THE QUEST FOR LIFE ON ICY MOONS

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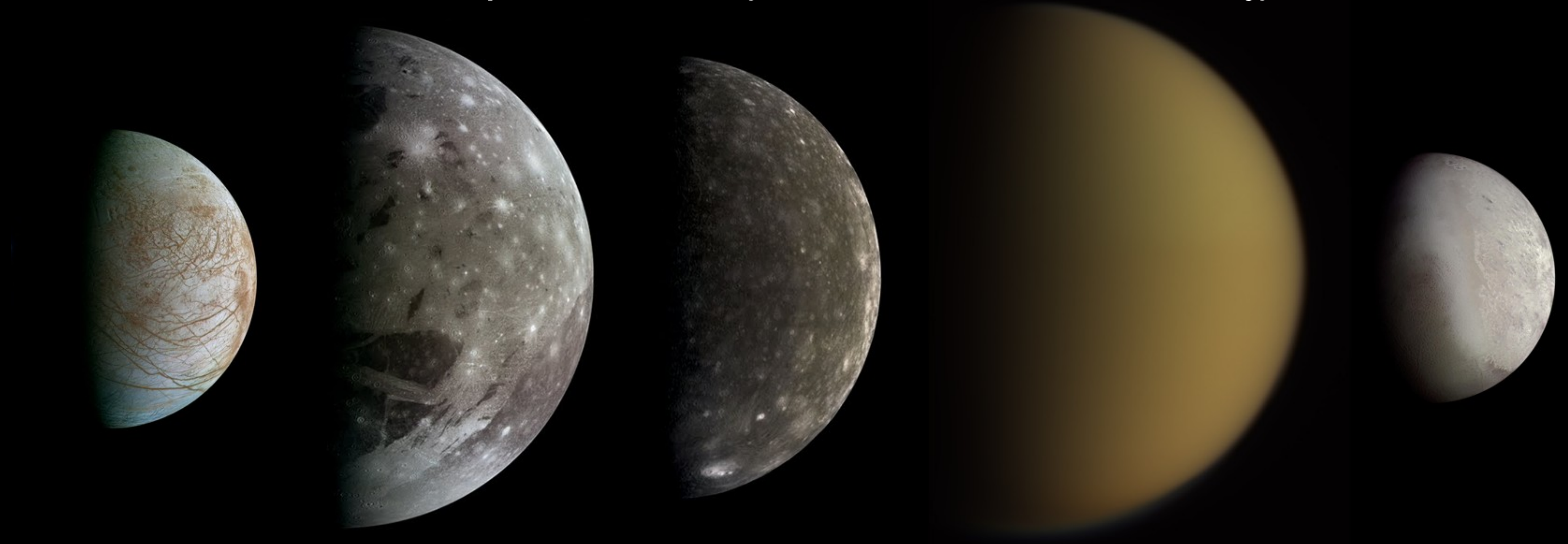
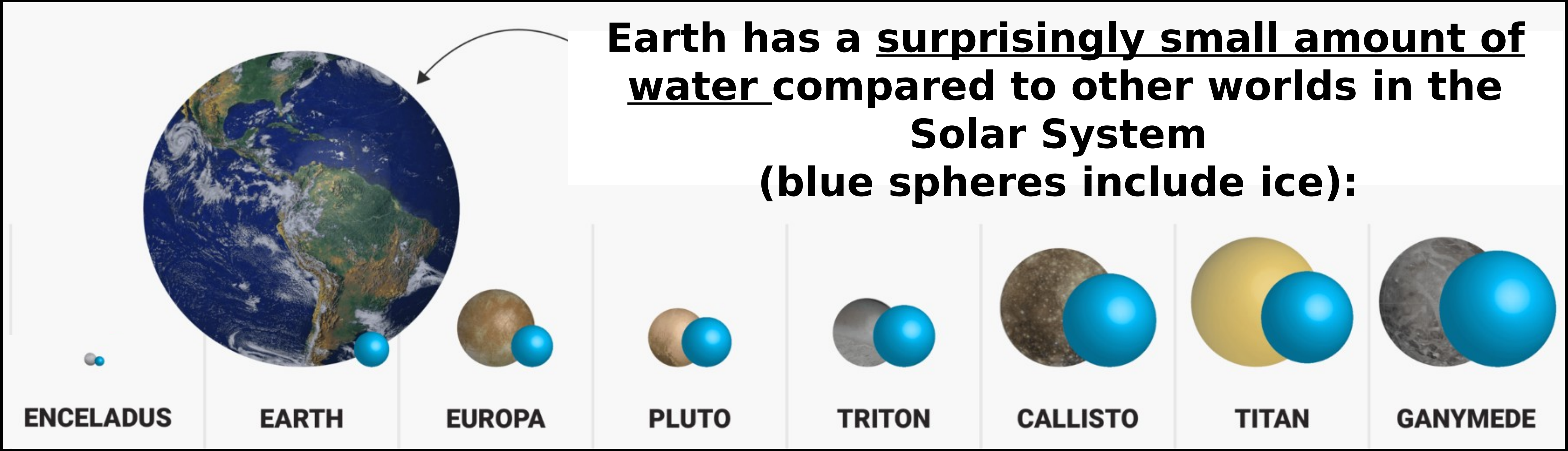


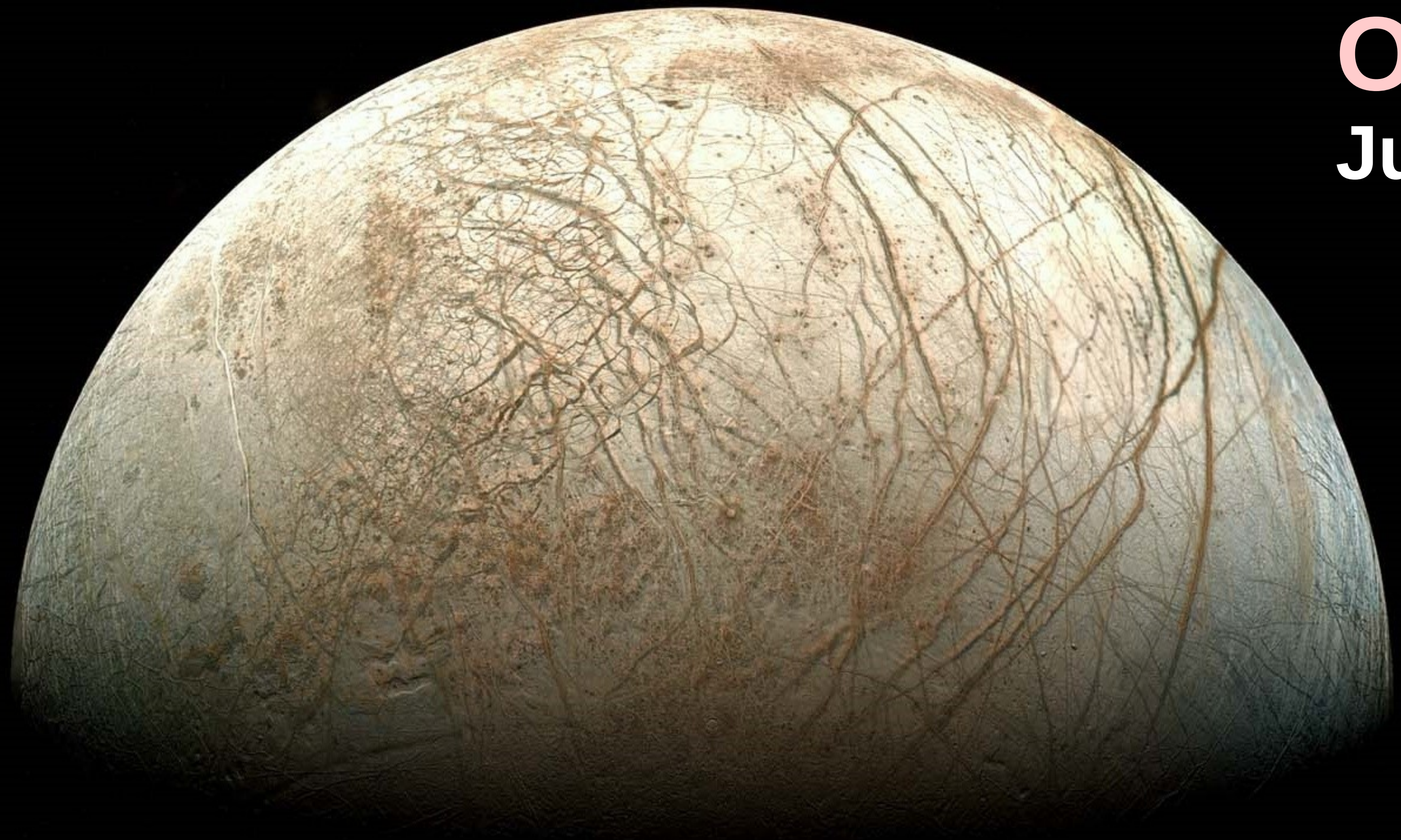
Ocean Worlds across our Solar System

Earth has a surprisingly small amount of water compared to other worlds in the Solar System
(blue spheres include ice):



% H_2O							
68%	0.12%	18%	62%	65%	33%	44%	69%

Many of these worlds have an ice crust with a deep subsurface ocean

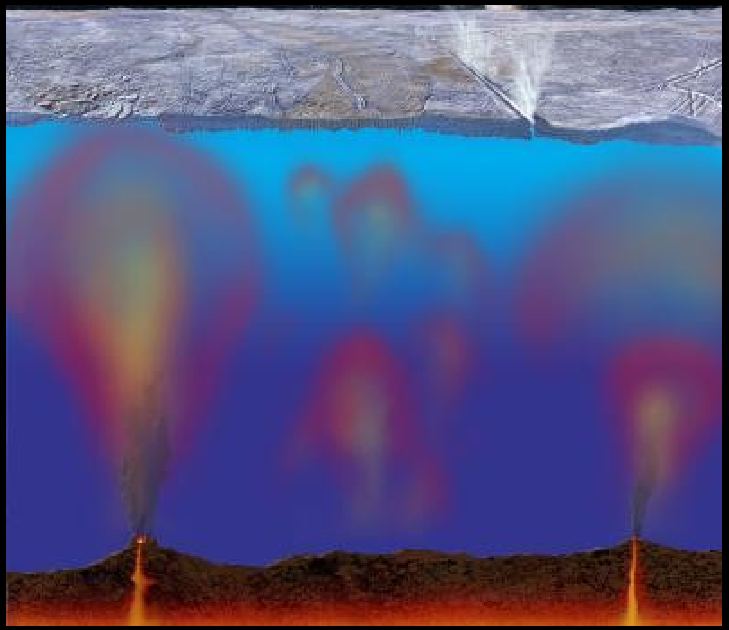


Ocean under ice

Jupiter's moon Europa

Ice crust 10's of km thick
Subsurface H_2O ocean

Geological activity

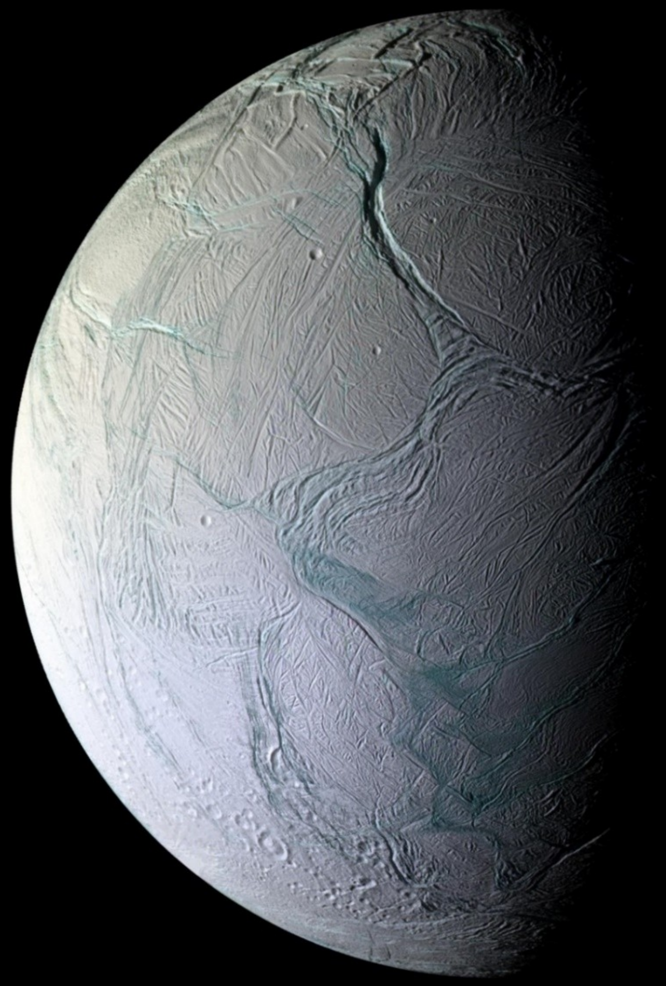


Possible Europa hydrothermal vent model

Image credits: NASA / JPL / Space Sciences Institute / Gordan Ugarkovic

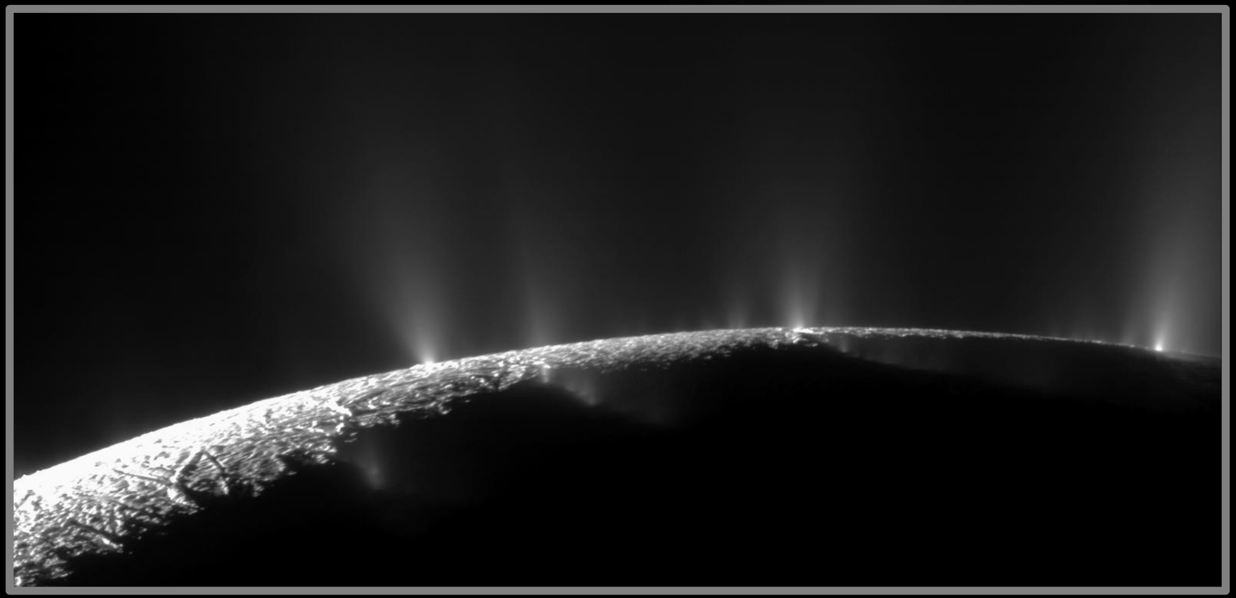
Water jets into space

Saturn’s moon Enceladus



- **Subsurface H_2O reservoir**
- **Geologic activity**
- **Organic molecules detected** (hydrogen cyanide, organic compounds detected in the analysis included acetylene, propylene and ethane)

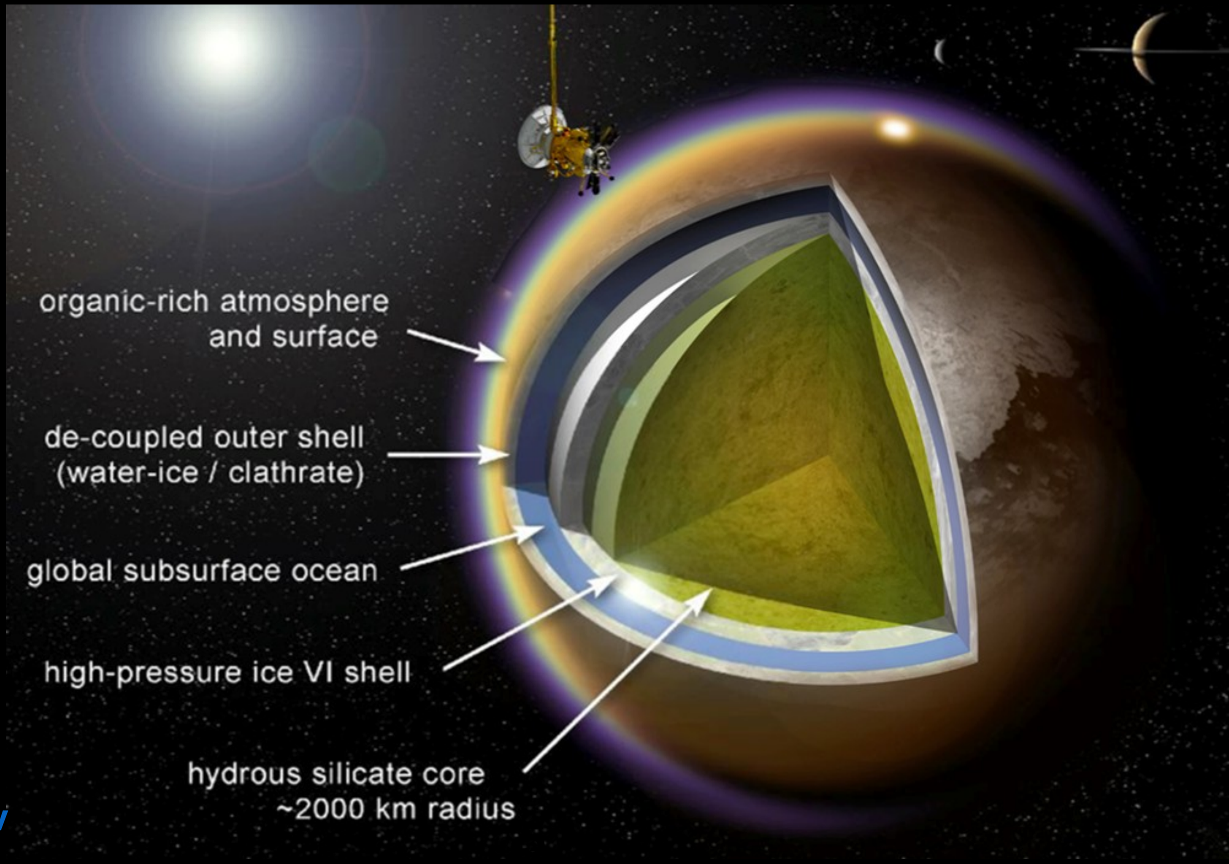
Backlit views showing H_2O jets



Planetary photojournal image PIA11133, PIA12713, and PIA11688: http://photojournal.jpl.nasa.gov
Image credits: NASA / JPL / Space Sciences Institute

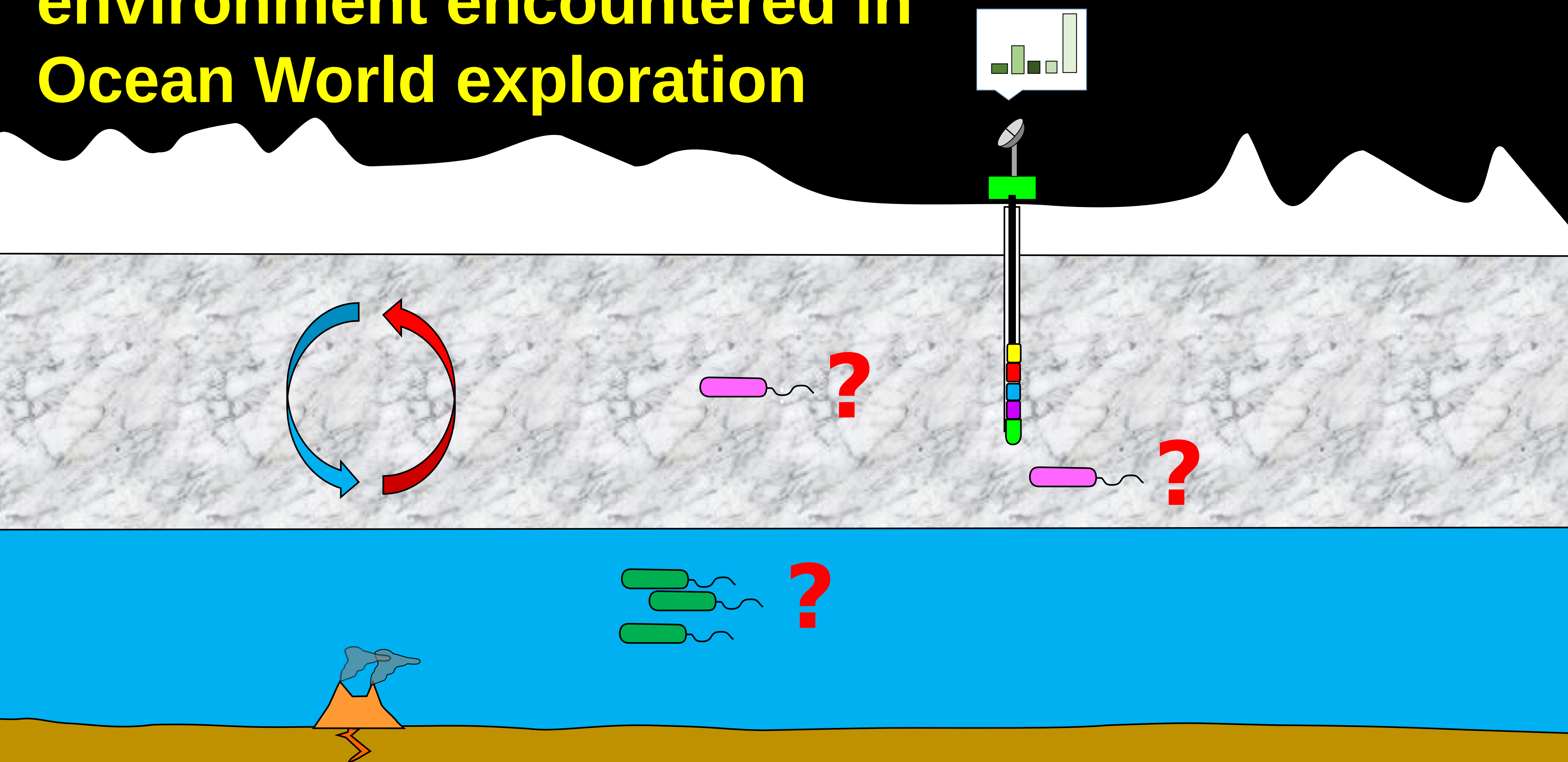
Organic World
Saturn's moon Titan

Thick atmosphere
Layer of organic molecules
Subsurface ocean 10x bigger than Earth's!



Planetary photojournal image PIA07774: http://photojournal.jpl.nasa.gov
Image credits: NASA / JPL / Space Sciences Institute

Deep Ice will be the first habitable environment encountered in Ocean World exploration



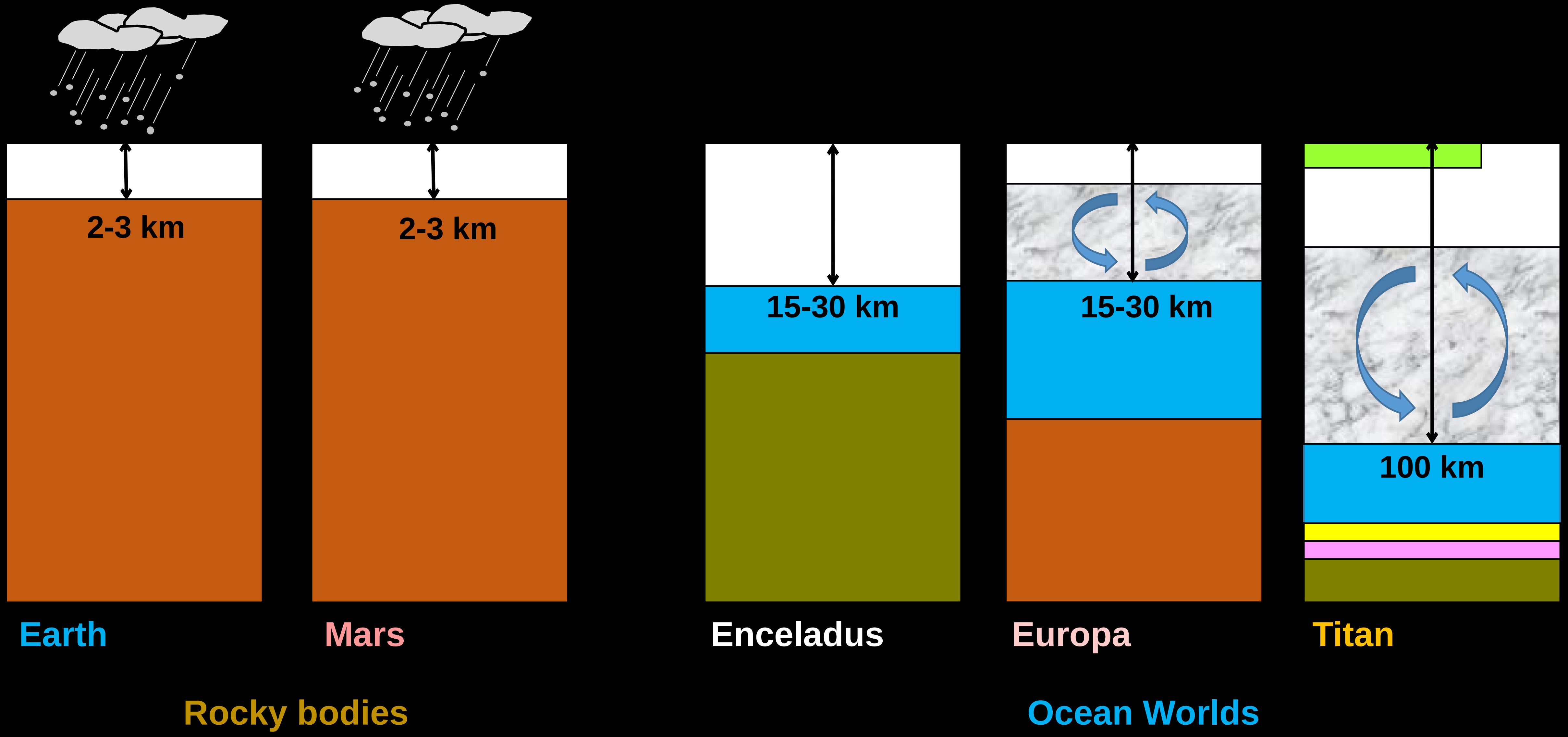
The Deep Ice

- No Sunlight
- High Pressure
- Low Temperature
- Physical microenvironments
- Chemical concentration

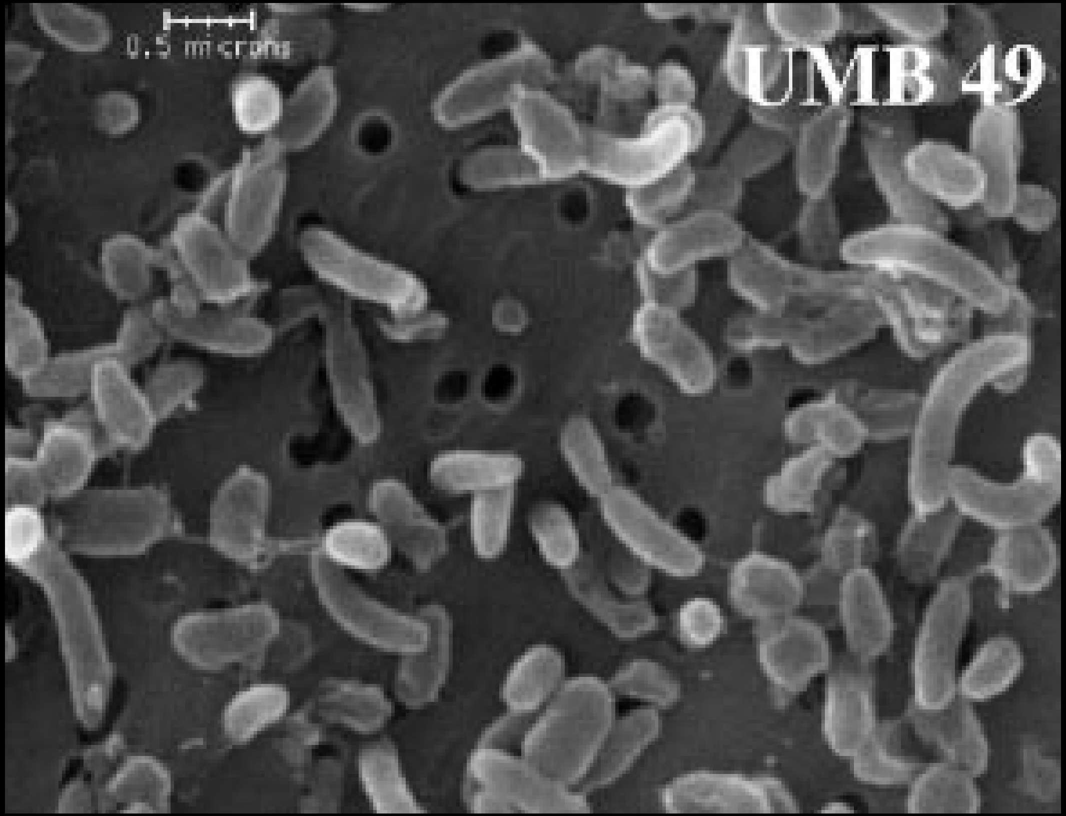
Deep Ice in the Solar System

Ocean Worlds have very deep ice; the largest have ice convection

(All figures show log scale from surface)



Life deep in the Greenland Ice Sheet

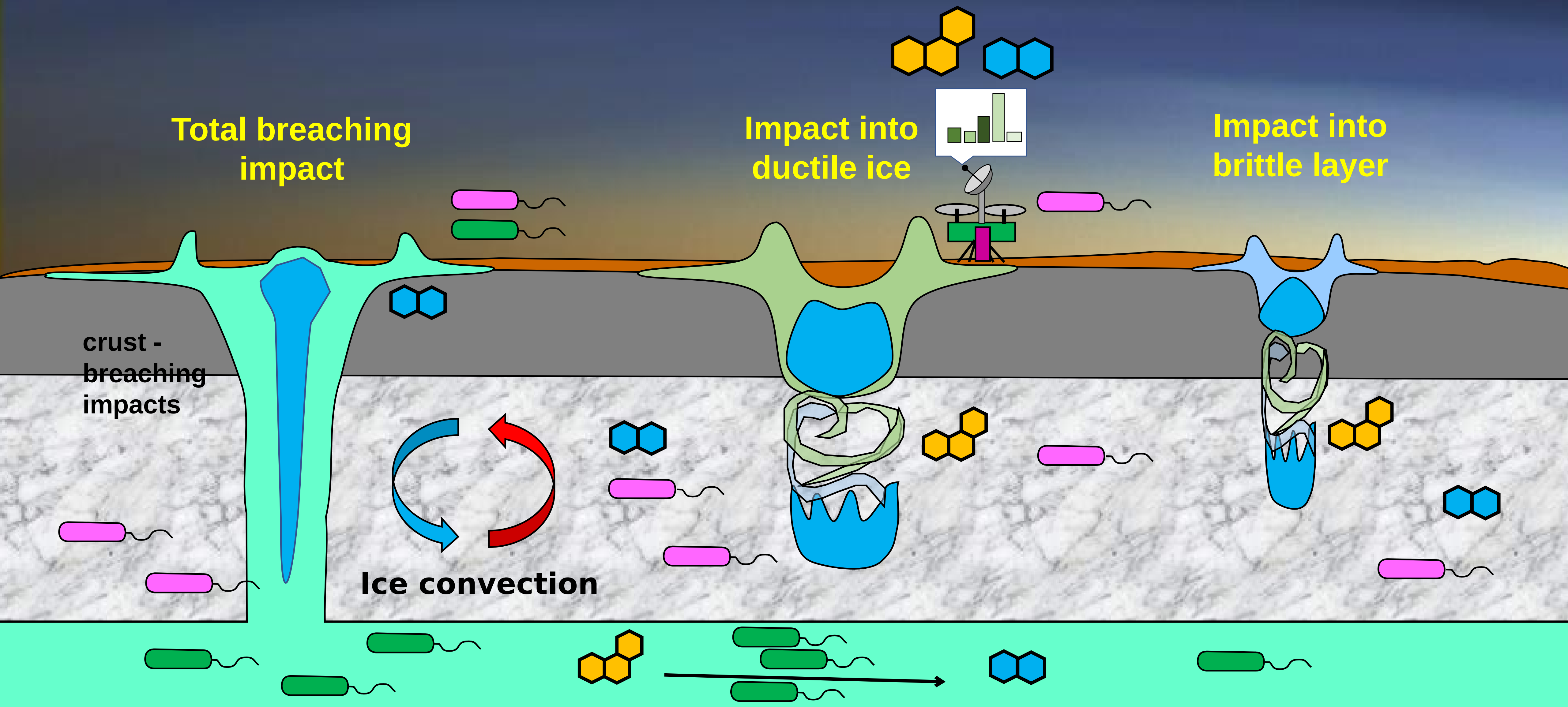


Herminiimonas glaciei UMB49 isolated from 3 km beneath the Greenland ice sheet GISP2 ice core, (264 K, 30 MPa)
120,000 year old ice

Image credit (above): Reto Stöckli, NASA GSFC (via NASA Earth Observatory)

Reference and left image credit:
Miteva and Benchley (2005). "Detection and isolation of ultrasmall micro-organisms from a 120,000-year-old Greenland glacier ice core".
App. Env. Microbio. 71, 7806-7818.

Impacts into deep ice and ocean habitats



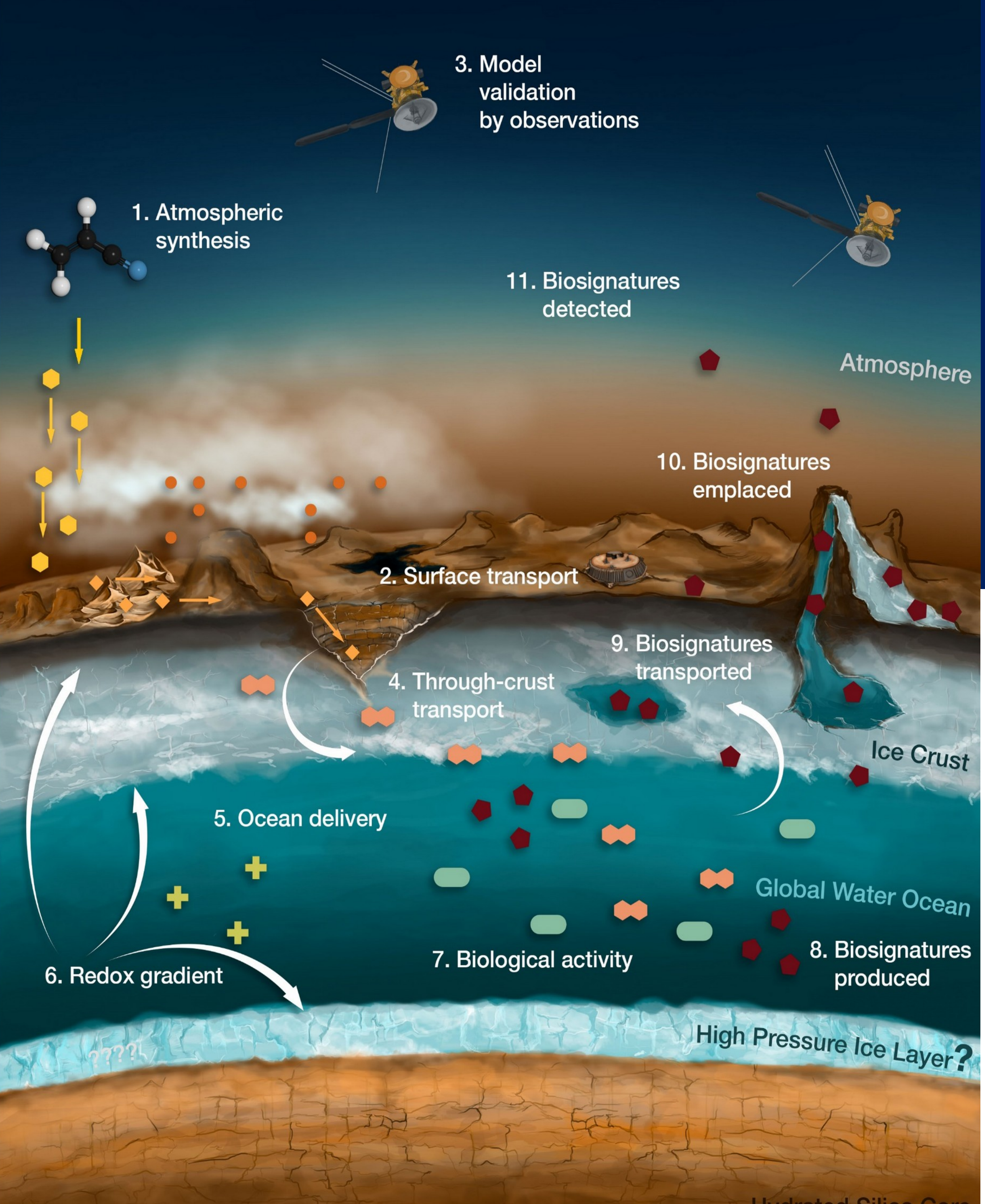
Jet Propulsion Laboratory
California Institute of Technology

Habitability of Hydrocarbon Wor
Titan and Beyond

NASA Astrobiology Institute Cycle 8

Rosaly Lopes, Michael J. Malaska, Steve D. Vance, Rob Hodyss, D. Meyer-Dombard, S. Fagents, and the NAI Team

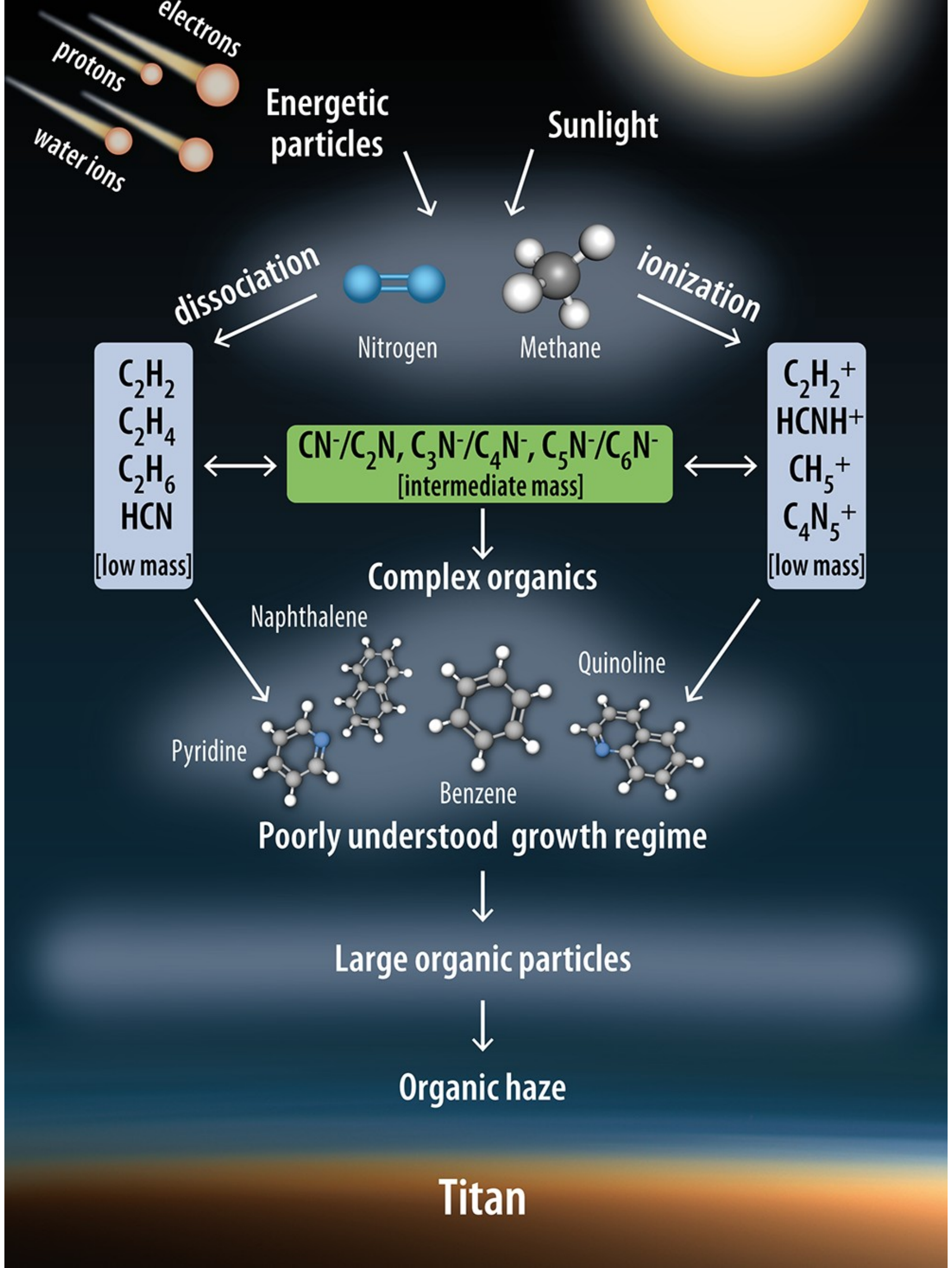
What habitable environments exist on Titan and what resulting potential biosignatures should we look for?



Follow the Organics

Organics □ Surface □ Ocean □ Biota
Biota□ Biosignatures □ Surface

HABITABILITY OF HYDROCARBON WORLDS
TITAN AND BEYOND



(From Conor Nixon: *ACS Earth Space Chem.*)

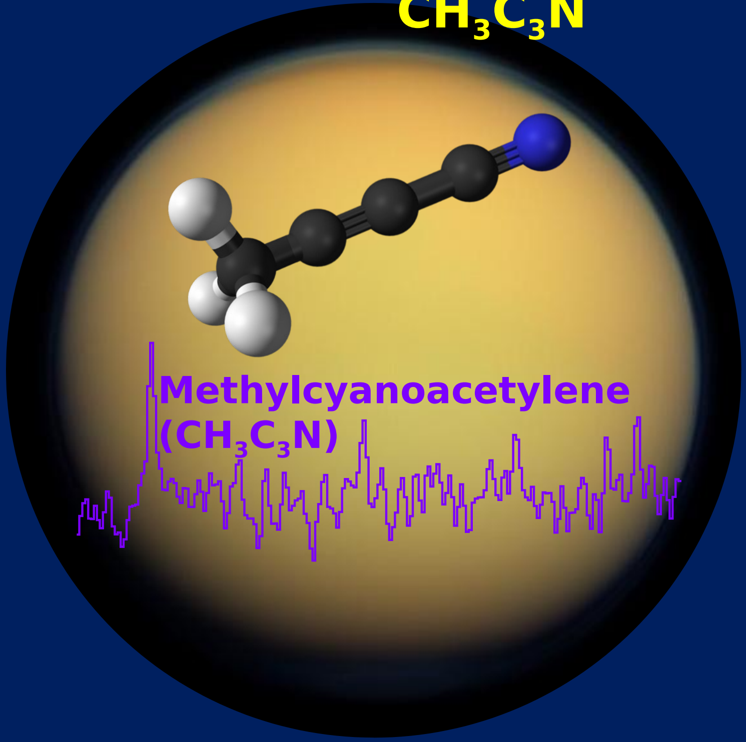
https://doi.org/10.1021/acsearthspacechem.2c00041

Atoms	Hydrogen and Hydrocarbons		Nitrogen Compounds		Oxygen Compounds	
2	H_2		N_2		CO	
3			HCN	HNC	H_2O	CO_2
4	C_2H_2		C_2N_2			
5	CH_4	C_3H_2	HC_3N			
6	C_2H_4	C_4H_2	CH_3CN			
7	CH_3CCH	CH_2CCH_2	C_2H_3CN			
8	C_2H_6		C_3H_3CN			
9	C_3H_6		C_2H_5CN			
10+	C_3H_8	C_6H_6				

Methylcyanoacetylene (CH_3C_3N) detection (Thelen et al. 2020)

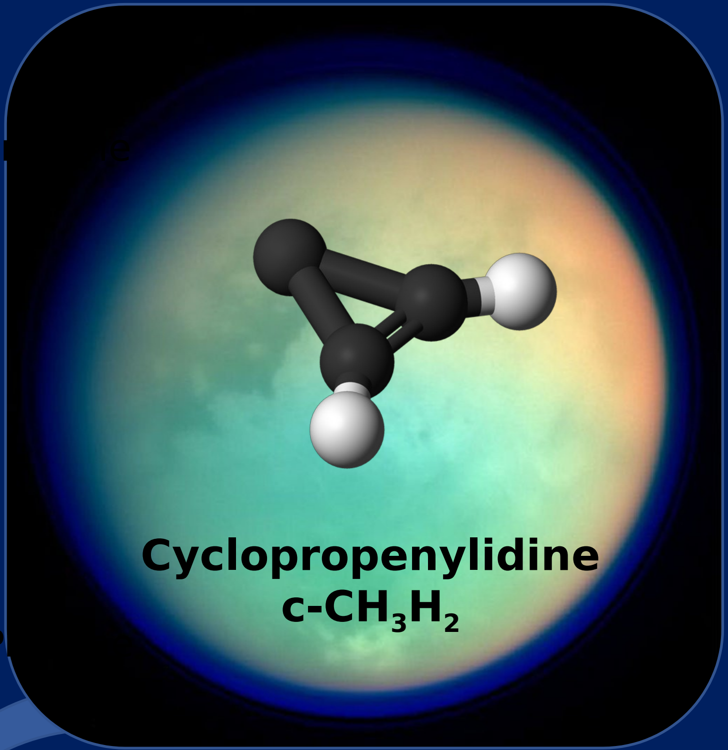
Cyclopropenylidene (c-C_3H_2) detection (Nixon et al. 2020)

Heaviest "polar" molecule found so far in the atmosphere of Titan - CH_3C_3N



CH_3C_3N detection on Titan by ALMA

A. E. Thelen et al., *The Astrophysical Journal,* 903 (1), L22 (2020).



Cyclopropenylidene

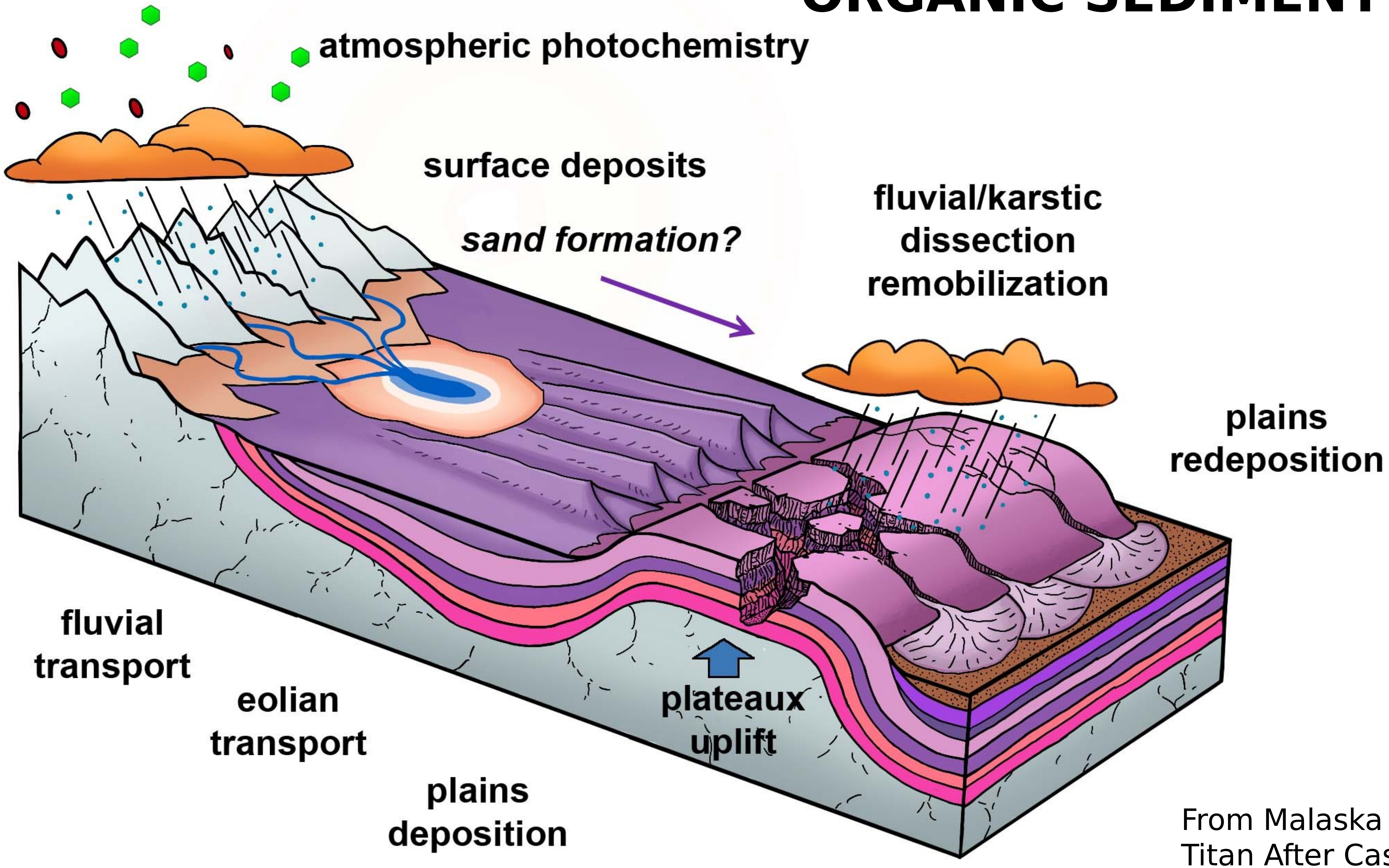
(c-C_3H_2)

a 3-carbon ring, not previously seen in any planetary atmosphere

Nixon et al. (2020), The Astronomical Journal

More detections□
More measurements
□ understanding Titan organic chemistry

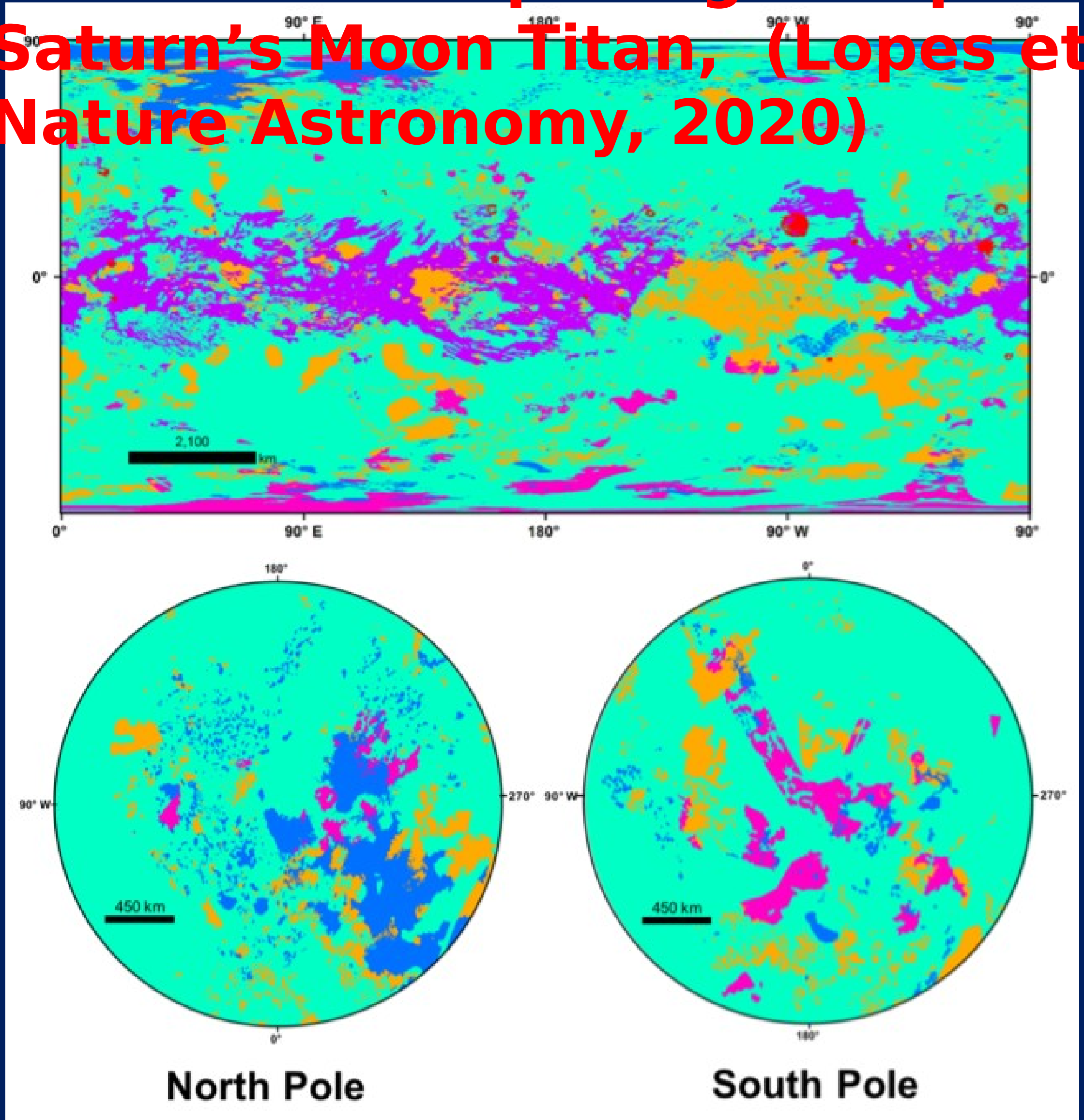
ORGANIC SEDIMENT CYCLE

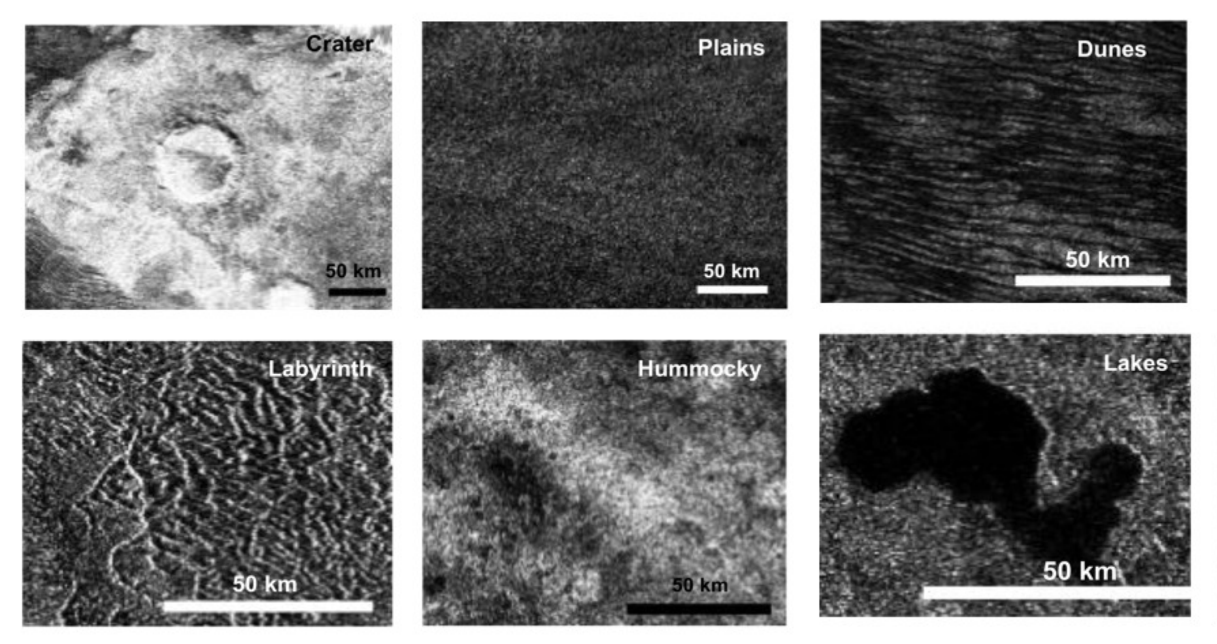


From Malaska et al., 2024,
Titan After Cassini-Huygens,
Elsevier, in press

Titan's surface has vast organic plains

Global Geomorphologic Map of Saturn's Moon Titan, (Lopes et al., Nature Astronomy, 2020)



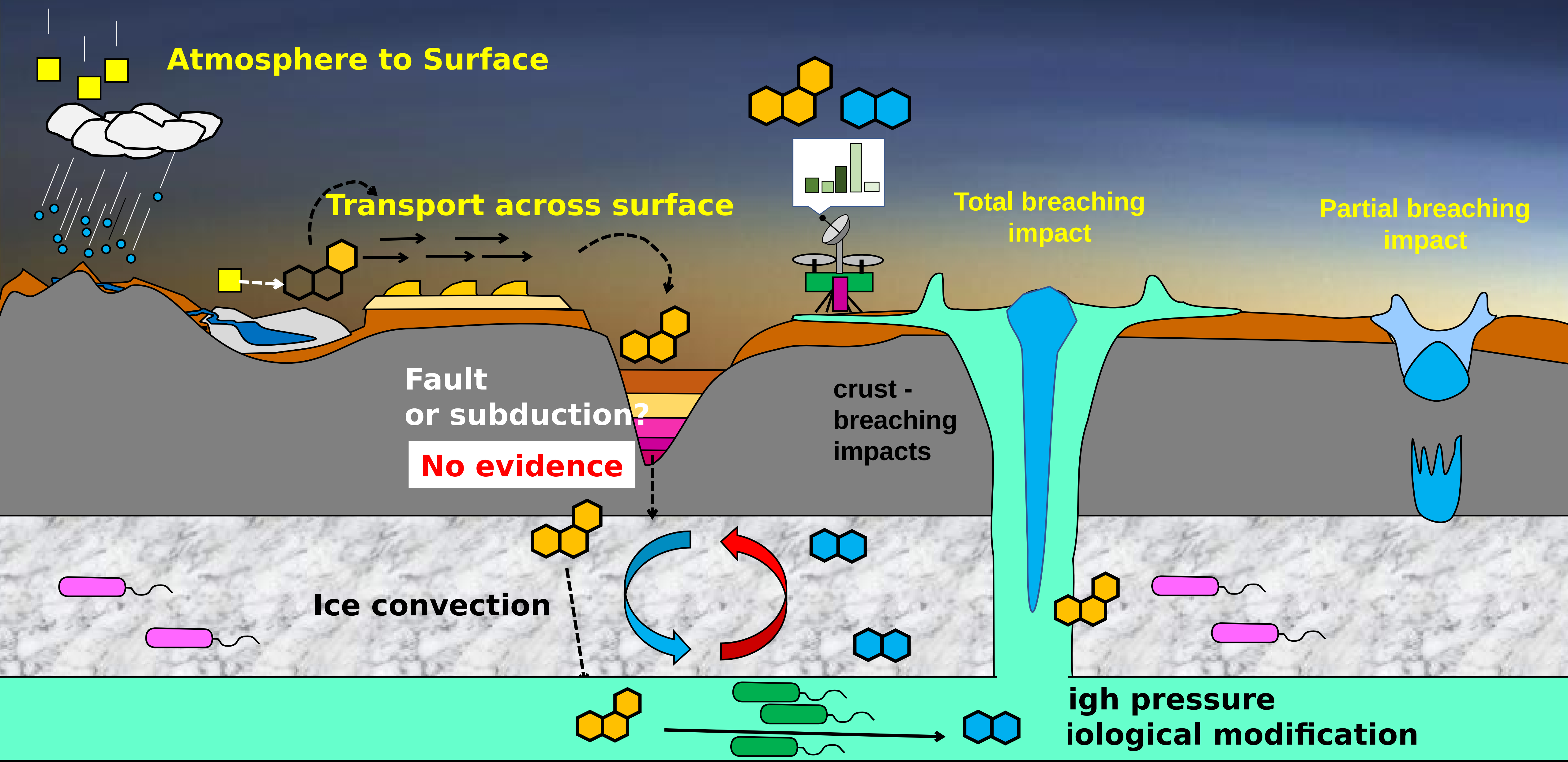


Terrain unit examples

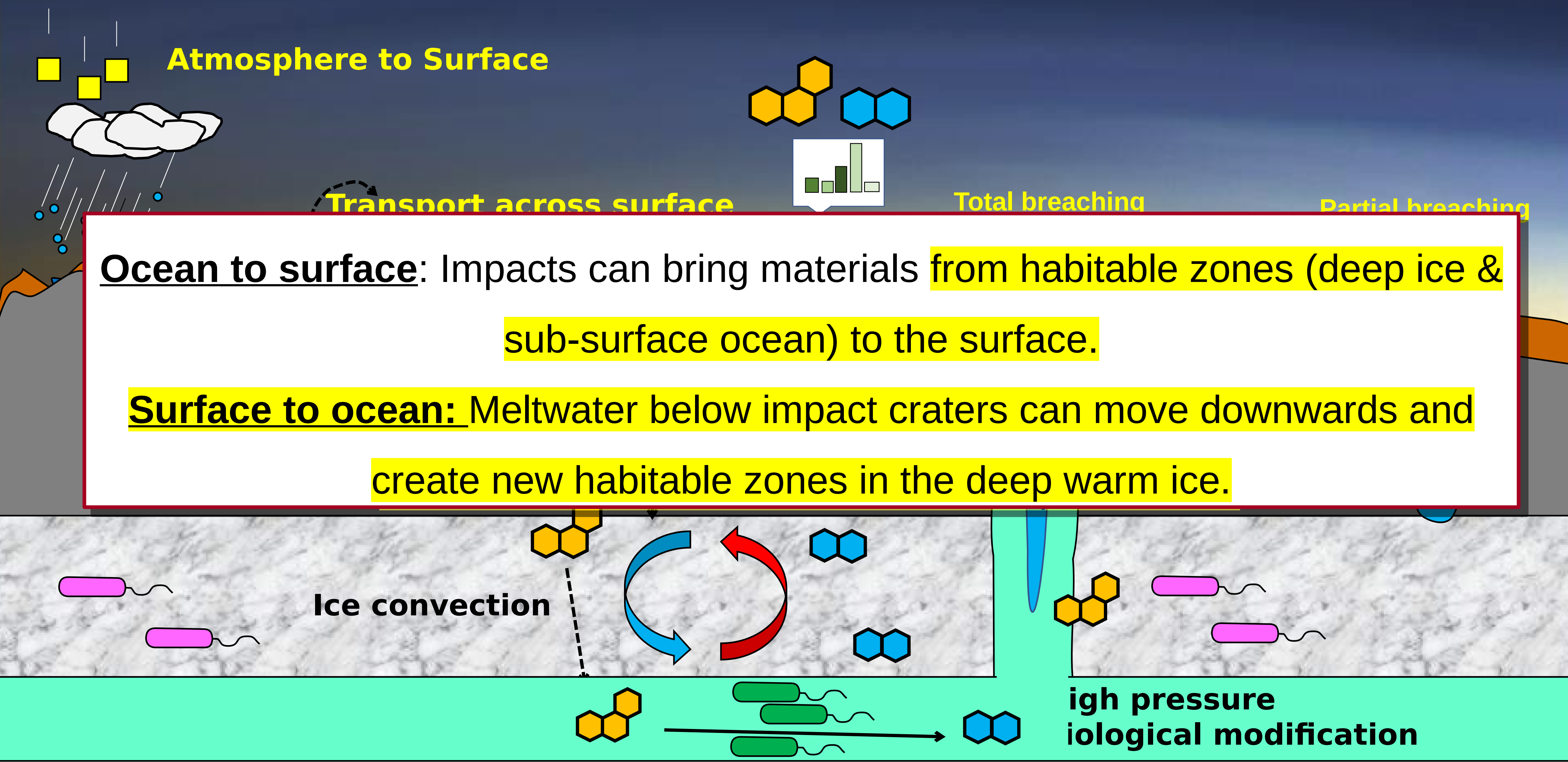
Total Area Percentage

Plains	64.93 %
Dunes	17.46 %
Hummocky	14.21 %
Basin and Lakes	1.47 %
Labyrinth	1.46 %
Craters	0.42 %

GETTING SURFACE ORGANICS INTO THE DEEP ICE AND OCEAN

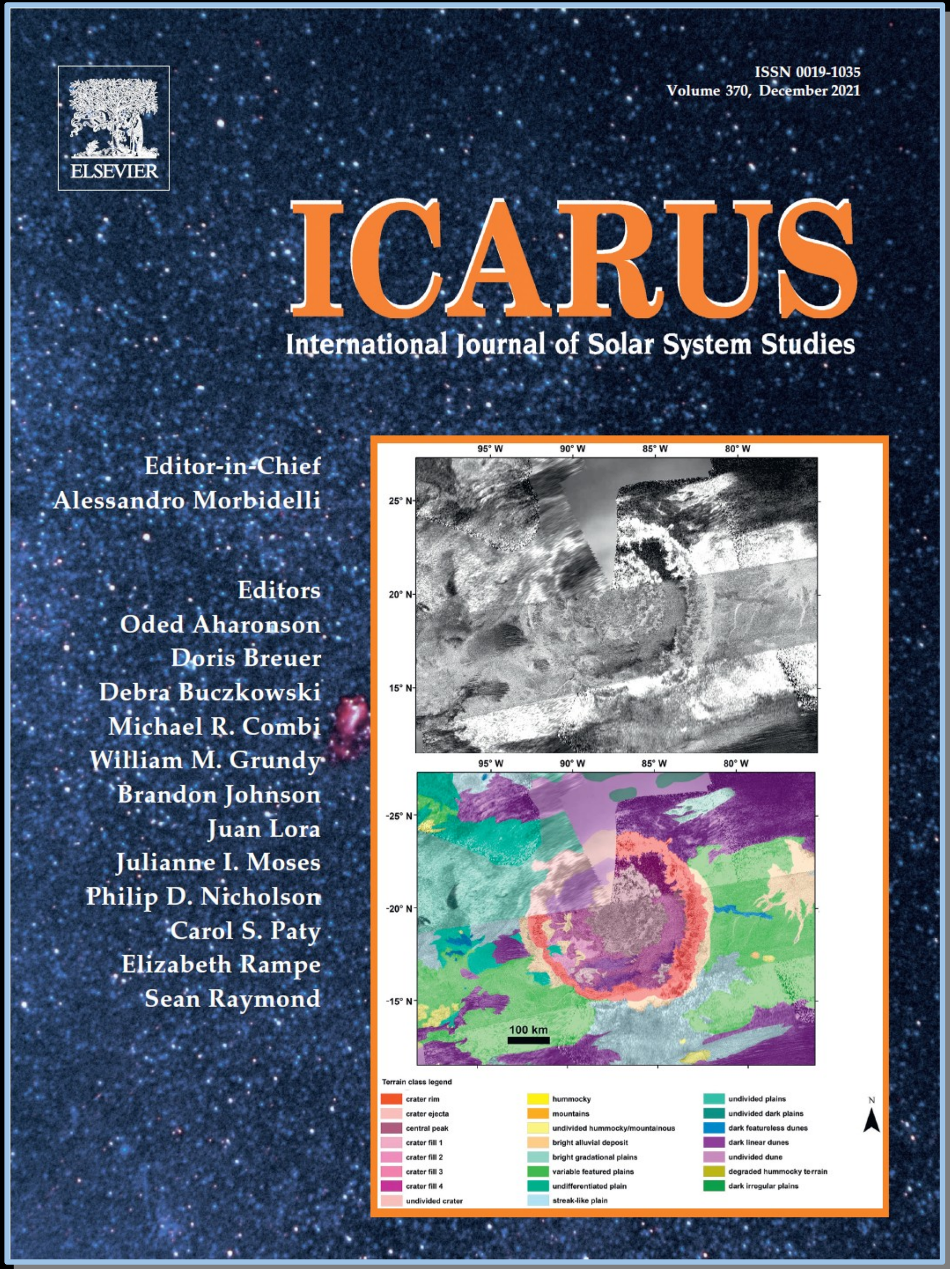


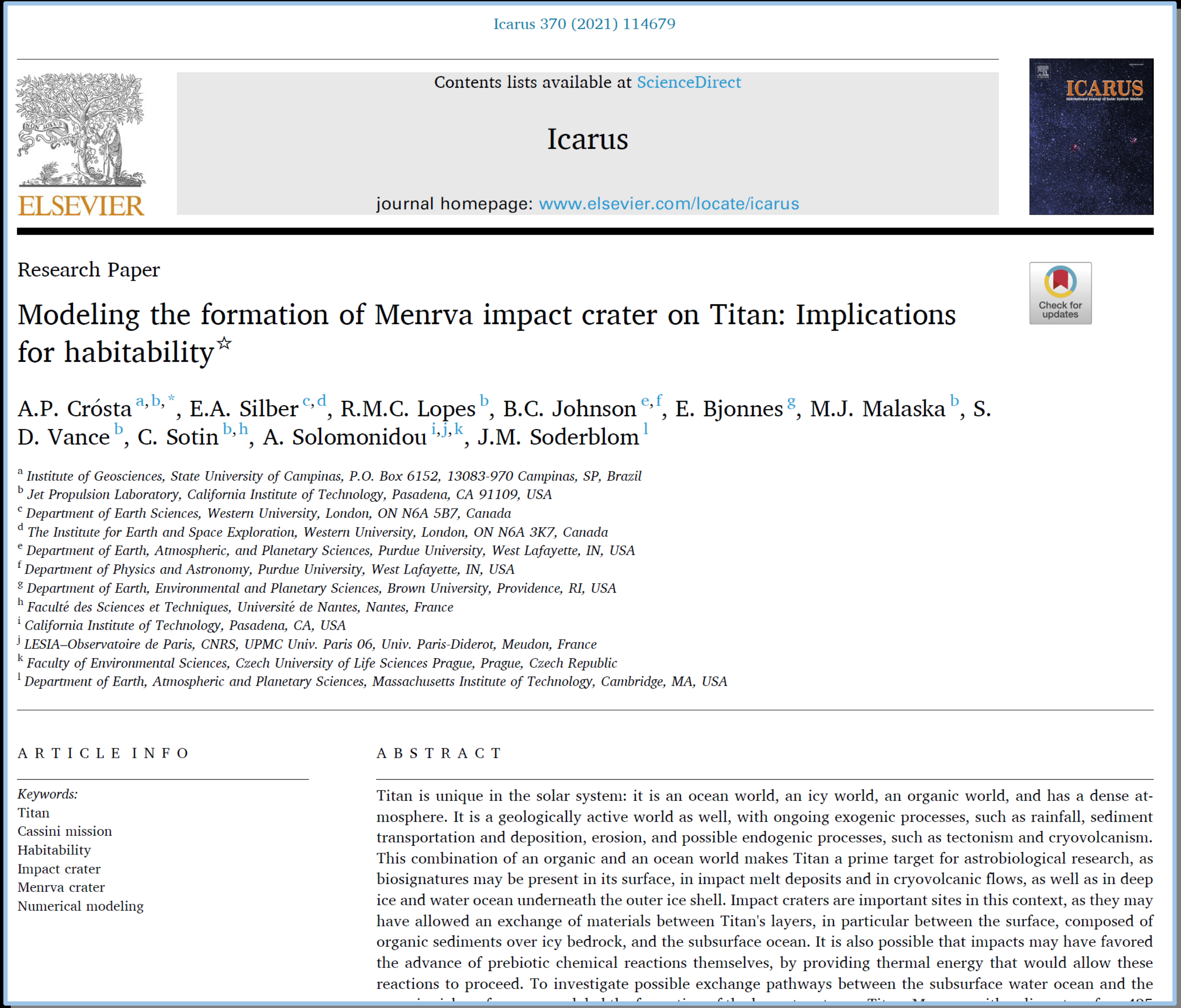
GETTING SURFACE ORGANICS INTO THE DEEP ICE AND OCEAN



<u>Ocean to surface</u>: Impacts can bring materials from habitable zones (deep ice & sub-surface ocean) to the surface.

<u>Surface to ocean:</u> Meltwater below impact craters can move downwards and create new habitable zones in the deep warm ice.





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Research Paper

Modeling the formation of Menrva impact crater on Titan: Implications for habitability☆

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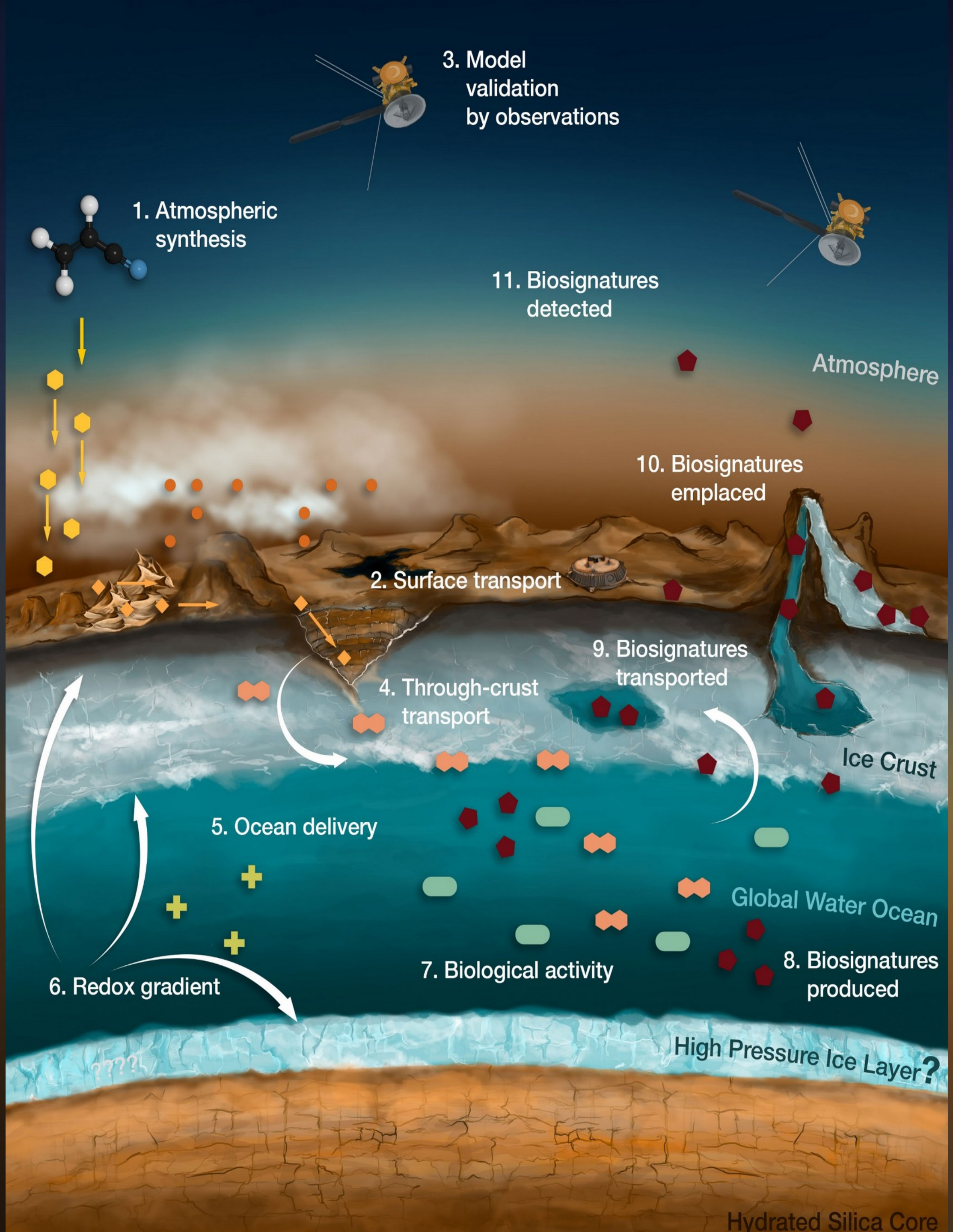
ABSTRACT

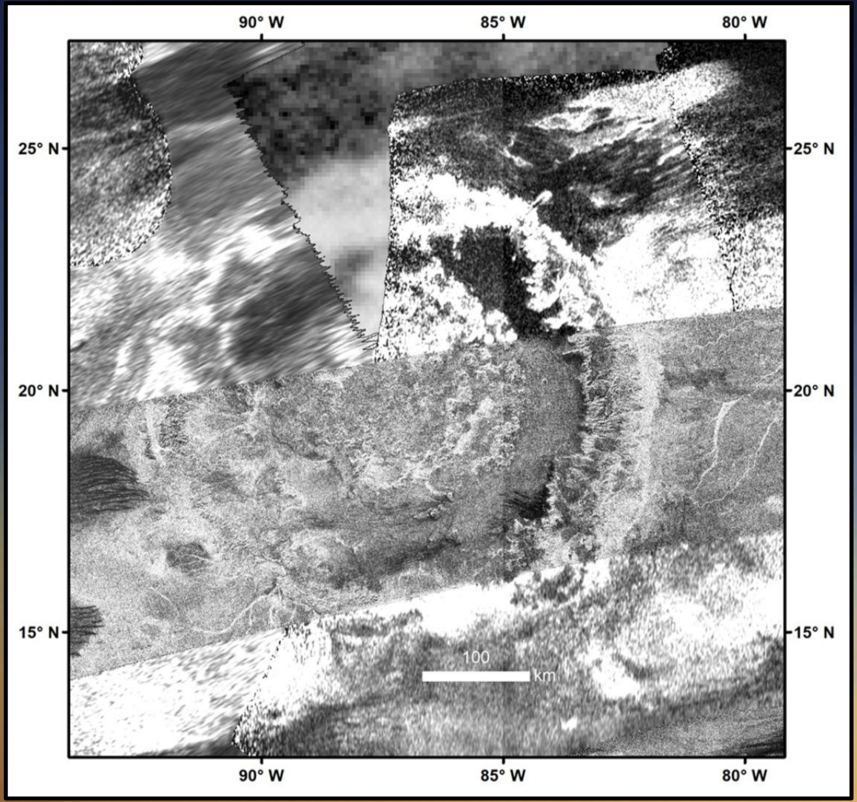
Titan is unique in the solar system: it is an ocean world, an icy world, an organic world, and has a dense atmosphere. It is a geologically active world as well, with ongoing exogenic processes, such as rainfall, sediment transportation and deposition, erosion, and possible endogenic processes, such as tectonism and cryovolcanism. This combination of an organic and an ocean world makes Titan a prime target for astrobiological research, as biosignatures may be present in its surface, in impact melt deposits and in cryovolcanic flows, as well as in deep ice and water ocean underneath the outer ice shell. Impact craters are important sites in this context, as they may have allowed an exchange of materials between Titan's layers, in particular between the surface, composed of organic sediments over icy bedrock, and the subsurface ocean. It is also possible that impacts may have favored the advance of prebiotic chemical reactions themselves, by providing thermal energy that would allow these reactions to proceed. To investigate possible exchange pathways between the subsurface water ocean and the

Crósta et al., 2021, Icarus 370: 114679.



Transport of materials: Surface￿Ocean

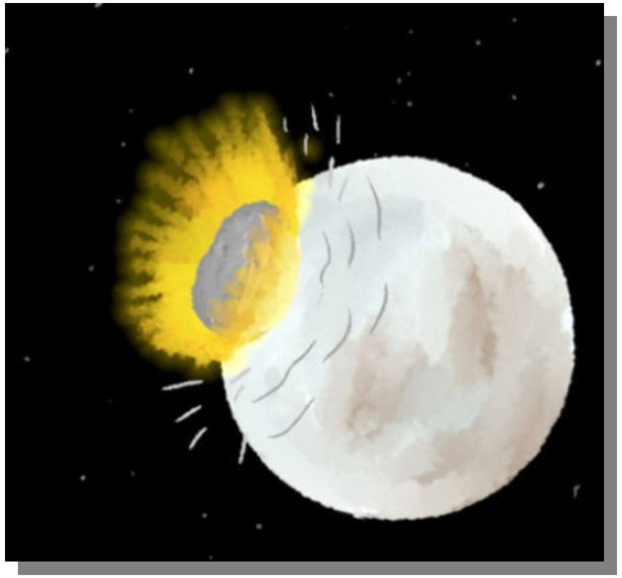
Can large impacts breach the ice shell and cause mixing?



Menrva (425 km in diameter)

GETTING SURFACE ORGANICS INTO THE DEEP ICE AND OCEAN

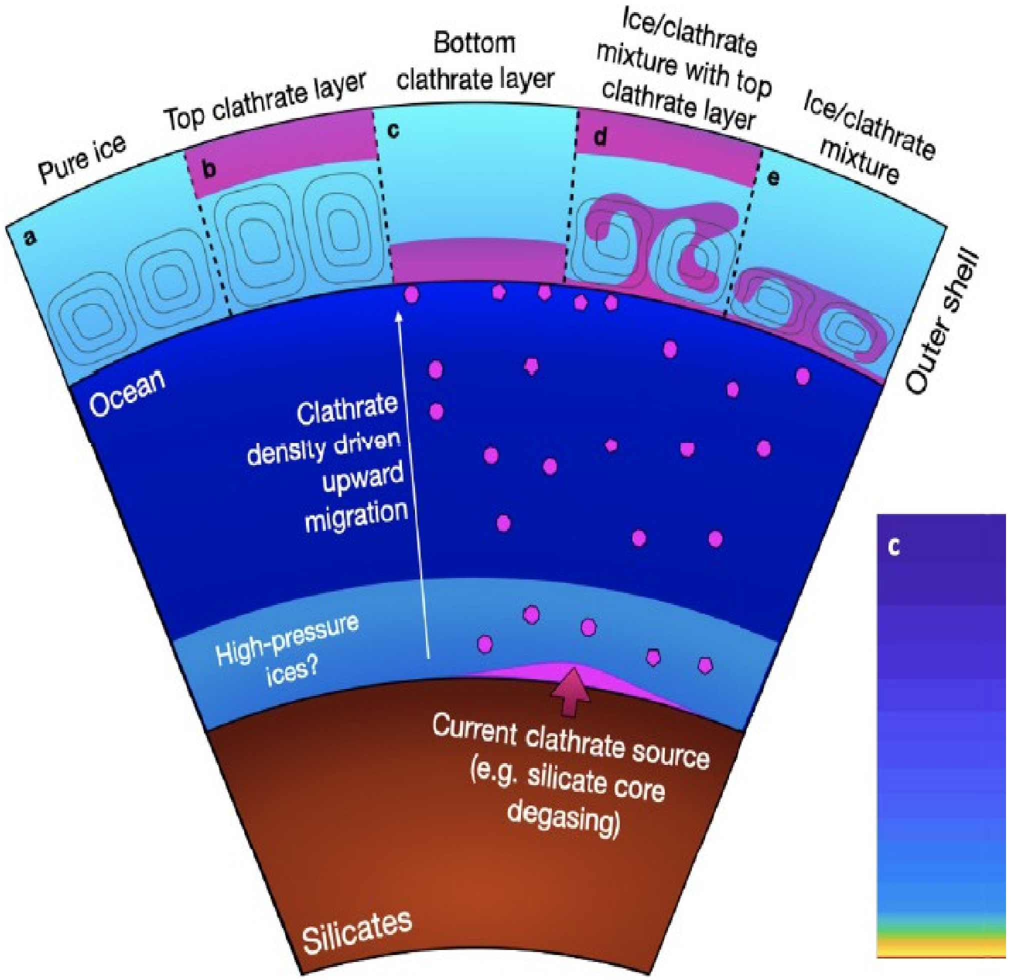
ASTEROID IMPACTS ON ICY BODIES



- **Impact processes on rocky bodies are relatively well understood, but not on icy bodies.**
- **Even less known when the <u>ice is made of mixtures of organic compounds</u> (e.g., <u>methane clathrates, etc.</u>).**

GETTING SURFACE ORGANICS INTO THE DEEP ICE AND OCEAN

- ❖ **How frequently/how much organics traverse the ice crust into the ocean (if at all…)?**
- ❖ **Unknown properties of Titan´s crust: ice composition, impurities, thickness, yield strength, and whether solid state convection occurs.**
- ❖ **Role of methane clathrates in regulating the properties of the ice crust?**



Clathrates in Titan's interior depends on the dynamics of the ice I lithosphere, on the presence (or absence) of high-pressure ices. (from Carnahan et al. 2022a).

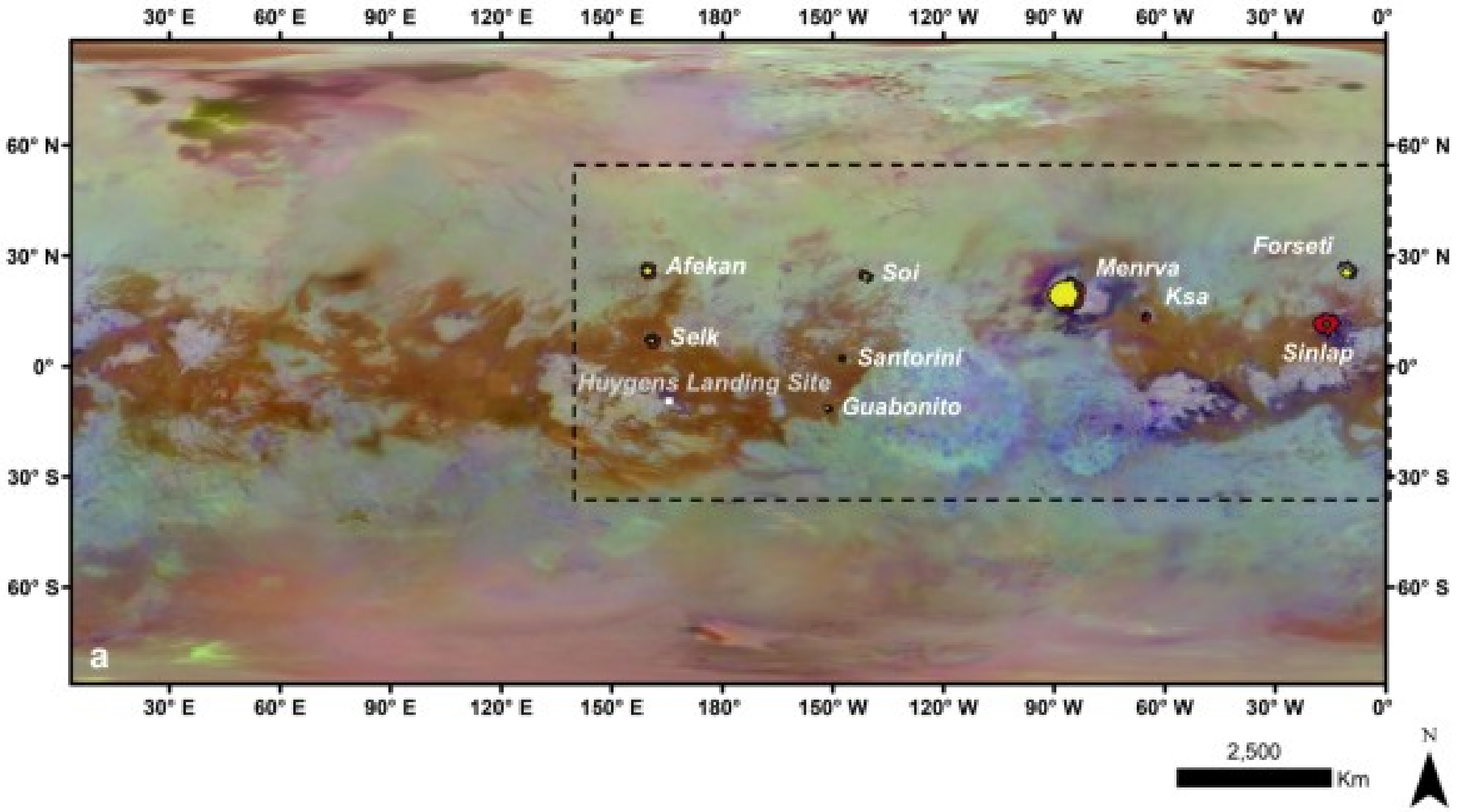
GETTING SURFACE ORGANICS INTO THE DEEP ICE AND OCEAN

Hypotheses:

- **Given a large enough hypervelocity impact, the resulting crater could breach into Titan's ice shell and reach the subsurface ocean, creating pathways connecting the organic-rich surface and the ocean.**

- **Eventual pathways could work bi-directionally, with ocean materials (salts and putative subsurface biota), being transported to the surface, and atmospherically derived organics being injected into the warmer ice and/or subsurface ocean.**

TITAN’S IMPACT RECORD

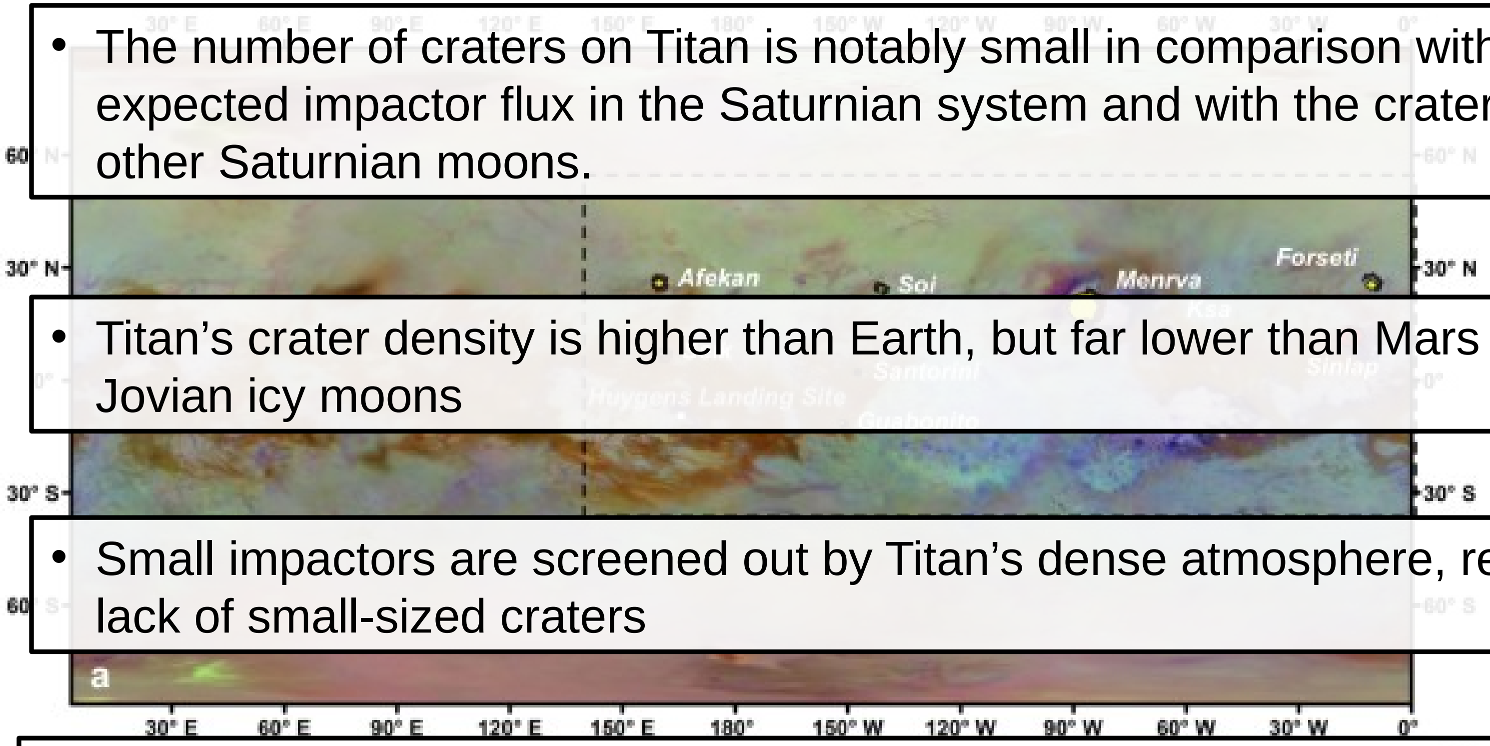


VIMS *(Visual and Infrared Mapping Spectrometer)* color mosaic showing 9 impact craters on Titan formed in dune and plain terrains.

Titan has approximately <u>90 craters</u>, of which 12 are certain (26 < Ø > 400 km), 25 are nearly certain, and the others are probable (47) and possible (6) (Hedgepeth et al. 2020).

TITAN’S IMPACT RECORD

- The number of craters on Titan is notably small in comparison with the expected impactor flux in the Saturnian system and with the crater density of other Saturnian moons.



VIMS (Visual and Infrared Mapping Spectrometer) color mosaic showing 9 impact craters on Titan formed in dune and plain terrains.

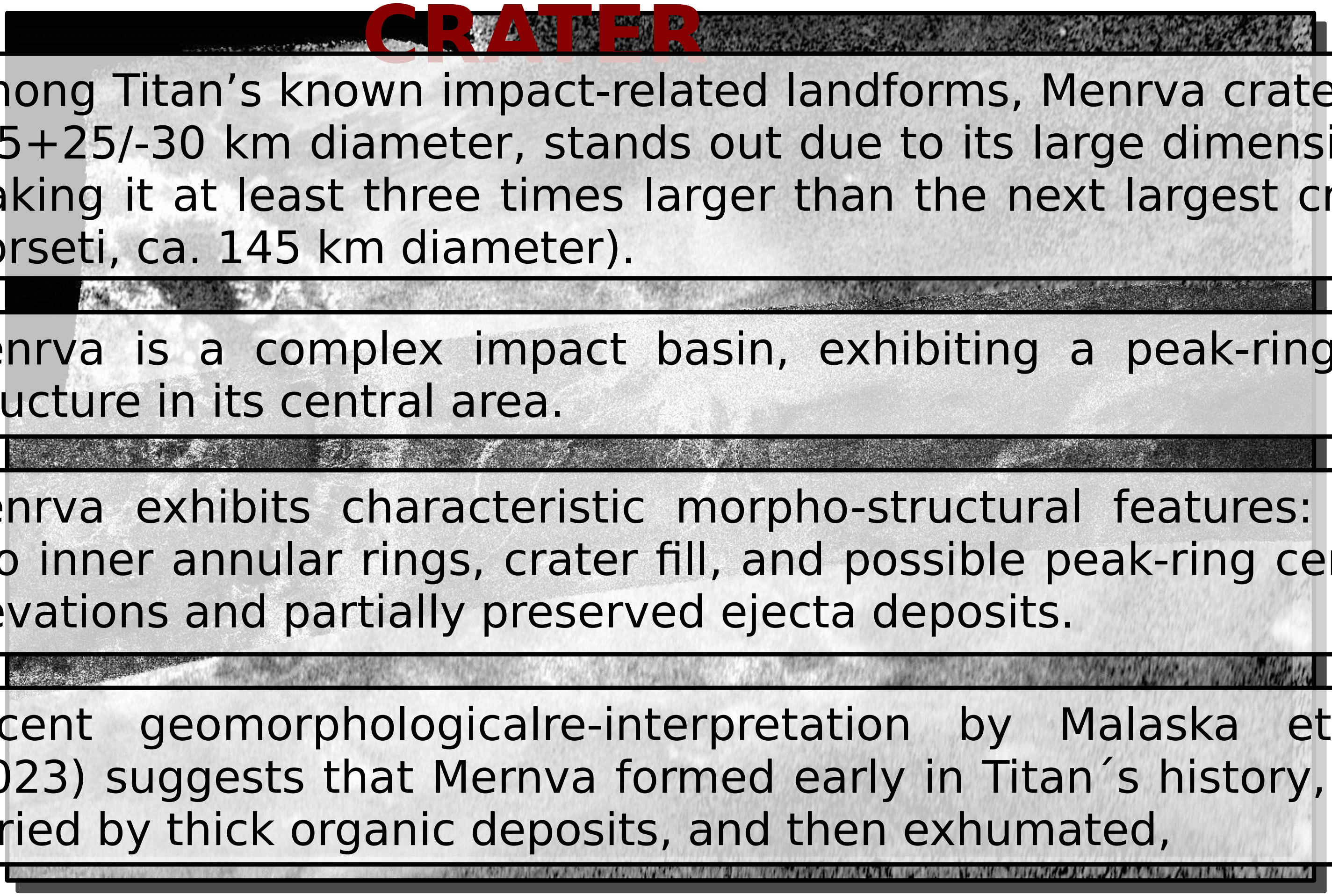
- Titan’s crater density is higher than Earth, but far lower than Mars and the Jovian icy moons
- Small impactors are screened out by Titan’s dense atmosphere, resulting in a lack of small-sized craters
- The spatial distribution of the known craters is heterogeneous, with most craters located in the equatorial and mid-latitude regions and a paucity of these structures in both polar regions

Titan has approximately 90 craters, of which 12 are certain (26 < Ø > 400 km), 25 are nearly certain, and the others are probable (47) and possible (6) (Hedgepeth et al. 2020).

MENRVA CRATER

Menrva Crater as seen by Cassini higher resolution RADAR (300 m/pxl)

MENRVA CRATER



- Among Titan's known impact-related landforms, Menrva crater, at 425+25/-30 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.

- Menrva exhibits characteristic morpho-structural features: rim, two inner annular rings, crater fill, and possible peak-ring central elevations and partially preserved ejecta deposits.

- Recent geomorphologicalre-interpretation by Malaska et al. (2023) suggests that Mernva formed early in Titan´s history, was buried by thick organic deposits, and then exhumated,

Menrva Crater as seen by Cassini higher resolution RADAR (300 m/pxl)

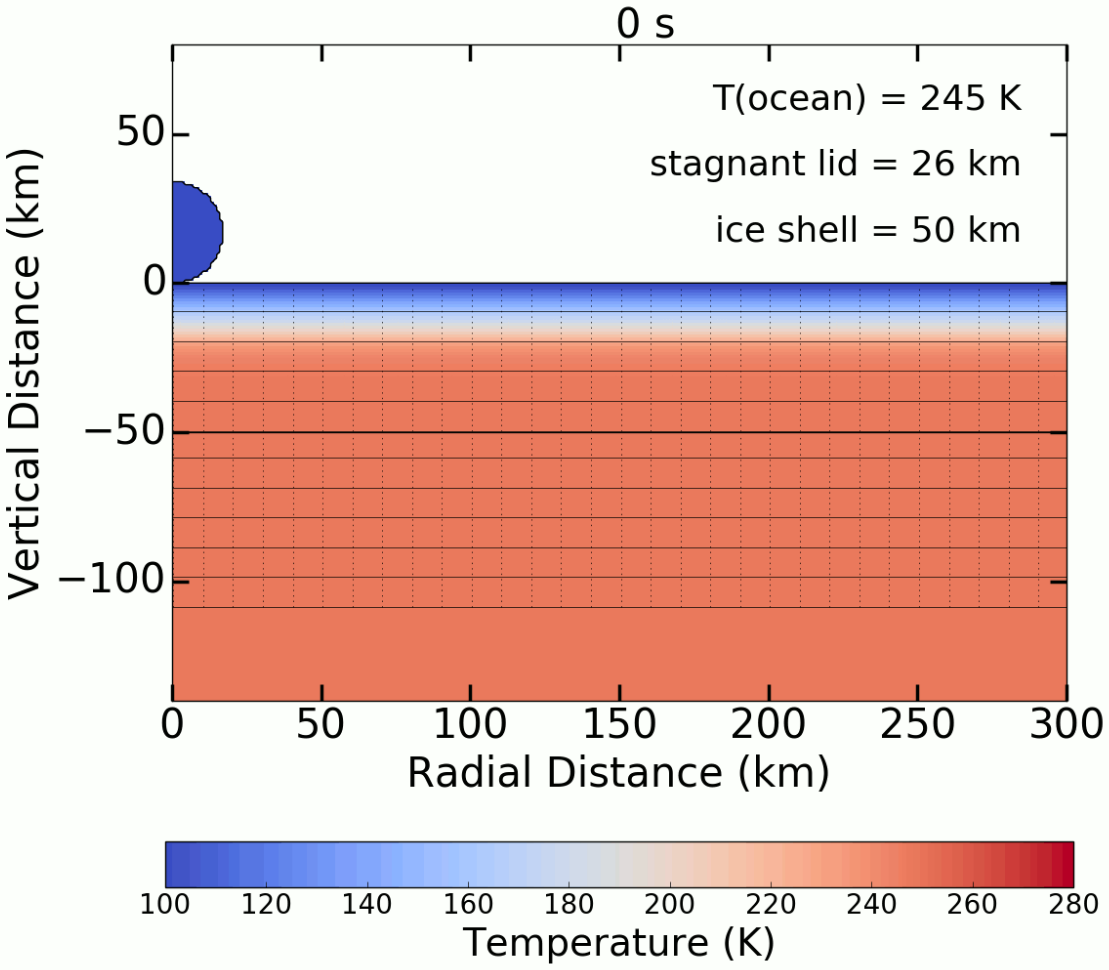
MENRVA CRATER: IMPACT MODELING

- 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.

MENRVA CRATER: INITIAL IMPACT MODELING

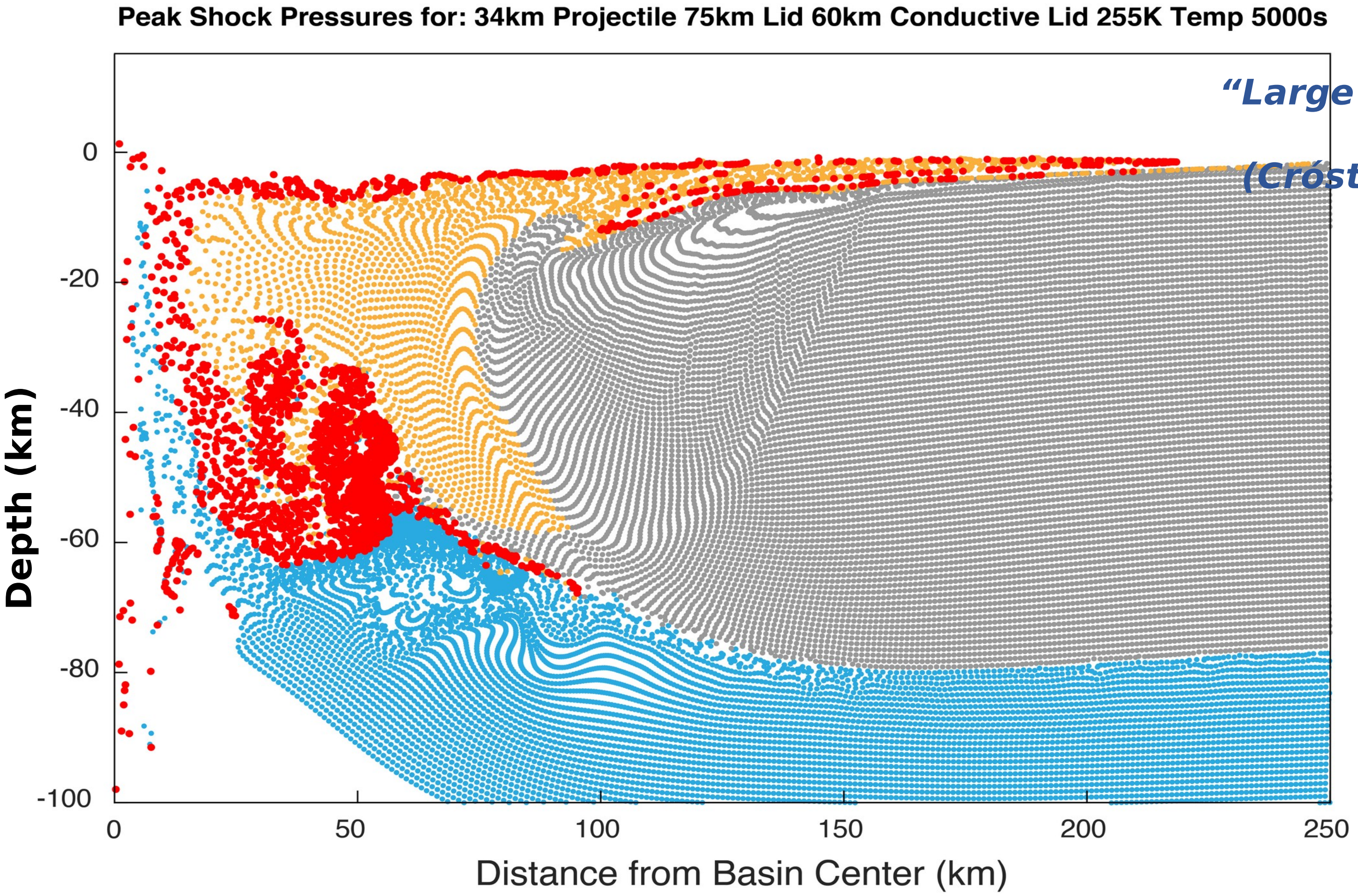


"Large Impacts can breach Titan ice shell (Crósta et al., 2021, Icarus) "

- **Impactor: 34 km**
- **Velocity: 7 km/s**
- **EOS for H_2O ice only (no clathrates)**

MODELING OF THE MENRVA IMPACT: ASSESSING HABITABILITY IMPLICATIONS

MENRVA CRATER: IMPACT MODELING – I



"Large Impacts can breach Titan ice shell (Crósta et al., 2021, Icarus) "

Material mixing at t = 5000 s based on peak shock pressures. Red indicates complete melt, yellow partial melt, grey is the ice shell (peak pressure required for incipient melt) and blue represents the water ocean.

CONCLUSIONS – INITIAL MODELING

- Results indicate that the **working hypotheses were basically met:**
  - **(i) Titan's ice shell can be 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.
- Results showed that relatively large volumes of these materials may be **heated and melted,** mainly at the central area of the crater; these relatively warm conditions may be long-lasting, therefore **providing adequate temperature conditions for habitable environments to develop.**

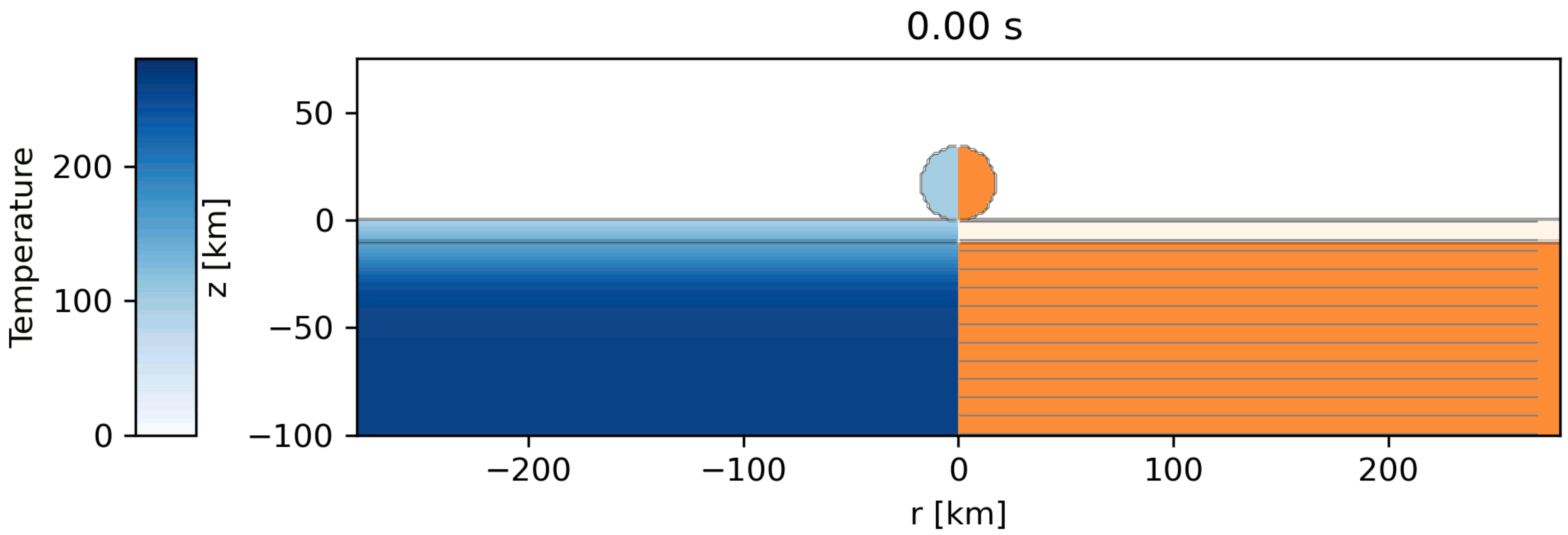
MENRVA CRATER: NEW MODELING WITH CLATHRATE LAYER & ICY SHELL (NO OCEAN) – VARYING THERMAL PROFILES

Input parameters for modeling using iSALE-2D

Description	Clathrate	Water Ice
Equation of state	ANEOS	ANEOS
Thermal softening parameter	0.8	1.2
Cohesion, undamaged (MPa)	10	10
Cohesion, damaged (MPa)	0.01	0.01
Frictional coefficient, undamaged	2.0	2.0
Frictional coefficient, damaged	0.6	0.6
Damage model	CH_4 ICE	ICE

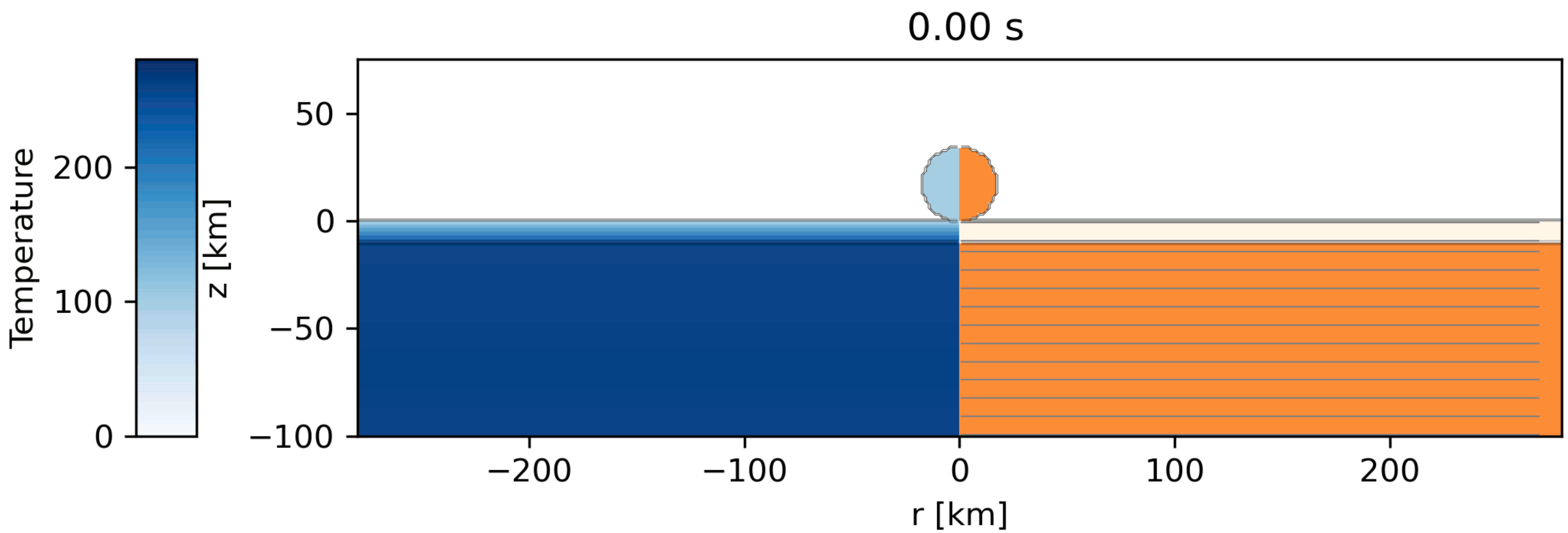
- **Surface T = 94 K**
- **Impactor diam. = 34 km**
- **Impact velocity = 7 km/s**

MENRVA CRATER: NEW MODELING WITH CLATHRATE LAYER & ICY SHELL (NO OCEAN) – VARYING THERMAL PROFILES



- **EOS for H_2O ice and clathrates**
- **Thermal gradient (dT/dz): 5 K/km**

MENRVA CRATER: NEW MODELING WITH CLATHRATE LAYER & ICY SHELL (NO OCEAN) – VARYING THERMAL PROFILES



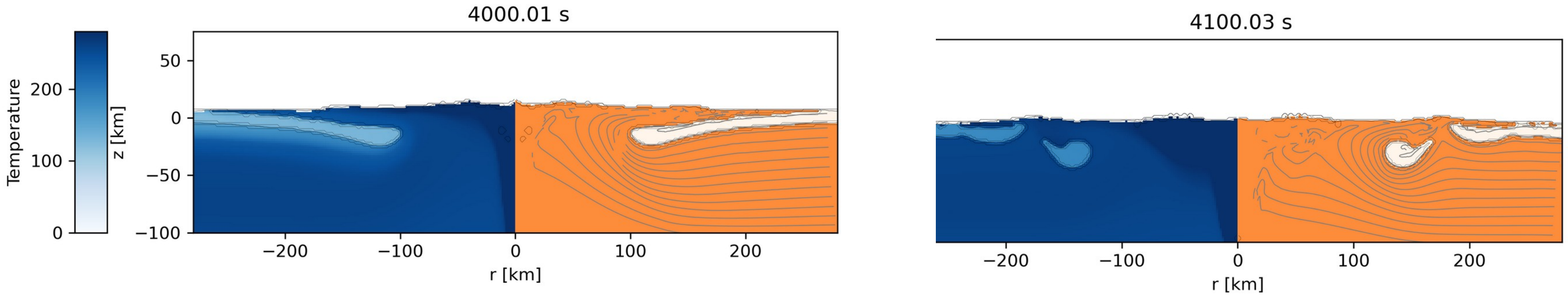
- **EOS for H_2O ice and clathrates**
- **Thermal gradient (dT/dz): 15 K/km**

MENRVA CRATER: NEW MODELING WITH CLATHRATE LAYER & ICY SHELL (NO OCEAN) – VARYING THERMAL PROFILES

CONCLUSIONS (PRELIMINARY)

The thermal profile will highly influence how the clathrate layer will behave in terms of final morphology.

Even if dT/dz is relatively high, the clathrate layer will modulate the morphology and might even lead to reproducing the rings.



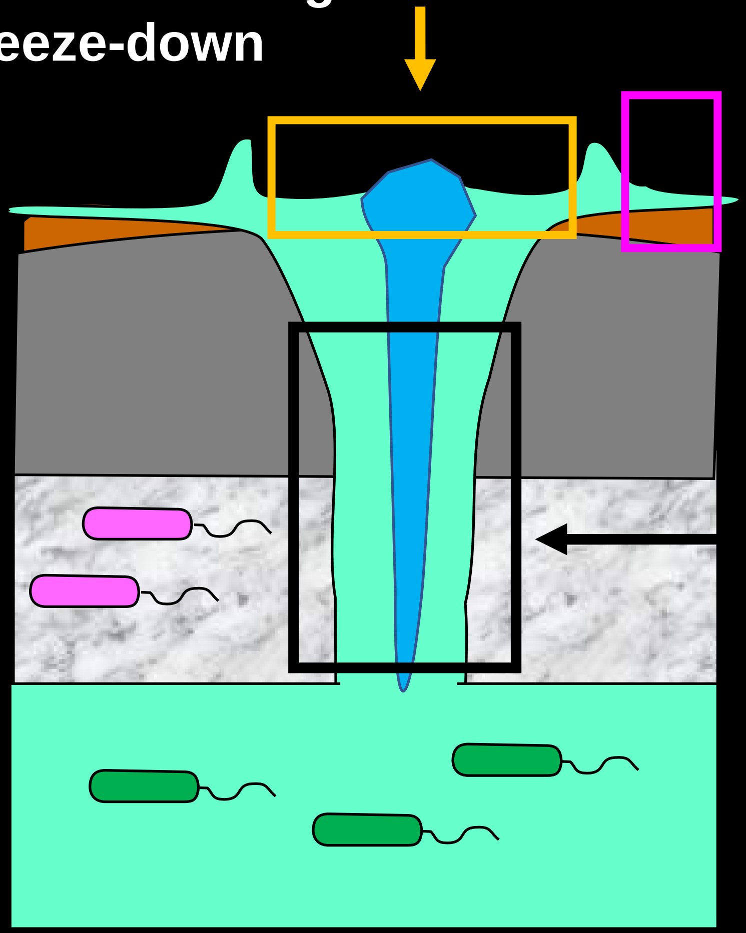
The temperature of the warm convective ice is 255 K in our model, which represents the boundary between convective ice and ocean.

Where to look for life near Menrva

Best case: Total breach (Menrva)

Interior preserved life (uplifted habitat?)
Deep ice and ocean biota freeze-preserved longer-lived habitats during freeze-down

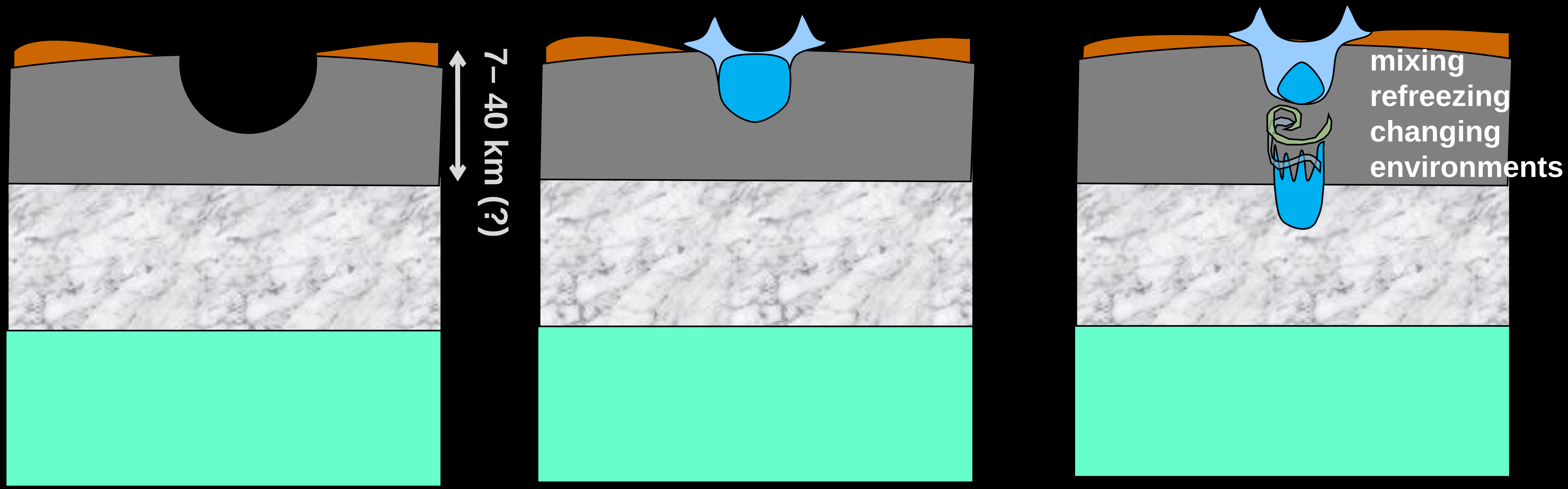
Ejected preserved life
Deep ice and ocean biota freeze-preserved
Temporary habitats during rapid freeze-down



Active biosphere: Life loves disequilibria!
Nutrient mixing
Refreezing concentration
Diverse changing environments near-equilibrium conditions of freeze-down and convection evolution forcing!

Smaller impacts create habitat mixing from crater melt plume

Surface material and mixing delivered to Deep Ice habitats
eventually to ocean from Deep Ice convection



1. Initial transient crater

2. Melt pool forms
More dense than crust

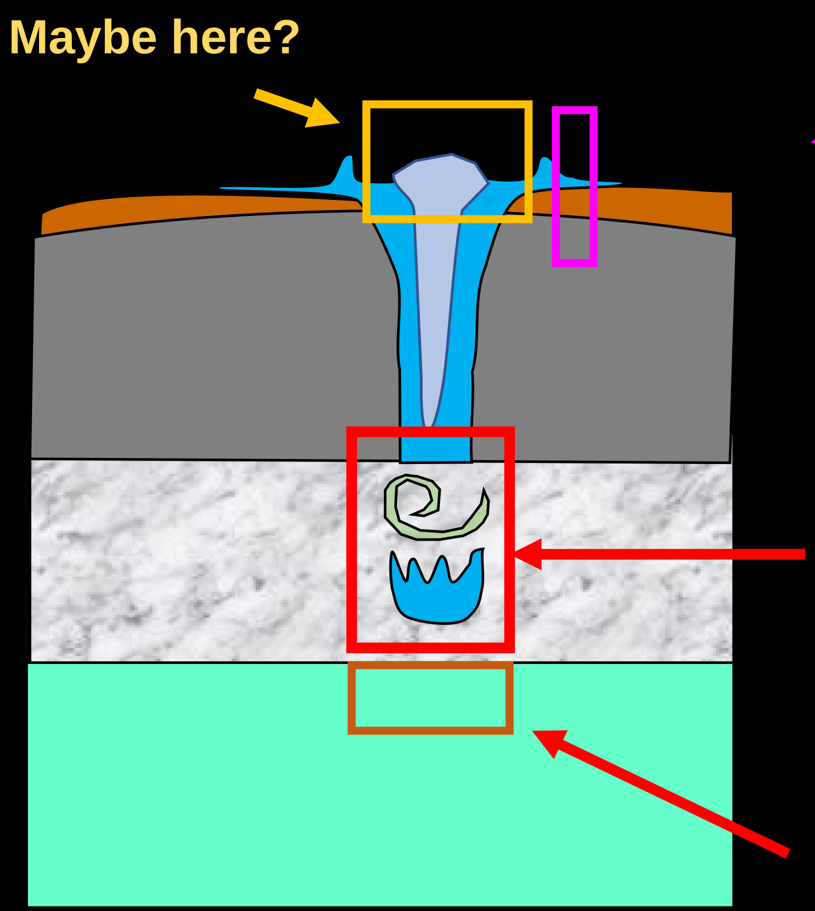
Melt pool plume descends
> 1,000 years to convective

Carnahan et al., LPSC (2002), Abstract 2242; Carnahan et al., JGR, in review.

Where to look for life near an impact crater

Bigger is better!

Good case: Impact into ductile ice habitat



Surface mission
Preserved life
Deep ice freeze-preserved
Temporary habitats during rapid freeze-down

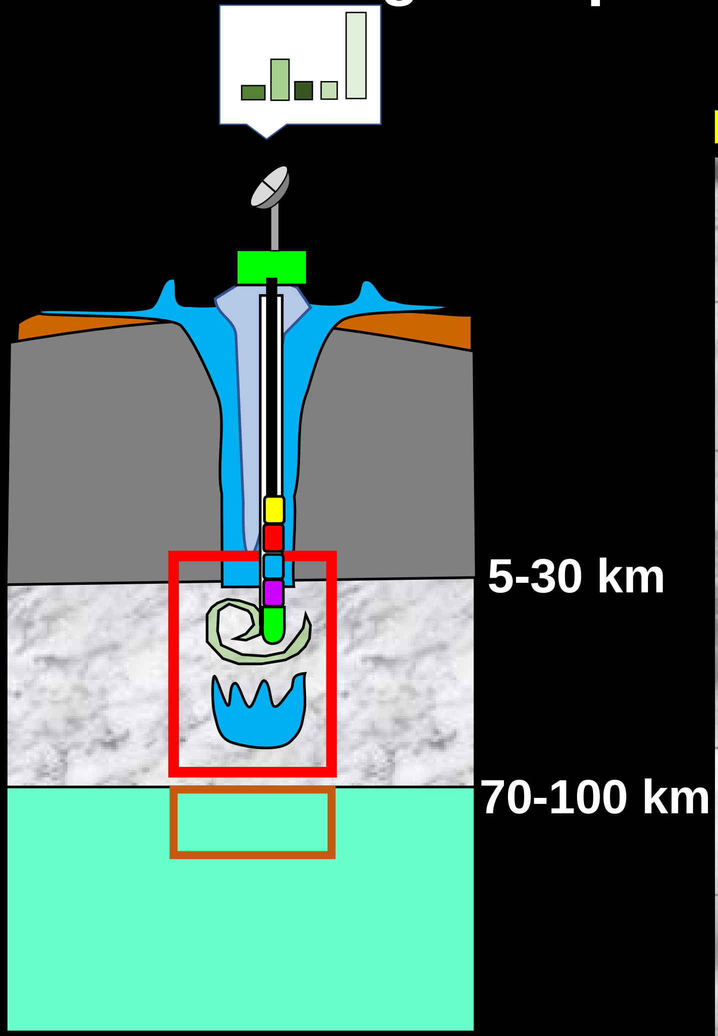
Deep drill mission
Active biosphere: Life loves disequilibria!
Nutrient mixing during plume descent
Diverse environments during freezedown
and convection

Possible injection of materials at ice-ocean interface
During plume arrival
May be short-lived?

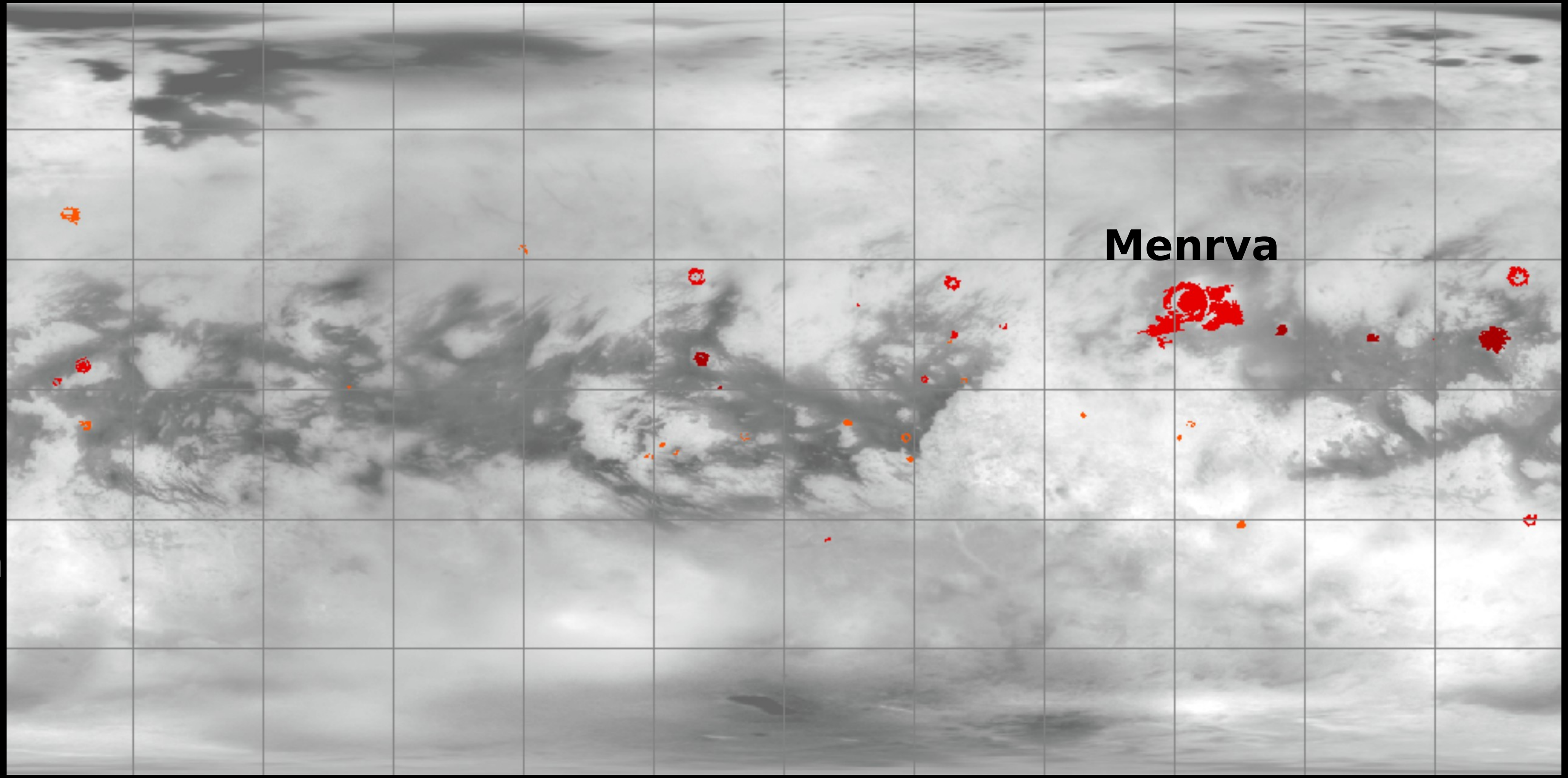
Titan impact crater astrobiology targets

Deep ductile ice directly underneath impact craters may be the best place to look for life on Ocean Worlds

Descending melt plume provides new chemical environments



Locations of larger impact craters om Titan



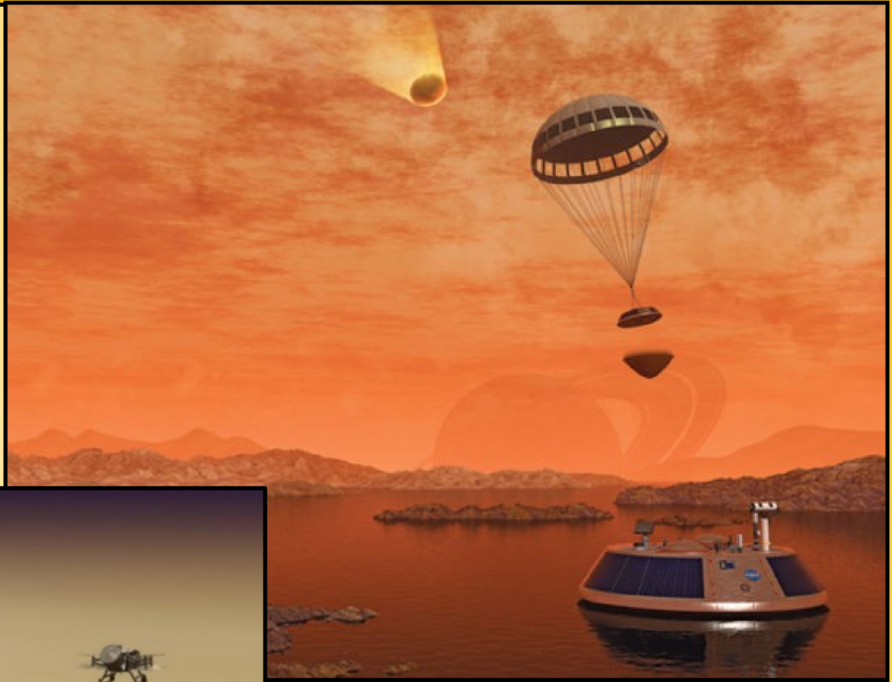
DRAGONFLY

Flights of Exploration Across Saturn's Moon Titan

RETURN TO TITAN

DRAGONFLY

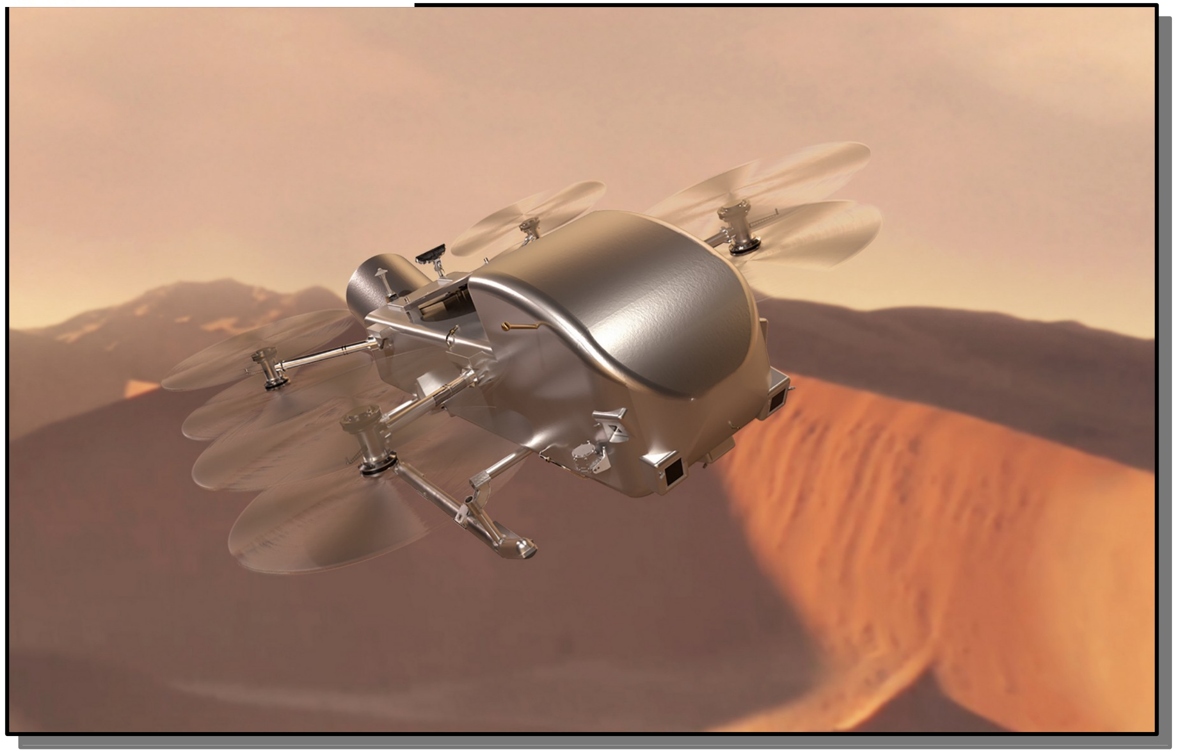
Dragonfly is a mission that will land on Titan to collect samples to determine the composition of its surface. The concept is revolutionary and includes the use of a drone landing at predetermined locations, selected from geological characteristics and chemical composition. **The objective is to look for evidence of prebiotic life based on water or hydrocarbons.**



NASA's Dragonfly Rotorcraft Mission to Saturn's Moon Titan Confirmed

NASA Science Editorial Team

APR 16, 2024



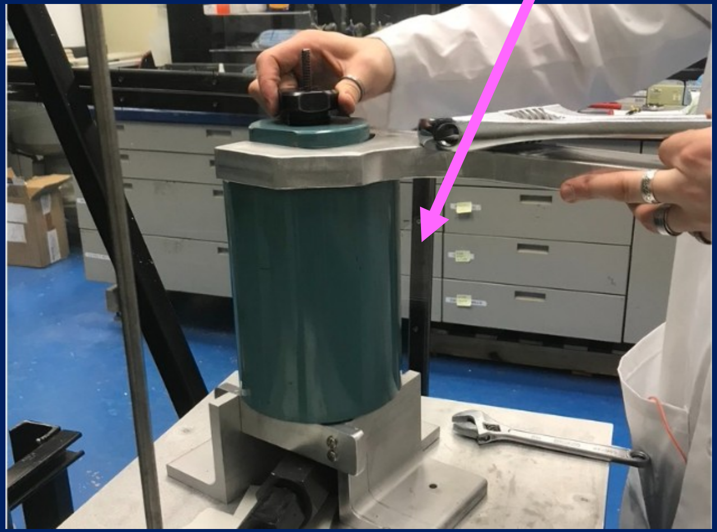
- Dragonfly is confirmed with a total cost of $3.35 billion and a July 2028 release date
- The helicopter, expected to arrive at Titan in 2034, will fly to dozens of promising locations on the Moon, looking for prebiotic chemical processes common on Titan and early Earth before life developed.
- It will be the first time that a vehicle equipped with scientific instruments will fly on another planetary body.
- The helicopter has eight rotors and flies like a large drone.

Ocean: Is Titan habitable, inhabited?

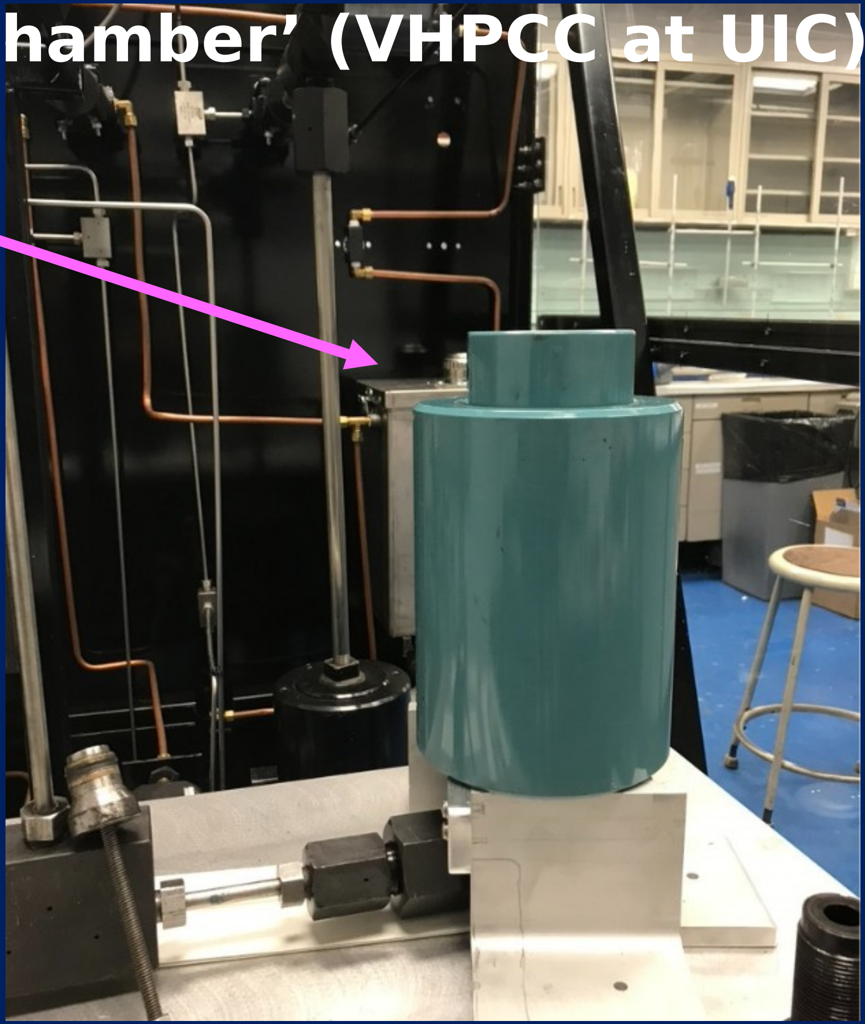
How do organisms adapt to high pressure environments?

High Pressure Experiments with *Shewanella oneidensis*

Developed a ‘very high pressure culturing chamber’ (VHPCC at UIC)

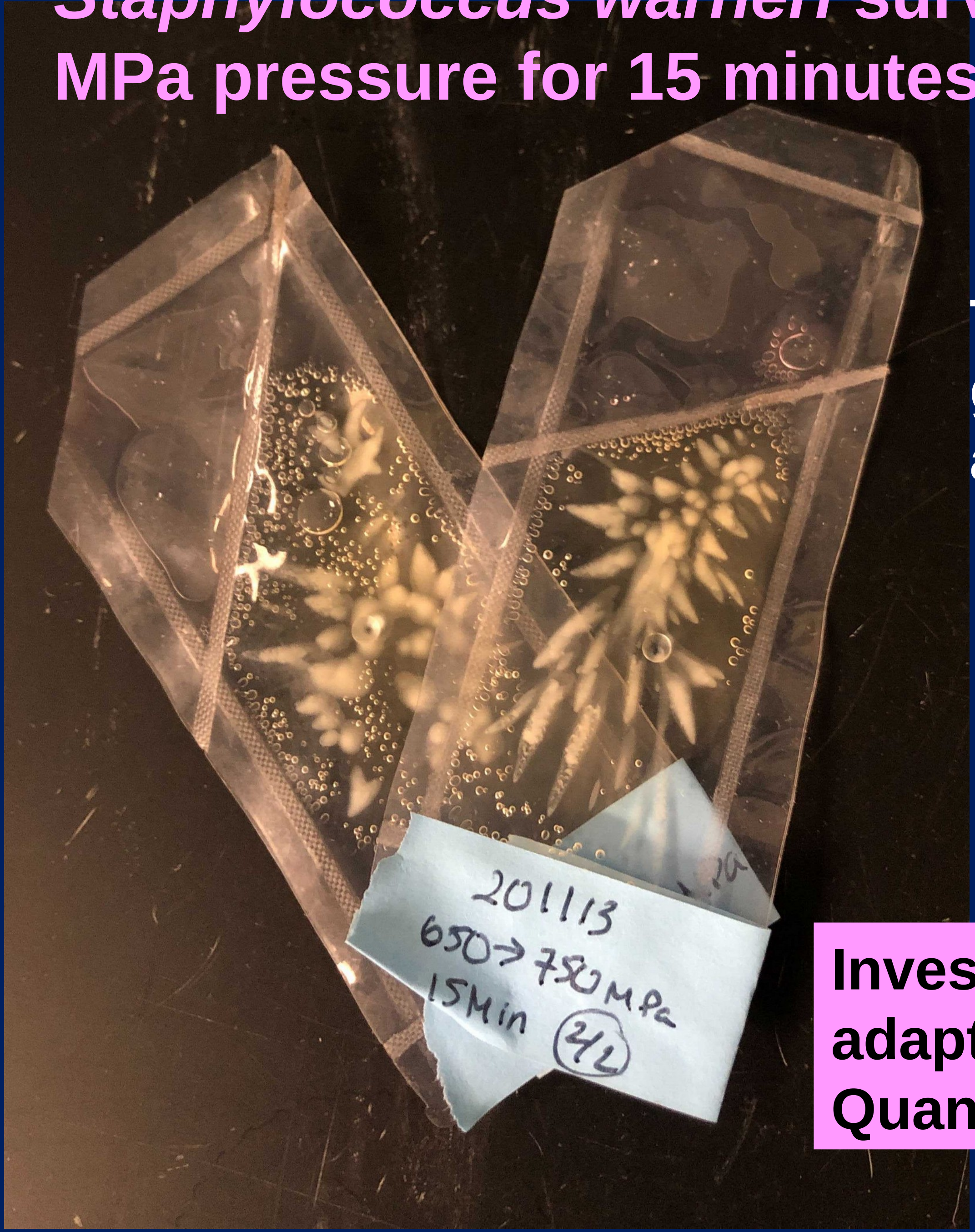


Pressure culture chamber

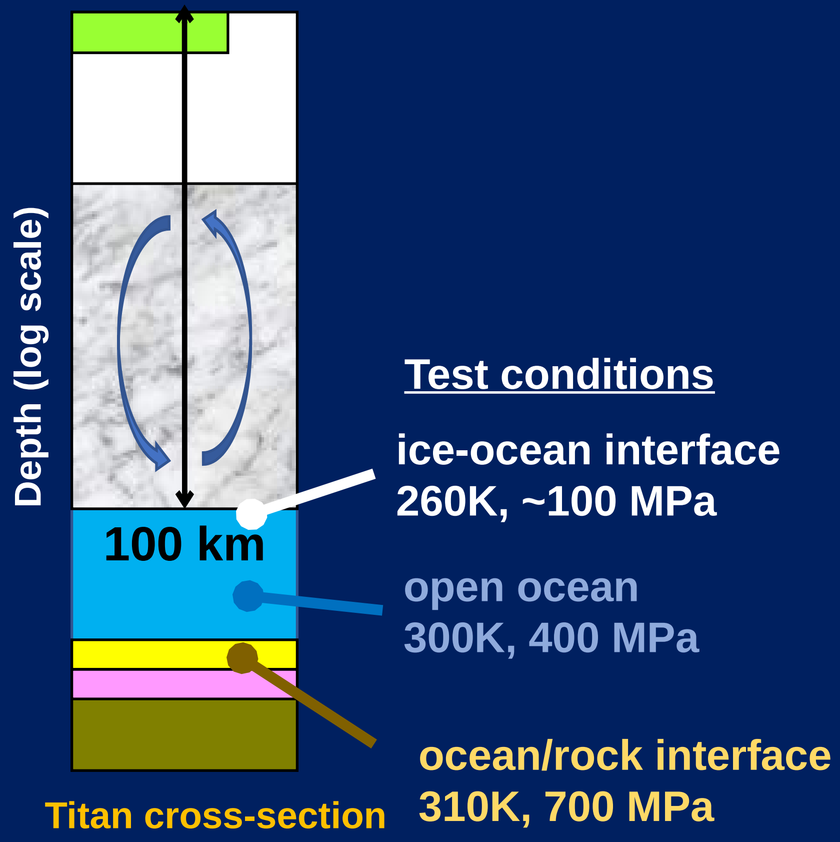


Pressure rig and support

Staphylococcus warneri survives 750 MPa pressure for 15 minutes



Testing for growth/metabolism at 750 MPa



Investigated the strategies biology could use to adapt to deep Titan pressures
Quantify nutrients biosignature concentrations

Malas et al., 2024, Frontiers in Microbiology

CAN ENOUGH ORGANICS GET INTO OCEAN?

- Assumed that Titan’s craters produce impact melt deposits composed of liquid water that can founder in its lower-density ice crust and estimated the amount of organic molecules that could be incorporated into these melt pockets.
- Used photochemical models to calculate proportion of organics in the form of HCN and organic aerosols, to determine the amount of amino acids (glycine) produced in the melt pockets
- Found a range of possible flux rates of glycine from the surface to the subsurface ocean.
- These fluxes suggest an upper limit for biomass productivity of ~10^3 kg C/year from a glycine fermentation metabolism, significantly less than recent estimates of the hypothetical biomass production supported by Enceladus’s subsurface ocean.

CAN ENOUGH ORGANICS GET INTO OCEAN?

Organic Input to Titan's Subsurface Ocean Through Impact Cratering

Catherine Neish,[1] Michael J. Malaska,[2] Christophe Sotin,[3] Rosaly M.C. Lopes,[2] Conor A. Nixon,[4] Antonin Affholder,[5] Audrey Chatain,[6] Charles Cockell,[7] Kendra K. Farnsworth,[8] Peter M. Higgins,[9] Kelly E. Miller,[10] and Krista M. Soderlund[11]

ASTROBIOLOGY
Volume 24, Number 2, 2024

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- These fluxes suggest an upper limit for biomass productivity of ~10^3 kg C/year from a glycine fermentation metabolism, significantly less than recent estimates of the hy

Unless the thickness of organics is greater than estimated, or biologically available compounds can be sourced from Titan's interior, or be delivered from the surface by other mechanisms, <u>calculations suggest that Titan may not be able to support a large biosphere</u>.

COSPAR Series

Series Editor Jean-Louis Fellous

TITAN AFTER CASSINI-HUYGENS

Titan After Cassini-Huygens is the most up-to-date and comprehensive coverage of our knowledge on Titan, including results and insights from the joint NASA/European Space Agency/Italian Space Agency mission Cassini-Huygens and the conclusions drawn by experts following detailed analysis of the mission data. Our knowledge of Titan has increased substantially due to observations from the Cassini-Huygens mission, which ended in 2017. Since then, observations from Earth, as well as laboratory and theoretical studies, have continued to add to our knowledge. These conclusions, combined with the latest ground-based and theoretical research, provide the most recent understanding of the science of Titan, covering the origin and evolution of Titan, its magnetic and plasma environment, surface, interior structure, geology, atmosphere, and the astrobiological potential for the oceans on the moon.The first book of the new COSPAR book series, Titan After Cassini-Huygens, is an integral reference for scientists, researchers, and academics working on Titan or ocean worlds.

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About the Editors

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Dr. Ingo Mueller-Wodarg is Professor in Physics at Imperial College London and an expert in the study of atmospheres of planets and moons in our solar system. He was a science team member of the Cassini Ion and Neutral Mass Spectrometer.

Dr. Anezina Solomonidou is a planetary scientist with expertise in planetary geology and was a member of the Cassini RADAR team. She is now the Scientific Officer for Space Sciences and Space Exploration at the space agency of Greece.

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TITAN AFTER CASSINI-HUYGENS

Chapter 13: **Exchange processes between surface, atmosphere, and interior.**

This chapter will discuss exchange processes (e.g. impact cratering, cryovolcanism, degassing)

Steven Vance[1], Alvaro Crósta[2], Mohit Melwani Daswani[1], Sarah Fagents[3], Baptiste Journaux[4], Catherine Neish[5]

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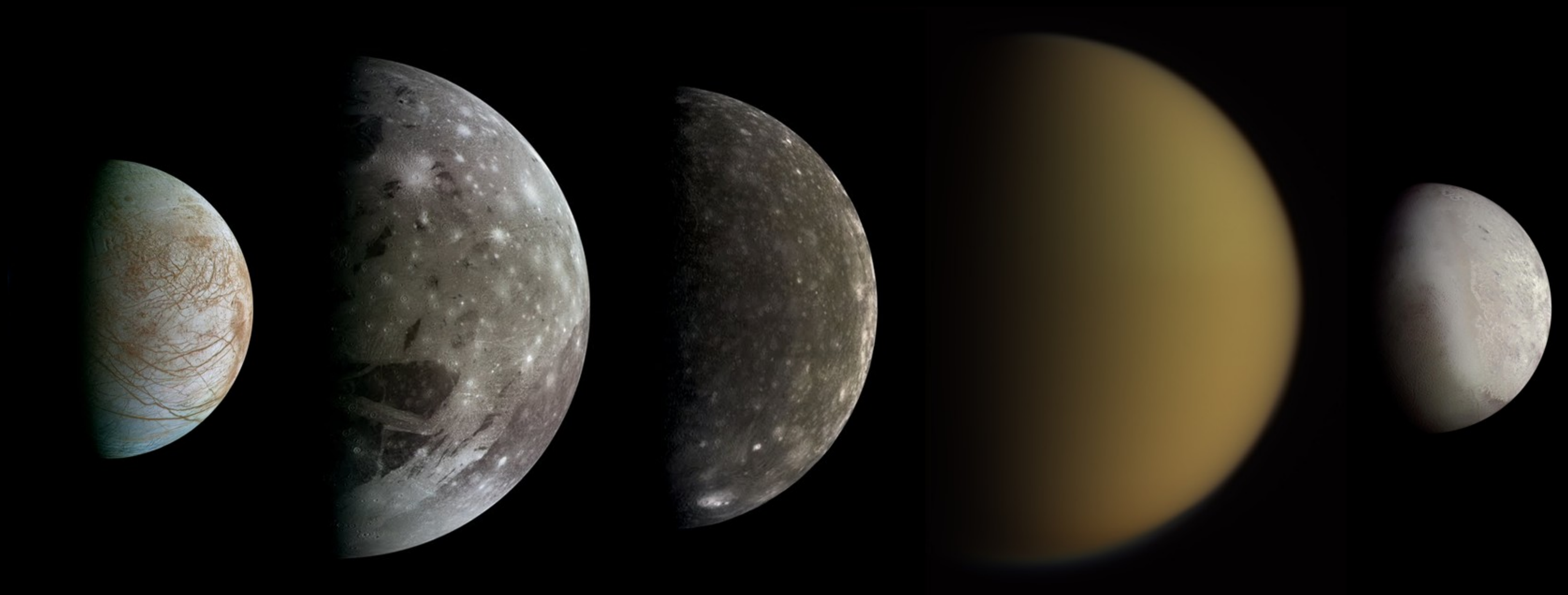
Summary:

- New molecules identified in atmosphere
- Atmospheric modeling progressing, taking into account newly discovered molecules
- Distribution of surface organics and other geologic units mapped globally
- Large impacts can transport organics to ocean and bring materials from ocean to surface
- Materials from core can get into ocean
- High pressure experiments show that some organisms can survive ocean conditions
- Cryovolcanism (and large impacts) can bring material from ocean to surface
- Major questions remain, such as amount of organics in the ocean.



The Planetary Science Journal, 5:176 (7pp), 2024 August https://doi.org/10.3847/PSJ/ad656b

Impacts on Ocean Worlds Are Sufficiently Frequent and Energetic to Be of Astrobiological Importance

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Abstract

Evidence for the beneficial role of impacts in the creation of urable or habitable environments on Earth prompts the question of whether meteorite impacts could play a similar role at other potentially urable/habitable worlds like Enceladus, Europa, and Titan. In this work, we demonstrate that to first order, impact conditions on these worlds are likely to have been consistent with the survival of organic compounds and/or sufficient for promoting synthesis in impact melt. We also calculate melt production and freezing times for crater sizes found at Enceladus, Europa, and Titan and find that even the smallest craters at these worlds offer the potential to study the evolution of chemical pathways within impact melt. These first-order calculations point to a critical need to investigate these processes at higher fidelity with lab experiments, sophisticated thermodynamic and chemical modeling, and, eventually, in situ investigations by missions.

Unified Astronomy Thesaurus concepts: Titan (2186); Enceladus (2280); Europa (2189); Impact phenomena (779); Craters (2282)

Impacts on Ocean Worlds Are Sufficiently Frequent and Energetic to Be of Astrobiological Importance

- Impacts can also generate ephemeral microcosms: any liquid water melted during impact freezes out over timescales commensurate with the impact energy.
- The exciting potential for chemistry within these pockets has been established, from concentrating salts to driving amino acid synthesis.
- Furthermore, shock-driven chemistry of icy, sometimes organic-rich (in the case of Titan especially) target materials may generate new "seed"

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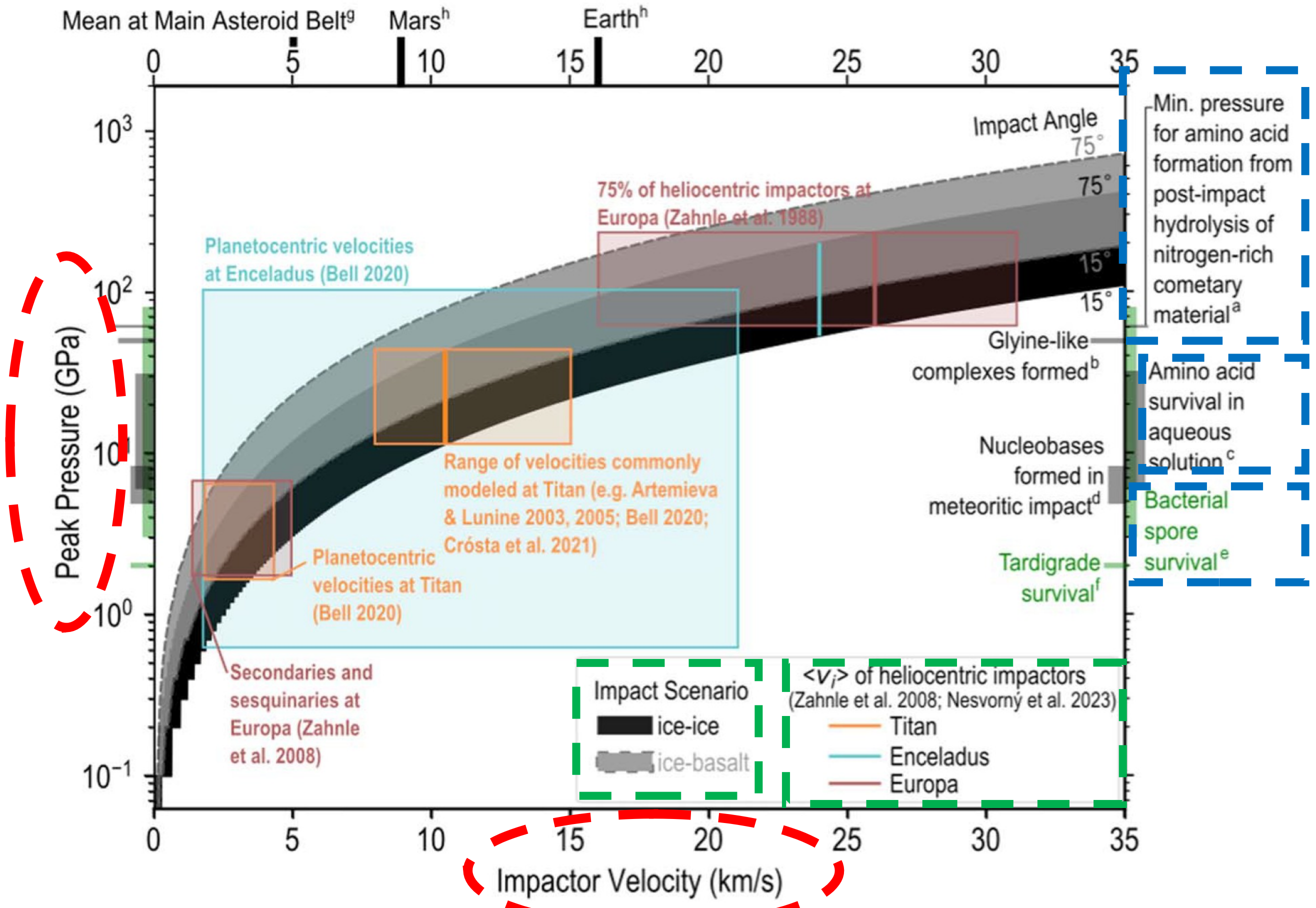

Figure 1. Impact velocities and first contact pressures relevant to OW for ice (solid, black) and basalt (dashed, gray) projectiles into ice targets at a representative span of impact angles between 15° and 75°. Shock studies of biota (green) or biologically relevant molecules (black) shown along the *y*-axes; impactors in the inner solar system shown at the top for context. Vertical orange, teal, and magenta bars indicate the average impact velocity of heliocentric impactors calculated by Zahnle et al. (2008); Nesvorný et al. (2023)[a]; Martins et al. (2013)[b]; Goldman et al. (2010)[c]; Blank et al. (2001)[d]; Furukawa et al. (2015)[e]; Horneck et al. (2001); Burchell (2007); Stöffler et al. (2007); Burchell et al. (2014)[f]; Traspas & Burchell 2021[g]; O'Brien & Sykes (2011)[h]; Le Feuvre & Wieczorek (2008).

Impacts on Ocean Worlds Are Sufficiently Frequent and Energetic to Be of Astrobiological Importance

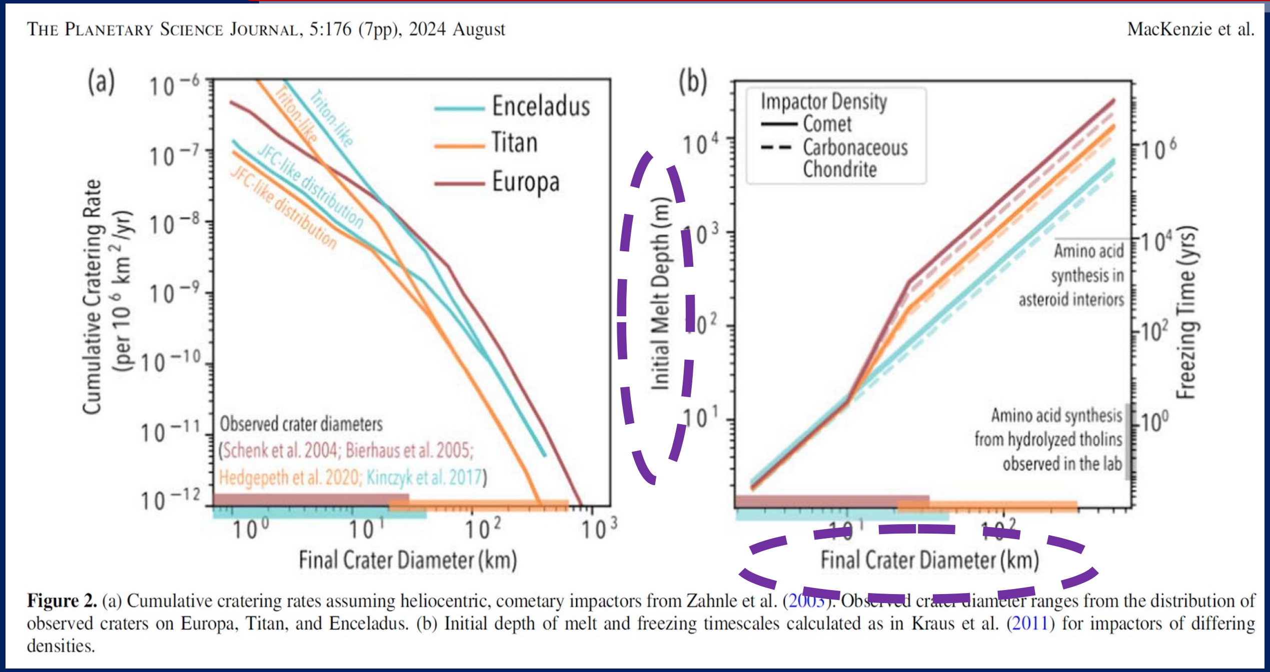

Figure 2. (a) Cumulative cratering rates assuming heliocentric, cometary impactors from Zahnle et al. (2003). Observed crater diameter ranges from the distribution of observed craters on Europa, Titan, and Enceladus. (b) Initial depth of melt and freezing timescales calculated as in Kraus et al. (2011) for impactors of differing densities.

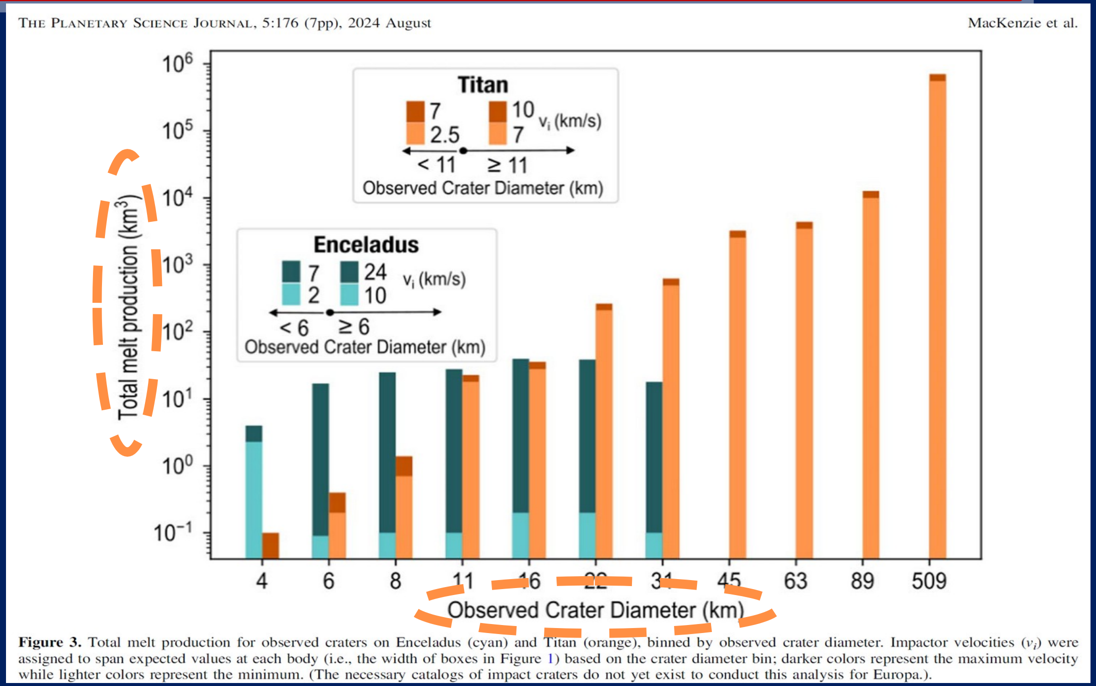

Figure 3. Total melt production for observed craters on Enceladus (cyan) and Titan (orange), binned by observed crater diameter. Impactor velocities (v_i) were assigned to span expected values at each body (i.e., the width of boxes in Figure 1) based on the crater diameter bin; darker colors represent the maximum velocity while lighter colors represent the minimum. (The necessary catalogs of impact craters do not yet exist to conduct this analysis for Europa.).

- Impact conditions at Enceladus, Europa, and Titan create environments relevant to prebiotic chemistry and, thus, have astrobiological implications.
- Each impact event’s impact velocity, impactor size, impactor composition, and ice target composition creates an experiment in which chemical pathways relevant to prebiotic chemistry may be taking place.
- Even the small, more frequent impacts that produce little melt offer the opportunity to investigate shorter lived hydrolysis.
- Alternatively, lower velocities that frustrate melt production enable the survivability of impactor material,thereby seeding the surface with exogenic material.