EXPLORING HABITABILITY CONDITIONS IN TITAN'S IMPACT RECORD: THE FORMATION OF MENRVA CRATER

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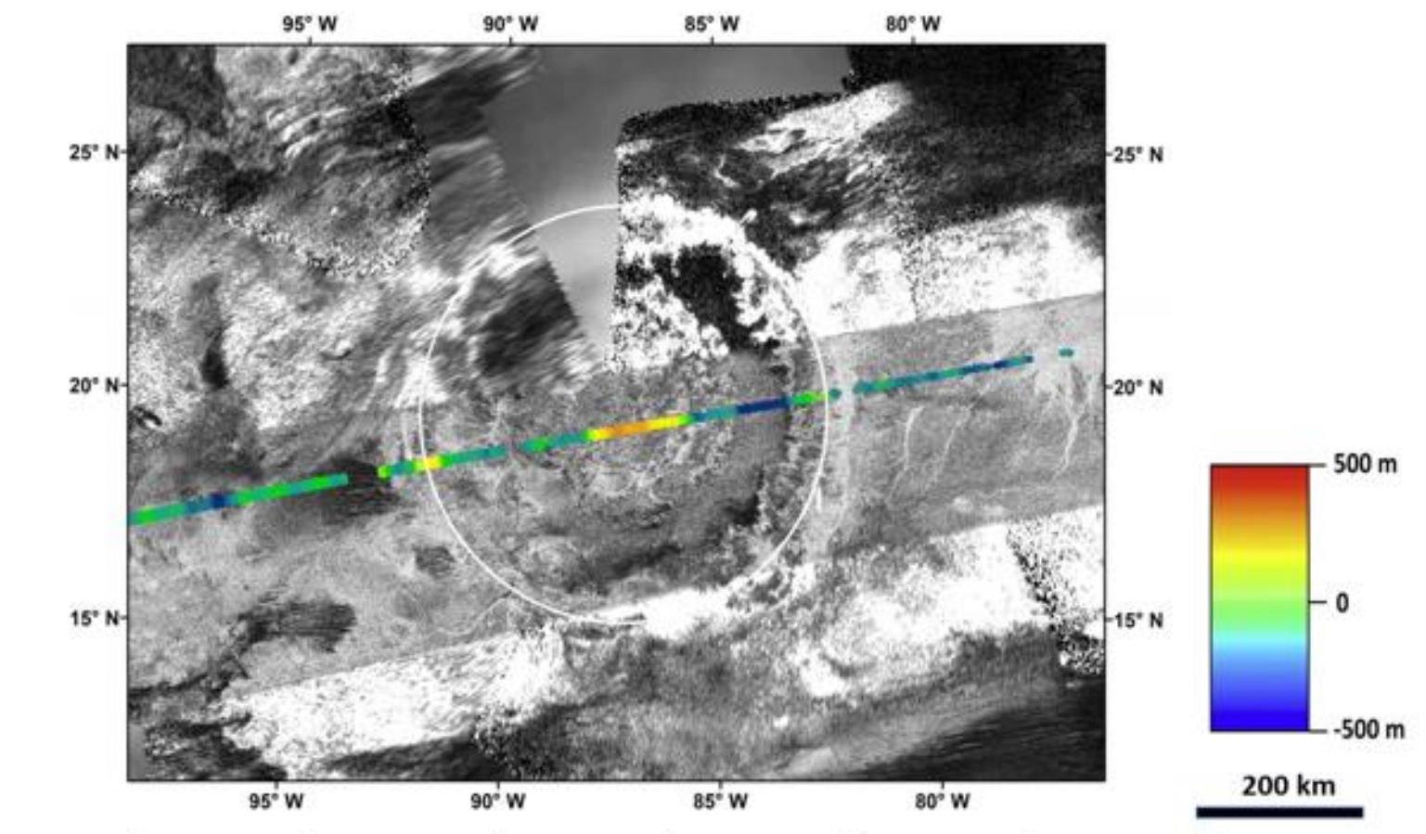
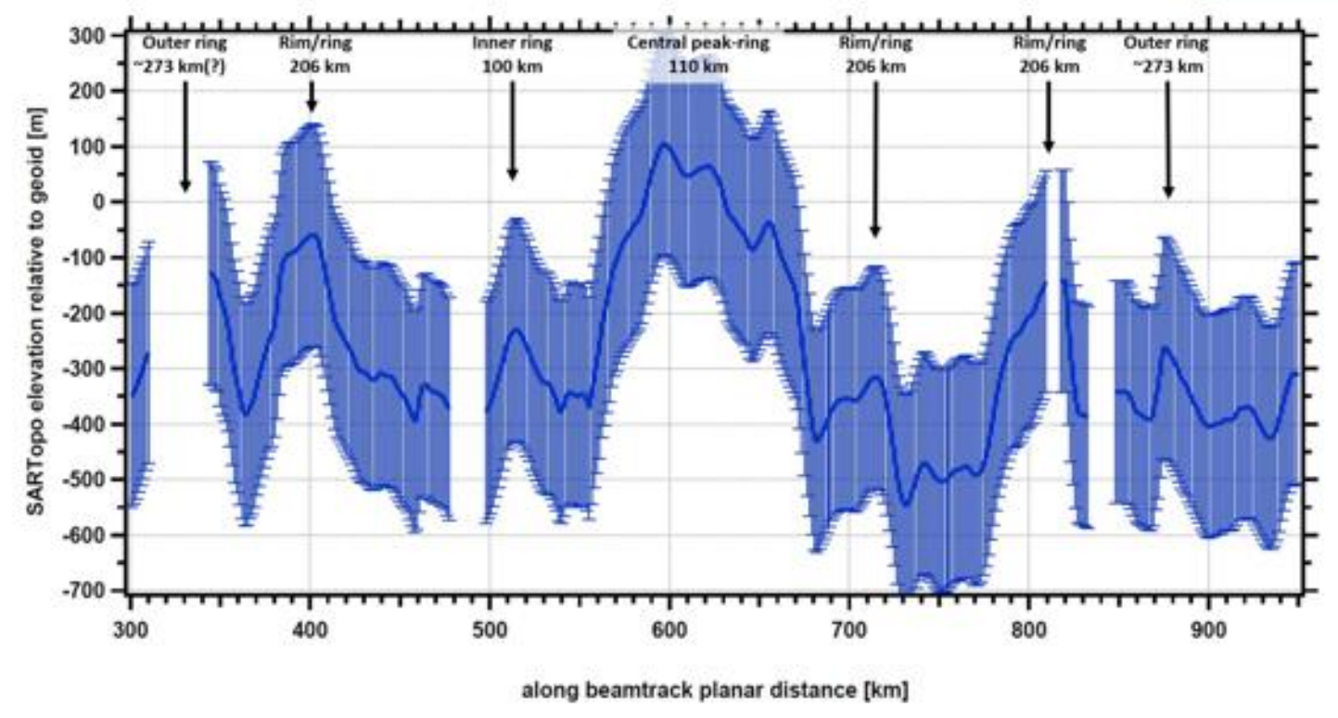
MENRVA CRATER: THE LARGEST IMPACT ON TITAN

- Among Titan's known impact-related landforms, Menrva crater, at 425 km diameter, stands out due to its large dimensions, making it at least **three times larger than the next largest crater** (Forseti, ca. 145 km diameter).
- Menrva is a **complex impact basin**, exhibiting a **peak-ring-like structure** in its central area.
- Despite degradation, **Menrva still exhibits characteristic morpho-structural features**: rim, two inner annular rings, crater fill, and possible peak-ring central elevations and partially preserved ejecta deposits.

MENRVA CRATER: REMOTE SENSING ANALYSIS

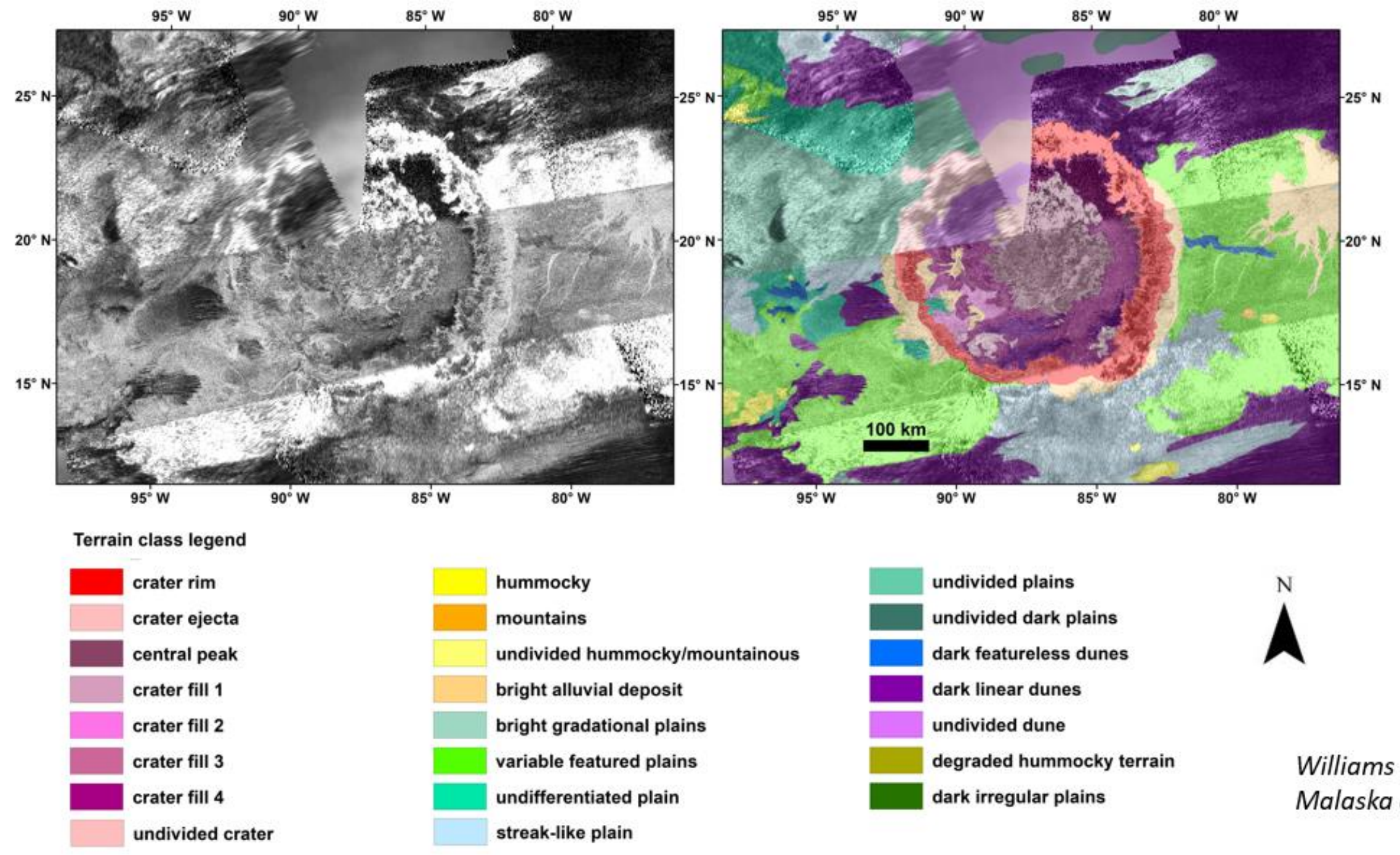


- **Topographic transect** cutting across the center of the crater using SARTopo data) overlaid on the SAR image.
- Warmer colors represent higher elevations, whereas cooler color the lower ones.
- The relative heights range from ca. **-600 to +200 m** along the transect.



- **Topographic section** of Menrva Crater along WSW-ENE using SARTopo.
- Error bars are positioned at +/- 200 m.
- The **main rim is at ~206 km radius** (~412 km diameter) and **the inner ring is at ~100 km radius** (~200 km diameter).
- The central section **(peak-ring)** extends out from the center to **~55 km** (~110 km diameter).
- The subtle **outer ring shows at ~273 km radius**.

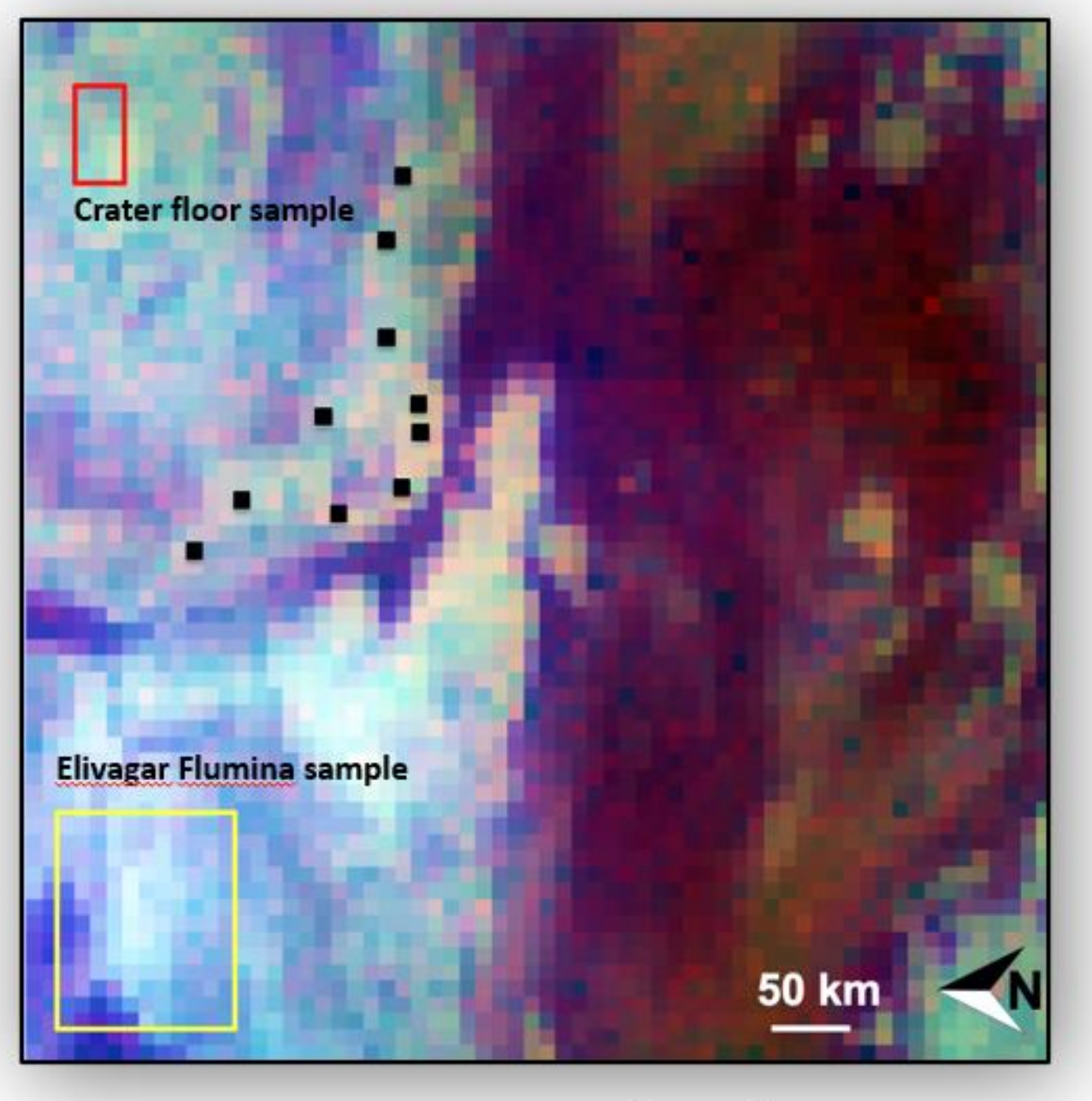
Geomorphological Map of Menrva Crater



Williams et al. (2011)
Malaska et a. (2020)

MENRVA CRATER: REMOTE SENSING SPECTRAL ANALYSIS

Multispectral VIMS data (B=1.28 µm, G = 2 µm, R= 4.8–5.2 µm)



Menrva: spectrally a low emissivity but high albedo target

Major constituents for the crater floor and ejecta blanket (adapted from Solomonidou et al., 2020)

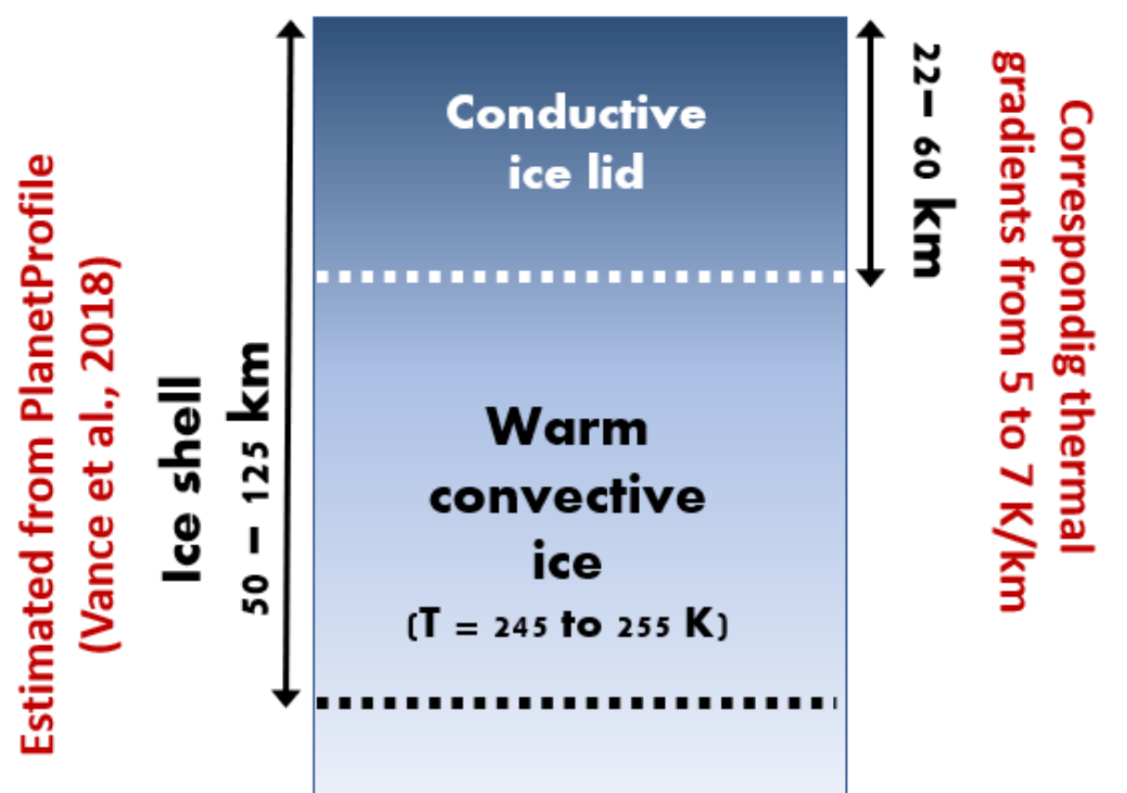
	Menrva	
Unit	Floor	Ejecta
H_2O	18 ± 5%	17 ± 4%
Tholin	82 ± 19%	83 ± 18%
Dark material	-	-
Total organic	85%	85%
Emissivity	0.90	0.87
Degradation state	Somewhat degraded, but still retains main morpho-structural features	

- The ejecta blanket and crater floor of Menrva seems to comprise a combination of **water-ice-like spectra**, **NH_3 ice**, **CO_2 ice**, and **tholin** components.
- No **NH_3** or **CO_2** spectra were found, nor the **dark material** that is present is most of Titan's surface.

Solomonidou et al. (2018)
Crósta et al. (2021)

MENRVA CRATER: IMPACT MODELING

- To **simulate the formation of a Menrva-like crater**, we used **iSALE-2D**, a multi-material, multi-rheology shock physics code (Melosh et al., 1992; Ivanov et al., 1997; Collins et al., 2004; Wünnemann et al., 2006), which is based on the SALE hydrocode solution algorithm (Amsden et al., 1980).
- Our **model inputs are consistent** with the earlier modeling study that **examined the formation of impact craters on Europa** (Silber and Johnson, 2017; 2018), with a few minor adaptations, such as a **surface gravity** appropriate for Titan.
- Lagrangian tracer particles were implemented to **track the material position and state** during the crater formation process.



Structure of the icy shell overlying the water ocean and range of parameters used for ice thickness

Description	
Surface temperature (K)	94
Melt temperature at zero pressure (K)	273
Thermal softening parameter	1.2
Cohesion, intact (MPa)	10
Coefficient of internal friction, intact	2
Limiting strength at high pressure, intact (GPa)	0.11
Cohesion, damaged (kPa)	10
Coefficient of internal friction, damaged	0.6
Limiting strength at high pressure, damaged (GPa)	0.11
Equation of state (EOS)	Tillotson, H_2O
Impact velocity (km/s)	7
Impact angle (degrees)	45
Impactor diameter (km)	34

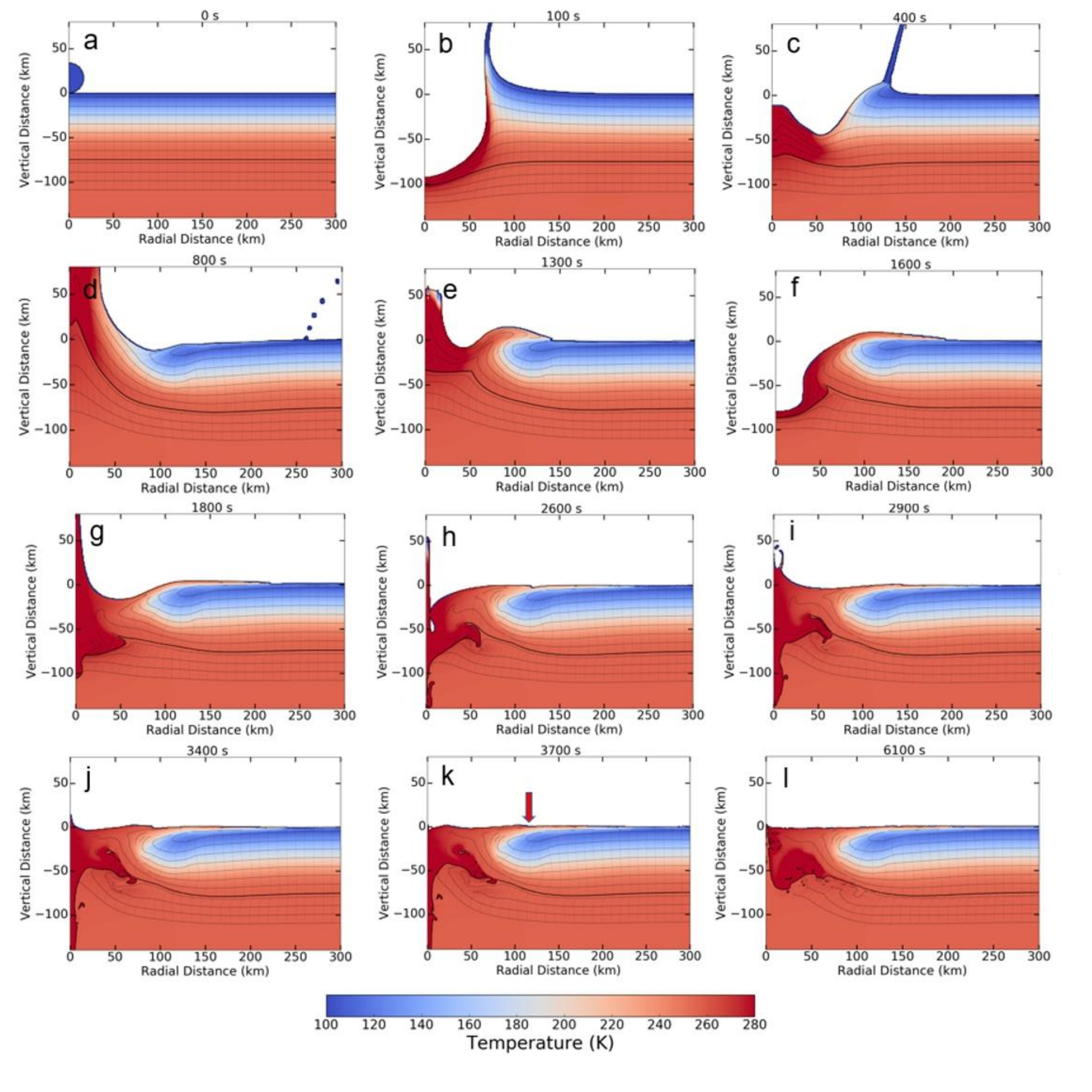
Input parameters for modeling using iSALE-2D

D_{ice} (km)	d_{lid} (km)	T_{ice} (K)	D_i = 34 km v_i = 7 km/s	D_i = 28 km v_i = 10 km/s
50	26	245	P	P
50	26	255	P	P
75	26	245	P	P
75	26	255	P	P
75	60	245	P	P
75	60	255	P	P
75	26	245	P	P
100	26	255	F	P
100	60	245	P	P
100	60	255	P	P
100	26	245	P	P
125	26	255	F	P
125	60	245	F	P
125	60	255	P	F

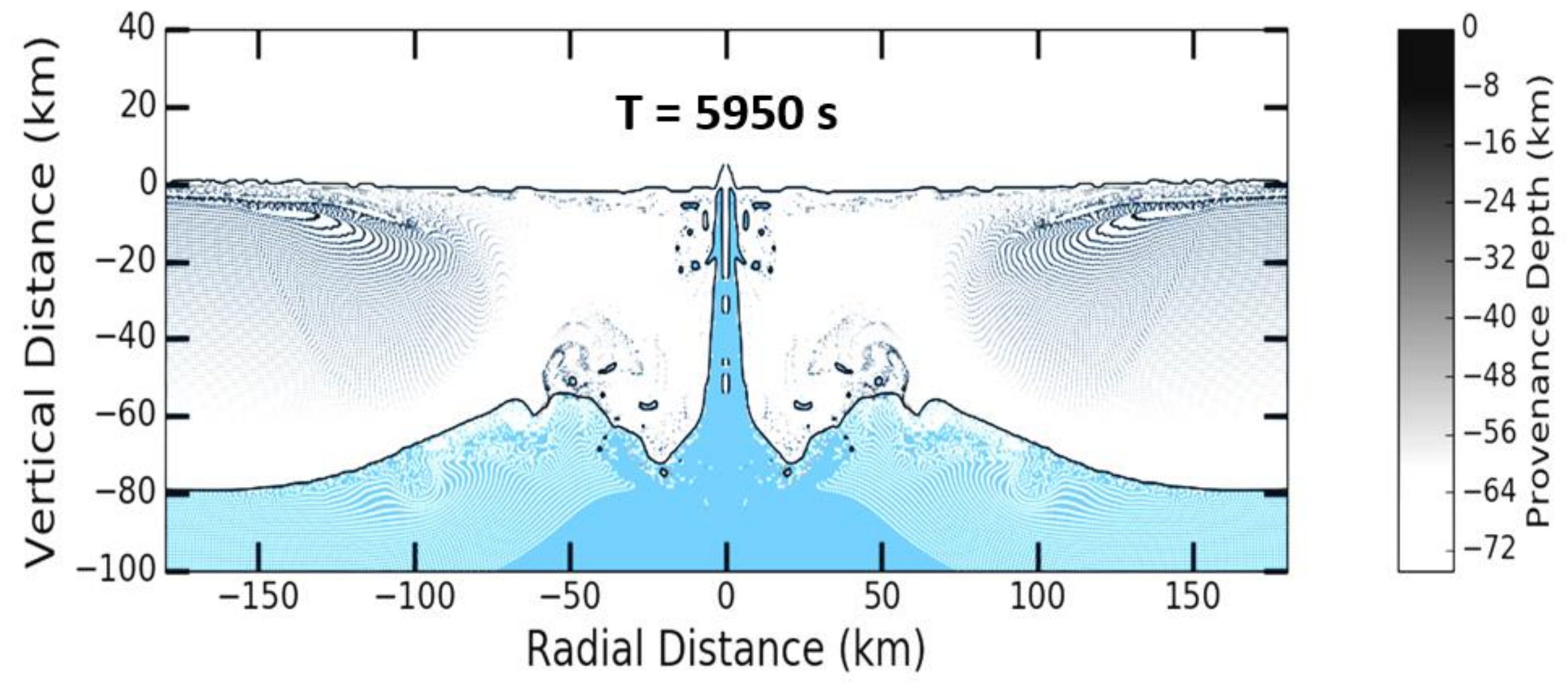
P = a total breach of the ice shell
F = do not result in a complete breach
D_{ice} = thickness of the ice crust
d_{lid} = thickness of the conductive ice lid
D_i = diameter of the impactor
v_i = velocity of the impactor
T_{ice} = temperature of the warm convective ice.

The scenario highlighted in yellow shows the parameters used in the following figures

Parameter space and combinations used for modeling

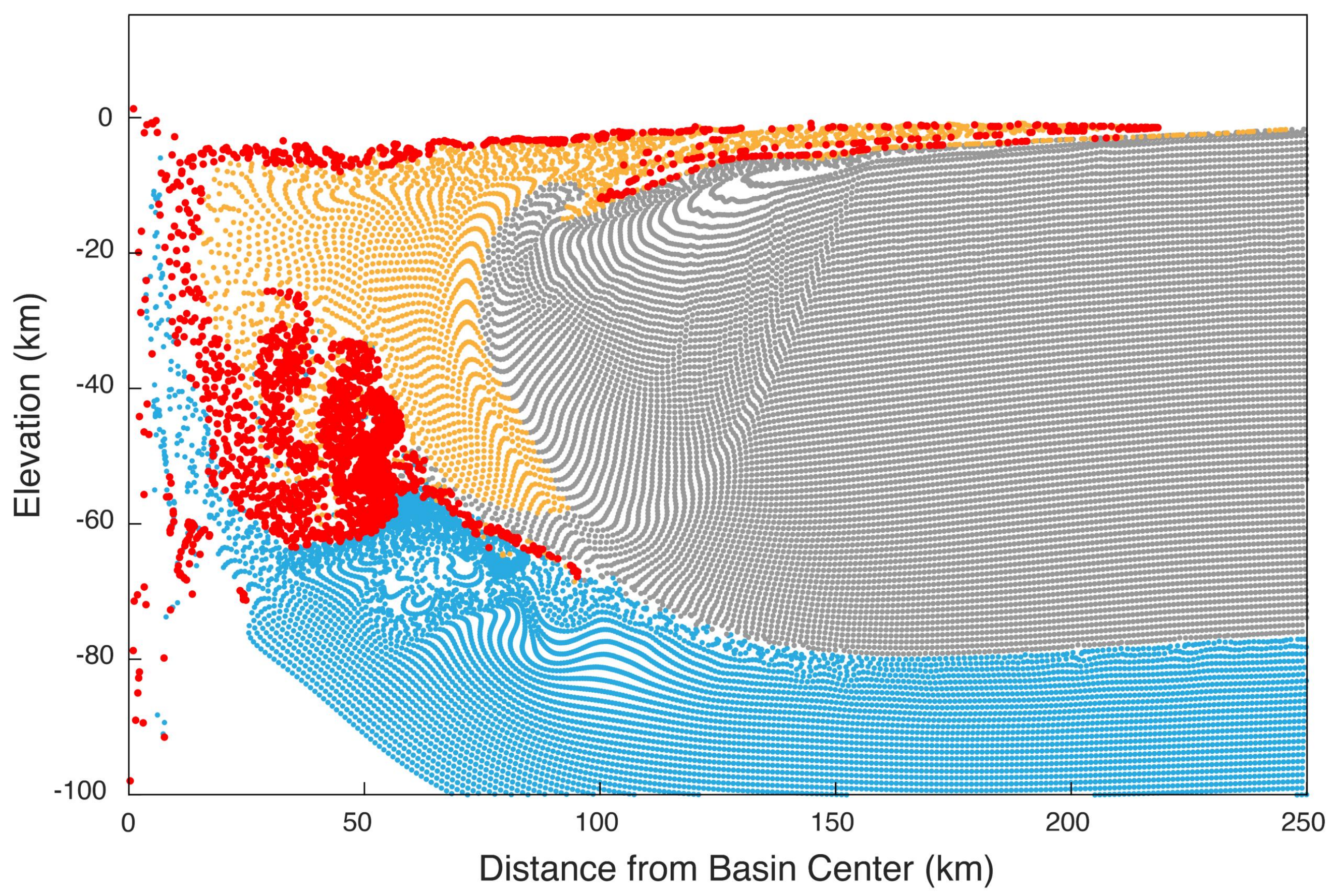


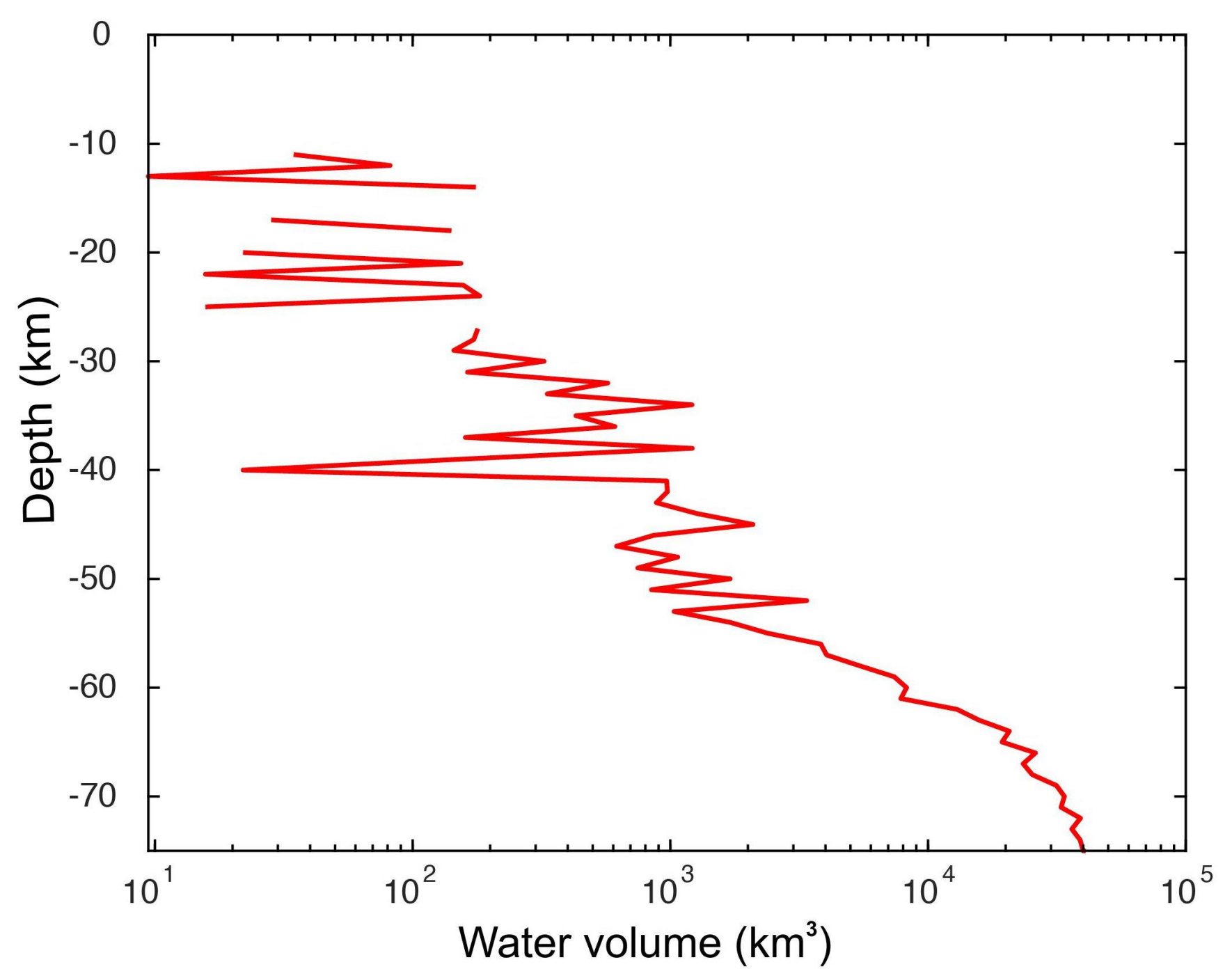
Time series showing the example case of the formation of Menrva. The impactor's diameter is 34 km and the vertical component of impact velocity is 7 km/s. The sequence of figures (7a to 7l) depicts the evolution of the transient crater from the moment of impact (t = 0 s) until it reaches gravitational stabilization (t = 6100 s) (see the text for details on each stage). The red arrow in Fig. 7k indicates the approximate position of the inner ring at ca. 130 km from the center.



A **substantial upwelling** takes place, with **vertical mixing and material exchange between the surface and the ocean**, at distances of **up to 70 km from the center** and **up to ca. 80 km in depth**. Tracers within the ice shell are colored according to their original depth for the same model shown in the previous figure.

Peak Shock Pressures for: 34km Projectile 75km Lid 60km Conductive Lid 255K Temp 5000s





Total water volumes as a function of depth for the example case

CONCLUSIONS

- Large hypervelocity impacts can have **an important role in creating habitable** environments or niches. When viewed from the perspective of a **geobiological process**, **impact cratering** can influence the **biological evolution of planetary bodies** and control **planetary habitability**.
- Our models clearly indicate that **our working hypotheses were basically met** in most of the scenarios tested, i.e., (i) **Titan's ice shell is indeed breached by a large impact,** such as the one that formed Menrva crater and, **possibly, even smaller impacts** depending on the thickness of the icy shell at the time of the event; (ii) **materials from the three uppermost layers on Titan's interior (organics, ice, and ocean) mix in considerable amounts** because of deformation processes.
- Deformation processes associated with crater formation provide two of the necessary conditions for a habitable world: **the adequate substrates (organic compounds, ice, and water)** and **large enough volumes of these materials** to provide the media for prebiotic life development.
- A third, and key condition, is **temperature**. Our models showed that relatively large volumes of these materials may be **heated and melted,** mainly at the central area of the crater; as for the duration of these relatively warm conditions, inferences can be drawn from Earth's analogues, which show evidence of **long-lasting hot fluid circulation,** of up to **a million years**.

Acknowledgments

This research was supported partly by the JPL-led NASA Astrobiology Institute team "Habitability of Hydrocarbon Worlds: Titan and Beyond". Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Government sponsorship is acknowledged. A.P.C. acknowledges the financial support from the São Paulo Research Foundation (FAPESP, grant #2017/27081-1) and the State University of Campinas (Unicamp), which allowed part of this research to be developed during his stay at JPL as a visiting scientist. The research was also partly supported by the Cassini Data Analysis and Participating Scientists Program (CDAPS), through grant #NH16ZDA001N to R.L. A.S. is partly supported by the Czech Science Foundation (grant no. 20-27624Y). B.C.J. and J.M.S. were supported by Cassini Data Analysis Program grant 80NSSC20K0382. We gratefully acknowledge the developers of iSALE-2D (www.isalecode.de), the simulation code used in our research, including Gareth Collins, Kai Wünnermann, Dirk Elbeshausen, Boris Ivanov, and Jay Melosh. Data associated with this study are listed in tables in the supplementary information. The simulations were performed using iSALE r-2114.