Probing the Effects of Shallow Low Viscosity Layers on Crater Formation

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Introduction:

- Europa is an icy satellite of Jupiter with a subsurface ocean [1]
  - Europa's icy shell may contain tunnel networks, consisting of liquid water pockets or low viscosity layers (LVLs) [2-3]
  - The structure of these systems have ramifications for future missions and for the potential of extraterrestrial life
- Bolides have already mechanically probed the surface of Europa and may reveal information about what lies beneath the ice (Fig 1) [2,4]
  - Prior research has been done to examine the formation of impact craters on rocky surfaces
  - How do these processes differ on non homogenous icy surfaces?

Methods:

- Our goal is to identify morphological characteristics diagnostic of LVLs embedded within ice shells
  - We are using impact craters as a proxy to determine the mechanical properties of the ice shells
- We used iSALE, a shock physics hydrocode software
  - Gridsize=31 m, surface temp=100 K, incident angle=90°, ice impactor diameter=0.5 km, impactor velocity= 15 km/s
- We varied the depth of the LVL embedded in the ice shell and the viscosity of the LVL (Table 1) (Fig 2)

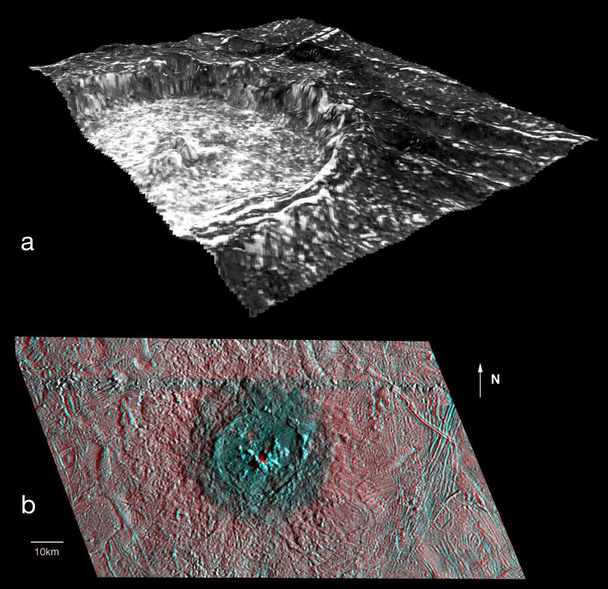
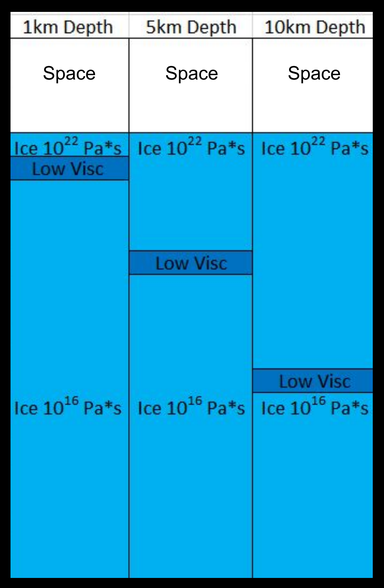


Figure 1 (above): Two craters on Europa. (a) 3D model of Cilix Crater. Image courtesy of NASA: PIA17851. (b) A red-blue 3D representation of Pwyll Crater. Image courtesy of NASA: PIA01665

Table 1 (below): Table listing the levels of each parameter we changed.

Parameter	Levels
Depth of Low Viscosity Layer (km)	1, 5, 10
Viscosity of Low Viscosity Layer (Pa*s)	0, 10^{14}, 10^{15}, 10^{16}



- We ran 12 simulations at 3 different depths and 4 viscosities (Table 1)
- From these simulations, we examined the crater radius and depth over time
  - Specifically, we analyzed the effects of the viscosity and depth of the LVLs on these values

Figure 2 (left): Diagrams of the model space. The ice above the LVL has a viscosity of 10^{22} Pa*s. The LVL's viscosity varies as in the table above, with 0 Pa*s being liquid water. This 1km thick layer was embedded in the ice at the depths listed in Table 1. The ice below the LVL has a viscosity of 10^{16} Pa*s.

References: [1] Pappalardo et al., (1999) JGR Planets 104, 24,015-24,055. [2] Turtle E.P. and Pierazzo E., (2001) Science 294, 1326-1328. [3] Schmidt et al., (2011) Nature 479, 502-505. [4] Carr et al., (1998) Nature 391, 363-365.
Acknowledgements: We gratefully acknowledge the developers of iSALE-2D, including Gareth Collins, Kai Wünnemann, Dirk Elbeshausen, Tom Davison, Boris Ivanov and Jay Melosh.

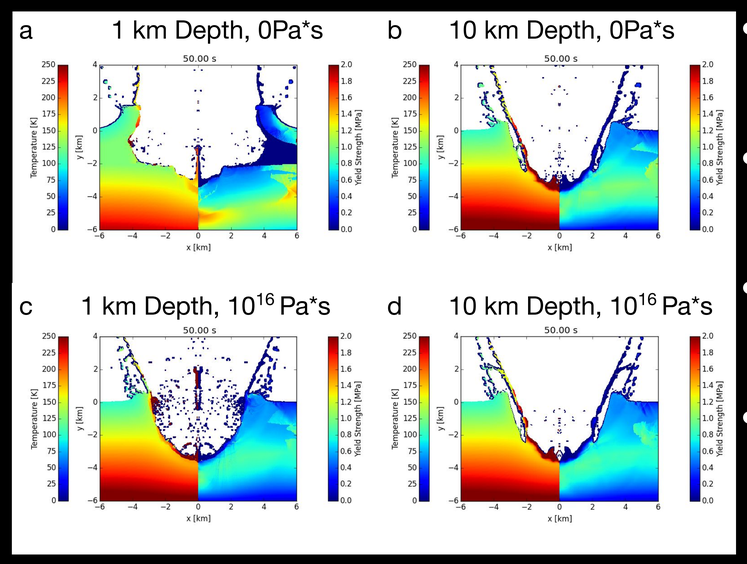
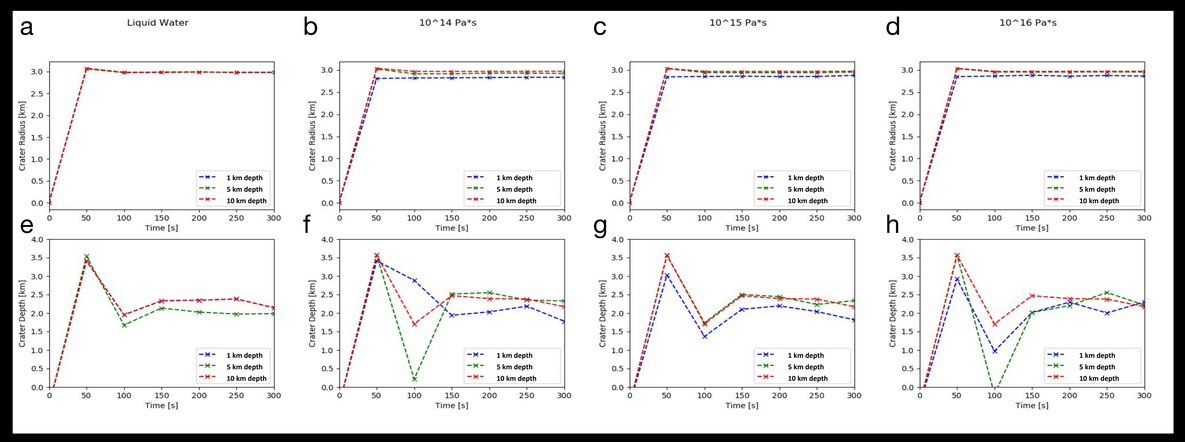


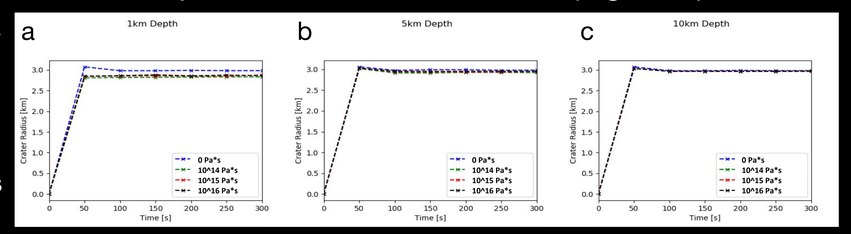
Figure 3 (above): Snapshots of the temperature in K (left) and the yield strength in MPa (right) 50 seconds after impact for 4 different runs.

Figure 4 (below): Plots of crater radius in km (top) and depth in km (bottom) for the 4 different viscosities. Each plot displays data for the 3 depths. 1 km depth is blue, 5 km depth is green, and 10 km depth is red.



- In general, the shallower the LVL, the smaller the crater radius (Fig 4)
- The 1 km depth most radically constrains the crater radius (Fig 4b-d)
- The liquid water layer has little change in crater radius for the 3 depths, possibly due to model deficiencies (Fig 4a)
- There is a lot of noise in the crater depth plots, likely due to software errors, but there are definite differences to explore further in future work (Fig 4e-h)

Figure 5: Plots of crater radius in km for the 3 different depths. Each plot displays data for the 4 viscosities. Liquid water (0Pa*s) is blue, 10^{14} Pa*s is green, 10^{15} Pa*s is red, and 10^{16} Pa*s is black.



- We can also compare the different viscosities at each depth (Fig 5)
- In general, the liquid water layers result in the largest radii, then the largest viscosity, 10^{16} Pa*s, then the second largest viscosity, with the smallest nonzero viscosity 10^{14} Pa*s resulting in the smallest radii (Fig 5)
- The liquid water LVL at the 1 km depth resulted in the largest crater radius (Fig 5a)

Discussion:

- For the 1km depth runs, the bolide penetrated through the LVL (Fig 3a,c)
- In general, at higher viscosities the crater walls were less steep (Fig 3c,d)
- At shallower depths, there was more ejecta at higher viscosities (Fig 3c)
- At deeper depths, there was more ejecta at lower viscosities (Fig 3b)

Conclusion:

- We do see detectable differences in crater radii in response to the differing LVL viscosities and depths tested
- The shallower the LVL, the smaller the radius
- Liquid water LVLs result in the largest radii, and the smaller nonzero viscosities resulted in smaller radii
- Further modelling will refine our data and address noise in the crater depth data
- We will also further explore the parameter space and include more variables