Curtin University

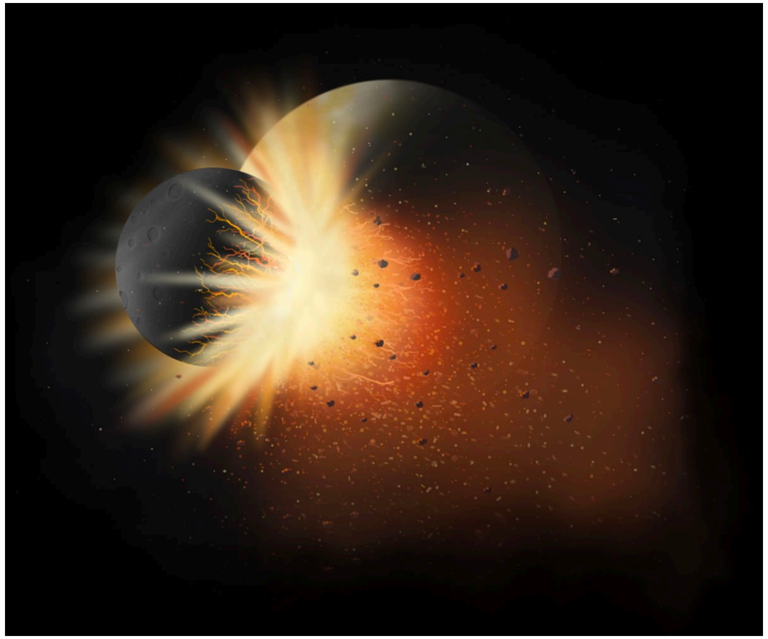
Katarina Miljković, Mark A. Wieczorek, Matthieu Laneuville, Alexander Nemchin, Phil A. Bland & Maria T. Zuber (2021)

Large impact cratering during lunar magma ocean solidification.

EGU22-2214

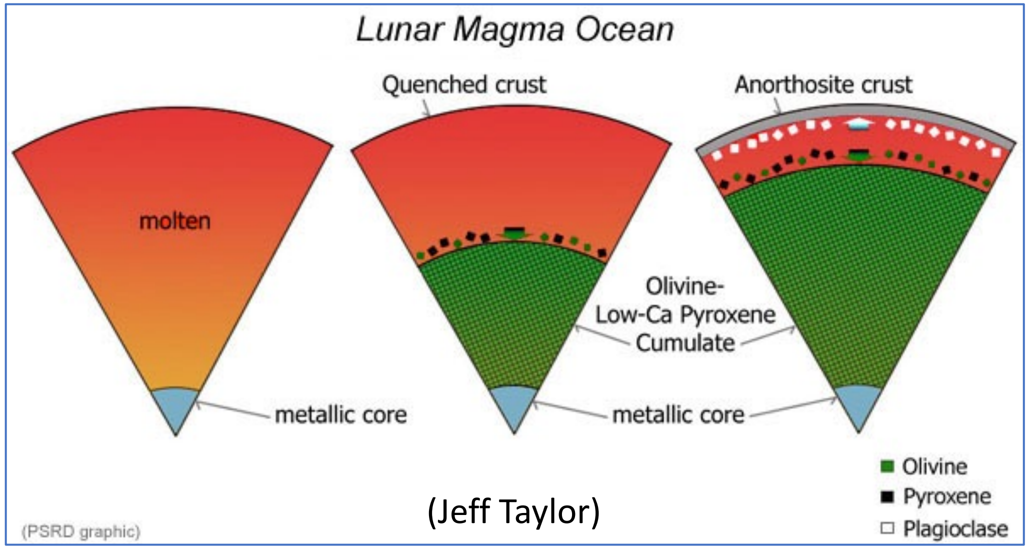
Nat Commun **12,** 5433
https://doi.org/10.1038/s41467-021-25818-7

Moon formation timeline



The Moon-forming impact event was followed by solidification of the lunar magma ocean (LMO)

- Radiogenic lunar crustal ages span **4.47-4.31** Ga and the age of the giant impact has been estimated to have occurred at ~**4.54-4.425** Ga (e.g., Shearer et al., 2006; Borg et al., 2004, Elkins-Tanton, 2012)
- Flotation crust (anorthite plagioclase) started forming very early on and once ~80% of the LMO was solidified (e.g., Norman et al., 2003 and others)
- What about the other 20%?

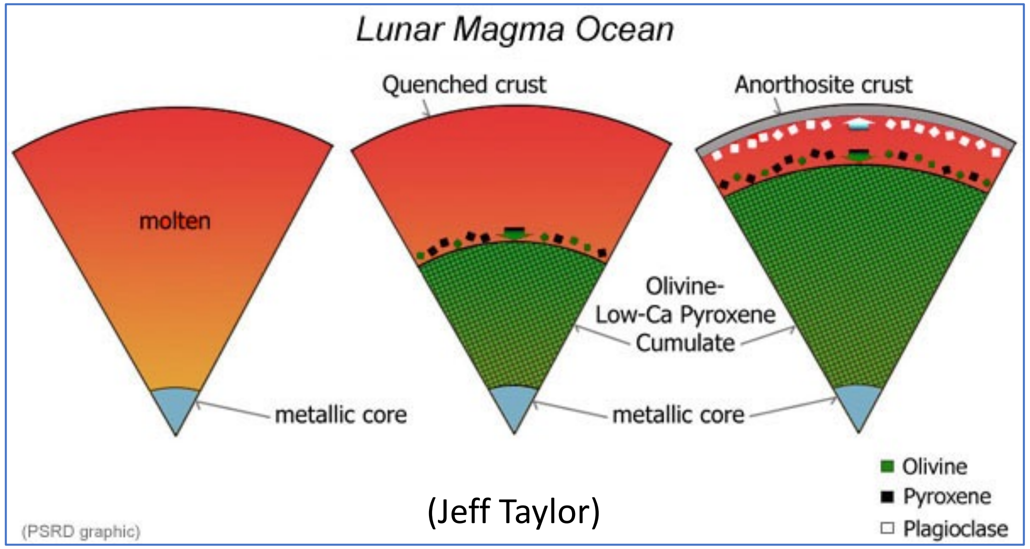


(Jeff Taylor)

Fir0002/Flagstaffotos

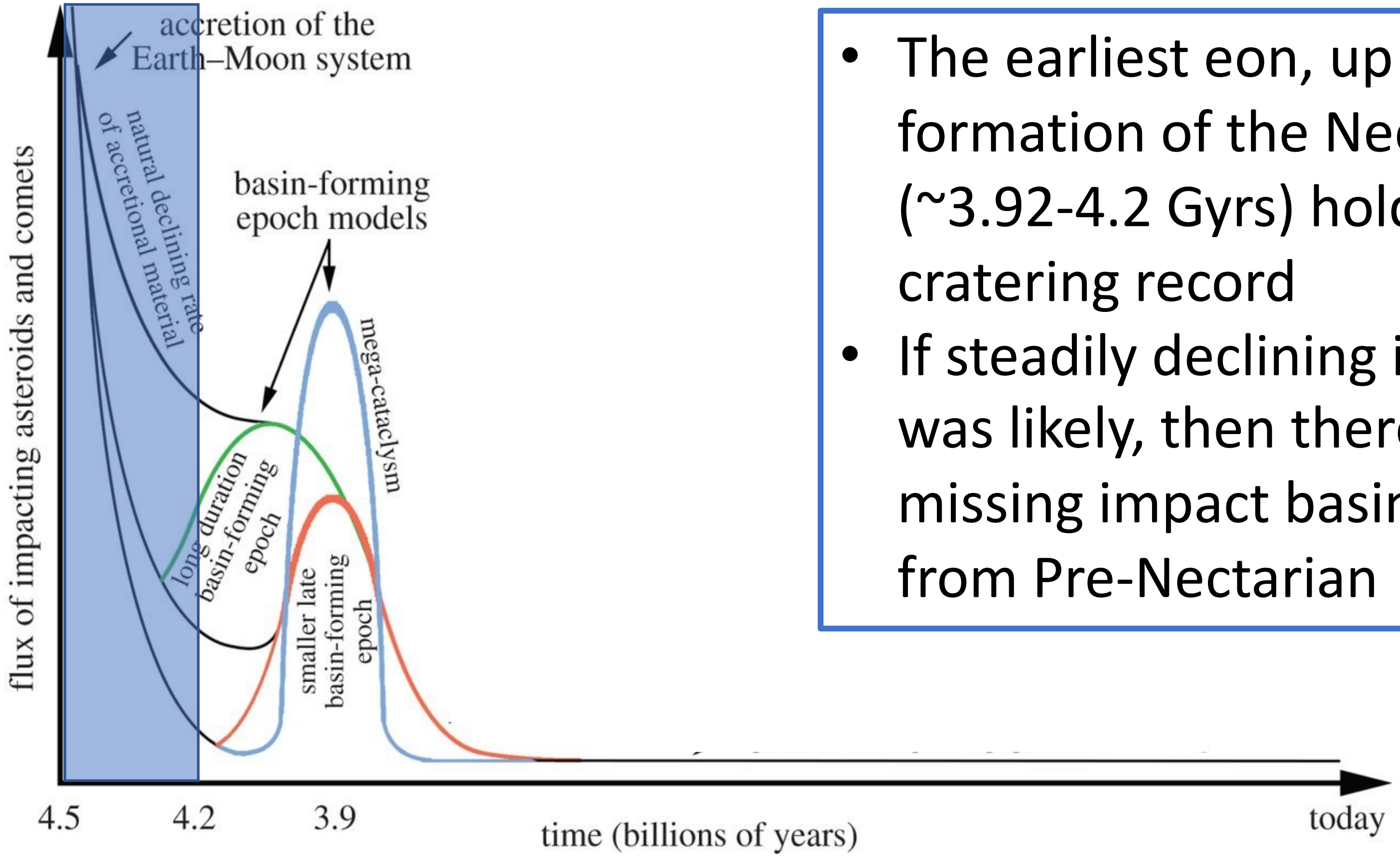
The late stage of the lunar magma ocean cooling

- Lifetime of LMO residue?
  - A few Myrs, 10-50 Myrs:
    - E.g., Elkins-Tanton et al., 2012 → compositional differentiation
  - Up to ~200 Myrs:
    - Maurice et al., 2020 → updated thermal evolution
    - Tian et al., 2017; Cuk et al., 2018 → dynamics of early Moon orbit
    - Nemchin et al., 2009 → age of Apollo zircons
    - Kamata et al., 2015 → long-term crustal relaxation
  - Up to 500 Myrs
    - Wieczorek et al., 2000; Laneuville et al., 2018 → asymmetric thermal evolution



(Jeff Taylor)

How did heavy impact bombardment looked like in this period?

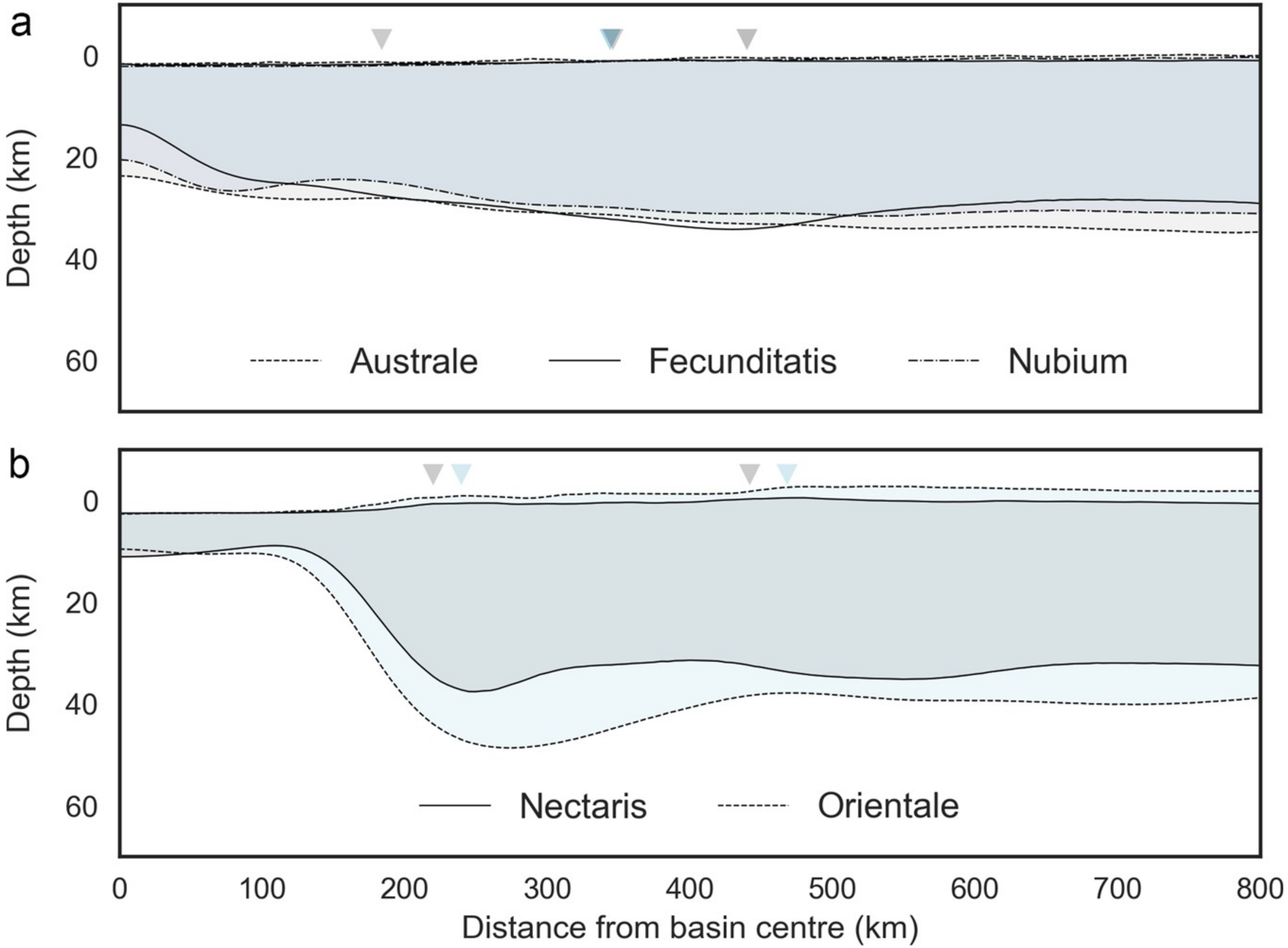


Crawford and Joy, 2014

- The earliest eon, up to the formation of the Nectaris basin (~3.92-4.2 Gyrs) holds poor cratering record
- If steadily declining impact flux was likely, then there is a missing impact basin record from Pre-Nectarian

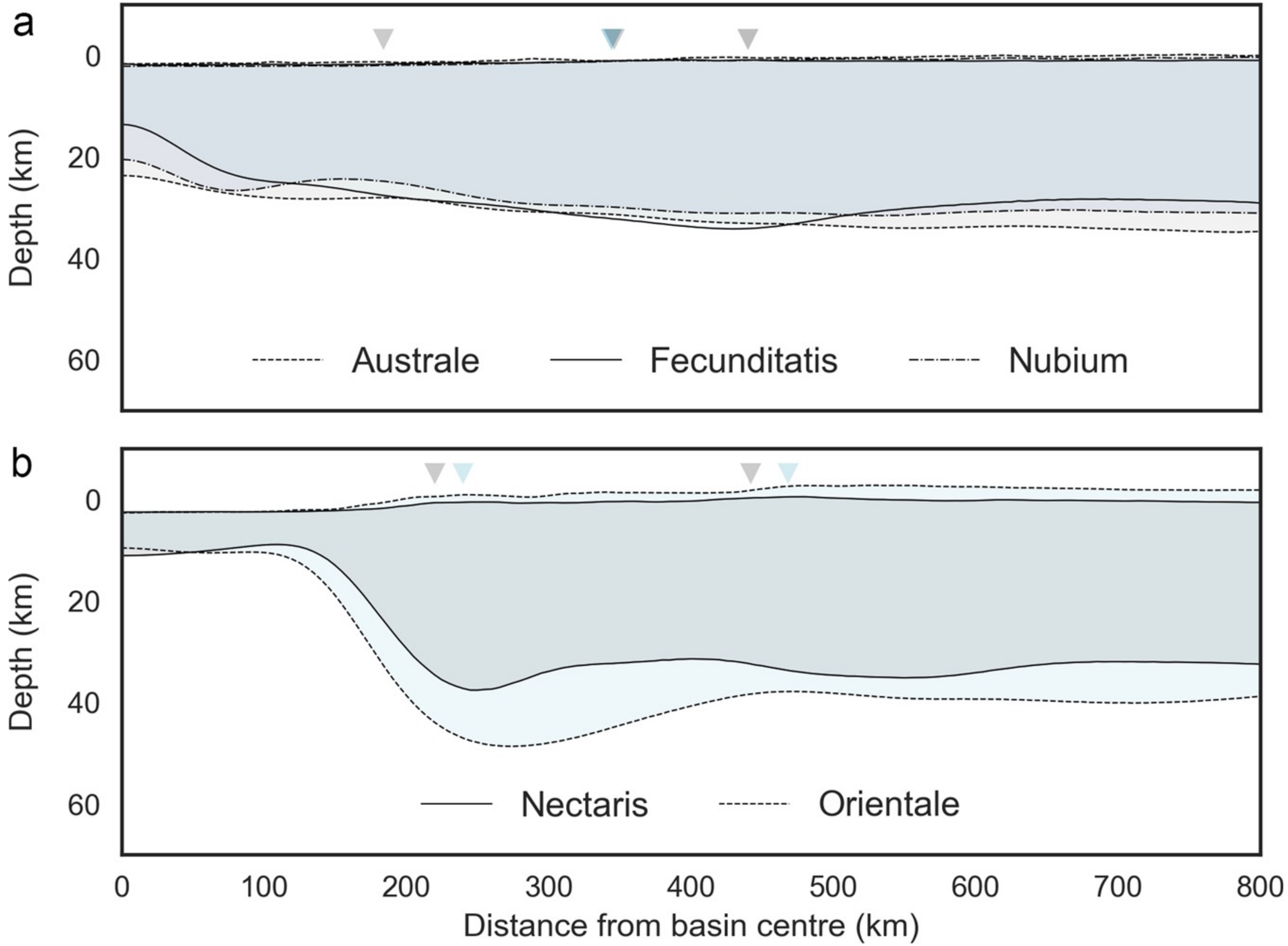
Morphology of Pre-Nectarian impact basins

- **Topography** degraded by subsequent bombardment with possibly one ring identified (Neumann et al., 2015), while younger basins are multi-ringed
- **Gravity/crustal structure**: large and stratigraphically oldest pre-Nectarian impact basins show muted crustal signatures compared to the younger impact basins (Wieczorek et al., 2012; Neumann et al., 2015)



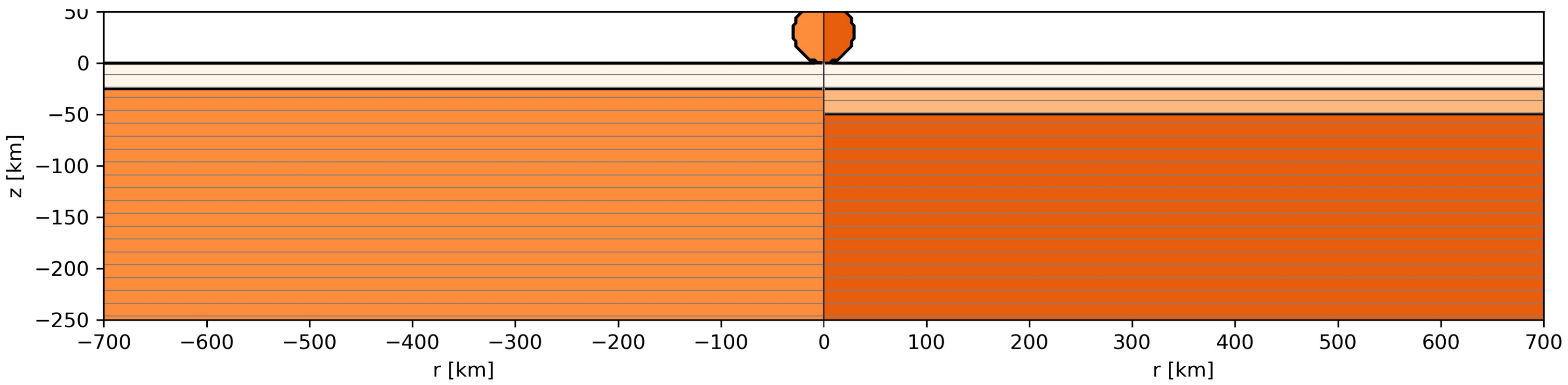
Long-term crustal relaxation?

Viscous relaxation could contribute to the muted crustal thickness signatures assuming sufficient T at the base of the crust (Mohit & Phillips, 2006; Conrad et al., 2018), but would not remove the smaller-scale topographic signatures of the crater rings at the colder surface (Solomon et al., 1982).

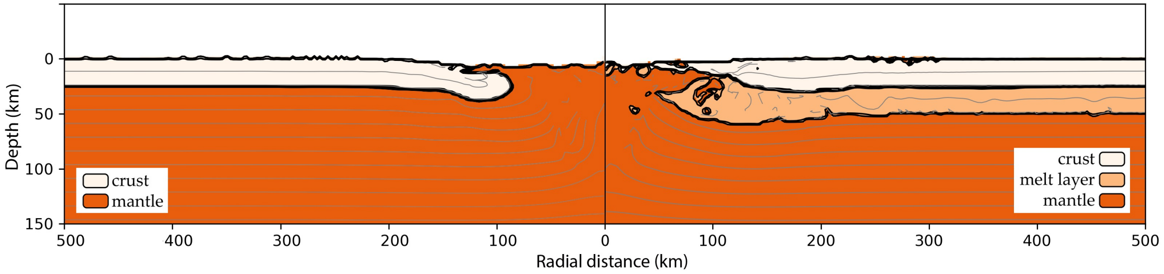


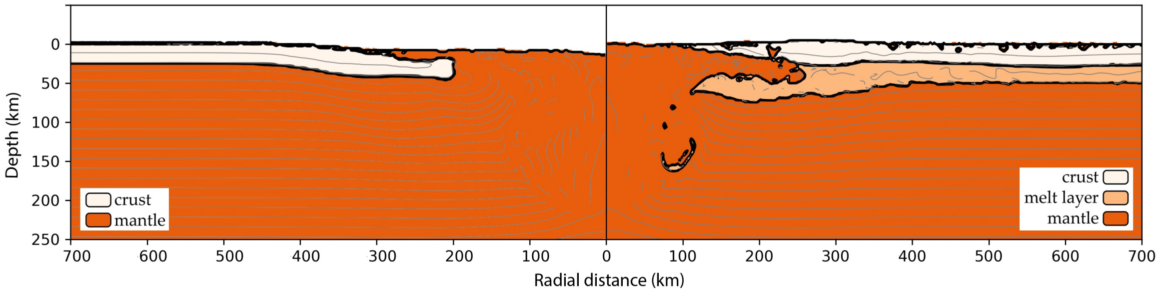
Numerical impact modelling: iSALE-2D setup

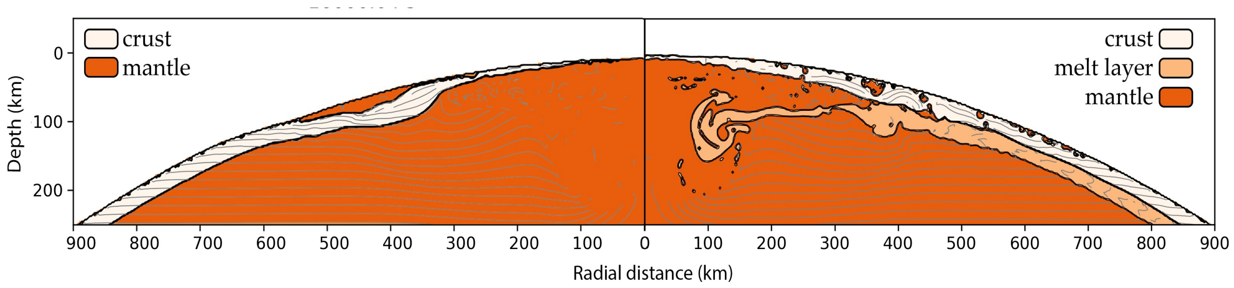
- Impact parameters to cover the **entire range of lunar basin sizes**:
  - 15, 30, 60 km impactor diameter into flat Moon
  - 90, 120, 160, 200 km impactor diameter into curved Moon
  - 10 and 17 km/s vertical impact
- Target properties:
  - Crust: 10, 25, 50 km thick (basalt/granite EOS)
  - Melt layer: 10, 25, 50 km (100 Pas viscosity, mimicking high fraction of melt)
  - Temperature profiles: 50 K/km through the crust and adiabatic below, and similar applied from initial conditions used in thermal evolution models (Laneuville et al., works)

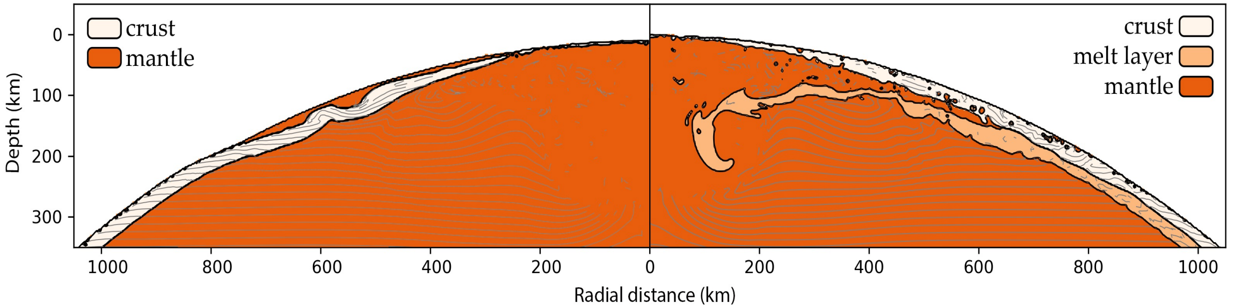


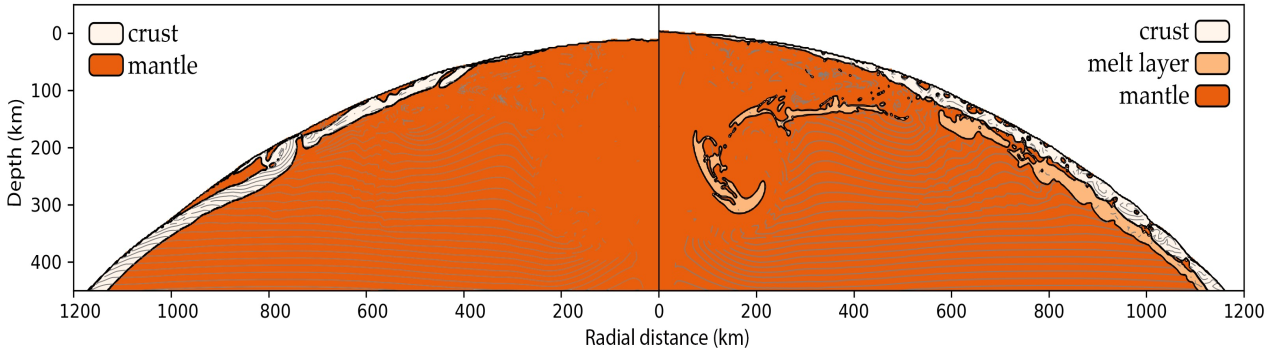
Basin morphology with respect to basin size











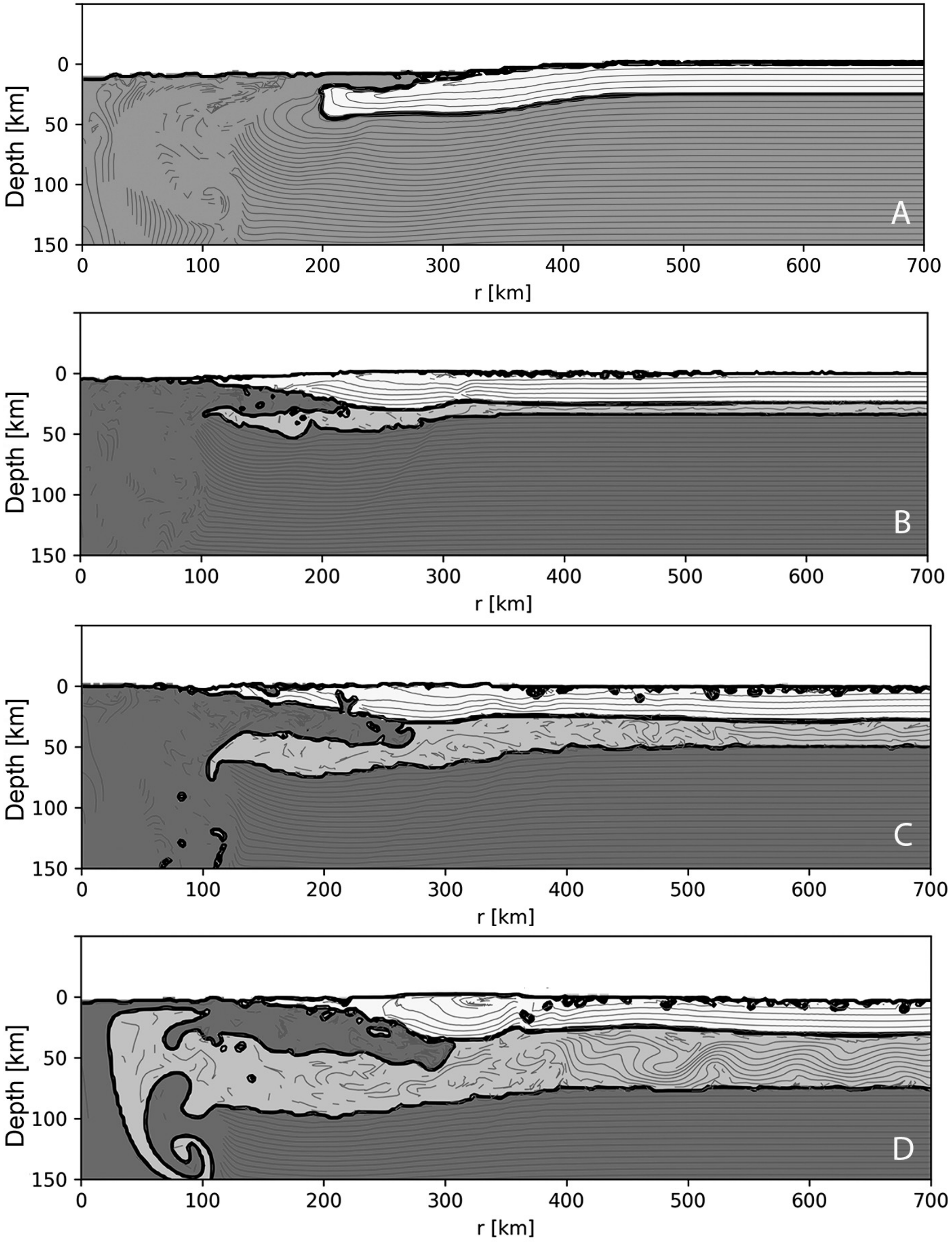
Change in basin morphology and stratigraphy with increasing basin size:

- More relaxed crustal structure with melt layer
- Difference between w/out melt smaller as size is increased

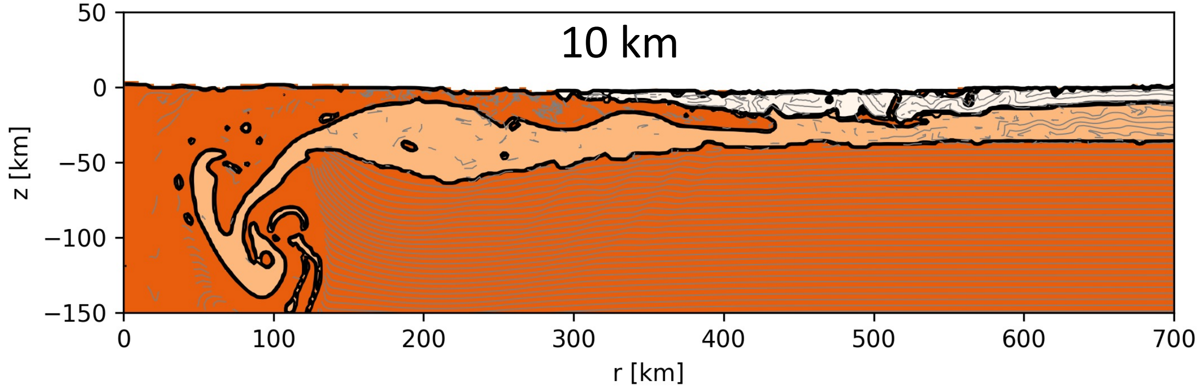
Basin morphology with respect to the melt layer thickness

- A: no melt
- B-D: 10, 25, 50 km melt layer

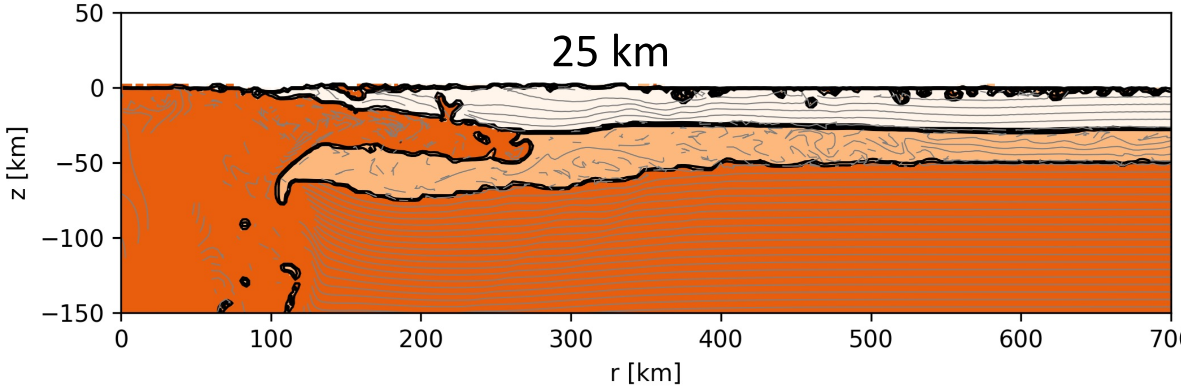
- Suggesting no significant change in morphology when melt layer is >25 km thick, but **it is sufficient to have at least 10 km melt layer to change basin morphology**

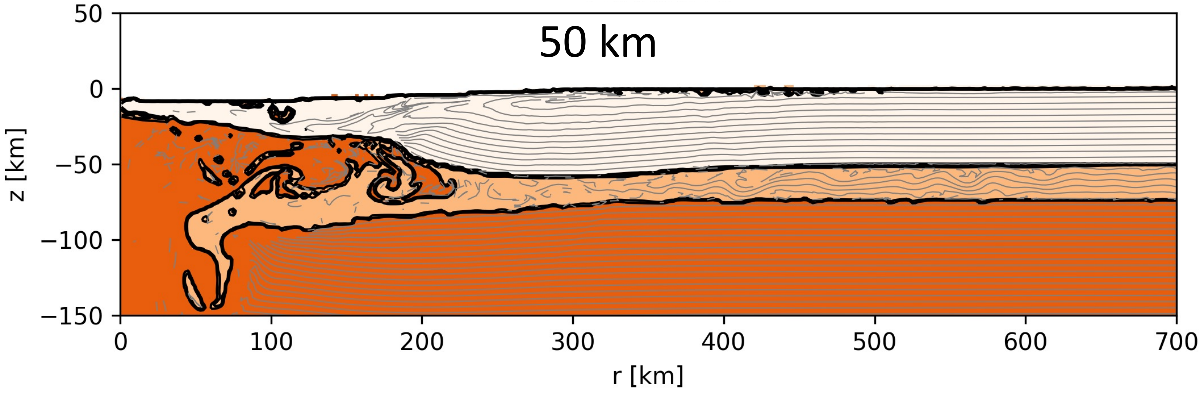


Basin morphology with a melt layer and different crustal thicknesses

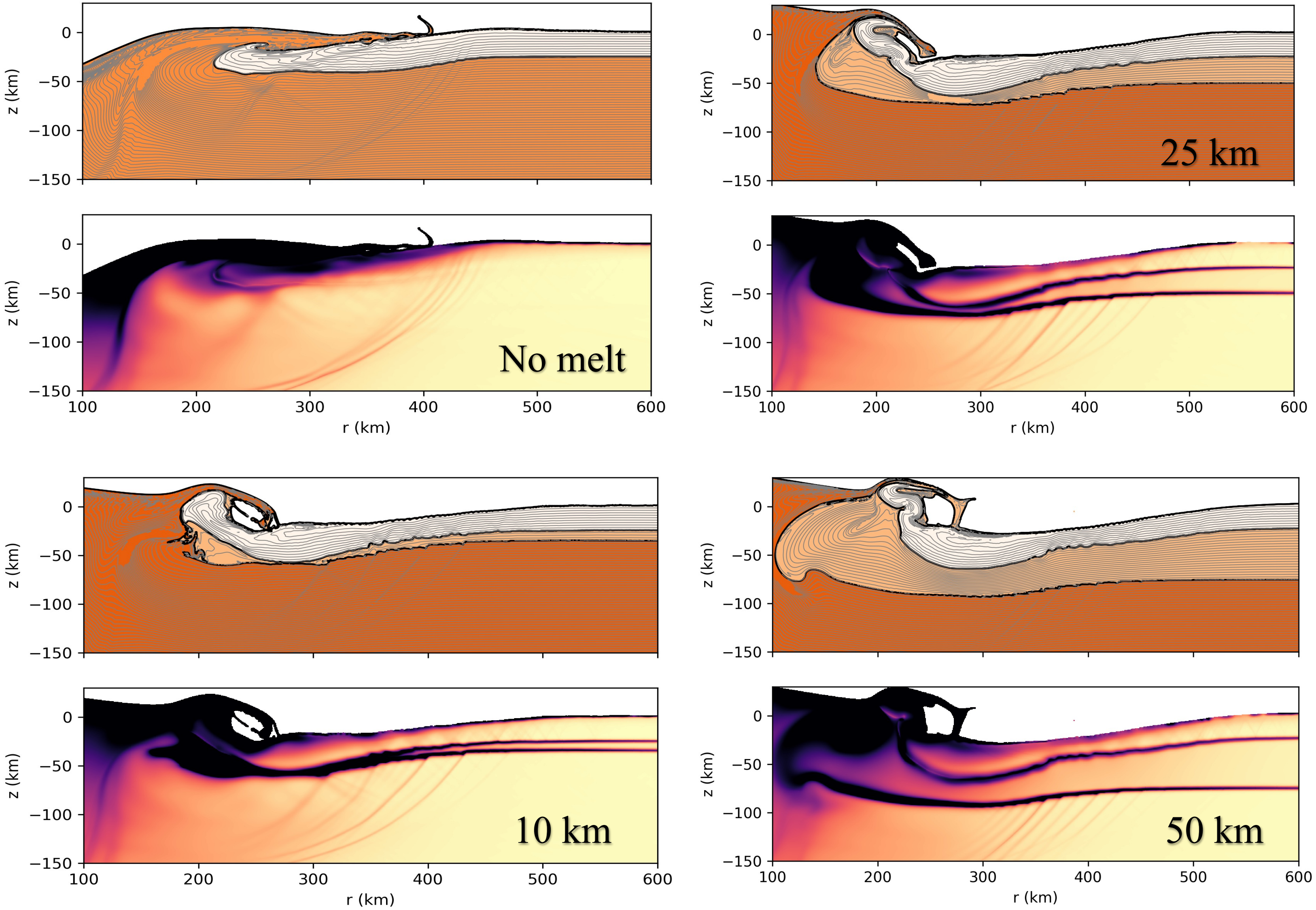


- 10 km: melt pool/mantle exposed
- 25 km: disconnected crustal cap
- 50 km: full crustal cover





Topographic signatures



The impactor diameter was 60 km and the impact speed was 17 km/s.

- No melt layer shows 2 rings forming: peak ring and main ring (Johnson et al., 2016)
- With melt: all cases show multi-rings/graben/dense fault lines from main rim outwards

Conclusions

- Pre-Nectarian impact basins on the Moon, including the SPA basin, could have formed while the lunar magma ocean was still solidifying:
  - Those basins would have formed with a different topographic and crustal signature in comparison to younger basins, if a low viscous layer existed.
  - When compared to younger basins, the crustal thickness signature would be less prominent, and the topographic signature would not exhibit prominent concentric rings.
  - The thicker the melt layer and the thinner the crust, the higher the chances not to be recognizable in the cratering record (even before any long-term viscous relaxation were to take place).
  - We can't tell how many craters could have formed like this, but the work is consistent with recent predictions of higher impact fluxes in Pre-Nectarian.