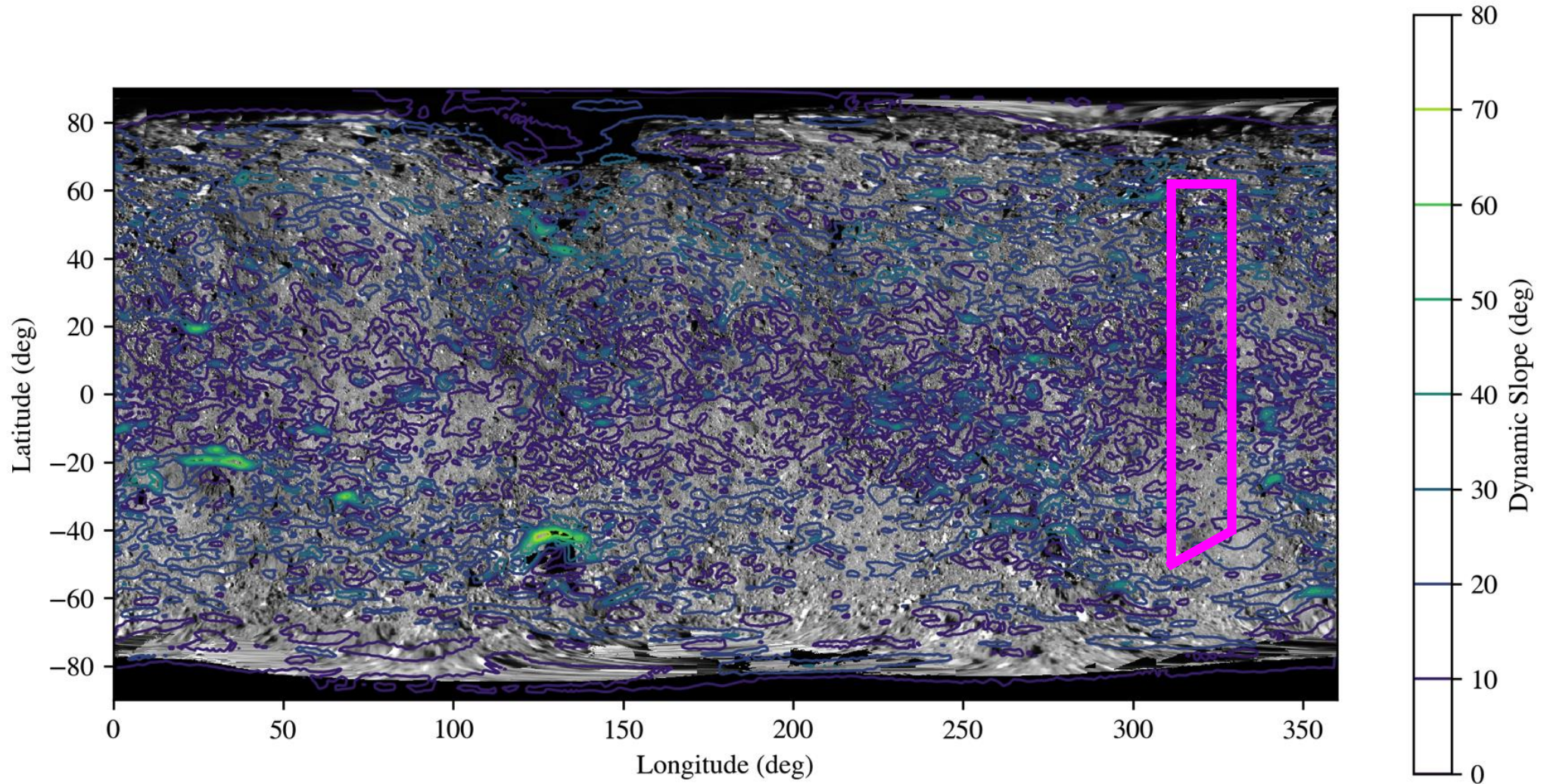
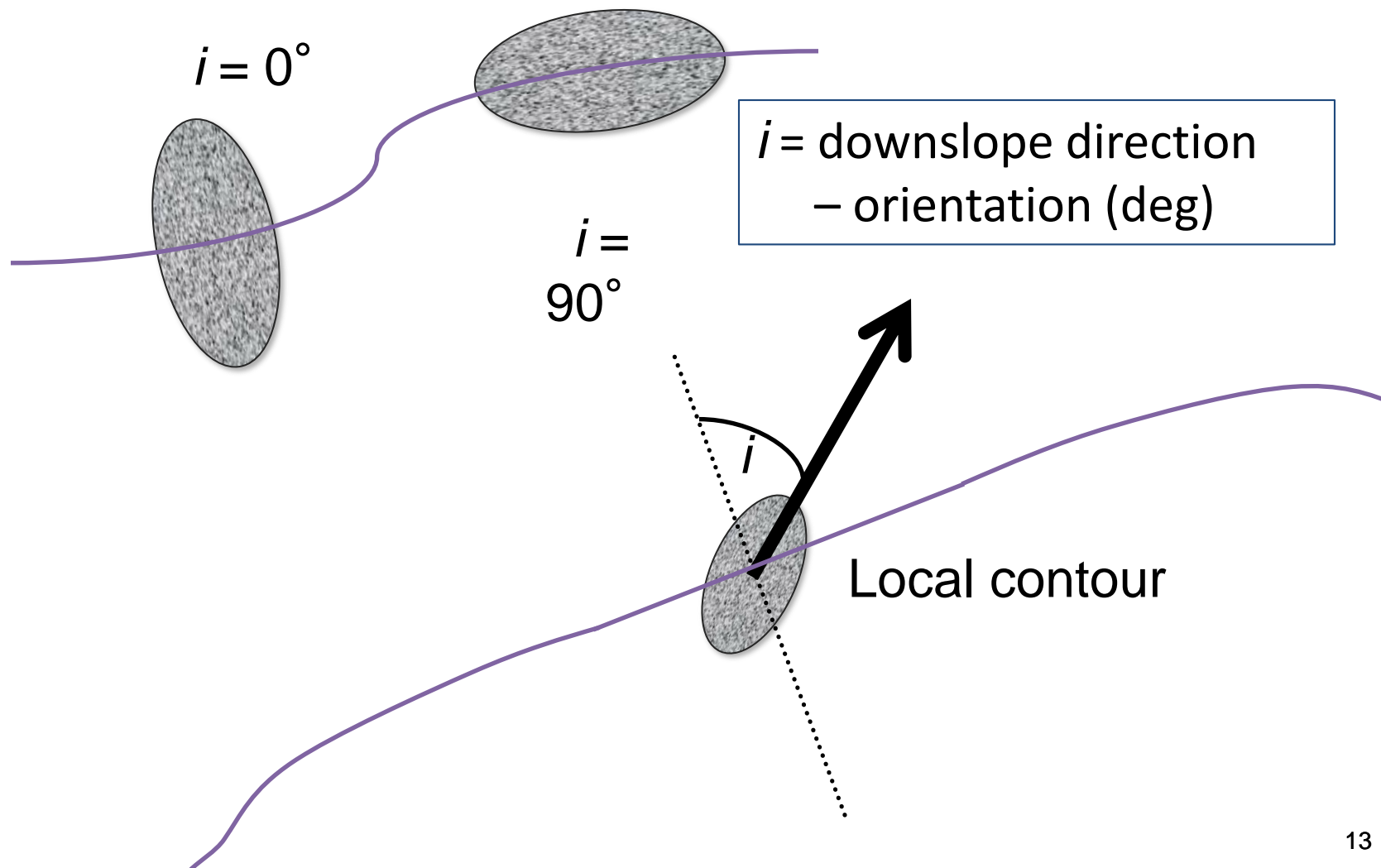


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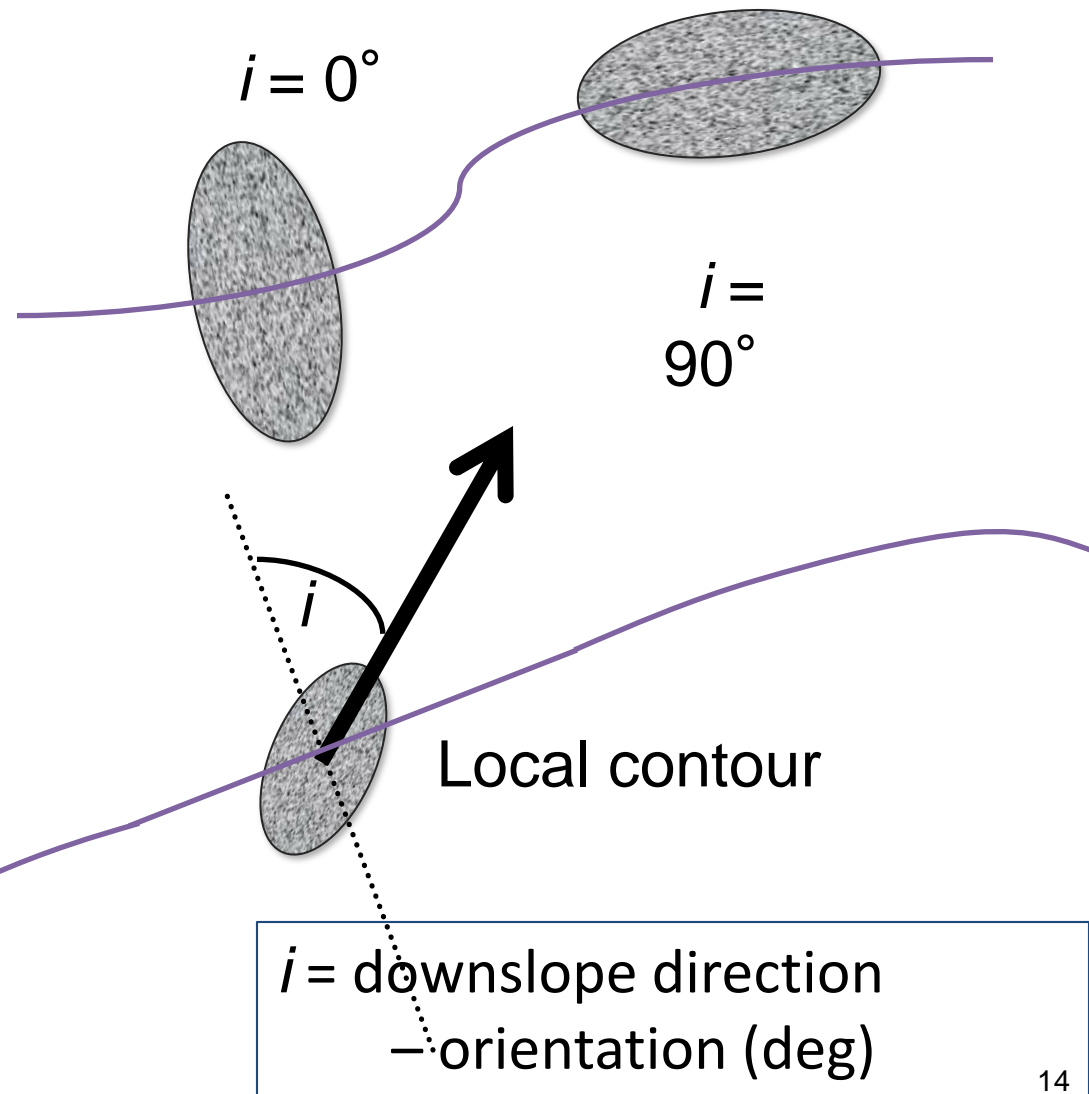
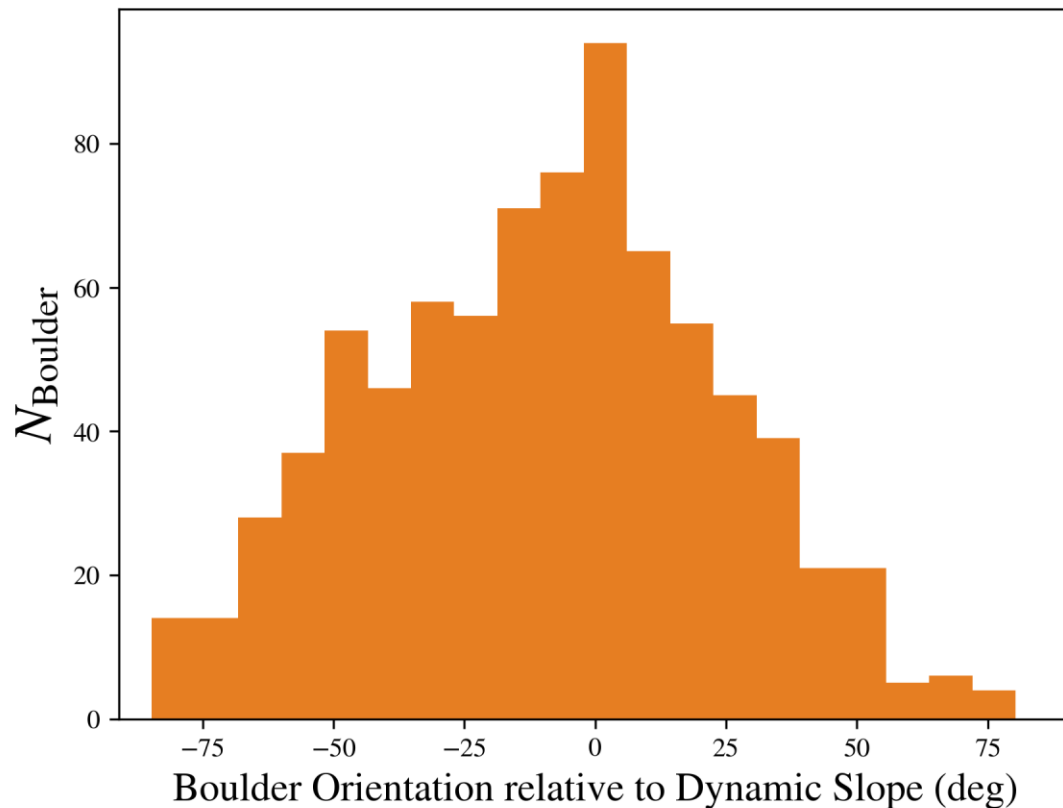


Orientation w.r.t. Local Downslope Direction



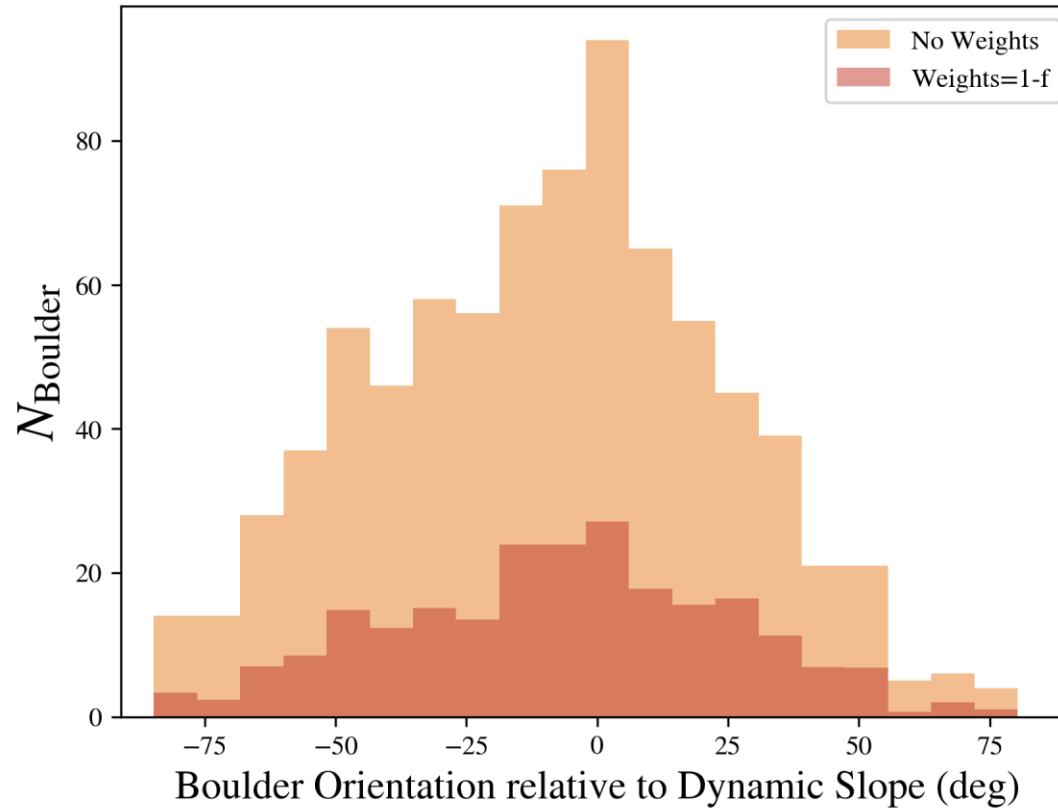


Orientations Relative to Dynamic Slope



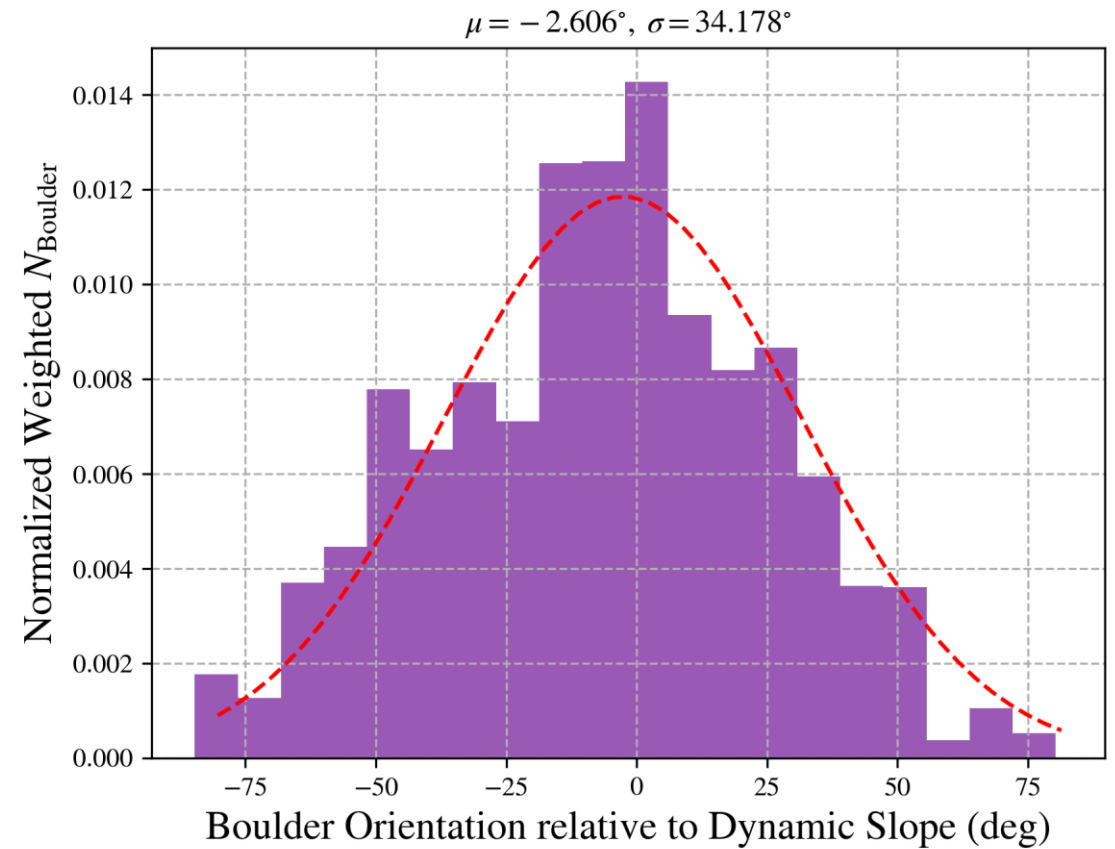
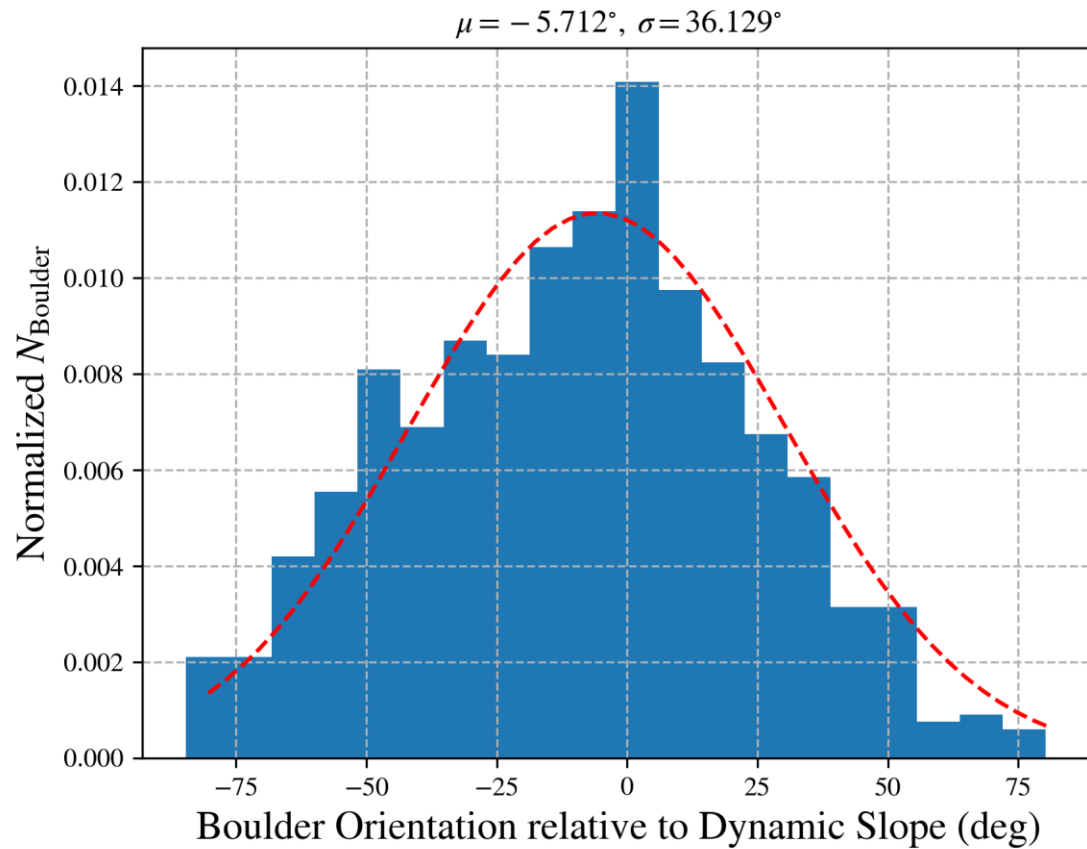


Orientations Relative to Dynamic Slope





Histogram





Simulations

Gravity

- pkdgrav: “Parallel k -D tree GRAVity code”
 - Combine parallelism and tree code to compute forces rapidly.
- Started as pure cosmology code written at U Washington (Stadel 2001).
- pkdgrav solves the equations of motion for gravity (point masses):

$$\ddot{\mathbf{r}}_i = -\sum_{j \neq i} \hat{\mathbf{a}} \frac{Gm_j (\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^3}$$

m = mass
 \mathbf{r} = vector position

Collisions

- Introduce collision constraint (Richardson et al. 2000)
- Use (already-built) tree:

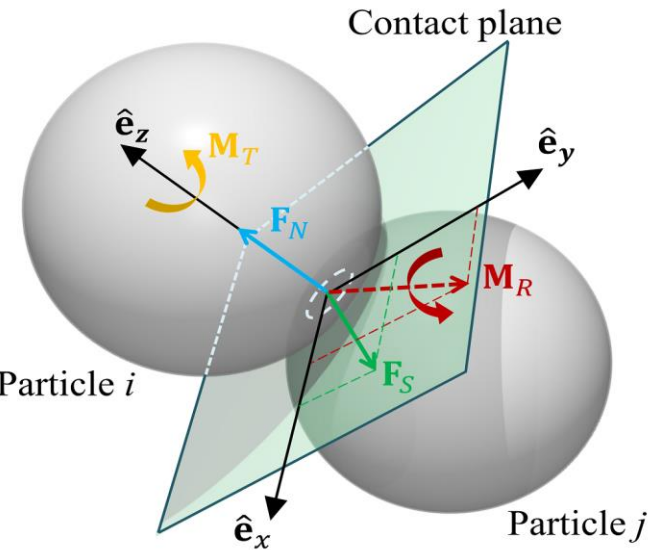
Separation

$$|\mathbf{r}_i - \mathbf{r}_j| = s_i + s_j$$

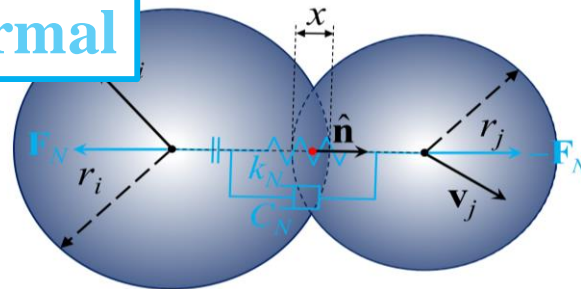
Sum of radii

SSDEM Contact Model in pkdgrav

Cundall & Strack 1979, *Geotechnique* **29**, 47.

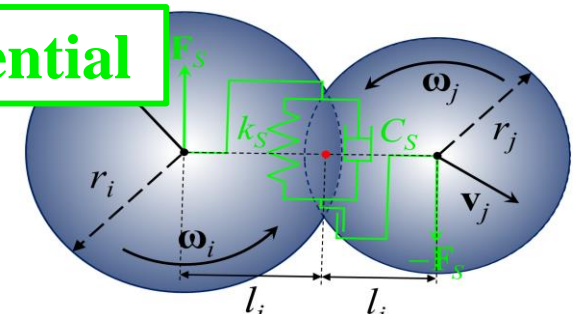


Normal



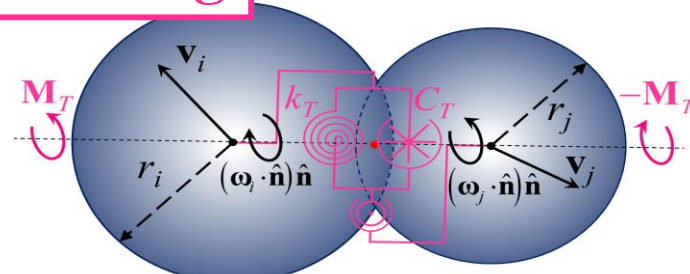
$$\mathbf{F}_N = -k_N x \hat{\mathbf{n}} + C_N \mathbf{u}_n$$

Tangential



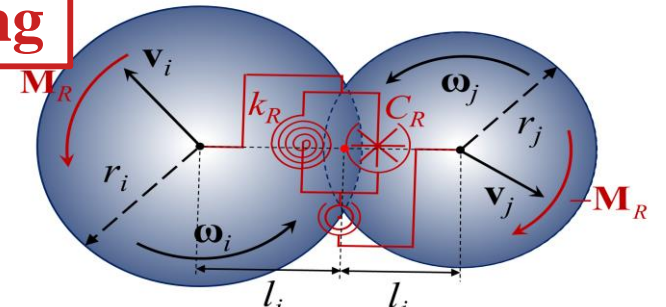
$$\mathbf{F}_S = \begin{cases} k_S \delta_S + C_S \mathbf{u}_t, & |k_S \delta_S| < \mu_S |\mathbf{F}_N| \\ \mu_S |\mathbf{F}_N| \hat{\delta}_S, & |k_S \delta_S| \geq \mu_S |\mathbf{F}_N| \end{cases}$$

Twisting



$$\mathbf{M}_T = \begin{cases} k_T \delta_T + C_T \boldsymbol{\omega}_T, & |k_T \delta_T| < \mu_T \beta R \mu_S |\mathbf{F}_N| \\ \mu_T \beta R \mu_S |\mathbf{F}_N| \hat{\delta}_T, & |k_T \delta_T| \geq \mu_T \beta R \mu_S |\mathbf{F}_N| \end{cases}$$

Rolling



$$\mathbf{M}_R = \begin{cases} k_R \delta_R + C_R \boldsymbol{\omega}_R, & \text{if } |k_R \delta_R| < \mu_R \beta R |\mathbf{F}_N| \\ \mu_R \beta R |\mathbf{F}_N| \hat{\delta}_R, & \text{if } |k_R \delta_R| \geq \mu_R \beta R |\mathbf{F}_N| \end{cases}$$

Schwartz et al. 2012, *Granular Matter* **14**, 363. **ling**
quasi-static/dynamical
granu
 Zhang et al. 2017, *Icarus* **294**, 98.



Simulations

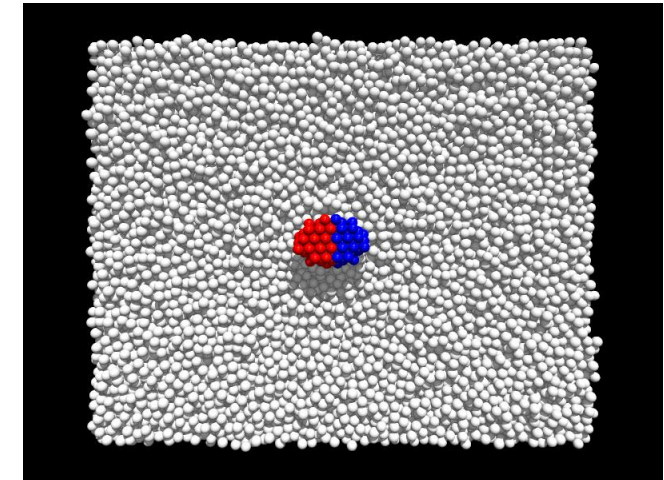
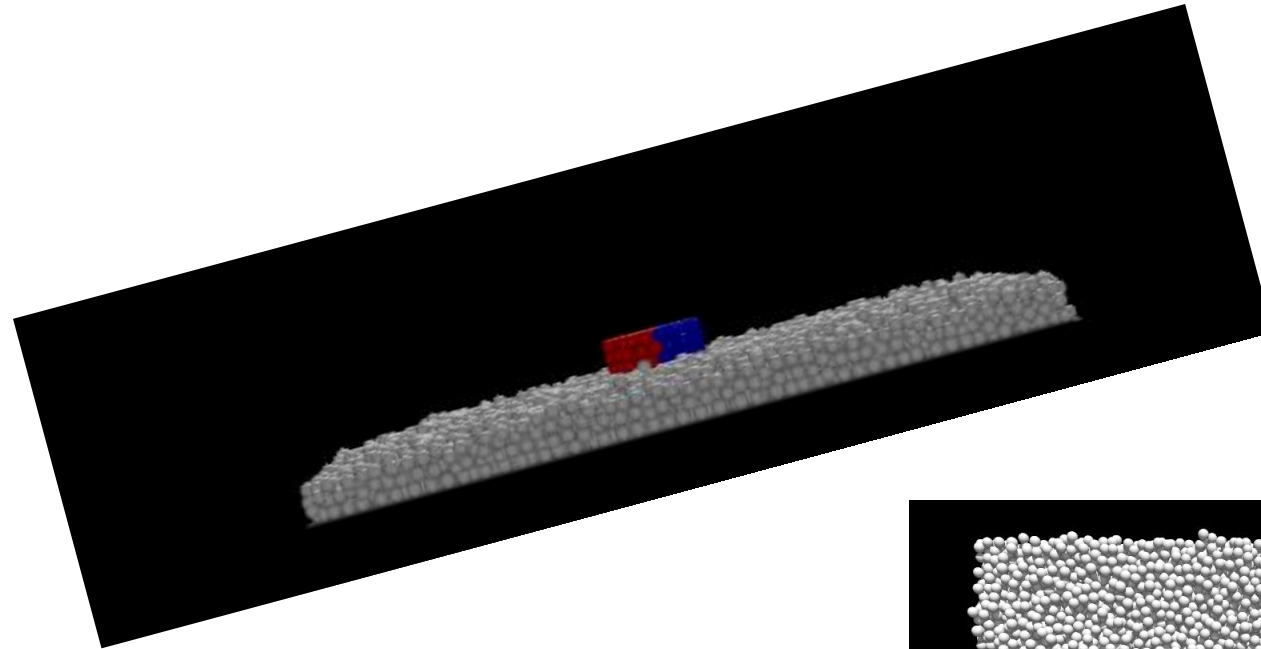
Methodology

- Form a rigidly bonded aggregate of particles.



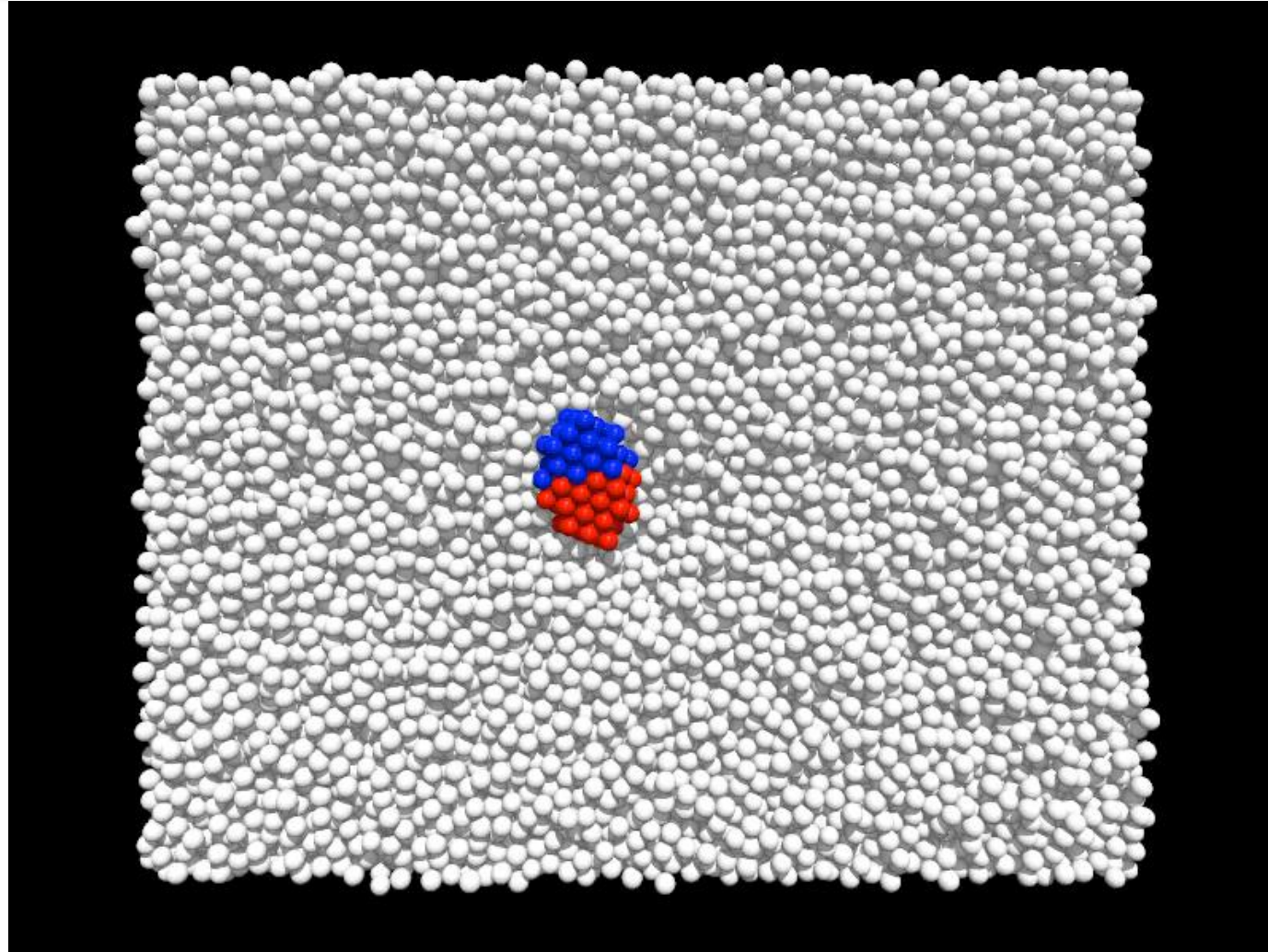
(Richardson et al. 2009)

- Place atop a sloping bed of loose grains simulated in periodic boundary conditions.
- Vibrate bed and track orientation of aggregate in time.





Simulations





Conclusions and Discussion

- On Ryugu, linear features can come from boulder arrangements.
- Some of these lie directly along lines of local slope.
- On Bennu, our work thus far strongly suggests that individual boulders orient themselves along lines of local slope.
- Upcoming work and things to look for:
 - Analyze the rest of Bennu and in greater detail.
 - Is this slope/orientation correlation stronger at certain sizes?
 - If so, what are the implications?
 - Is inertia important? (Brazil-nut analogy)
 - Are we seeing buried boulders?
 - Quantitative comparison of this correlation between Bennu & Ryugu.

Enormous thanks to the Hayabusa2 Science Team and to NASA's OSIRIS-REx Participating Scientist Program!

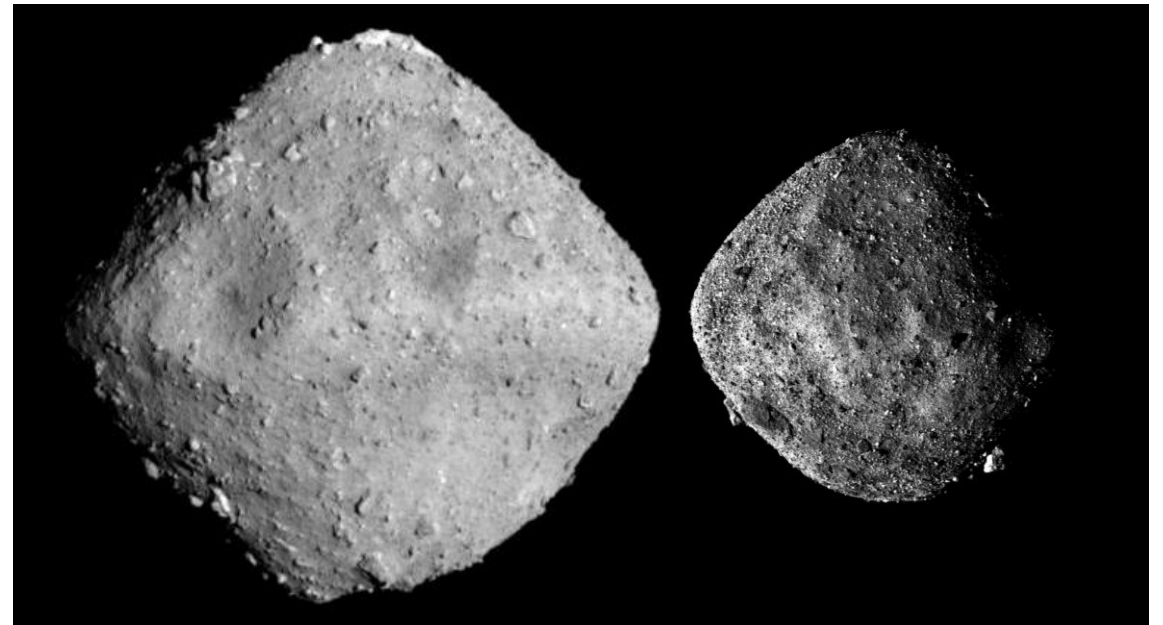


Image credits: Hayabusa2 ONC Team: JAXA/Tokyo/Kochi/Rikkyo/Nagoya/Meiji/Aizu/AIST; OSIRIS-REx IPWG Team: NASA/LL Arizona/PL



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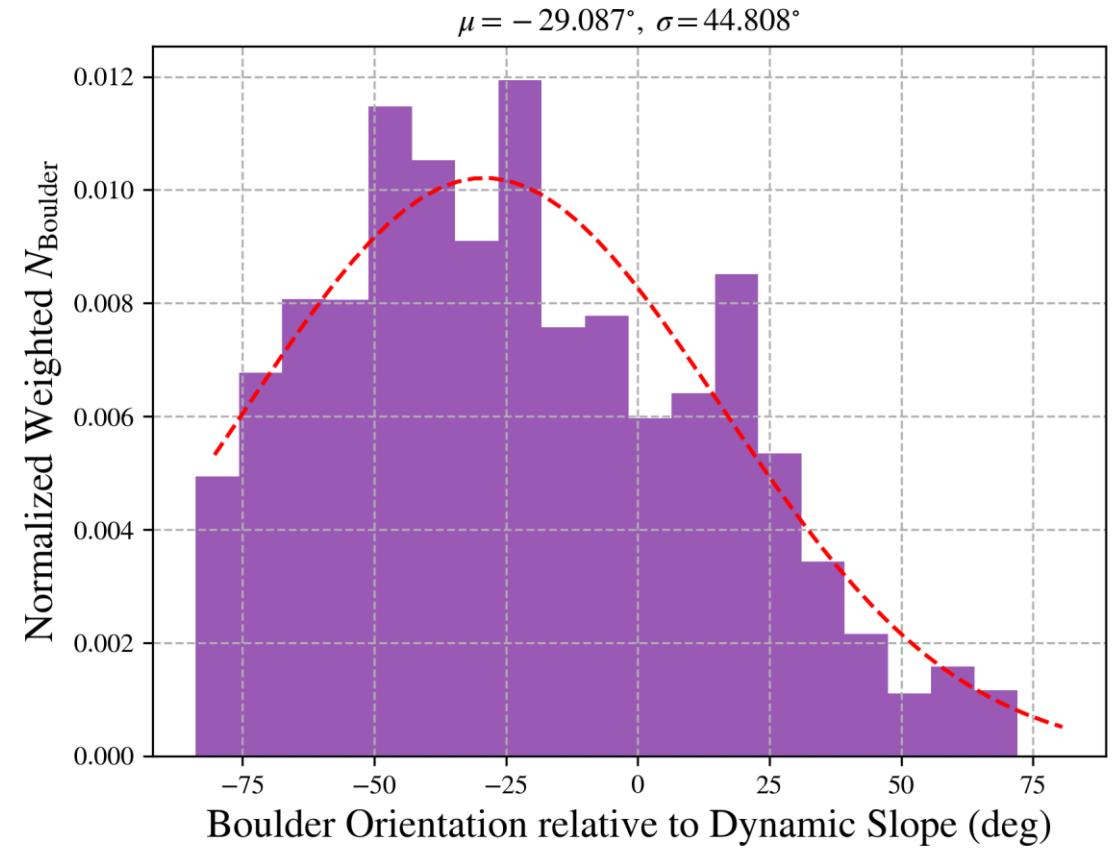
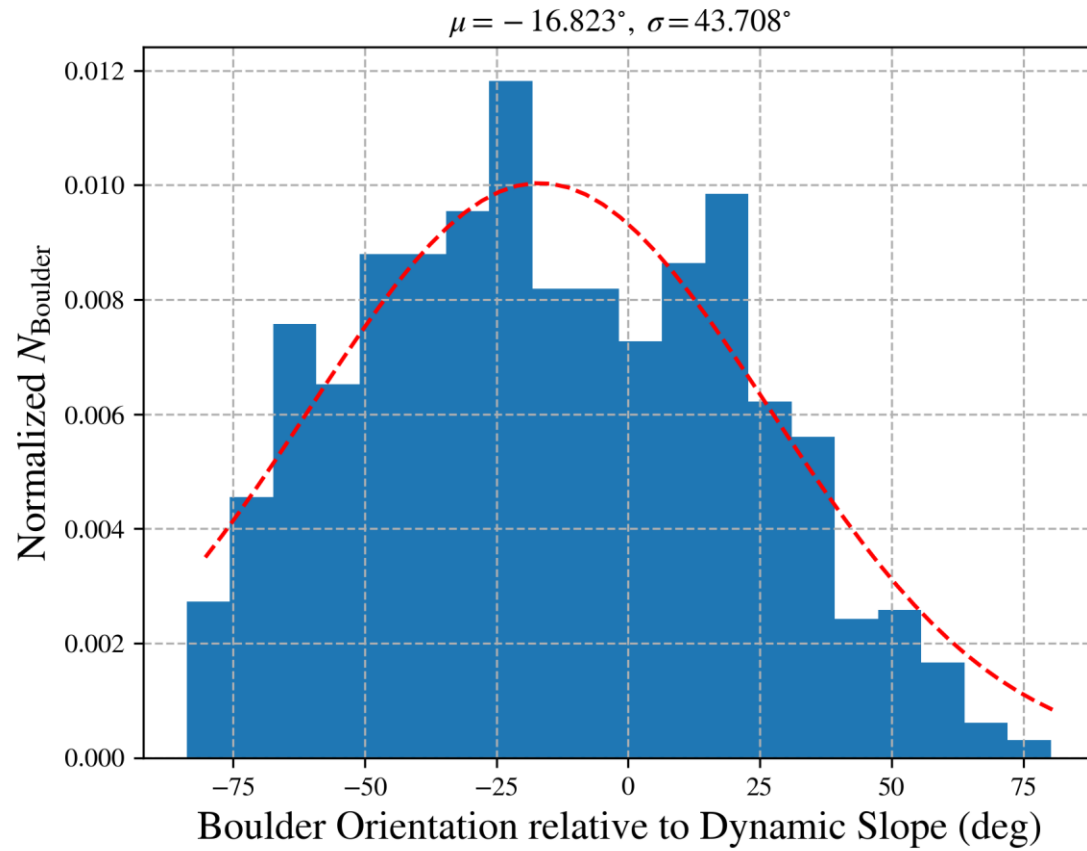




Extra Slides

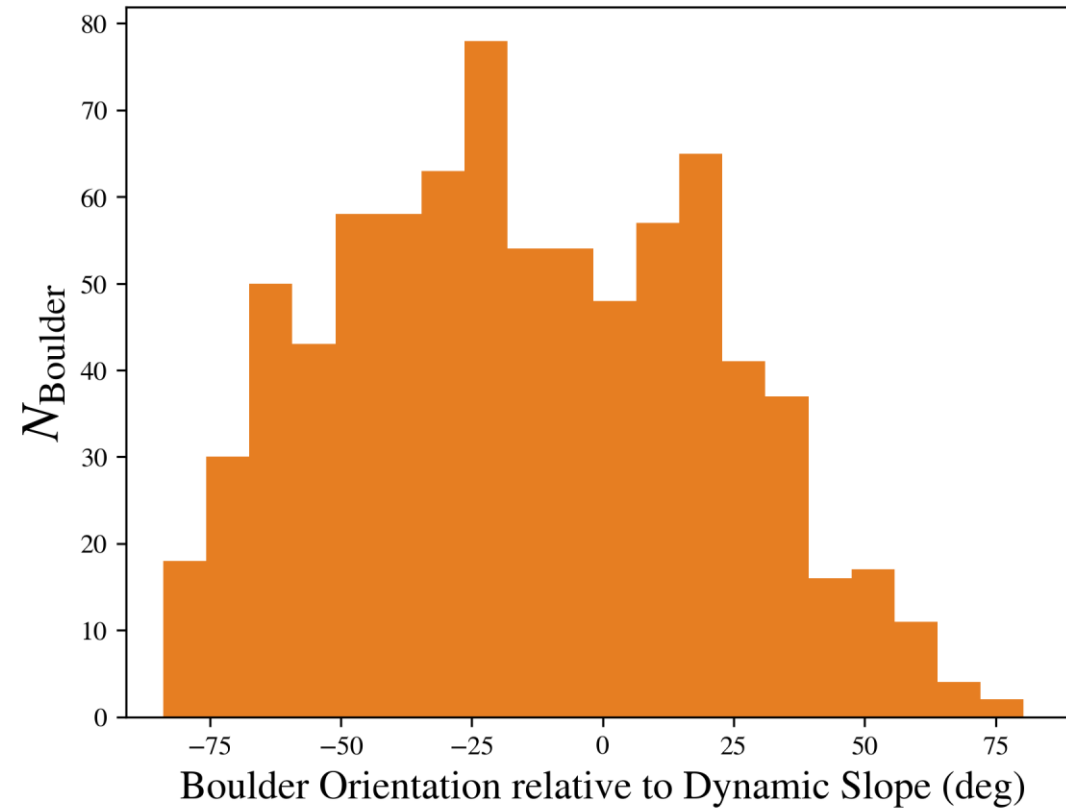


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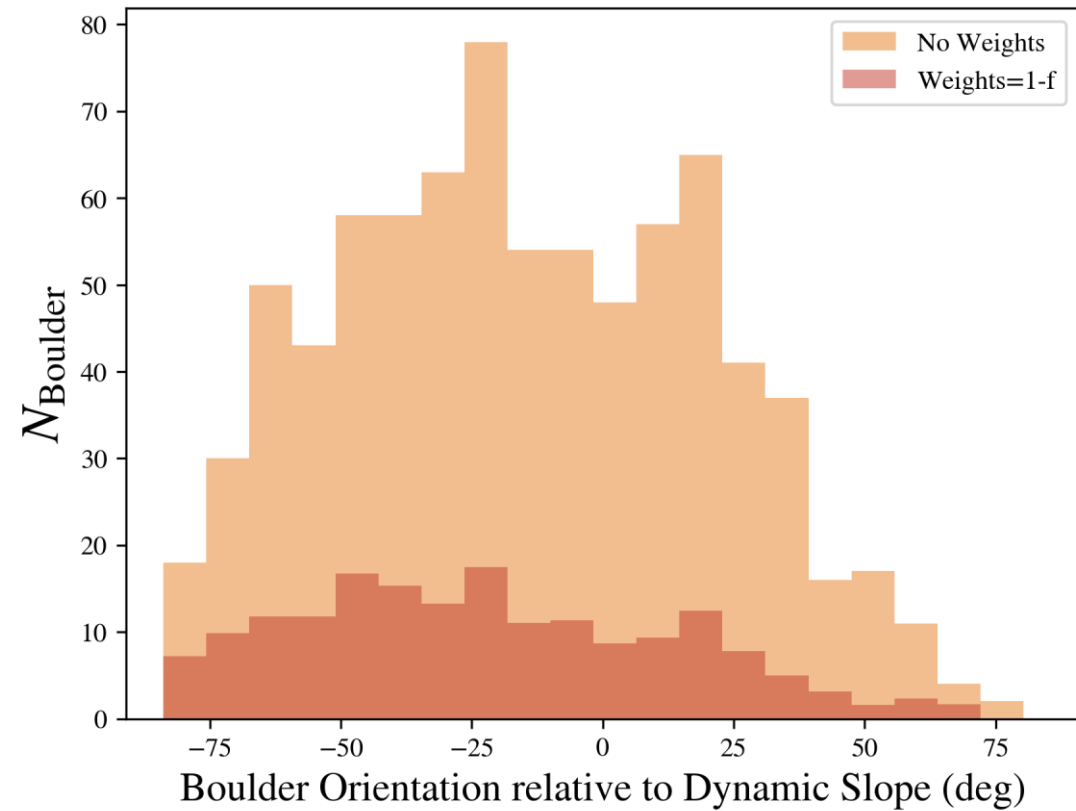


Polygon 3



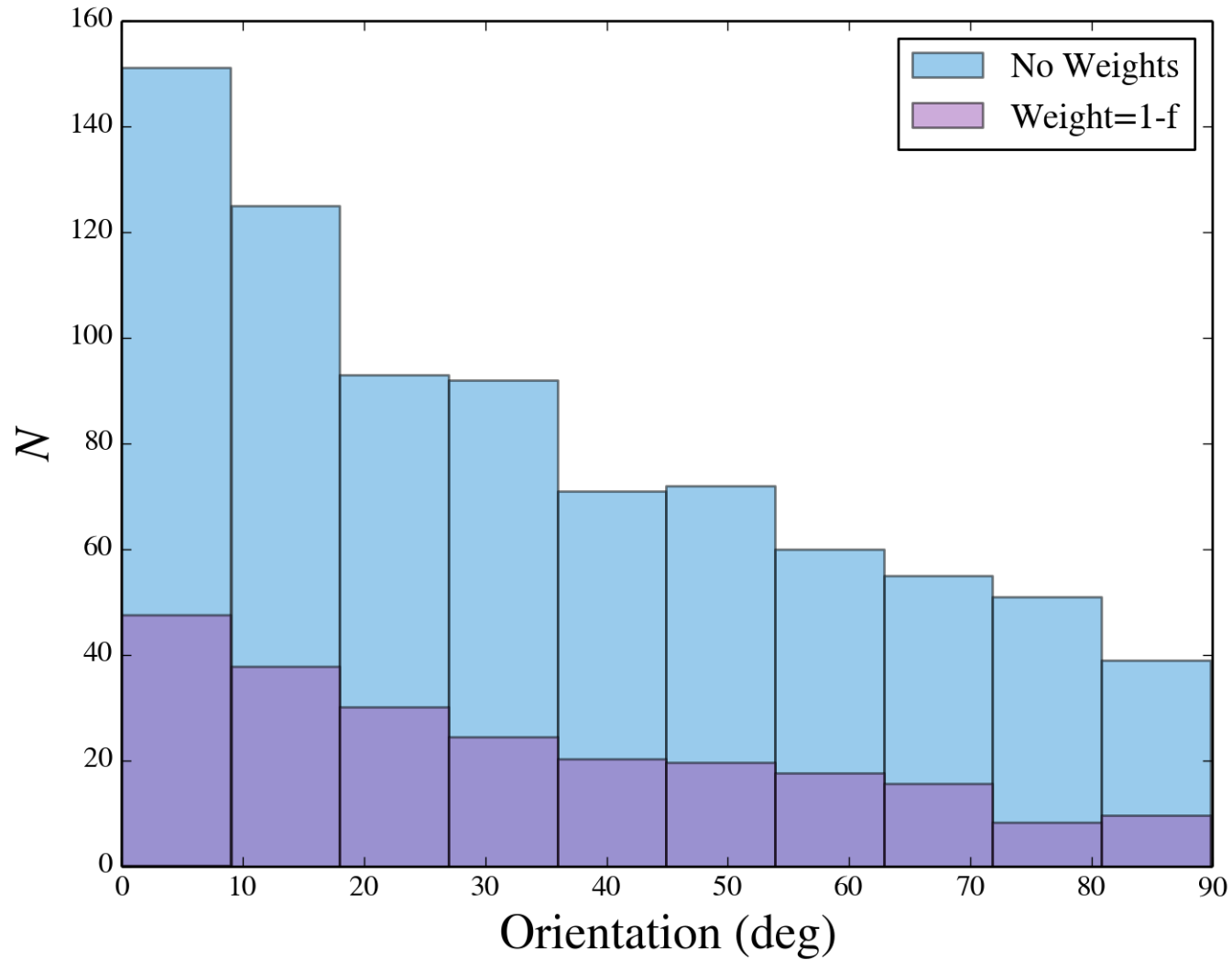


Polygon 3



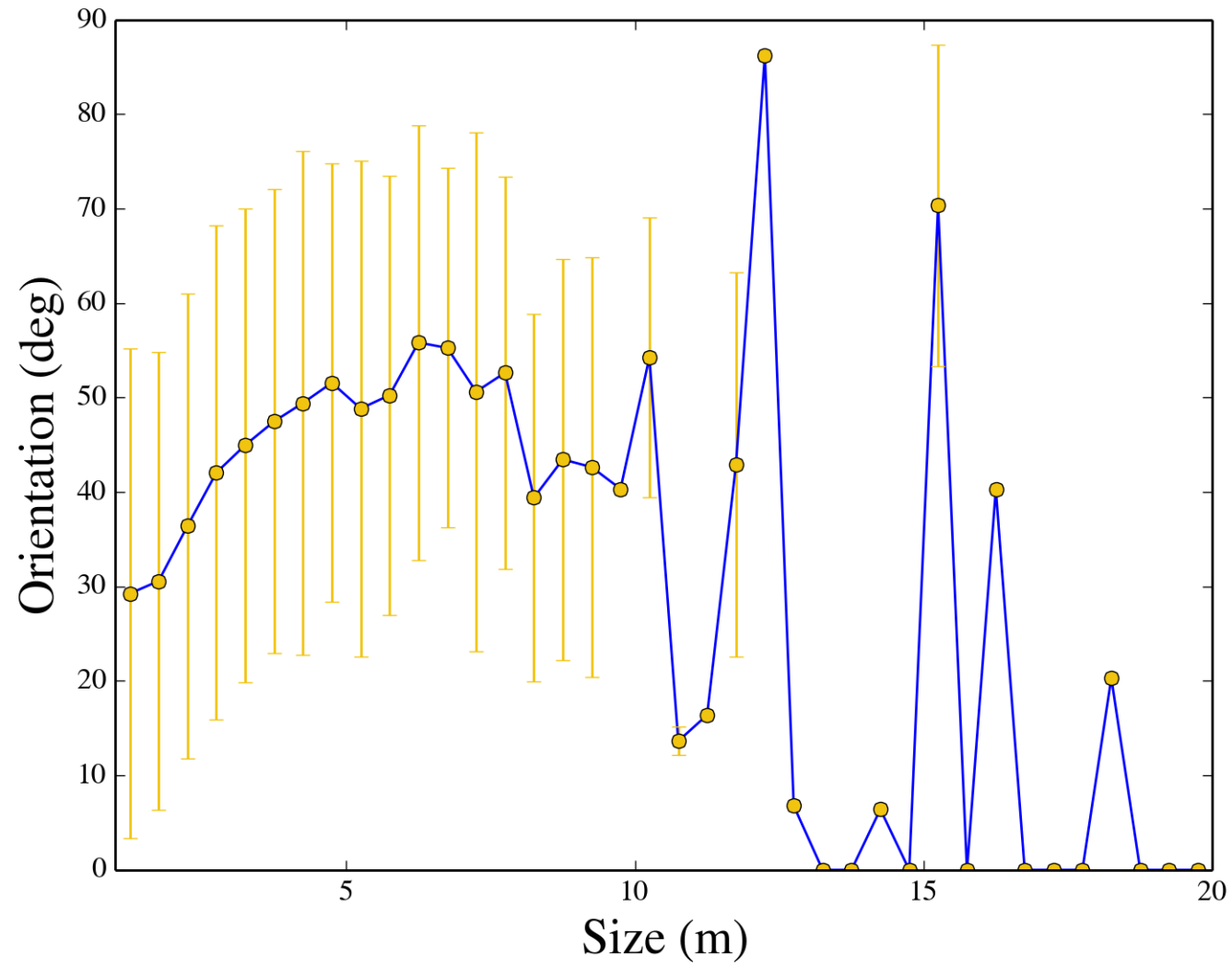


Extra Slides





Polygon 3





Extra Slides



Extra Slides



Suggestions of Mass Wasting

- Color uniformity (mixing?)
- Dearth of small craters <100m
- Diffuse crater rims
- Regolith could be >20m because 200m crater has 0.14-0.2 d/D
- Some wall slumping in circular depressions
- Momotaro crater exhibits concentrations in larger boulders on its floor

