

Evolution of impact melt pools on Titan

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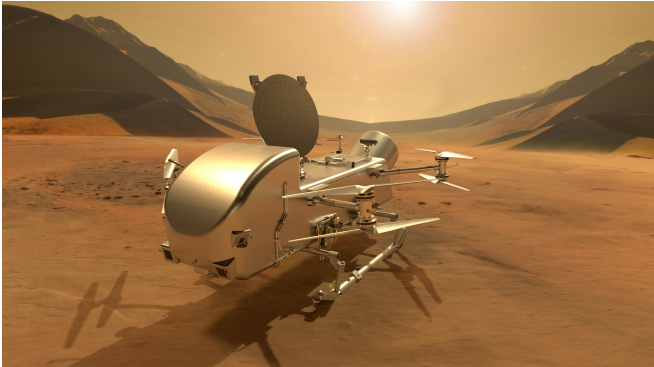
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Motivation

- ▶ Dragonfly mission will investigate Titan's Selk crater (8th largest)
 - ? How much liquid was generated during the impact?
 - ? How long it stays liquid?
 - ? Can it mix with surface organics to create biomolecules?
- Q1** Habitability of subsurface melt pools?
 - ? Can some melt mixed with organics/oxidants get to the ocean?
- Q2** Habitability of the ocean?



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 - **subduction** on Europa - not wide spread (if present at all)

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 - **penetrating impacts**
- + direct connection between the surface and the ocean
- + rapid transport of large quantities of surface material
- not clearly identified

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 - drainage of near-surface melt pool
- + suggested based on morphology of several surface features
 - ? energy source?

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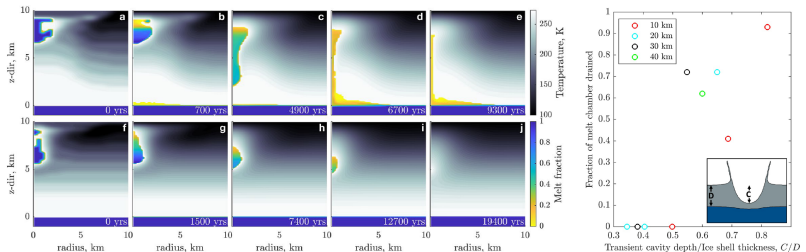
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 - drainage of near-surface melt pool
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 - ? energy source? → **non-penetrating impact**
 - most evolution models - melt pools freeze in place
 - often neglected: warming of surrounding ice → viscous deformation

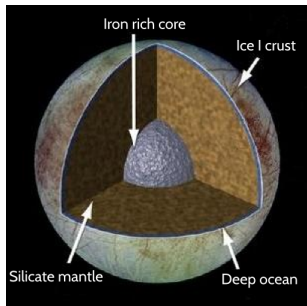
Carnahan et al., 2022, Surface-to-ocean exchange by the sinking of impact generated melt chambers on Europa, GRL.

- ▶ post-impact evolution of non-penetrating impact into Europa's shell
- ▶ ice & water move together (no porous flow), conductive temp. profile
- ▶ deep transient craters ($C/D > 0.5$): $> 40\%$ of melt drains into the underlying ocean $\rightarrow$ delivery of oxidants needed for habitability?
- ▶ drainage of near-surface impact melts to the ocean in $\sim 10^3$ - 10^4 yr



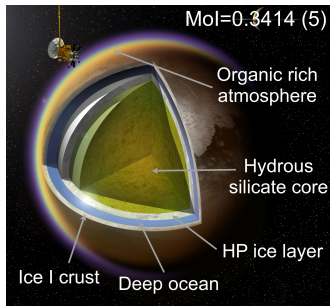
Europa

- ▶ $R \sim 1560.8 \pm 0.5$ km
- ▶ $d_J \sim 0.67 \times 10^6$ km
- ▶ $e \sim 0.9\%$, Laplace resonance
- ▶ tides: key source of energy
- ▶ hydrosphere ~ 80 – 170 km
- ▶ ice I shell ~ 10 – 30 km
- ▶ $N_{ic}(> 1\text{km}) \sim 150$



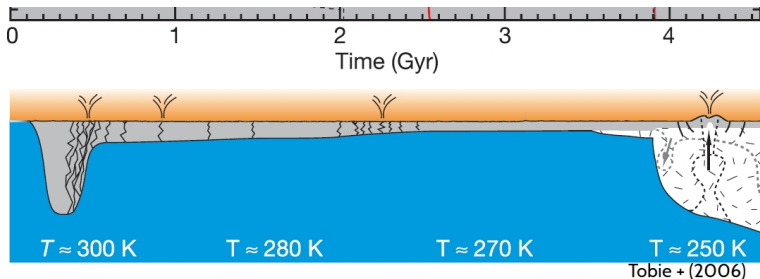
Titan

- ▶ $R \sim 2574.73 \pm 0.09$ km
- ▶ $d_S \sim 1.22 \times 10^6$ km
- ▶ $e \sim 2.8\%$, no resonance
- ▶ tidal heating not that significant
- ▶ hydrosphere ~ 500 km
- ▶ ice I shell ~ 50 – 150 km
- ▶ $N_{ic}(> 4\text{km}) \sim 90$
- ▶ dense atmosphere



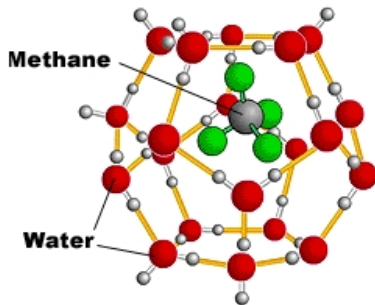
Titan - the only known moon with a dense atmosphere

- ▶ $> 90\%$ N_2 , few % of CH_4 , ...
- ▶ photolysis + further reactions $\rightarrow$ complex organic molecules $\rightarrow$ surface $\rightarrow$ subsurface
- ▶ atmospheric CH_4 photolyzed in 20–30 Myr – how is it replenished?
- ▶ Tobie + (2006): episodic outgassing of methane stored in the ice shell in the form of clathrate



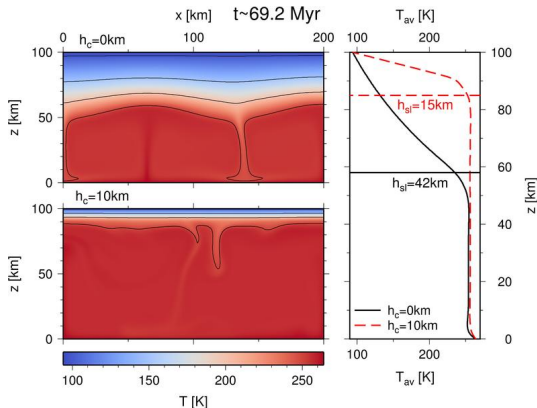
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- ▶ **methane clathrates:**
 - methane trapped in cages of hydrogen bonded water molecules
 - stable at Titan's surface p , T
 - similar density as water ice
 - stronger than water ice
 - very low thermal conductivity
 $\rightarrow$ thermal insulator



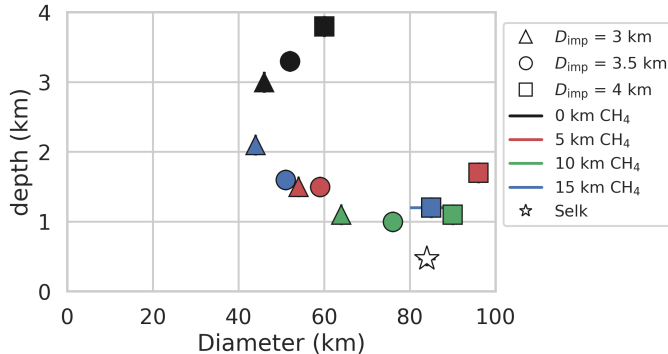
Kalousova & Sotin, 2020, The Insulating Effect of Methane Clathrate Crust on Titan's Thermal Evolution, GRL.

- ▶ thermal convection in icy shell capped with methane clathrate crust
- ▶ clathrate crust ($k_c \sim 0.1k_i$ at surface):
 - reduces stagnant lid thickness $\rightarrow$ warm material closer to surface
 - increases convective temperature



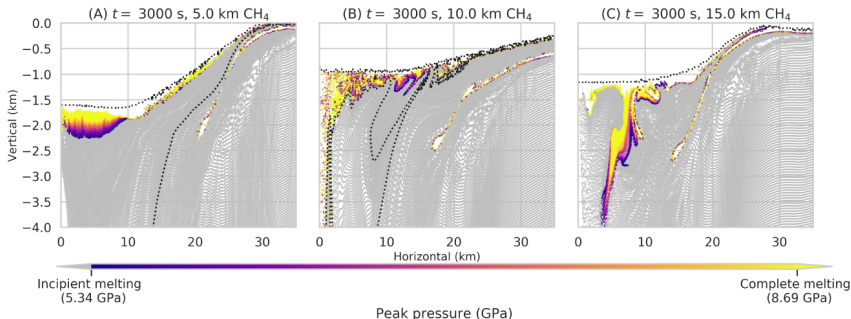
Wakita et al., 2023, Modeling the formation of Selk impact crater on Titan: Implications for Dragonfly, Planet. Sci. J.

- ▶ icy impactor hitting methane clathrate crust over Titan's ice shell
- ▶ $h_c = 0, 5, 10, 15$ km, temp. profiles from Kalousova & Sotin (2020)
- ▶ $d_i = 4$ km produces a Selk-sized crater if $h_c = 10 - 15$ km



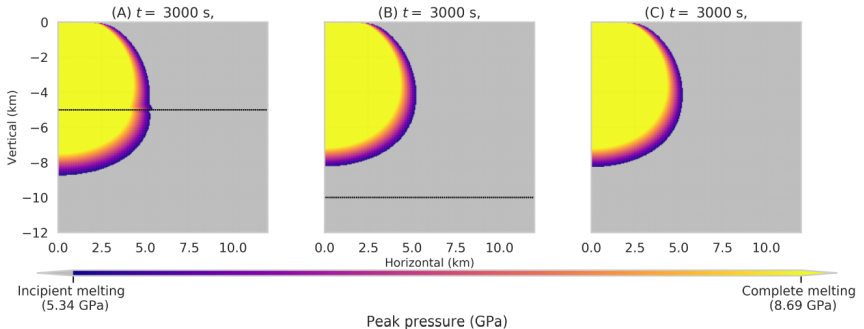
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Numerical model

► impermeable limit of 2-phase thermal convection eqs.

→ ice & water move together ($v_w = v_i = v$)

$$\nabla \cdot \mathbf{v} = 0$$

$$-\nabla \Pi + \nabla \cdot \boldsymbol{\sigma} - \phi \Delta \rho \mathbf{g} - (1 - \phi) \rho_i \alpha_i \Delta T \mathbf{g} = 0$$

$$\rho \frac{\partial h}{\partial t} + \rho \mathbf{v} \cdot \nabla h - \phi \Delta \rho \mathbf{v} \cdot \mathbf{g} = \nabla \cdot (k \nabla T) + Q$$

Numerical model

- ▶ impermeable limit of 2-phase thermal convection eqs.
- ▶ enthalpy method to treat the melting/freezing process
 - specific (and gravity reduced) enthalpy of the mixture $h(T, p, \phi)$:

$$h(T, p, \phi) = \phi L_0 + (\phi c_w^p + (1-\phi)c_i^p)(T - T_0) + \left[\phi \frac{1 - \alpha_w T}{\rho_w} + (1-\phi) \frac{1 - \alpha_i T}{\rho_i} - \frac{1}{\rho_i} \right] (p - p_0)$$

- the maximum enthalpy of solid ice:

$$h_i^{\max}(p) = \max_{T=T_m, \phi=0} h(T, p, \phi) = c_i^p (T_m - T_0) - \frac{\alpha_i T_m}{\rho_i} (p - p_0)$$

- depending on the value of h , the mixture can either be completely solid ($h < h_i^{\max}$) or partially molten ($h \geq h_i^{\max}$):

$$h < h_i^{\max} \quad T = T_m + \frac{h - h_i^{\max}}{c_i^p - \frac{\alpha_i}{\rho_i} (p - p_0)} \quad \phi = 0$$

$$h \geq h_i^{\max} \quad T = T_m \quad \phi = \frac{h - h_i^{\max}}{L_0 + (c_w^p - c_i^p)(T_m - T_0) + \left[\frac{1 - \alpha_w T_m}{\rho_w} - \frac{1 - \alpha_i T_m}{\rho_i} \right]}$$

- selfconsistently evaluates amount of melt & its subsequent evolution

Numerical model

- ▶ impermeable limit of 2-phase thermal convection eqs.
- ▶ enthalpy method to treat the melting/freezing process
- ▶ ice viscosity: composite rheology, effect of melt, min/max cutoff ($10^{12}/10^{24}$ Pa s)

$$\frac{1}{\eta_i} = \frac{1}{\eta_{\text{diff}}^v} + \frac{1}{\eta_{\text{diff}}^b} + \frac{1}{\eta_{\text{disl}}} + \frac{1}{\eta_{\text{gbs}} + \eta_{\text{bs}}}$$

$$\eta_j = \frac{1}{2} \frac{d^{m_j} T^{l_j}}{A_j \sigma_{\text{II}}^{\eta_j - 1}} \exp\left(\frac{E_j}{RT}\right)$$

$$\eta = \min\{\max[\eta_i \exp(-\gamma_m \phi), \eta_{\min}], \eta_{\max}\}$$

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- ▶ enthalpy method to treat the melting/freezing process
- ▶ ice viscosity: composite rheology, effect of melt, min/max cutoff ($10^{12}/10^{24}$ Pa s)
- ▶ thermal conductivity: function of temperature T , phase (solid or liquid), and composition (ice or clathrate):

1 conductivity of the solid phase (ice + clathrate):

$$k_{i,c} = (1 - C) \left(\frac{k_{i,1}}{T} + k_{i,2} \right) + Ck_c$$

2 mixture conductivity:

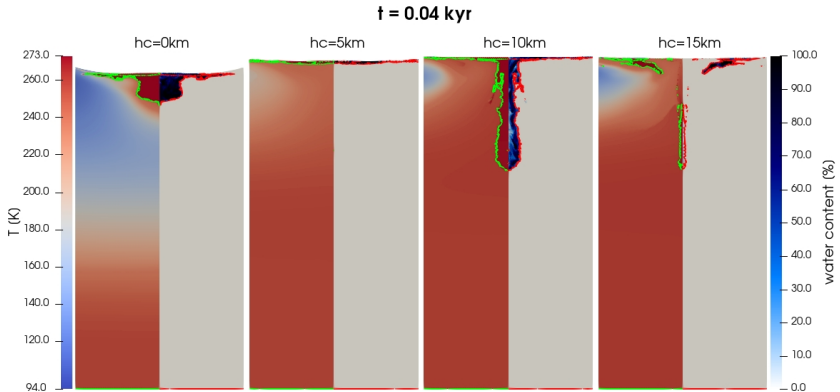
$$k = \phi k_w + (1 - \phi) k_{i,c}$$

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- ▶ thermal conductivity: function of temperature T , phase (solid or liquid), and composition (ice or clathrate):
- ▶ cylindrical geometry, FEniCS (Logg et al., 2012, Alnaes et al., 2015)
- ▶ data from Wakita et al. (2023): T , water content, clathrates distribution, crater morphology
- ▶ key parameters:
 - thickness of the clathrate layer: $h_c = 0 - 15$ km
 - impactor size: $d_i = 3 - 4$ km
 - grain size (ice viscosity): $d = 0.5 - 2.0$ mm
 - surface porosity: $\xi = 0 - 20\%$
 - tidal heating: $Q_m = 0 - 5 \times 10^{-8}$ W/m³

Results - effect of clathrate layer thickness

$d_i = 4$ km, $h_c = 0, 5, 10, 15$ km, $d = 1.0$ mm

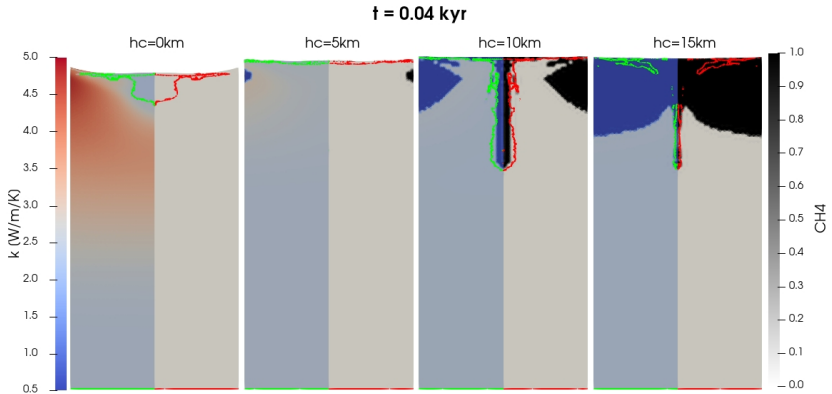


Post-impact melt geometries for a range of h_c :

- 0 km deep (~ 5 km) melt pool
- 5 km very shallow (~ 1 km) melt pool
- 10 km narrow ($\sim 1 - 2$ km) melt column around the symmetry axis
& very shallow (~ 1 km) melt pool
- 15 km very narrow (< 1 km) melt column around the symmetry axis
& shallow ($\sim 2 - 3$ km) melt pool

Results - effect of clathrate layer thickness

$d_i = 4$ km, $h_c = 0, 5, 10, 15$ km, $d = 1.0$ mm

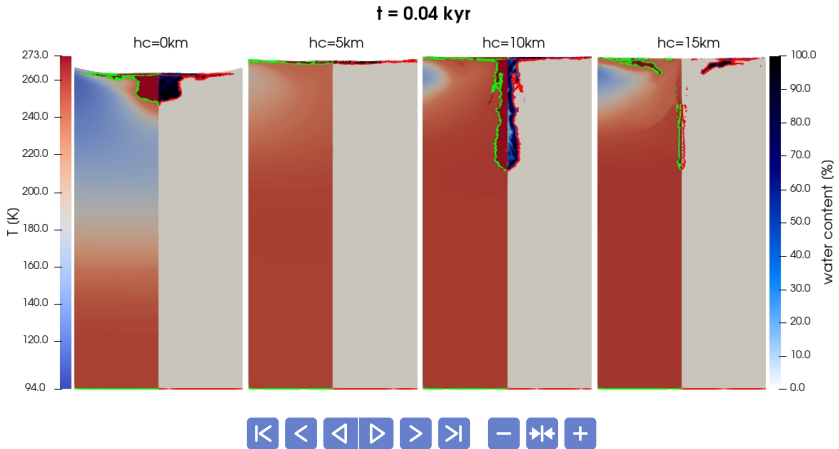


Post-impact clathrates distribution: effect on thermal conductivity:

- 0 km no clathrates, $k \in \langle 2.2, 4.8 \rangle$ W/m/K
- 5 km clathrate layer destroyed at the impact site, $k \in \langle 0.5, 2.9 \rangle$ W/m/K
- 10 km clathrate layer breached through, $k \in \langle 0.5, 2.5 \rangle$ W/m/K
- 15 km clathrate layer almost intact, $k \in \langle 0.5, 2.4 \rangle$ W/m/K

Results - effect of clathrate layer thickness

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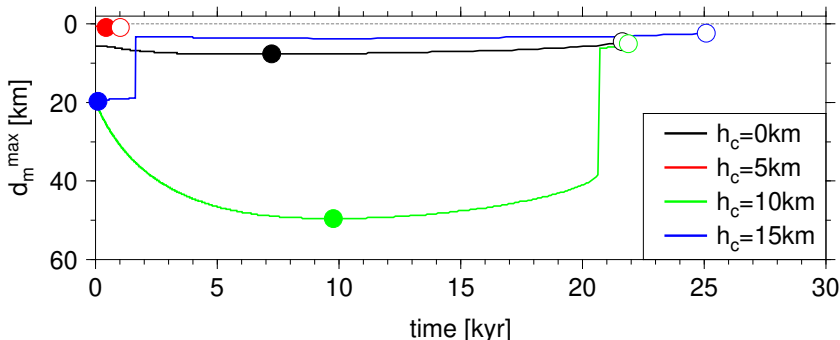


Melt evolution depends on the value of h_c :

- 0 km melt freezes within the stagnant lid in a few tens of kyr
- 5 km melt freezes within the stagnant lid in a few kyr
- 10 km initial deep melt transported downwards but freezes on the way
- 15 km initial deep melt does not move and freezes in a few tens of kyr

Results - effect of clathrate layer thickness

$d_i = 4$ km, $h_c = 0, 5, 10, 15$ km, $d = 1.0$ mm



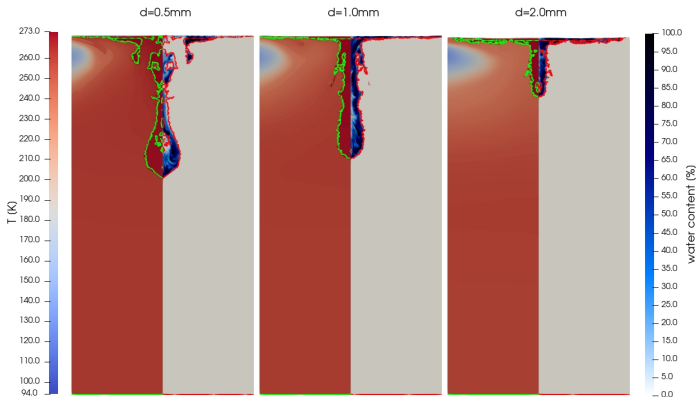
- maximum depth reached by melt $d_m^{\max}$ (full circles)
- freezing time t_f (empty circles)

h_c [km]	0	5	10	15
$d_m^{\max}$ [km]	7.6	0.9	49.6	19.7
t_f [kyr]	21.7	1.1	22.1	25.2

Results - effect of grain size (viscosity)

$d_i = 4 \text{ km}$, $h_c = 10 \text{ km}$, $d = 0.5, 1.0, 2.0 \text{ mm}$ ($2\text{e}14$, $6\text{e}14$, $3\text{e}15 \text{ Pa s}$)

$t = 0.04 \text{ kyr}$



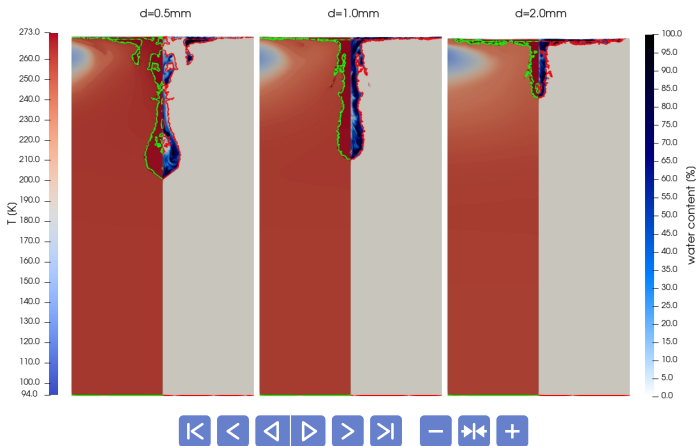
Melt geometries:

- ▶ small grain size (small viscosity) → deeper melt penetration during the impact

Results - effect of grain size (viscosity)

$d_i = 4$ km, $h_c = 10$ km, $d = 0.5, 1.0, 2.0$ mm ($2e14, 6e14, 3e15$ Pa s)

$t = 0.04$ kyr



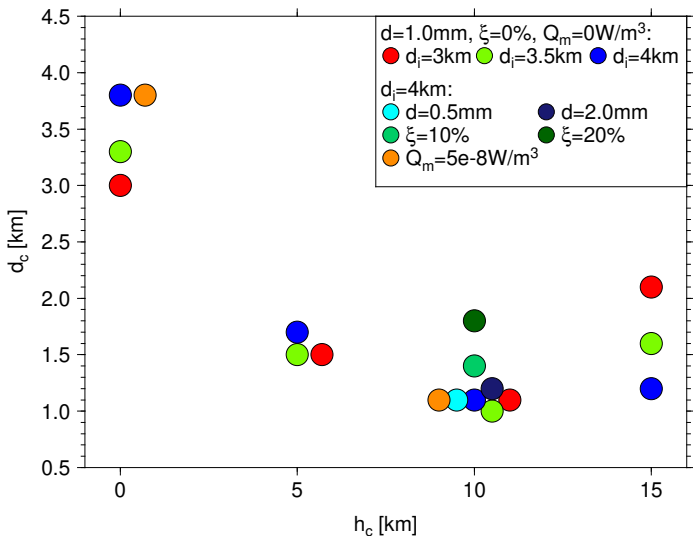
Melt evolution strongly depends on the value of d :

0.5 mm melt reaches the ocean in less than 1 kyr

1.0 mm melt freezes on the way to the ocean

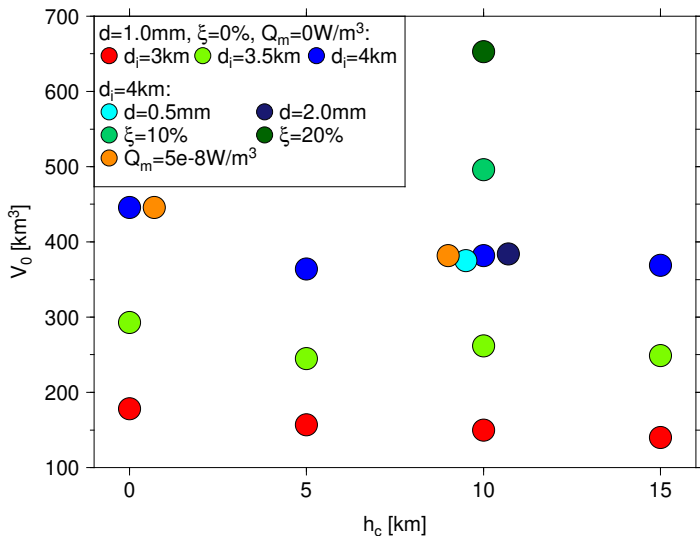
2.0 mm melt freezes within the stagnant lid in ~ 15 kyr

Results - crater depth d_c



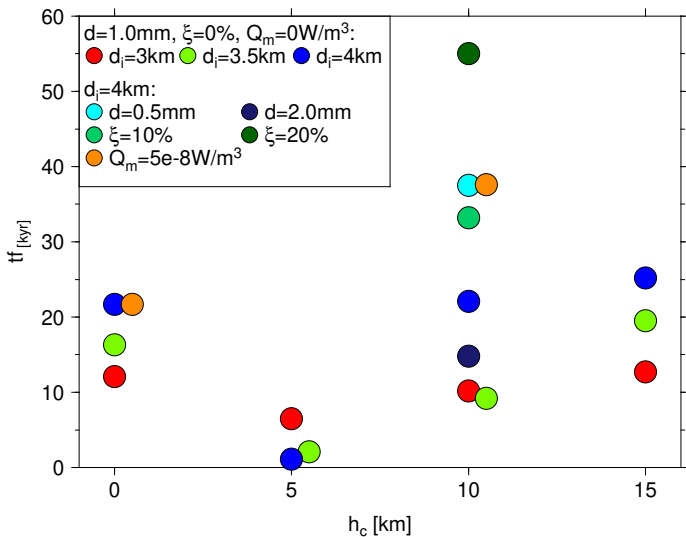
- depends primarily on the presence or not of the clathrate layer
- h_c , d_i , and ξ play secondary roles

Results - initial melt volume V_0



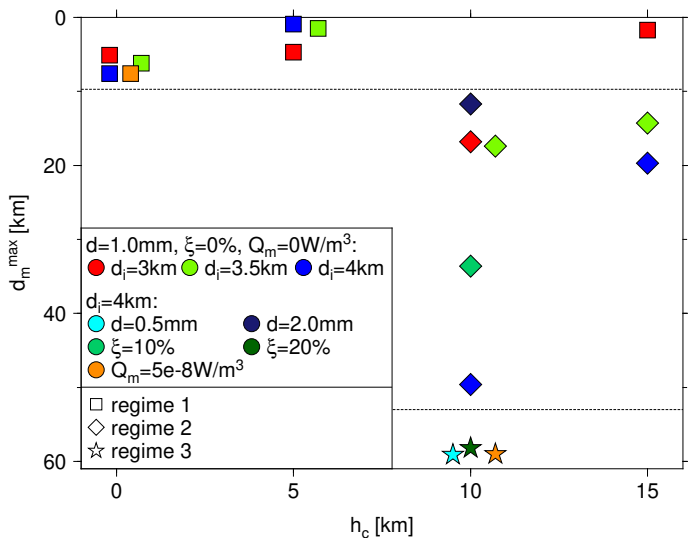
- depends mainly on d_i and ξ
- presence or absence of clathrates only slightly modulates V_0

Results - freezing time t_f



- depends on melt distribution (given by h_c) & melt volume V_0 (governed by d_i and ξ)
- $t_f > 30$ kyr: due to melt presence in the warm parts of the ice shell

Results - maximum depth reached by melt $d_m^{\max}$



- 1: □ melt freezes within the stagnant lid without significant movement
- 2: ◇ deep melt initially present but does not reach the ocean
- 3: ☆ initial deep melt gets to the ocean (surface-to-ocean-exchange)

Conclusions:

- ▶ we investigated evolution of melt pools that potentially lay beneath the Selk-sized crater on Titan
 - ▶ clathrates determine melt distribution which governs melt evolution
 - ▶ $h_c=0$ & 5 km: melt freezes in the stagnant lid in a few tens of kyr
 - ▶ $h_c=10$ & 15 km: deep melt is generated:
 - most cases: freezes in different parts of the shell in a few tens of kyr
 - few special cases: surface-to-ocean-exchange
 - only a few impacts on Titan could lead to surface-to-ocean exchange
- Q2 strong limitation to ocean's habitability potential (unless organics come from the core)
- Q1 ~half of our results: melt freezes at shallow depths
- NASA's Dragonfly mission may be able to sample organics that reacted with impact induced liquids during the formation of Selk

Thank you for your attention!

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