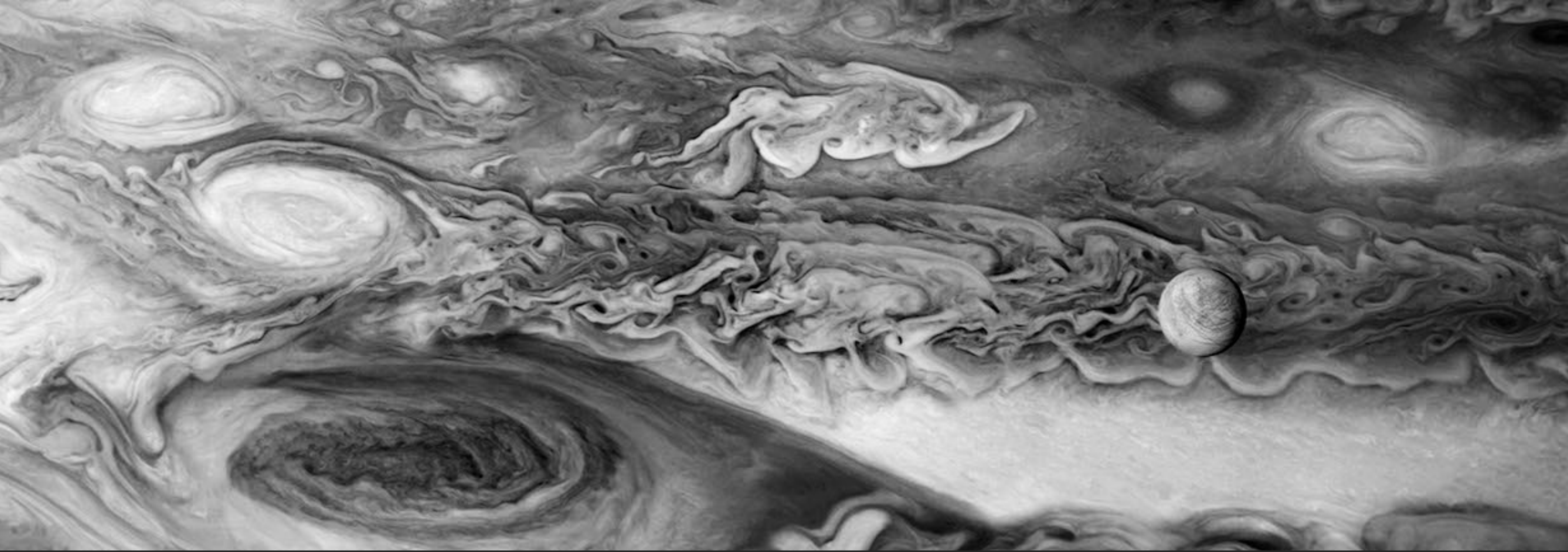

Cratering and Debris Scatter after Inadvertent Impact of Europa Clipper onto an Icy Body

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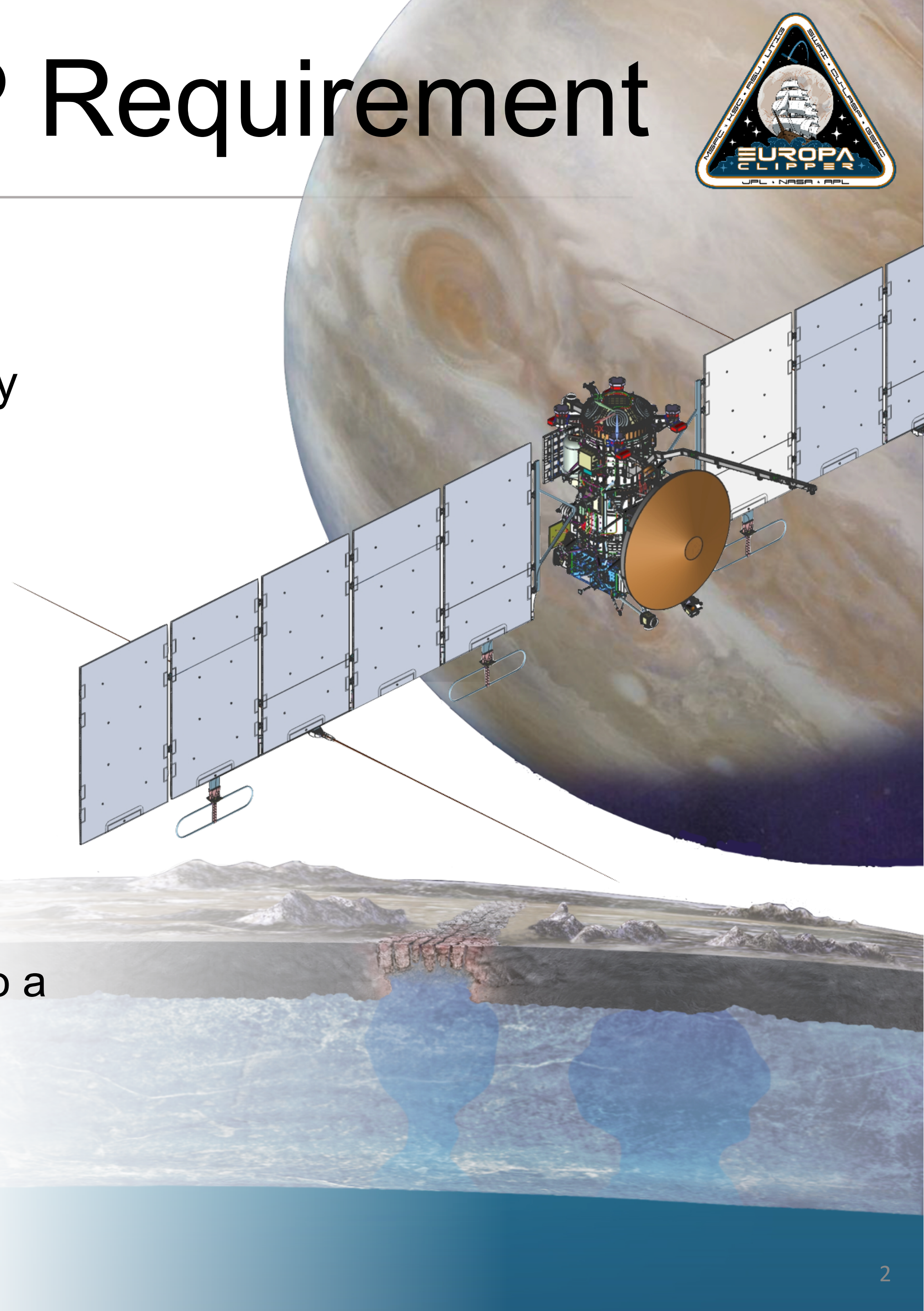
EUROPA CLIPPER

Background: Clipper PP Requirement

- Europa Clipper Planetary Protection: 10^-4 probability of introducing a single viable organism into the Europa ocean
- Very likely to reduce the number viable of organisms by many many orders of magnitude due to space environment and radiation around Jupiter
- Nearly 0 likelihood of sterilizing every organism on the entire spacecraft
- Therefore, must consider:
  - Probability of Clipper failure
  - Probability of Europa impact *given failure*
  - Probability of Clipper hardware being involved in a resurfacing event *given Europa impact*
  - Probability of Clipper hardware moving from near-subsurface to a liquid water environment *given resurfacing*
  - Probability of organism survival *given transport to ocean*
- Held successful workshop at JPL November 2018 to discuss modeling with PPO and a variety of experts



Context: Resurfacing Model 1

- Probability of Clipper hardware being involved in a resurfacing event *given impact*
  - After resurfacing, any surviving organisms are assumed to be shielded from radiation and we do not know enough about the ice or ocean chemistry (yet) to quantify any additional lethalities or determine if proliferation is possible

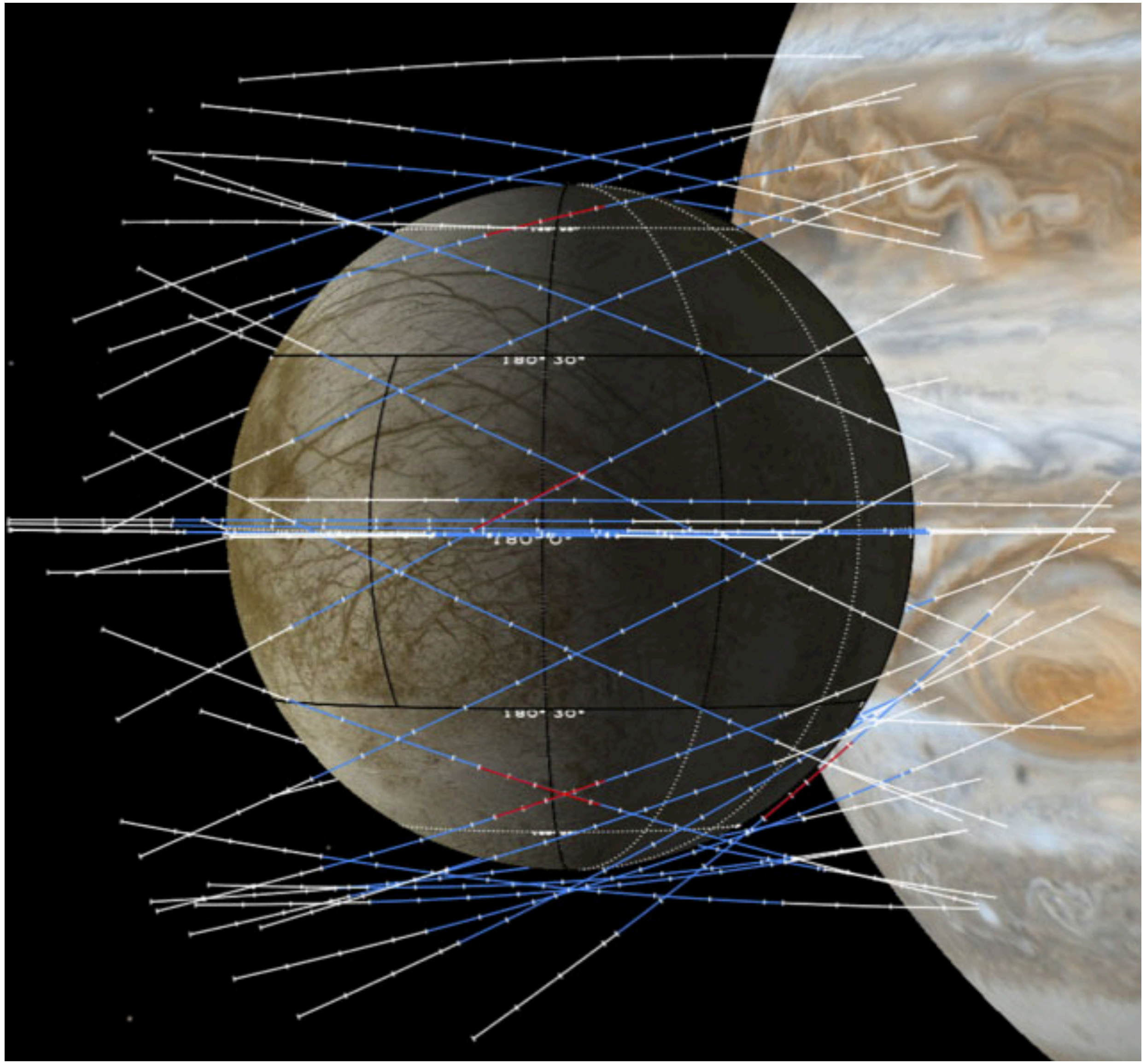
- With enough time, this probability approaches 1
  - The average surface age of Europa is approximately 65 million years old

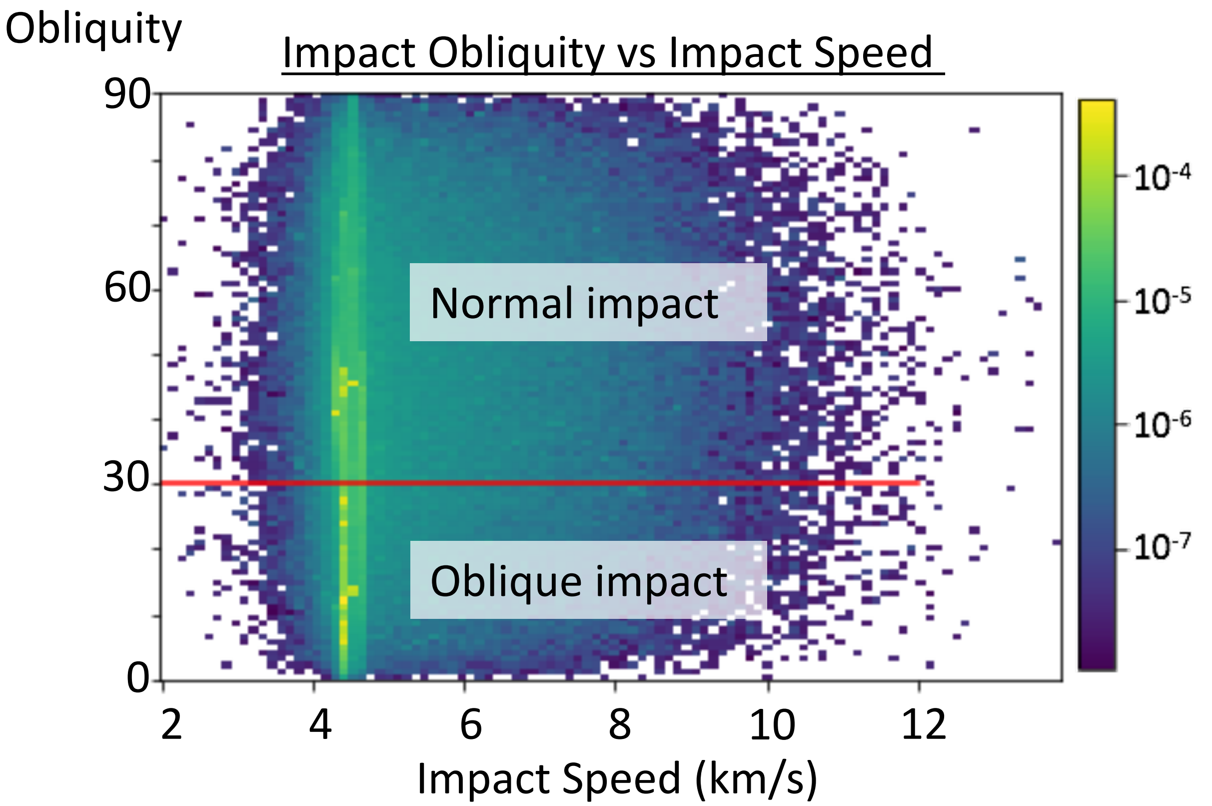
- Therefore, PPO agreed to limit period of concern for the requirement to 1000 years
  - 1000-year countdown to determine Europa habitability started in the year 2000

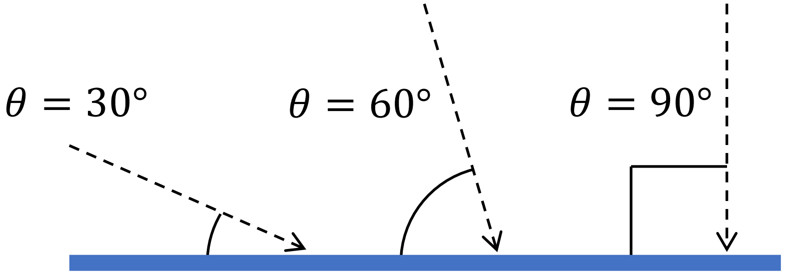
Context: Resurfacing Model 2

- Goal is to credibly and conservatively approximate and bound the likelihood of Clipper hardware being involved in a resurfacing event
- Assumptions:
  - The smallest resurfacing events will disrupt at least 1 km^2 of the surface
    - If larger, the probability of Clipper hardware resurfacing decreases => conservative
  - Resurfacing is equally likely over the entire surface of Europa
    - If resurfacing occurs only in select locations on the surface, probability decreases
  - Resurfacing is no more likely to occur adjacent to a recently resurfaced area (independence between pieces of the surface)
    - If correlation between pieces of the surface, probability decreases
  - Liquid water could exist anywhere below the surface and environment could be habitable immediately after resurfacing
    - Very conservative, avoids assumptions about unknown subsurface
- Parameter to quantify: In how many 1 km^2 portions of the Europa surface could Clipper hardware reside after an inadvertent impact?

Trajectory Considerations For Impact





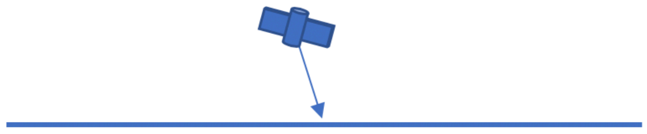


Resurfacing Model: Impact Considerations

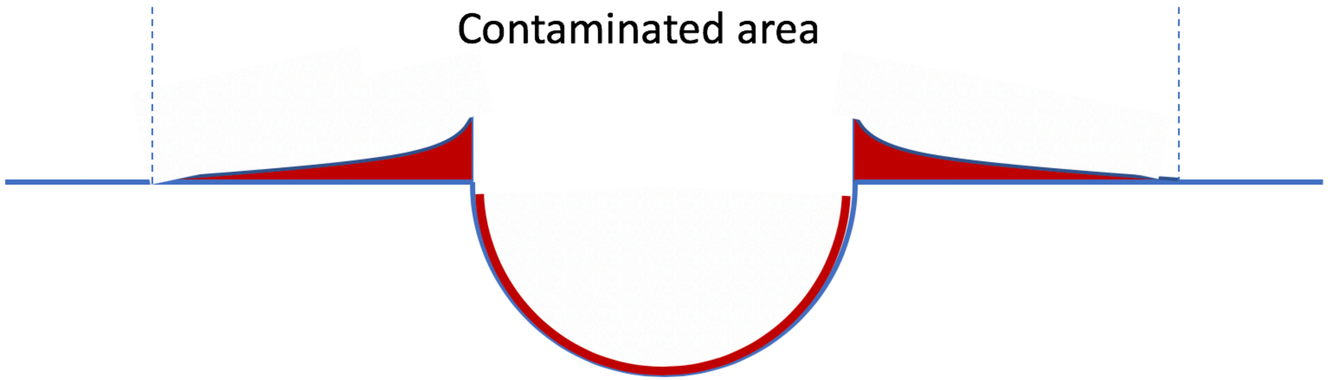
Assumptions about **non-oblique** impacts (> threshold between 15° and 30°)

- Spacecraft digs into the ice, all major spacecraft parts remain within the crater
- Ejecta that may have significantly mixed with the spacecraft will land ~1 crater radius from the crater rim based on evidence of craters on icy bodies
  - Any smaller particulates that travel farther will likely only interact with the exterior of the spacecraft that is sterile due to radiation during cruise, and then provide no shielding and be guaranteed to sterilize before resurfacing mechanisms are likely to occur
- **Small number of 1 km^2 pieces of Europa surface will be contaminated: < 5**

Initial impact



< 100m crater



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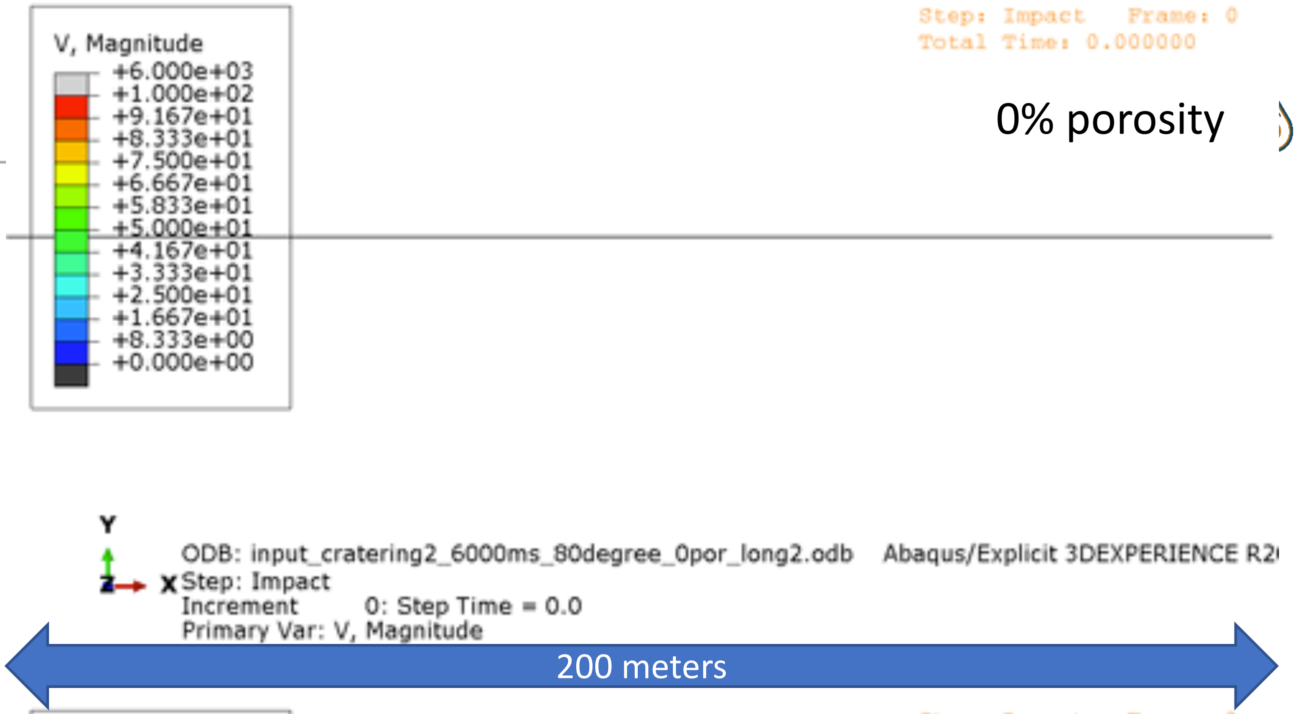
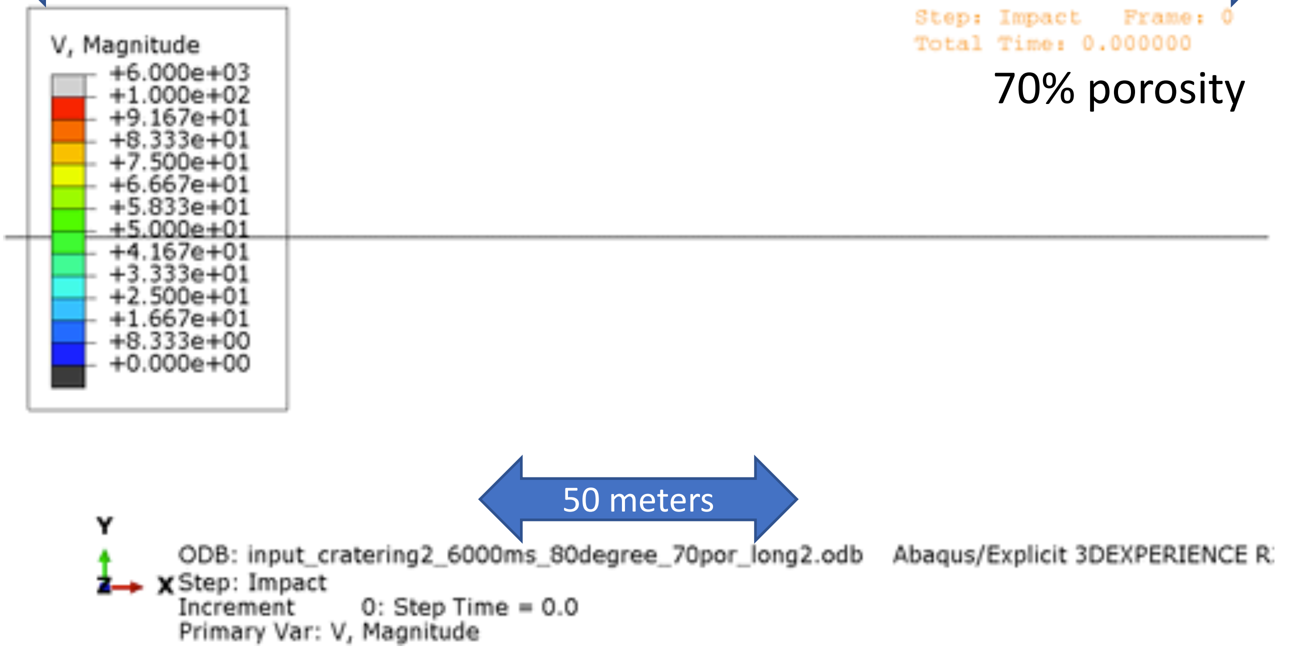
Normal Impact Cratering

- ABAQUS simulations and empirical scaling laws used to estimate crater size
- ABAQUS shows approximately hemispherical crater of **less than 50 m diameter for large range of porosities for nearly normal impacts at 6000 m/s and less**
- Gault's scaling laws (Gault 1978):
  - For "loose soil or regolith", 6000 m/s impact results in 46 m diameter crater

- Applying 100% margin to simulated and predicted crater size and assuming all craters are 100 m diameter

- Significant fragments provide 5 cm (CBE) of aluminum radiation shielding, but remain in crater
- Ejecta that is mixed with spacecraft material remains within 1 crater radius from crater rim
- Small, fast particulate ejected early in impact, unlikely to interact with spacecraft fragments, but particles will be too small to provide radiation shielding anyway





Resurfacing Model: Impact Considerations

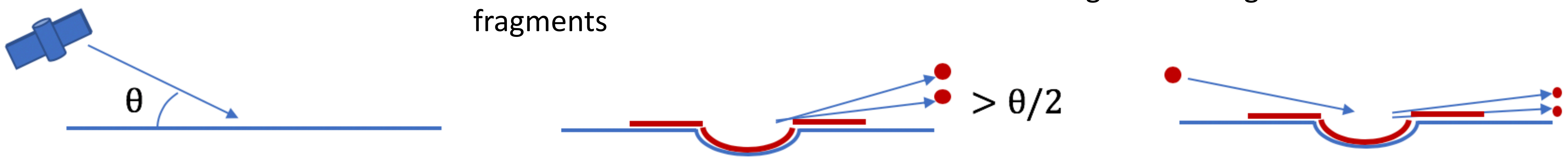
Assumptions about **oblique** impacts (< threshold between 15° and 30°)

- Below extreme velocities, spacecraft will fail in shear => worst case scenario results in large ricocheting fragments
- Bouncing spacecraft fragments will have unknown ejection velocity and typically less than half the initial obliquity (escape precluded though certainly possible)
  - Any small, fast particulates again can not carry particles capable of providing radiation shielding
  - After at most a few bounces, surface topography will restrict further distribution of fragments into new pieces of Europa (skidding or stopping on cliff/hill)
- **Larger number of pieces of Europa surface will be contaminated, number of pieces a function of number of expected spacecraft fragments after bouncing impacts: > 1600**

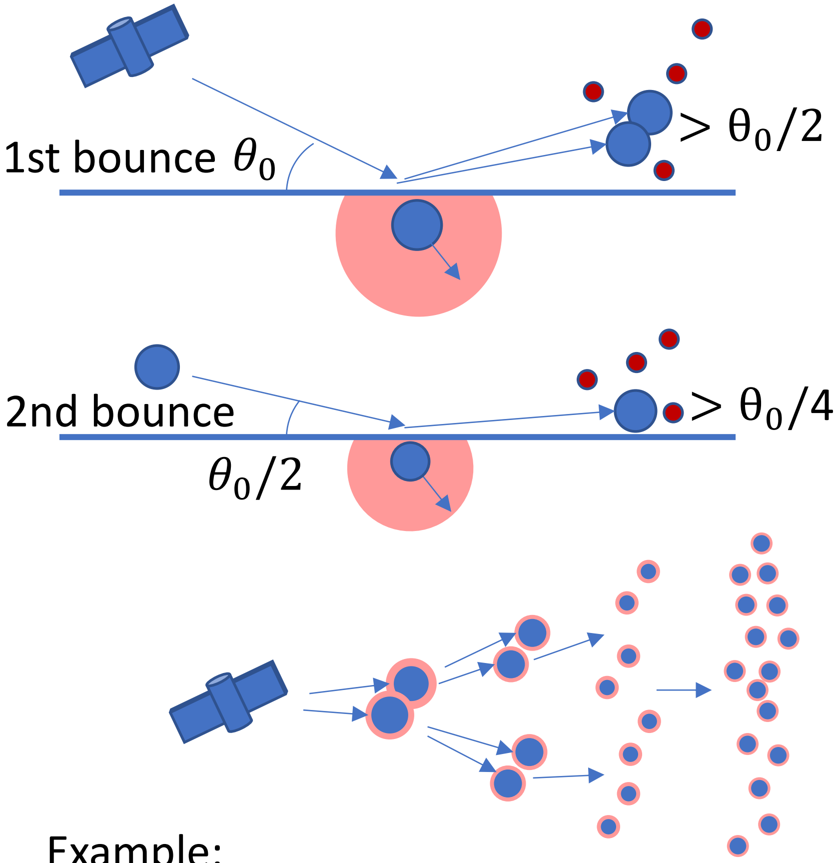
Initial impact

First crater, Downrange fragments

Successive bounces of significant fragments



Bouncing Model for Oblique Impacts



Example:

Bounce #	1st	2nd	3rd
New bouncers	2	4	8
Total bouncers	3	7	15
Total pieces	324	756	1620

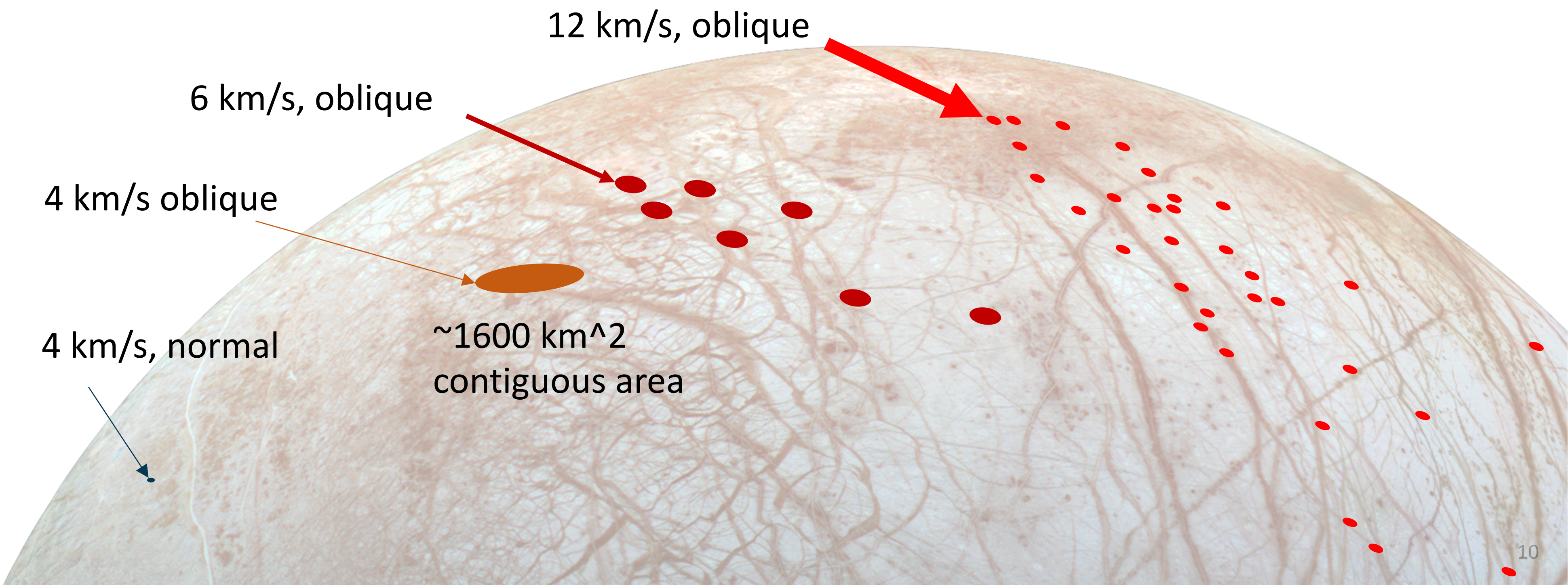
- First bounce creates crater less than 100 m diameter with significant ejecta contaminating at most the same number of pieces contaminated per normal impact (Melosh 1989, Stewart 2010)
- Decapitated impactor creates ~10 significant fragments large enough to escape the ejecta cloud and travel ballistically with high velocity (Gault 1978, simulations)
  - Each of those fragments also creates a crater less than 100 m diameter with that ejecta again contaminating a certain number of pieces of Europa surface
- One or two large fragments may be large enough to undergo the same process again as seen in ABAQUS hydrocode simulations, relevant experiments, and secondary crater formation in meteor/spacecraft impact event (may also escape Europa, but assumed to all stay and remain contamination risk)
  - These fragments bounce again, again generating ~10 smaller fragments with 1 or 2 capable of rebouncing. [Assumed none maintain escape velocity (2050 m/s) after initial impact]
- Angle is less than half with each successive impact of large pieces capable of continuing to bounce (Shultz 1982, Gault 1978)
- Pieces impacting with obliquity of a few degrees will be prevented from continuing to bounce by the characteristic roughness of the surface of Europa
  - Only expect ejected fragments when obliquity is *at most* 30 degrees => can only be cut in half 4 times before ejected angle is less than 4 degrees, then contained by surface topography (Schenk 2009)

$$Total\ pieces = (pieces\_per\_frag)(1 + small\_frag) \sum_{i=0}^{N\_bounces} large\_frag^{i}$$

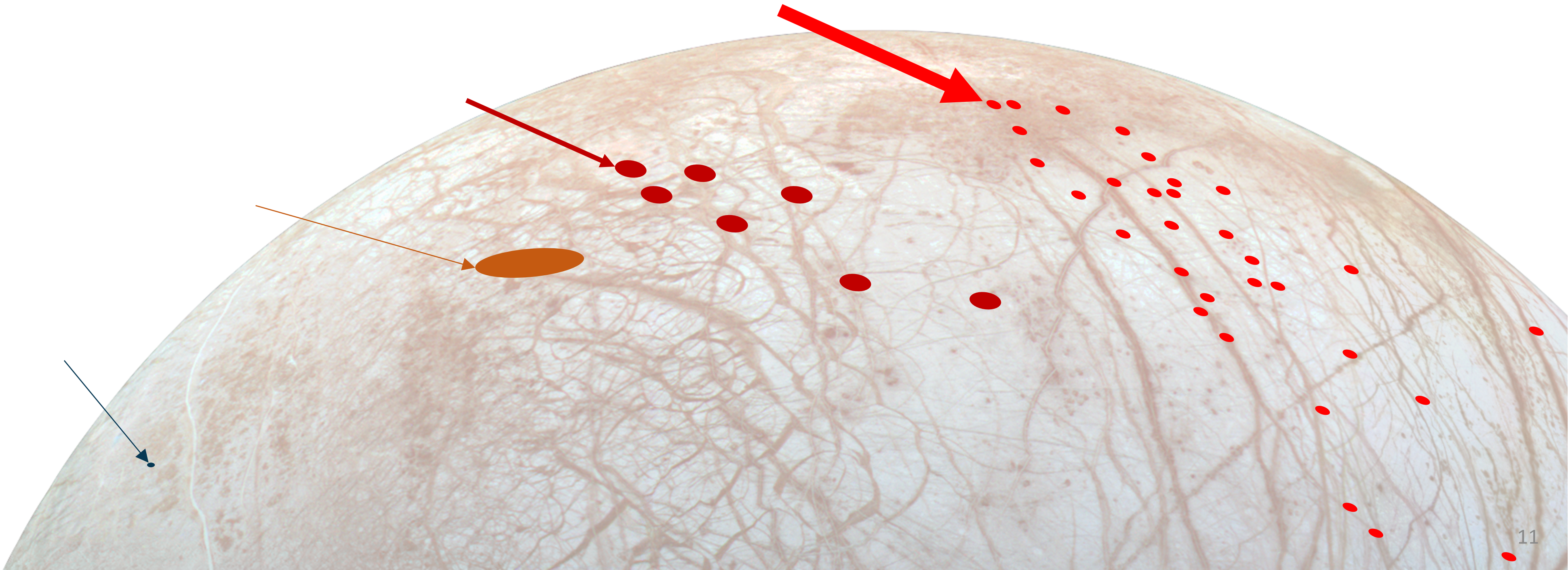
Results: Resurfacing Model

- Goal was to make as few assumptions about hypervelocity impacts of complex assemblies into unknowns icy surfaces as possible
- Demonstrated that even with conservative assumptions about the number of significant fragments formed and the extremely conservative assumption that each fragment permanently remains in its own 1 km^2 area of Europa that is maximally likely to resurface given the average surface age, Europa Clipper can meet the planetary protection requirement

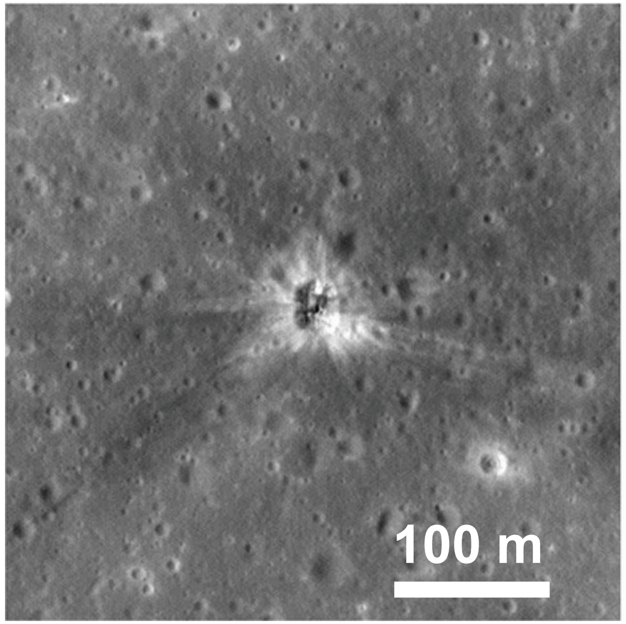
- Low probability of failure (~5%)
- Low probability of impact given failure (< 20%)
- High probability unable to 100% sterilize hardware before an impact (> 90%)
- Low probability of non-sterile Clipper hardware residing in a region that resurfaces in the next 1000 years (< 1%)
- **< 10^-4 probability of contamination**

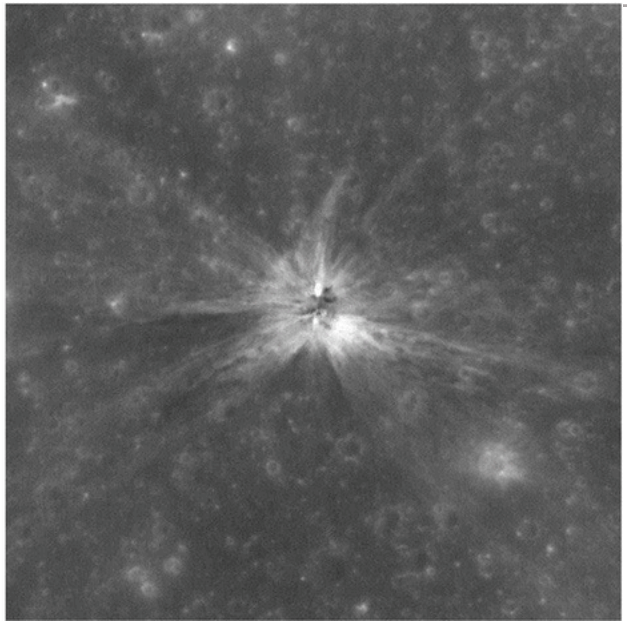


Supporting material and backup depending on presentation time



Expectations for Impact Debris Field

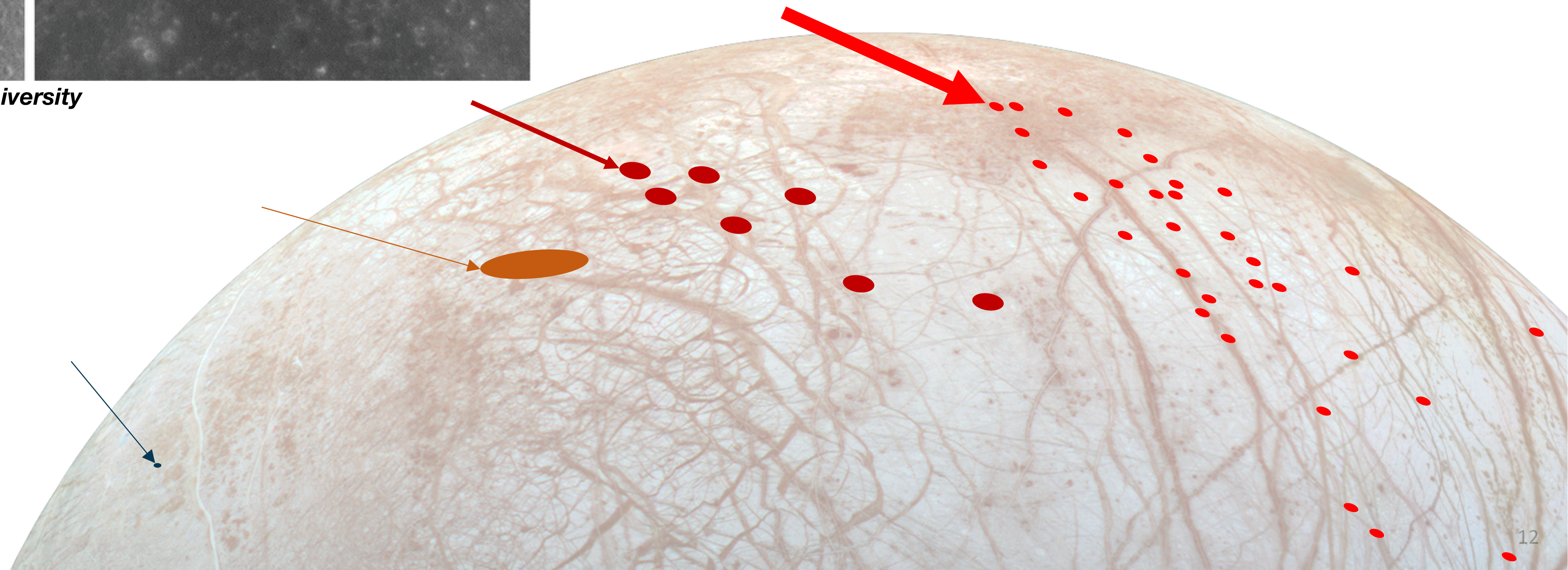




Credits: NASA/Goddard/Arizona State University

Lunar impacts by Apollo missions' upper stages (11 tons):
~1.8 km/s, normal [comparable KE to 3.2 km/s Clipper impact]

- 20 m crater
- Ejecta about 500 m across, circular w/ bands (~0.75 km^2)



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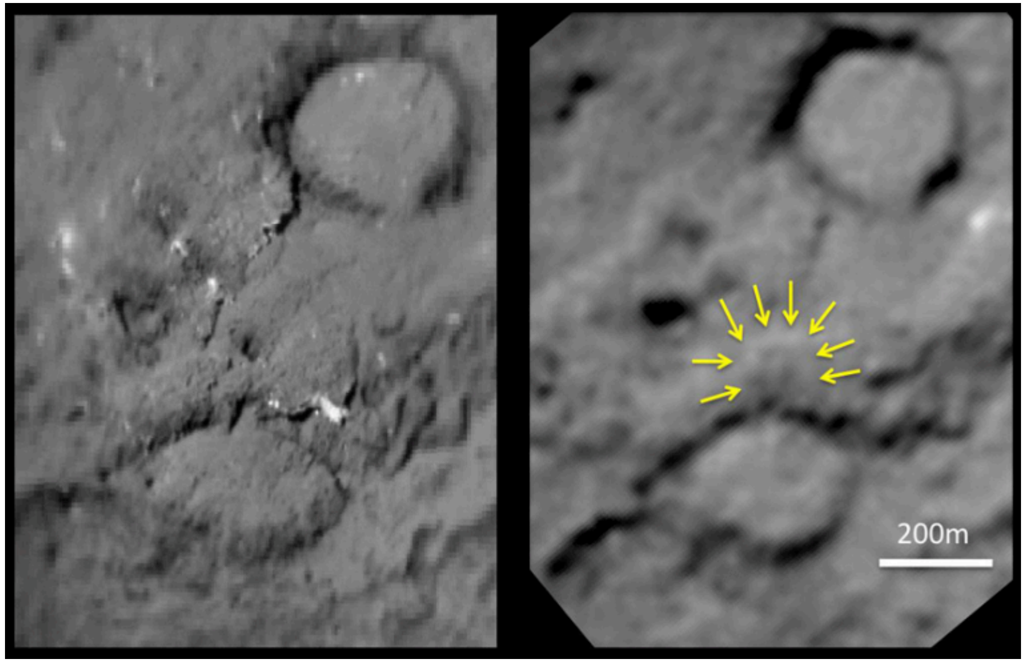
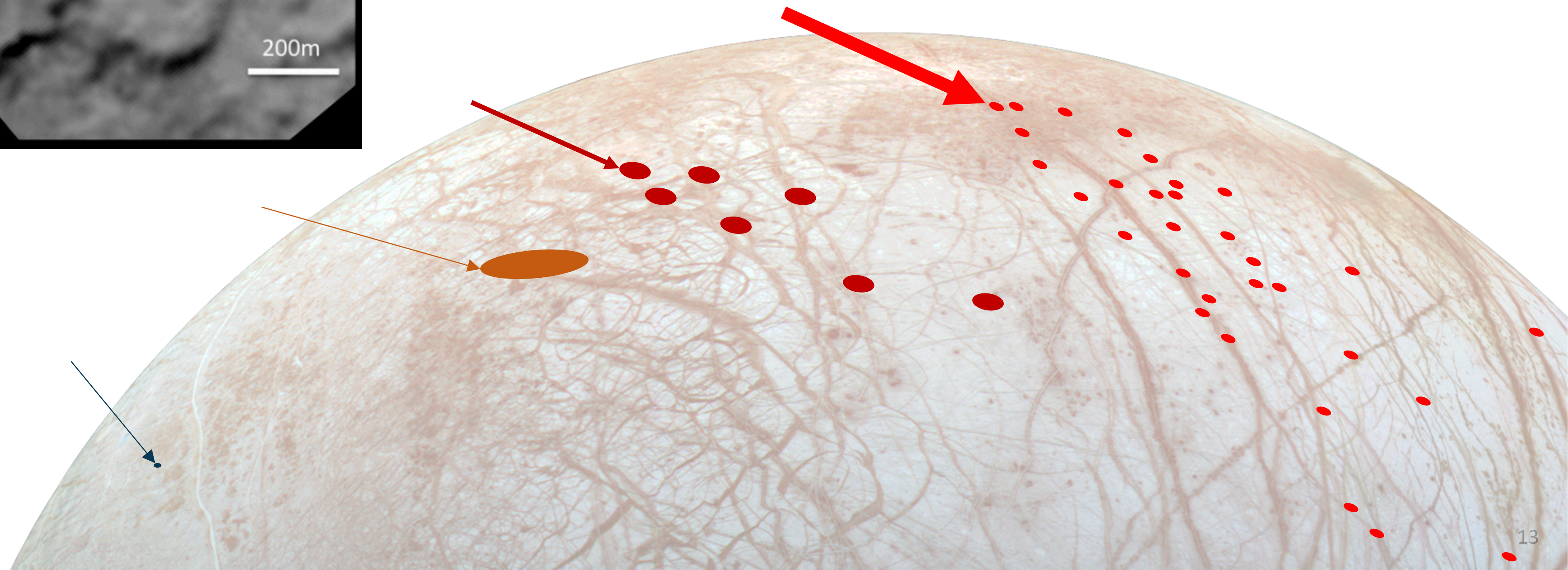


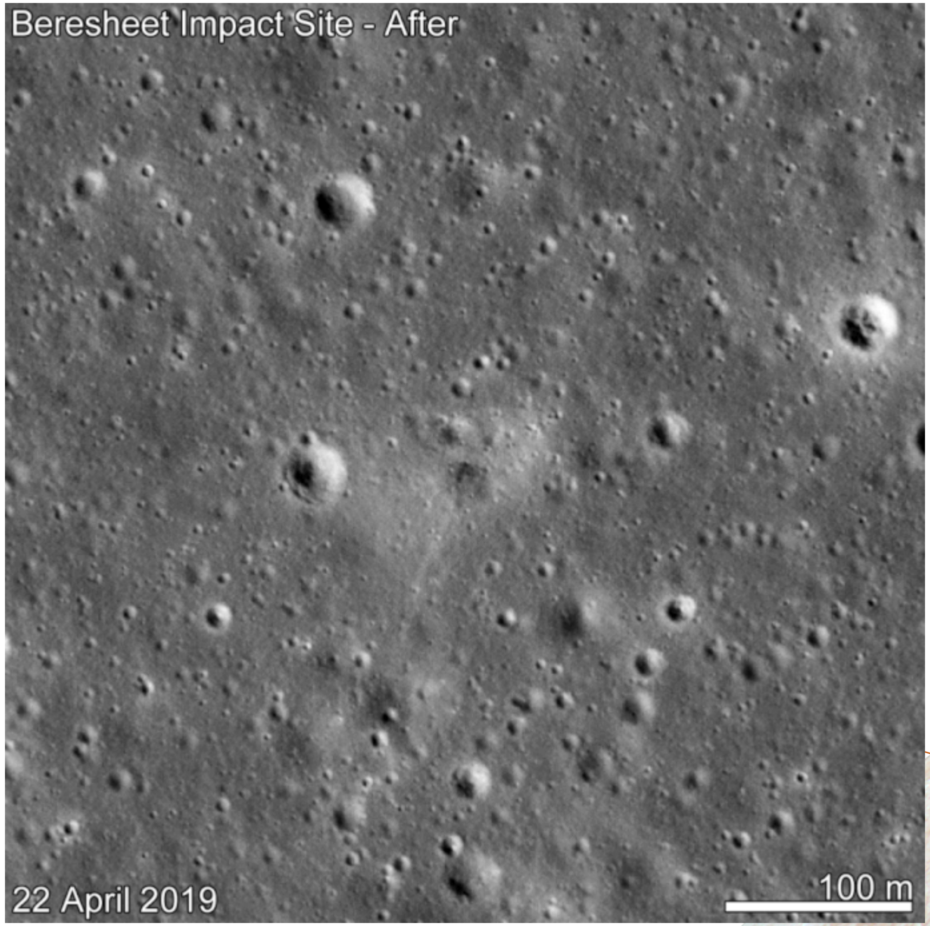
Credits: NASA/Caltech/JPL

JPL Deep Impact mission into Comet Tempel 1 (380 kg impactor):
10.3 km/s, normal impact [comparable KE to 3.5 km/s Clipper impact]

- 150 m crater
- Significantly more porous than expected (> 75%)
- Vaporized gas/dust ejected with significant velocity (well above escape)



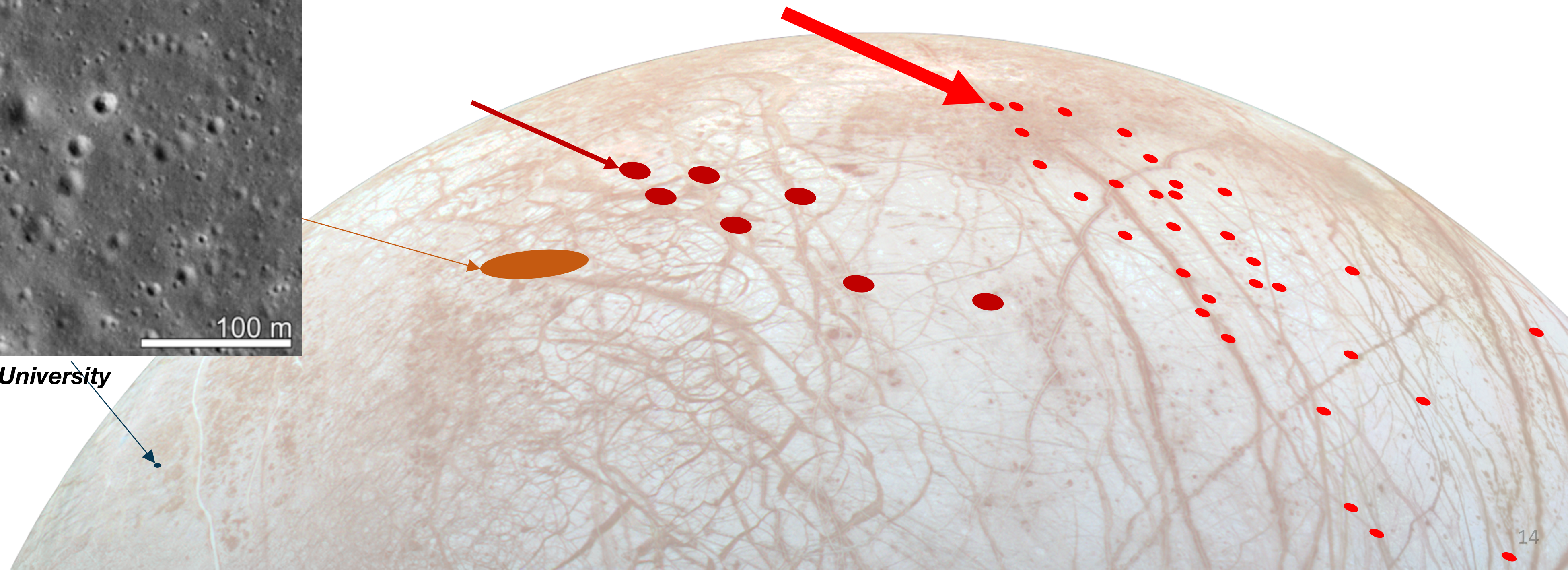
Expectations for Impact Debris Field



Credits: NASA/Goddard/Arizona State University

Recent lunar impact by Beresheet lander (250 kg):
~1 km/s, very shallow ~8°

- No significant crater
- Spacecraft debris about 10 m across
- Ejecta about 100 m, eccentric (~0.03 km^2)



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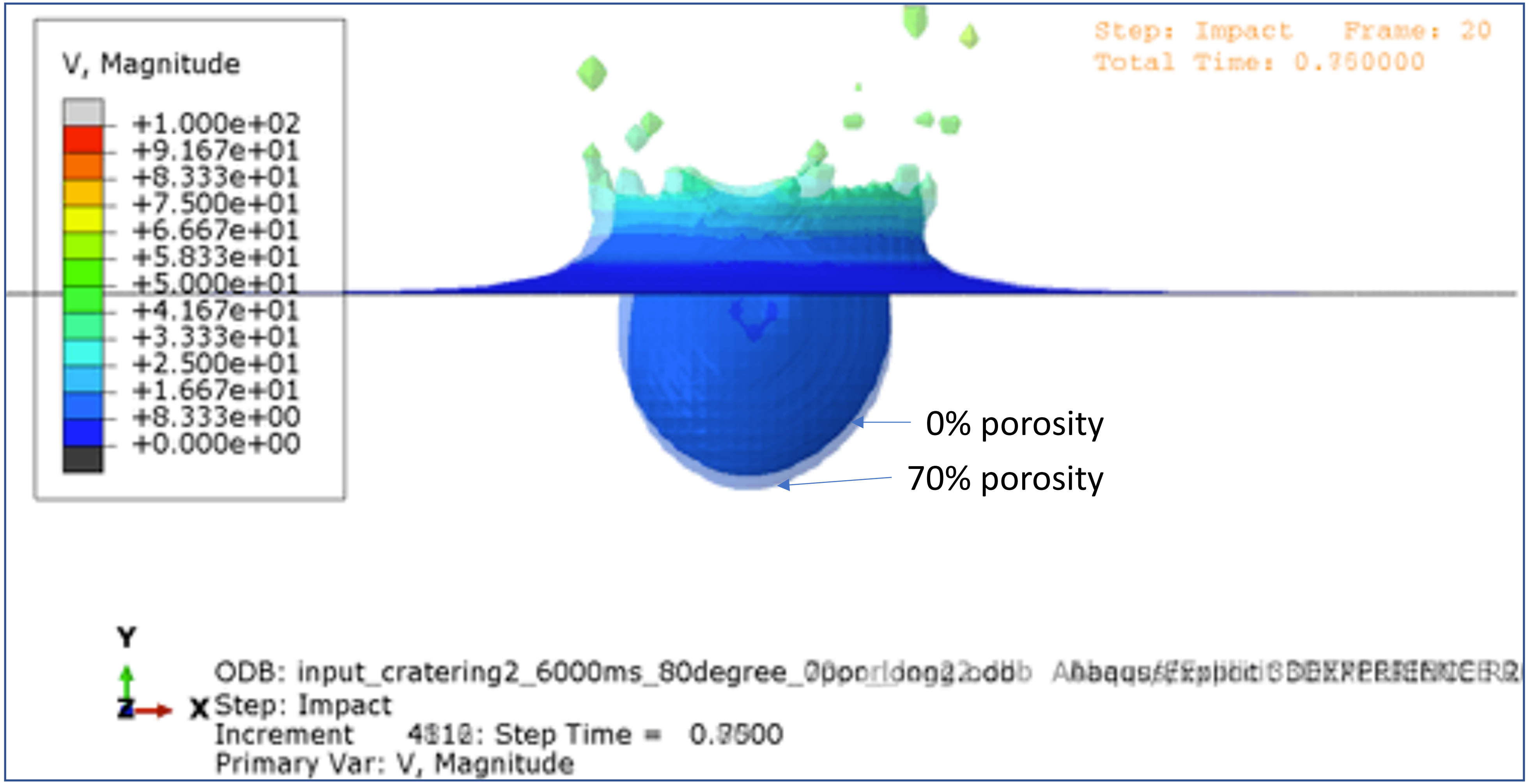
Porosity and Cratering

Overlay of cratering sim results for 0% and 70% porous ice

After initial penetration of the ice, ABAQUS suggests that the **crater is relatively similar regardless of porosity**

Scaling laws suggest some dependence on porosity leading to ~30% larger crater, but simulation shows quick compaction given the speeds and relative densities



Relevant Oblique Hypervelocity Experiments

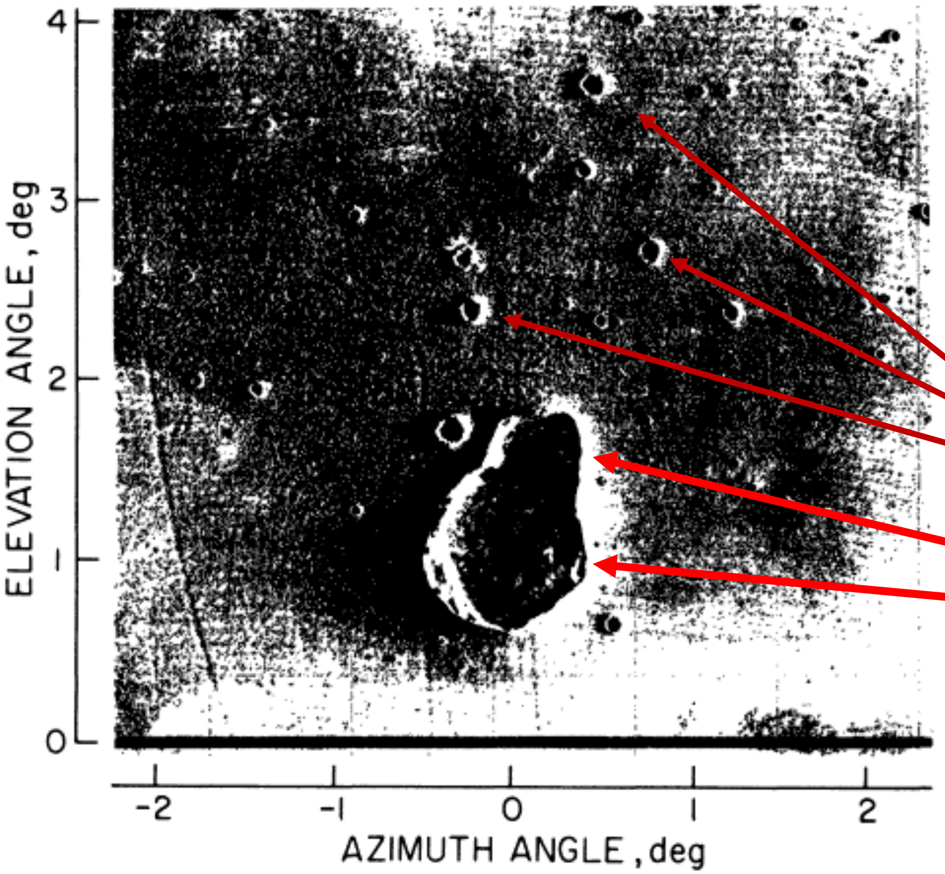
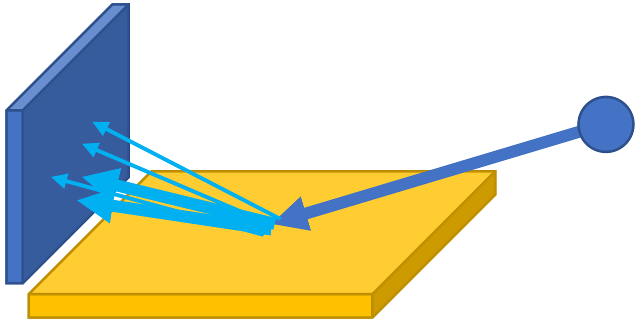


Fig. 20. Aluminum witness plate record for an aluminum sphere into non-cohesive quartz sand at 6.5 km/sec, θ = 4.75°. Projectile fragmented into two main pieces and numerous fine particles. 1° in azimuth = 2.7 cm.

Witness plate, shown in photo



Small fragments

One or two large projectile fragments

- 6.5 km/s impact of aluminum onto unconsolidated sand at 5 degree obliquity
- One or two large fragments at less than half the initial obliquity with enough mass to bounce again
- A handful of small particles, less than 10

Title: Experimental studies of oblique impact. **Authors:** Gault, D. E. & Wedekind, J. A.
Journal: In: Lunar and Planetary Science Conference, 9th, Houston, Tex., March 13-17, 1978, Proceedings. Volume 3. (A79-39253 16-91) New York, Pergamon Press, Inc., 1978, p. 3843-3875.

Experimental results provides velocity regimes, estimate for numbers of fragments when aluminum projectile fails in shear, ejection angle is less than half initial angle

Relevant Oblique Hypervelocity Experiments

- 4.4 km/s impact of aluminum onto pumice at 30 degree obliquity (in argon atmosphere)
- Fragments *from the projectile* come off at around 10 degrees (ionizing some of the atmosphere in the experiment)
- Most of the ejecta *from the target material* comes off at higher angles (close to the initial 30 degrees) at slower velocities than the initial ricocheting impactor material. Tiny fragments entrained in ejecta can't provide radiation shielding

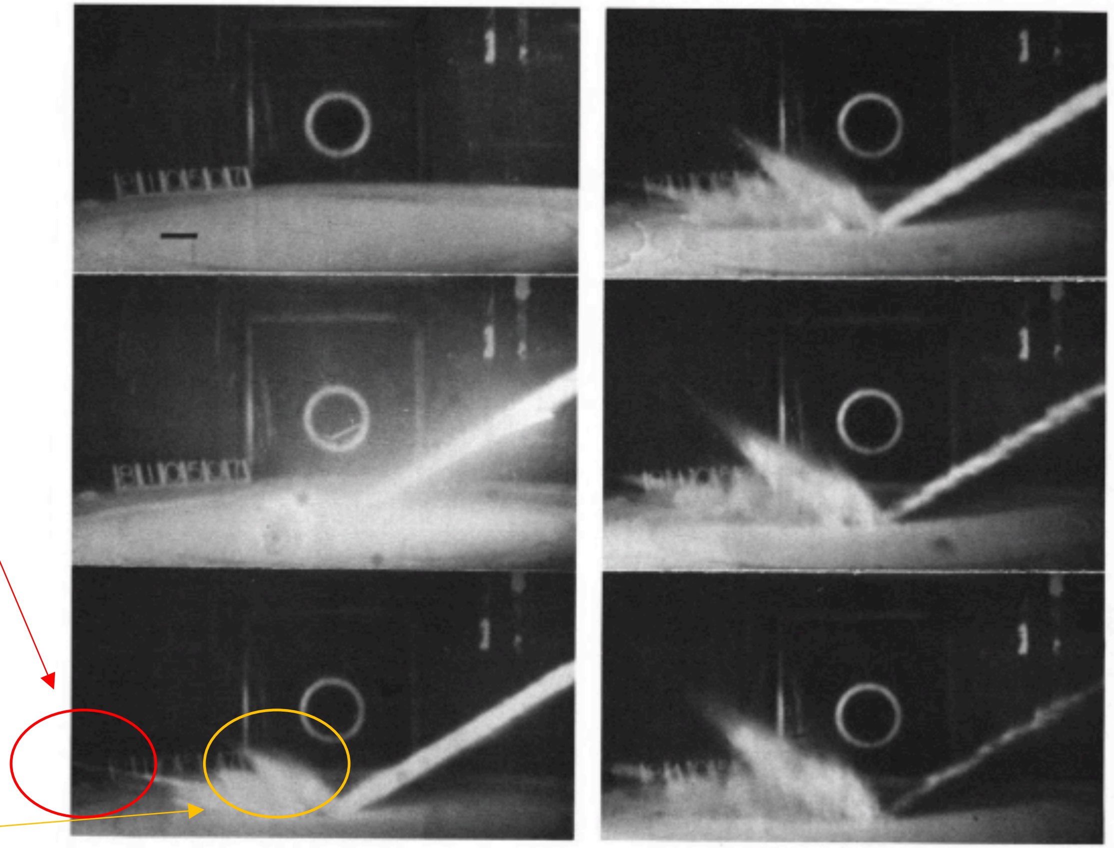


Figure 2. Oblique impact of 4.4 km/s aluminum projectile (0.635 cm; 0.375 g) at 30° from the horizontal into pumice with an argon atmosphere at 720 mm of mercury (0.2-ms time interval). High-speed ricochet of the projectile fragments is recorded by the downrange ionized wake at a low angle (10°) to the surface. The downrange wake is briefly trailed by a debris cloud, but the major component of high-speed target material is ejected at angles comparable to the angle of impact. Bar scale represents 5 cm.

Peter Schultz and Donald Gault. "Impact ejecta dynamics in an atmosphere: Experimental results and extrapolations". Geological Society of America, Special Paper 190, 1982

Shows ejection angle less than half initial angle, differences between ejected fragments and ejecta from the target material

Citations

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- Schenk, P.M.; *Slope characteristics of Europa: Constraints for landers and radar Sounding.* Geophysical Research Letters. Volume 36, Issue 15. 16 August 2009.

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