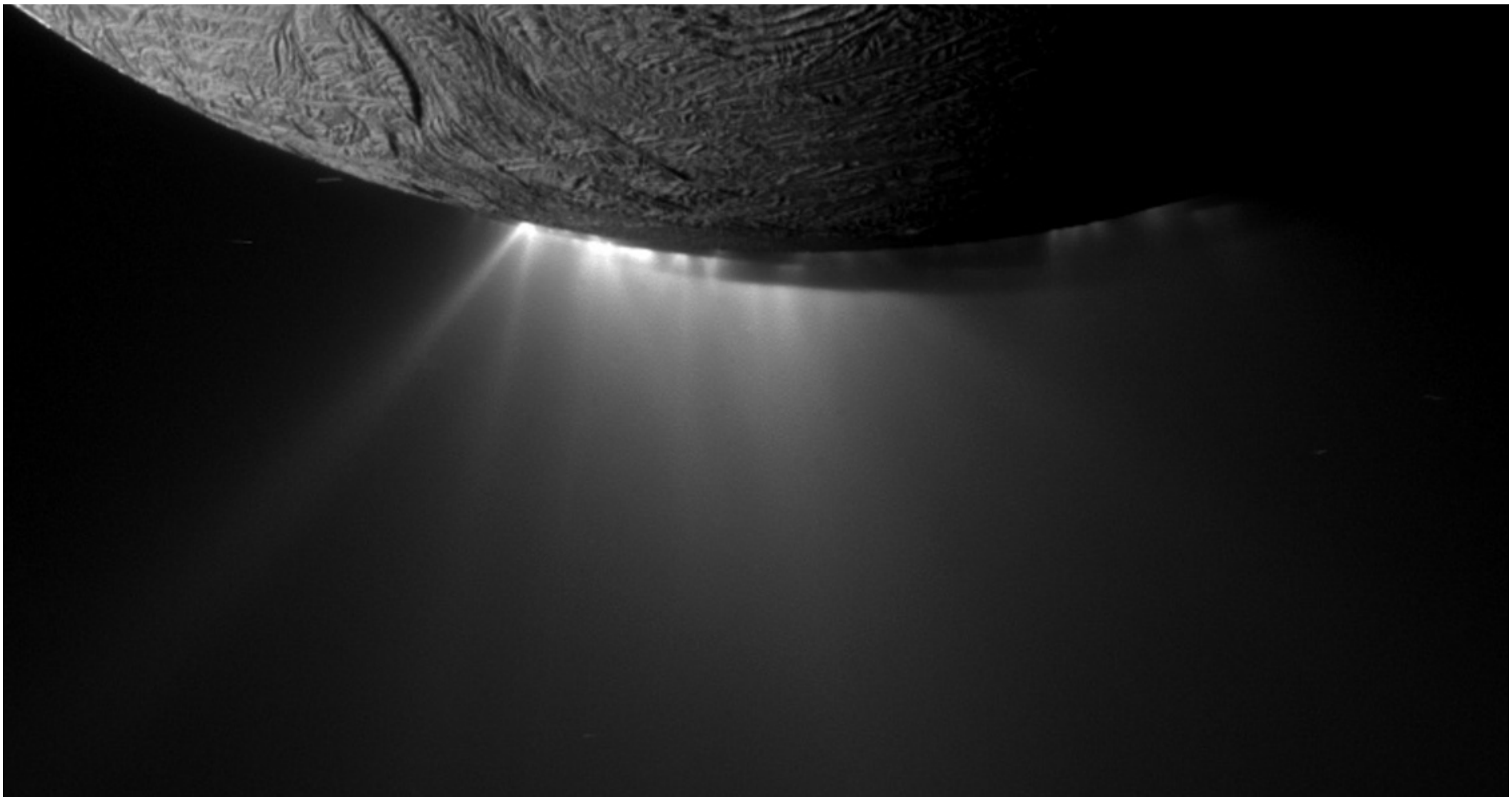

ENCELADUS AS A POTENTIAL OASIS FOR LIFE:
Science goals and investigations for future explorations

A White paper submitted to ESA'S Voyage 2050 call

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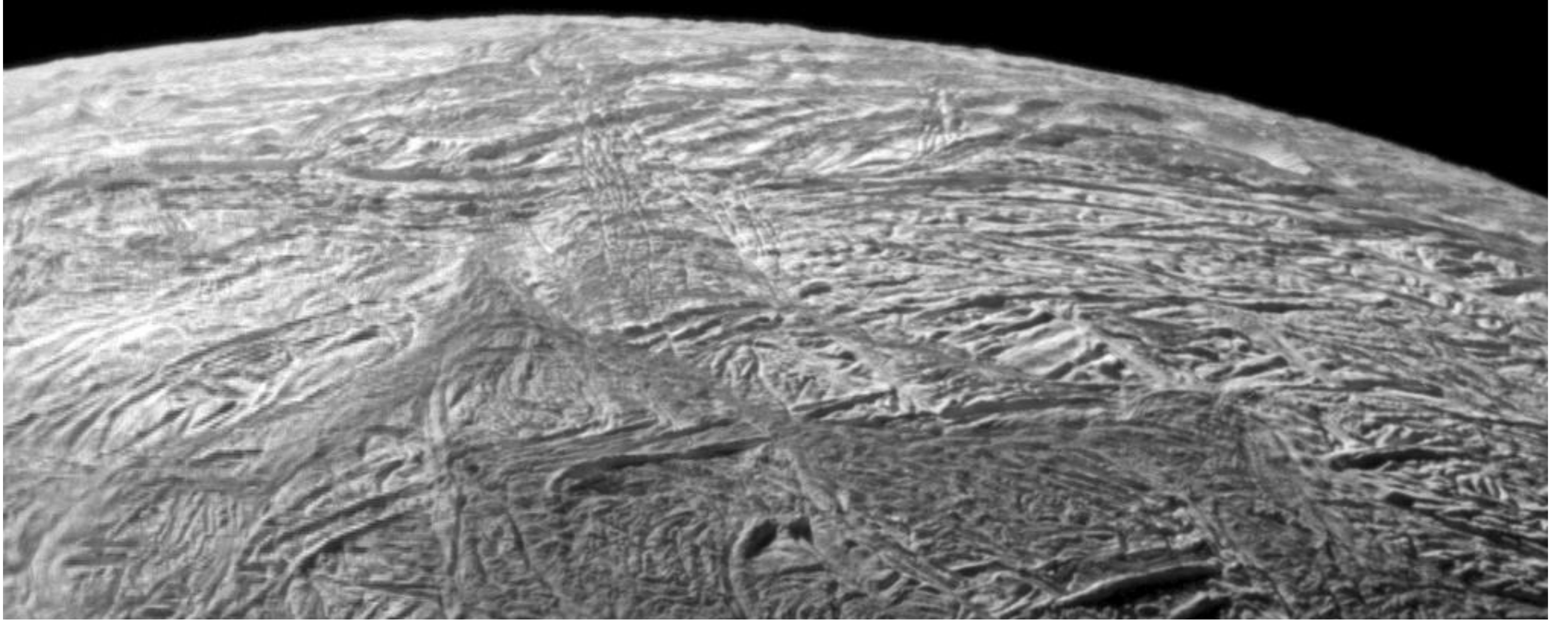

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EXECUTIVE SUMMARY: Enceladus is the first planetary object for which direct sampling of a subsurface water reservoir, likely habitable, has been performed. Over a decade of flybys and seven flythroughs of its watery plume, the Cassini spacecraft determined that Enceladus possesses all the ingredients for life. The existence of active eruptions blasting fresh water into space, makes Enceladus the easiest target in the search for life elsewhere in the Solar system. Flying again through the plume with more advanced instruments, landing at the surface near active sources and collecting a sample for return to Earth are the natural next steps for assessing whether life emerges in this active world. Characterizing this habitable world also requires detailed mapping and monitoring of its tidally-induced activity, from the orbit as well as from the surface using complementary platforms. Such ambitious goals may be achieved in the future in the framework of ESA large or medium-class missions in partnership with other international agencies, in the same spirit of the successfull Cassini-Huygens mission. For all these reasons, **exploring habitable ocean worlds, with Enceladus as a primary target, should be a priority topic of the ESA Voyage 2050 programme.**

1. INTRODUCTION:

The detection of **jets of water vapour and ice particles** emanating from the south polar terrain of Enceladus in 2005 is one of the **major discoveries of these two last decades** . During more than ten years, the Cassini spacecraft equiped with a suite of complementary instruments has studied this surprising activity, analyzing the plume structure (e.g. Porco et al. 2006, Hansen et al. 2011) and the composition of the vapour (Waite et al. 2006, 2009, 2017) and icy grain components (Postberg et al. 2009, 2011), identifying the plume sources (Porco et al. 2014), monitoring its variable activity (Hedman et al. 2013, Nimmo et al. 2014, Ingersoll and Ewald 2017) and its interactions with the Saturnian environment (e.g. Jones et al. 2009).

The discovery of this surprising activity rapidly hinted at an internal water reservoir. However, the nature and extent of this reservoir (local brine pockets, regional sea or global ocean) remained debated for more than ten years before we understood the origin of this activity. In 2015, two major findings brought Enceladus in the short list of planetary objects potentially harboring life: 1) chemical evidence for ongoing hydrothermal activities (Hsu et al. 2015, Sekine et al. 2015, Waite et al. 2017) ; 2) estimation of a significant physical libration (Thomas et al. 2016), implying the presence of a global ocean at depth. These findings were then complemented by the detection of complex organics in the ejected icy grains (Postberg et al. 2018) and an active source of hydrogen (Waite et al. 2017).

All this constitutes the **first direct evidence of a habitable environment elsewhere in the Solar system.** The existence of a global ocean containing salts and organics and powered by active hydrothermal systems at its seafloor makes Enceladus a key target for future exploration, as one of the best bodies to search for extant life (Lunine et al. 2018, McKay et al. 2018). The fundamental question now for Enceladus is not whether its ocean and hydrothermal sources are habitable environments, but rather whether they are inhabited. **Addressing the life potential of Enceladus is essential to understand how life may have emerged on the early Earth and to assess the conditions under which life might have emerged elsewhere in the Universe.** Enceladus with its watery plume consitutes an easy target to address these fundamental questions.

The natural next steps for the exploration of Enceladus is to search for evidence of **biological activity in its oceanic environment** and to better characterize the origin, evolution and present-day conditions of this **habitable environment**. Addressing these ambitious goals requires **complementary approaches combining sample analyses, remote-sensing and geophysical investigations from orbit and from a landing platform**. In the present document, after synthesizing the state-of-the art knowledge on Enceladus and the unanswered science questions after Cassini-Huygens, we propose an ensemble of comprehensive scientific investigations that need to be performed by future explorations and which mission concepts will allow their realisation.

2. SCIENCE GOALS AND QUESTIONS

2.1. EMERGENCE OF A HABITABLE WORLD IN THE SATURNIAN SYSTEM

In a context where time is a major characteristic when assessing the astrobiological potential of planetary objects, a key question opened, but left unanswered, by the Cassini-Huygens mission is how and when Enceladus formed and acquired its habitable environment (2.1.1). Clues to address this mystery necessarily involve further inspection of other inner mid-sized moons of Saturn (2.1.2). Other important aspects concerns how the moon interacts with the Saturnian dust-plasma environments and what signatures are left by its plume activity (2.1.3).

2.1.1. When and how did Enceladus form?

There is a debate on the origin of Enceladus and the other mid-sized satellites (Fig. 2.1.1): it is still uncertain if Enceladus and the mid-sized satellites accreted within the circum-Saturnian subnebular disk in the early Solar System (e.g., Canup and Ward, 2006, Sekine and Genda, 2012, Neveu and Rhoden, 2019), or formed later between 1 and 2 Gyr ago from the spreading of massive rings and migrated out (e.g., Crida and Charnoz, 2012; Ćuk et al., 2016; Salmon and Canup, 2017 ; Nakajima et al., 2019). In the latter case, Enceladus' interior could have been heated recently by tidal dissipation due to the orbital evolution (Ćuk et al. 2016; Neveu and Rhoden, 2019, Noyelles et al. 2019).

Recent observations of Saturn's rings by the Cassini spacecraft during the Grand Finale sequence provide a line of evidence that Saturn's rings would be much younger than Saturn itself (Buratti et al., 2019; Iess et al., 2019; Tiscareno et al., 2019), although the implications for the youth of the rings are still debated (Crida et al. 2019). A late formation would be consistent with a recent occurrence of the tidal disruption of a large Kuiper Belt object that coincidentally entered into the Roche limit of Saturn (Charnoz et al., 2009; Hyodo et al., 2017; Dubinski, 2019). Saturn's young rings are apparently consistent with the late origin of Enceladus; however, a recent model suggests a possibility that only Mimas formed recently from young rings, while Enceladus and the others can be as old as Saturn itself (Neveu and Rhoden, 2019). Until the next mission to Enceladus, there is no direct evidence to constrain the origin of Enceladus.

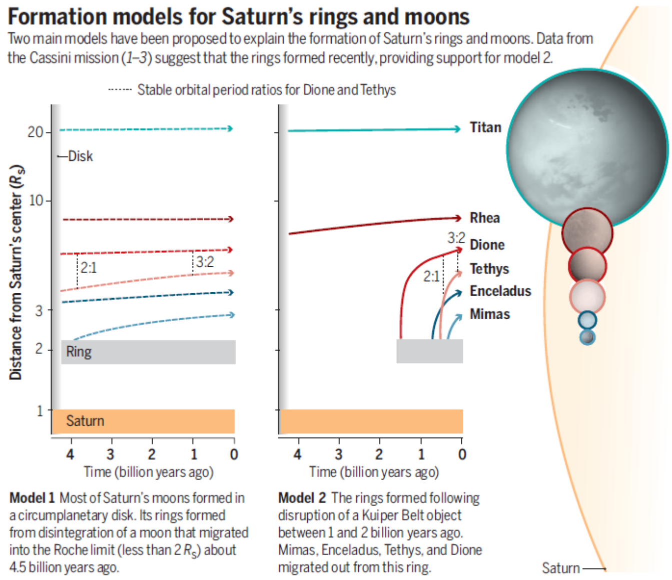

Figure 2.1.1. *Comparison of formation scenario of Saturn's mid-sized satellites (after Ida, 2019).*

The origin of Enceladus can be constrained by measuring precisely the isotopic compositions of the major volatile compounds (D/H in H_2O and CH_4, $^{13}C/^{12}C$ in CO_2 , CH_4 and other simple organics, $^{15}N/^{14}N$ of NH_3 , $^{18}O/^{16}O$ in H_2O and CO_2 ; see McKinnon et al. 2018) both in vapour and solid phases. For instance, comets are known to have high D/H ratios with some variations, suggesting isotopic heterogeneity in ice throughout the Solar system (Füri and Marty 2015). Enceladus' D/H in the plume water vapor (Waite et al. 2009) as well as at the icy surface of Enceladus, other moons and rings (Clark et al. 2019) have been estimated but uncertainties remain large and no other isotopic ratios are available. Comparison between high-precision isotopic ratios of the major volatile compounds in Enceladus, the main rings, the other inner mid-sized moons, as well as chondrites and comets (Mumma and Charnley, 2011) will reveal if Enceladus, the other inner mid-sized moons and the rings share a young common origin, or if the origin of Enceladus' ice is distinct from the ring. Such observations can be done by high-resolution mass spectrometry on the gas phase during plume crossing, and on the solid phase from icy grains collected during moon flybys and ring-grazing orbits, as well as directly on Enceladus surface ices using a lander.

2.1.2. What can the other icy moons of Saturn tell us about Enceladus' evolution?

Thermal interior, and orbital evolutions of regular icy moons are tightly coupled (e.g., Shoji et al., 2014;

Zhang and Nimmo, 2017; Nakajima et al., 2019; Neveu and Rhoden, 2019). Any orbital changes for one icy moon should affect its interior stress, deformation and heat budget as well as those of other neighbouring moons. In particular, dynamical excitation of one moon by others causes intense internal tidal heating for all the satellites involved. Such changes in dissipative heating can then change the interior structures and heat transport efficiency, which, in turn, affect the moons' orbits.

Thus, to better understand the thermal and interior evolution of Enceladus, a comprehensive understanding of the interior structures and thermal history of other Saturnian mid-sized icy moons is clearly needed. In particular, Enceladus probably has undergone dynamical excitation and intense heating by interacting with other moons, such as Tethys and Dione (e.g., Neveu and Rhoden, 2019, Noyelles et al. 2019): the current resonance with Dione provides a sufficient dissipated power to explain the present-day heat output (Lainey et al. 2012, 2017, Nimmo et al., 2018). However, how long the two moons have been in resonance, and whether past resonances with other moons may have influenced Enceladus' evolution are still unknown (Zhang and Nimmo 2009, Nimmo et al. 2018, Noyelles et al. 2019). The interior structures of the other inner moons are also still poorly constrained. While attempts to constrain Dione's interior structure have been made on the basis of preliminary gravity and shape data obtained by Cassini (cf. Beuthe et al. 2016), the interior structure of Tethys is essentially unknown since Cassini performed only one flyby of this icy moon.

Flybys of other moons, in particular Tethys and Dione, before orbit insertion around Enceladus will provide an opportunity to obtain key constraints on the gravity, topography and magnetic data, to map their surface and to analyse icy grains emitted by sputtering. Such information on the interior structures and surface composition will enable us to search for other habitable subsurface oceans in the Saturnian system. It is also essential for a better understanding of Enceladus' thermal evolution as it will set the context for Enceladus' ongoing hydrothermal activity: When did water-rock interaction initiate in the deep interior? What stage of the chemical evolution are we witnessing at present? (see section 2.2.3).

2.1.3 How does Enceladus interact with the dust-plasma environment of Saturn?

Orbiting deep within Saturn's magnetosphere, Enceladus is continuously overtaken by a plasma whose bulk flow almost corotates with Saturn itself. The moon's trailing hemisphere is therefore continually bombarded by ions and low-energy electrons, whilst its leading hemisphere is exposed to energetic (>1MeV) electrons that flow in the opposite direction around Saturn (e.g. Krupp et al. 2018). The moon's absorption of many energetic trapped particles largely evacuates the radiation belt region intersecting its orbit. Such interactions are seen at the other inner icy moons. The presence of Enceladus's plume however makes several aspects of its interaction with its surroundings of particular interest.

Much of the plume material, both ions and ejected grains, are electrically charged. Such charges are observed over all particle masses at least up to nanograin scales, indicating that charging is occurring through several process, including possible triboelectric charging in the erupting vents (e.g. Jones et al. 2009, Farrell et al. 2010, Marooka et al. 2011). Nanograins of opposite charges were clearly observed to have diverged in the plume; modelling studies also indicate that the local electric field deviates the grains' trajectories (Kriegel et al. 2014).

The ionosphere associated with Enceladus's plume leads to the generation of a current system linking it with Saturn's ionosphere. This electrodynamic interaction bears many similarities to the Jovian moons' magnetospheric interactions, but it differs in several ways, including the southward shift due to the plume's location, and the significant modification due to the presence of charged grains (e.g. Simon et al. 2011). The interaction of Saturn's magnetospheric plasma with Enceladus' plumes generate two Alfvén wings, which propagate towards Saturn (Dougherty et al. 2006). Where these wings intersect with Saturn's upper atmosphere auroral footprint emission is being generated (Pryor et al. 2011). Since the source of the Alfvén wings, the plumes, are located near the south pole, the northern wings are partially blocked by Enceladus's solid body. This leads to hemisphere coupling currents along the Enceladus flux tube and magnetic field discontinuities across this flux tube (Saur et al. 2007, Simon et al. 2014). The associated thin electric current sheets could be source of the auroral hiss observed near Enceladus (Gurnett et al. 2011). The negatively charged dust generates complex plasma physical phenomena and significantly modifies its ionospheric conductivities (Kriegel et al. 2011, Simon et al. 2001, Yahroshenko et al. 2018).

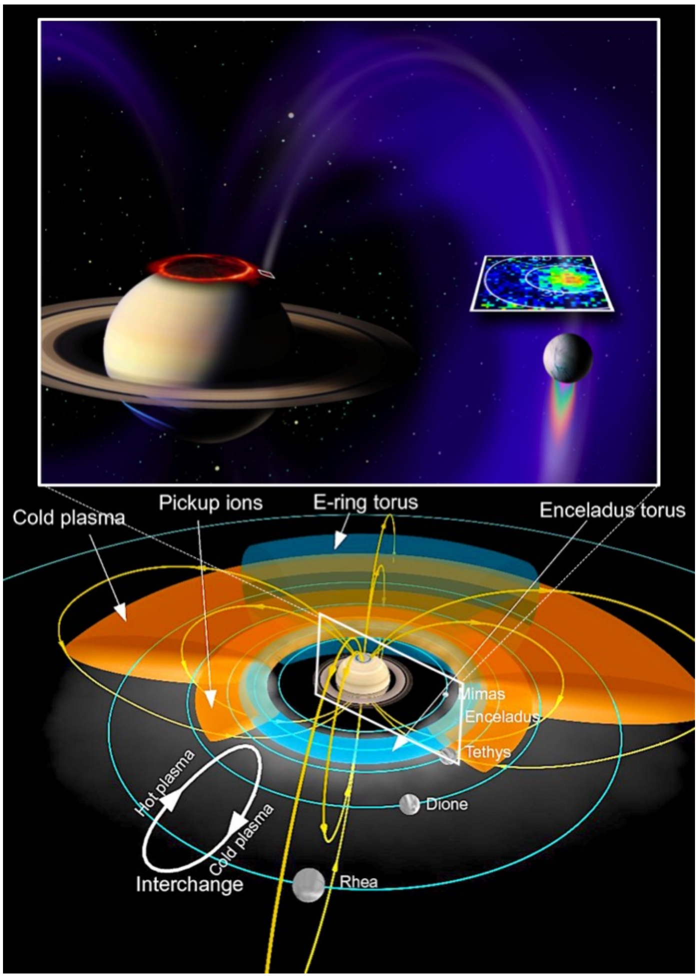

Figure 2.1.3 : *Schematic illustration of Enceladus' interactions with Saturn's complex magnetosphere (bottom), showing electrical connection between Saturn and Enceladus revealed by Cassini (top, Pryor et al. 2011). Credits : Mullard Space Science Laboratory, UCL – C. Arridge (bottom image); NASA/JPL/U. Colorado/Central Arizona College.*

In situ observations of this fascinating electrodynamic interaction were achieved by Cassini's instruments, but the coverage of the system was patchy: the presence of the current system could be inferred by deviations in the magnetic field, direct detections of field-aligned charged particles, and other observations (e.g. Simon et al. 2014, Engelhardt et al. 2015), but a full understanding of the system is still forthcoming. Understanding Enceladus's considerable influence on the Saturnian magnetosphere itself, including the latter's dominance by neutral gas and the extensive E-ring's presence (e.g. Smith et al. 2010), are further reasons for its further close study. The plasma interaction and the associated magnetic field fluctuations also display a time-variability due to diurnal control of Enceladus' plume activity along its orbit around Enceladus (Saur et al. 2008, Hedman et al. 2013), which requires detailed spatial and temporal monitoring.

SECTION SUMMARY: Understanding how and when Enceladus formed and acquired its habitable environment requires comparison with the other icy moons and rings as well as characterization of the interaction with Saturnian dust-plasma environments. This can be achieved in a preliminary Saturn science phase by performing multiple flybys of icy moons and ring-grazing orbits, before orbit insertion around Enceladus, using a suite of *in situ*, remote-sensing and geophysical instruments, in the same spirit of JUICE before orbit insertion around Ganymede.

2.2. ENCELADUS AS A GLOBAL HYDROTHERMAL SYSTEM

Cassini revealed that water-rock reactions probably occur at present, deep in Enceladus' interior. A plausible physical model involving porous convection in a tidally heated core has been proposed that accounts for the main observations (2.2.1). Yet, it relies on largely unconstrained characteristics of the core, and the timeframe over which this hydrothermal system has been operating is unclear (2.2.2) so that the global extent of rock alteration remains a major open question (2.2.3).

2.2.1 What are the physical properties of Enceladus' core? What does this tell us about exchanges with the ocean?

Enceladus's activity indicated that its interior is differentiated into an inner rock core surrounded by a hydrosphere (e.g. Schubert et al. 2007, Hemingway et al. 2018). This was confirmed from the analysis of the moon's shape (McKinnon et al. 2013) and gravity data (Iess et al. 2014), which first constrained the size of the rock core and its density. Based on joint inversion of the long-wavelength topography (Nimmo et al. 2011, Tajeddine et al. 2017), gravity data (Iess et al. 2014) and libration data (Thomas et al. 2016), several studies have estimated the core size between 180 and 195 km for a core density between 2450 and 2550 $kg.m^{-3}$ (Cadek et al. 2016, 2019, Beuthe et al. 2016, Hemingway et al. 2018).

Such a low core density requires significant porosity. Assuming chondrite-like iron-bearing hydrated minerals, Choblet et al. (2017) estimated the core porosity between 20 and 30%. The pores are likely filled with water, but may also contain a significant fraction of low-density organics or small particles of clay and silt (e.g. Bland and Travis 2017). Enceladus's core likely consists of a complex mixture of gravels, sands, clays and organics. However, the existing Cassini data does not constrain the nature of the core materials. Only future geophysical data will allow us to decipher the nature and thermo-mechanical properties of the core.

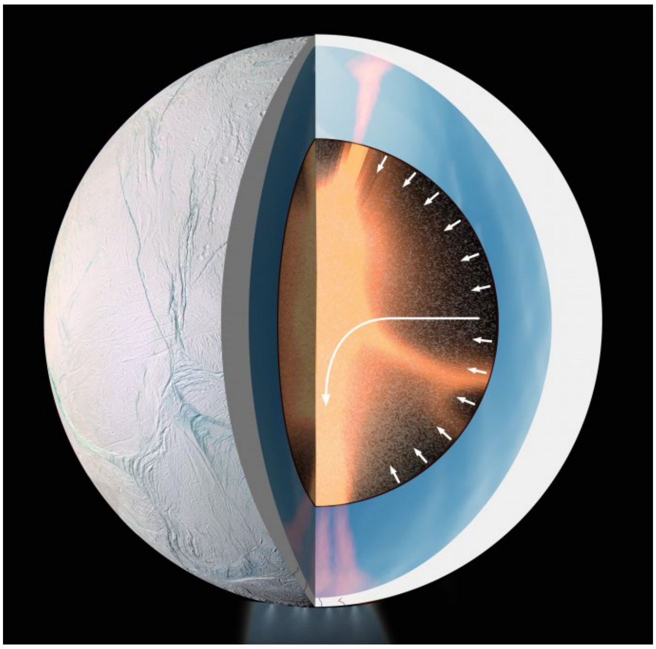

Figure 2.2.1: *Representation of tidally-heated water flow in Enceladus' porous core, following the 3D simulations of Choblet et al. (2017), (Credits: Surface: NASA/JPL-Caltech/Space Science Institute; interior: LPG-CNRS/U. Nantes/U. Angers. Graphic composition: ESA)*

Analysis of plume materials ejected from the south pole (see section 2.2.3) provide evidence that water-rock reactions are currently occurring at high temperatures (>50°C) in Enceladus' core. The existence of such a hydrothermal activity implies a large heat source inside the core, which may be attributed to enhanced tidal dissipation due to the low strength of the porous core. By modelling the flow of oceanic water in a porous core, Choblet et al. (2017) showed that tidal heating in the core leads to the formation of upwellings of hot water in narrow regions from the core center to the seafloor, preferentially beneath the poles and along the leading and trailing meridians (Figure 2.2.1). Such strong heat outputs at the seafloor may control the dynamics of the ocean and explain the strong thinning of the ice shell observed at the poles (Cadek et al. 2016, Beuthe et al. 2016 and Fig. 2.3.1-a,b).

While the "hot vibrating core" model seems consistent with the existing geophysical and chemical constraints provided by Cassini, many major questions remain unanswered. The permeability, porosity and composition are weakly constrained. Heterogeneity in the core is likely, but totally unconstrained. The consequences of core activity on the ocean dynamics still need to be tested. Future geophysical measurements (including gravity, topography, seismology, magnetic field) are required to confirm the existence of seafloor hotspots, and their signature in the oceanic flow and ice shell thickness variations.

2.2.2 What processes control the endogenous activity and for how long has it been active?

The intense endogenous activity observed in the South Polar Terrain (SPT), which cannot be explained by radiogenic decay in the silicate core (Schubert et al. 2007), clearly indicates that tidal dissipation is the key driver of Enceladus' activity (Nimmo et al. 2018). However, contrary to initial expectations (e.g., Nimmo et al., 2007; Tobie et al., 2008), the contribution of tidal heating in the ice shell to Enceladus' total heat production is negligible, suggesting that most of the heat must be generated by tidal dissipation in the porous core or by dissipation in the ocean. A careful analysis of tidal heating by Souček et al. (2019) shows that the total heat production in the shell is smaller than 2 GW, corresponding to less than 5% of the global heat loss through the ice shell (Cadek et al. 2019).

A porous unconsolidated rock core filled with liquid water may promote very large dissipation, potentially a power of 25-30 GW required to explain the present-day global ocean (Choblet et al. 2017). Enceladus's large physical libration (Thomas et al., 2016), catalysed by the pronounced planetary-scale roughness of the ice shell (see 2.3.1), may also induce instabilities in the ocean flow, providing a route toward turbulence that might constitute a non-negligible fraction of Enceladus' dissipated heat (Wilson and Kerswell, 2018). Based on Cassini data, it is impossible to determine what is the most likely dissipation process. Determining the source of dissipation inside Enceladus is crucial to assess the likelihood of seafloor activity and hence to evaluate the exobiological potential of the ocean.

Detailed monitoring of the tidal surface displacements and tidally-induced gravity potential from the orbit and from the ground will reveal the different contributions due to the deformation of the rock core, ocean and ice shell. A highly dissipative core similar to that proposed by Choblet et al. (2017) generates a gravitational signal that is about four times larger than the one due to a rigid core. Resonant tidal flow in the ocean may also amplify the tidal signal at harmonics other than that imposed by the external potential. Combining the tidal data with the information on the rock core and oceanic properties and flow (from seismology and electromagnetic sounding) will allow a separation of the different contributions, and hence a better understanding of where the heat powering the hydrothermal activity comes from.

Another issue concerns the duration of Enceladus' dissipative state. Estimation of the dissipation function of Saturn from astrometric data (Lainey et al. 2017) indicates that the strong dissipation inside Enceladus may be balanced by dissipation inside Saturn, potentially allowing sustained strong dissipation in the system for billions of years, especially if Enceladus is locked in resonance with an internal oscillation mode of Saturn (Fuller et al. 2016, Nimmo et al. 2018). Testing this last hypothesis requires additional accurate astrometric data from Enceladus, but also from the other inner icy moons. Such information is crucial to evaluate if the hydrothermal activity of Enceladus is long-lasting or just short-lived and episodic.

2.2.3 To what level have primordial volatile and organics been re-processed by water-rock alteration?

The detection of nanoscale silica grains by the Cosmic Dust Analyzer onboard Cassini was the first evidence of ongoing hydrothermal activity in Enceladus' rock core (Hsu et al. 2015; Sekine et al. 2015). This was then further constrained by the detection of molecular hydrogen in the plume by the Cassini mass spectrometer INMS (Waite et al. 2017), interpreted as internal hydrogen production, presumably associated with aqueous alteration. Cassini has also found macromolecular organic compounds within the plumes (Postberg et al., 2018, see section 2.3.3).

These observations raise some primary questions regarding chemical evolution: Is organic synthesis proceeding within Enceladus? What are reaction conditions (e.g., water-to-rock ratio, pH and temperature) that support the chemical evolution? What is the water chemistry within Enceladus' ocean? Answering these questions will be key science targets in future missions to Enceladus.

Important observables to address the above questions regarding organic synthesis are quantifications of C_2–C_6 hydrocarbons/N-bearing organic compopunds in the plumes and its comparison with those of comets. Macromolecular organic matter can be synthesized by polymerization of cometary simple C- and N-bearing compounds, such as HCHO, HCN, and NH_3, under hydrothermal conditions (Cody et al., 2011; Sekine et al., 2017). Cassini's INMS shows the presence of such simple molecules in the ocean (Waite et al., 2009); however, their abundances are less constrained. High-resolution mass spectrometers, such as ROSINA, are powerful instruments to quantify these simple organic compounds within the plumes. Comparisons of the measured abundances of these molecules with those of typical comets (Mumma and Charnley, 2011) will provide direct information whether polymerization of simple C- and N-bearing compounds proceeds under hydrothermal conditions within Enceladus. Idenfication of more complex macromolecular organic compounds, such those suggested by Cassini CDA analysis (Postberg et al. 2018) and comparison with organic matter in chondrites, using chromatography coupled to high-precision mass spectrometrer, such as Orbitrap™ techniques particularly adapted for analysis of complex organics (Briois et al. 2016, Gautier et al. 2016), will also allow us to understand their origin and their link with the hydrothermal system.

Another key observable to reveal the occurrence of chemical evolution is a difference ($\Delta^{13}C$) in the isotopic composition of $^{13}C/^{12}C$ between CH_4 and CO_2 in the plume. The $\Delta^{13}C$ value in methanogenesis is known to be ~30–60‰. (e.g. Allen 2006). High-resolution mass spectrometer, tunable laser spectrometer, or submillimeter wave instruments (such as SWI of JUICE) may be able to provide precise carbon isotopic values of C in CH_4 and CO_2 to constrain the occurrence of methanogenesis (either biotic or abiotic) in hydrothermal environments within Enceladus.

The water chemistry, namely major dissolved species, of Enceladus' ocean is largely unknown, except for Na^+ and Cl^- (Postberg et al., 2009). The abundances of other major cations (Mg, Ca, K, and Fe) in the ocean are useful proxy indicators to reveal many factors of the reaction conditions of water-rock interactions within Enceladus. One example is the Mg/Ca ratio in Enceladus' ocean. This ratio will provide information on an effective water-to-rock ratio of the water-rock reactions within Enceladus' ocean (e.g., Zolotov, 2007, 2012). Higher Mg/Ca values means higher water-to-rock ratios in the reactions, thus implying that unreacted rocks largely remain within the rocky core. Knowledge of the degree of alteration of the rocky core is essential for understanding when the present state of Enceladus' thermal activity initiated. Detailed chemical analysis of icy grains ejected in space and/or fallout at the surface will be essential to determine the water chemistry and the conditions of the water-rock interactions inside Enceladus.

SECTION SUMMARY: Confirming that Enceladus harbors a global hydrothermal system and assessing for how long it has been active requires a combination of geophysical and chemical measurements. While the chemical objectives may be largely addressed by analysing ejected gases and icy grains using high-precision mass spectrometer from plume flythrough approaches, detailed geophysical investigations require an Enceladus orbiter, complemented by surface investigations using at least one lander, equiped with a seismometer, a magnetometer and a radio transponder.

2.3. DYNAMICS AND EXCHANGE PROCESSES FROM THE OCEAN TO SPACE

Cassini's discovery of the spectacular activity at Enceladus' south pole resulted in a reasonably well-constrained knowledge of the state of the hydrosphere (ice crust and ocean, 2.3.1), the nature of the geological activity (2.3.2) as well as a careful analysis of the plume properties (2.3.3). Observing the present-day activity of Enceladus offers also an unique opportunity to observe processes that may have affected most icy worlds in the past. It is essential to better understand how such exchange processes were initiated and how they influence the moon's evolution.

2.3.1 How do the ice shell and the ocean dynamically evolve?

Spacecraft measurements of Enceladus' physical libration (Thomas et al., 2016) suggest that the ice shell accounts for about 15–30% of Enceladus' volume and is underlain by a global water ocean. Sensitivity tests including uncertainties in material parameters and internal structure show that the observed libration is compatible with an ice shell of average thickness between 14 and 26 km (Van Hoolst et al., 2016). Geological analysis of Enceladus' surface (Crow-Willard and Pappalardo, 2015; Patterson et al., 2018) indicates that the geological activity is not located only at the south pole and that a significant part of the ice shell experienced a complex deformation history. The shape of Enceladus' surface is currently known with a lateral resolution of about 50 km, corresponding to spherical harmonic degree l=16 (Tajeddine et al., 2017). Precise determination of Enceladus' shape/topography by a future mission would not only facilitate the interpretation of geological features but it would also permit a more precise determination of the local properties and thermal state of the ice shell through the modeling of viscoelastic relaxation (Cadek et al. 2017, Kamata and Nimmo 2017).

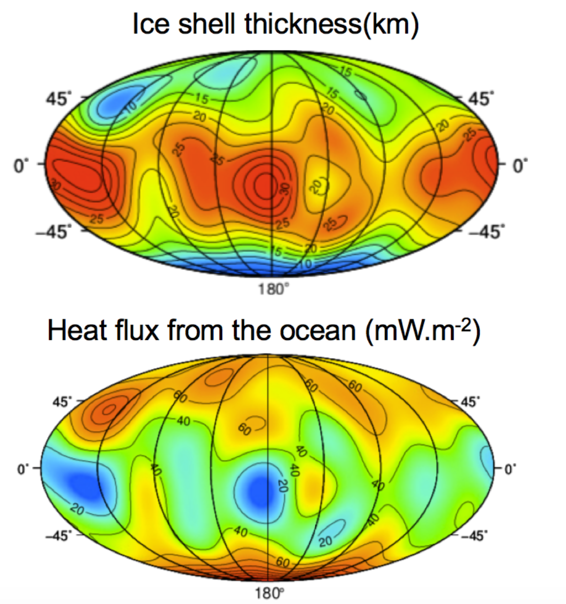

Figure 2.3.1: *(top) Ice shell thickness expanded to spherical harmonic degree 6 derived from topography (Tajeddine et al. 2017) and (bottom) corresponding heat flux from the ocean (Cadek et al. 2019).*

Key information about Enceladus' internal structure comes from measurements of gravity. The quadrupole (l=2) components of Enceladus' gravity field and its hemispherical asymmetry (J_3) have been determined from Doppler data obtained during three Cassini spacecraft flybys (Iess et al., 2014). Interpretation of the observed gravity signal in conjunction with the shape data led to the recognition that the ice shell thickness varies laterally (Iess et al., 2014; McKinnon, 2015), from a few kilometers in the south polar region to more than 30 km in the equatorial region (Van Hoolst et al., 2016; Čadek et al., 2016; Beuthe et al., 2016; Hemingway et al., 2018; Čadek et al., 2019).

Enceladus' large-scale topography (i.e. the distance between Enceladus' surface and an equipotential) exhibits an amplitude of 3 km peak to peak implying that the ice shell is not in hydrostatic equilibrium (Iess et al., 2014). Analysis of the gravity and topography at low harmonic degrees indicates that the ice shell is close to a dynamic steady state (Beuthe et al., 2016; Čadek et al., 2019) that is maintained by ice flow induced by phase changes (melting/freezing) occurring at the base of the ice shell (Cadek et al. 2019). The ice thickness is reduced/increased in regions where the heat flux coming from the ocean is higher/lower that the conductive heat flux through the ice shell (Beuthe 2019). In a steady state, the thickness of the ice shell does not change because the volume changes due to phase transitions are counterbalanced by the ice flow induced by pressure variations at the base of the shell (Čadek et al., 2019). This suggests that the long-wavelength topography of the ice shell is an imprint of the heat flux variations at the top of the ocean and its analysis can provide important constraints on the dynamics of Enceladus' ocean and possibly also on the thermal structure of the core.

Precise determination of higher-degree coefficients in the spherical harmonic expansion of gravity and shape by a future mission will allow an accurate determination of the depth of the ice/ocean, crucial to confirm or refute the notion of a dynamic steady-state versus alternative scenarios involving significant, net global melting or freezing of the ice shell. The thickness of the ice shell and its thermo-viscoelastic structure can also be surveyed by ice-penetrating radar and seismic measurements providing local, independent, estimates. A better description of the ice shell structure will allow the separation of the gravitational potential generated in the ice shell from that generated in the core, thus providing constraints on the magnitude of density and/or shape anomalies possibly associated with the hydrothermal circulation in the core (Choblet et al., 2017).

2.3.2 How active is the South Polar Terrain (SPT)? What processes control its activity and its current location at the South pole?

The central SPT (*csp*, Figure 2.3.2a) is mainly characterized by iso-oriented wide troughs (Tiger Stripes Fractures, TSF), which are defined as relatively long (> 100 km long and >> 2 km wide) curvilinear features in planar view, which often present branched tips and appear smooth in cross section (Schenk et al. 2011; Crow-Willard and Pappalardo 2015, Patterson et al. 2018, see cover page image and Fig. 2.3.2). The SPT also presents narrower branched troughs, which are commonly shorter than the wide troughs, crosscutting and interacting with the TSF (Crow-Willard and Pappalardo, 2015). Troughs are the most widespread structural feature on the surface of Enceladus and they are most likely related to recent/incipient brittle tensional deformation of the icy crust. These are particularly important because they can represent an interconnected fracture network, that extends deep enough (a few km) into Enceladus' ice shell to reach its internal ocean and work as pathway for fluid transport (see 2.3.3). An outer annulus of highly fractured terrain (*cl3*, Figure 2.3.2a) that includes corrugated ridge belts encloses the central region within the SPT, with two Y-shaped branches that depart radially from the *cl3* towards the trailing hemisphere (Patterson et al. 2018). These features are interpreted as contractional fold and thrust belts that transition into extensional structures to the north (Yin and Pappalardo, 2015).

As noted above (2.3.1), the SPT forms a topographic basin which suggests a locally thin ice shell. It is covered by icy material deposited from plume fallback onto the surface (Kempf et al. 2010; Scipionni et al., 2017; Southworth et al. 2018). In particular, the tiger stripe fractures have a strong UV signature which suggests large-grained ice exposed on the surface (Schenk et al. 2011).

The SPT is also associated with anomalously high heat flows; three Cassini instruments, namely Cassini's Composite InfraRed Spectrometer (CIRS), Visual and Infrared Spectrometer (VIMS) and RADAR used as a microwave radiometer, have provided evidence for high south polar heating. The highest temperatures have been recorded along the tiger stripes where a maximum of 197 ± 20 K was measured by VIMS on an active spot (Goguen et al., 2013). The total endogenic power averaged over the entire SPT has been estimated 15 GW from CIRS measurements (Howett et al., 2011) whereas the power is about 5 GW over the tiger stripes alone (Spencer et al., 2013). This suggests a broadly distributed heat production and transport system below the SPT as further supported by microwave radiometry observations from the Cassini RADAR. These observations have indeed revealed a warm subsurface region with prominent thermal anomalies about 50 km north the fourth central sulci (Le Gall et al., 2017). They bring a further argument for the idea that the liquid reservoir could exist at a depth of only a few kilometers under the ice shell at the south pole.

The origin of the SPT most probably involves the influence of global tidal deformation and the associated dissipative heating (Nimmo et al. 2018, Patterson et al. 2018). Preferential heating under the poles is predicted by the "hot vibrating core" model (Choblet et al. 2017, section 2.2.1) leading to a thinner ice shell in polar regions (Fig. 1 and 2.3.3). Furthermore, once fractures are triggered in the ice crust, tidal deformation is enhanced (Nimmo et al. 2007, 2018; Soucek et al. 2019). Yet a precise description of the fracturing mechanism at the south pole is still lacking. Alternatively, the tiger stripes may have formed elsewhere on the moon and have been relocated to the south pole as the result of a polar wander (Nimmo and Papparlado, 2006, Tajeddine et al. 2017).

The geologic history of the SPT definitely marks the most recent stage of regional geological activity on Enceladus but two other distinct geological terrains, LHT and THT (Leading and Trailing Hemisphere Terrains, respectively), share characteristics with the SPT. These are pervasive tectonized regions with a lower density of craters enclosed by circumferential belts (Crow-Willard and Pappalardo, 2015, Patterson et al. 2018). The THT is dominated by the so-called dorsa: large, smooth, mostly iso-oriented NW-SE ridges of few km in width, whose origin is likely related to fluid injection along pre-existing fractures (Spencer et al., 2009) or to pervasive thrusts blocks tectonics on the pre-existing striated plains (Pappalardo et al., 2010). On the other hand, the LHT is characterized by a smooth unit consisting of 10-15 km wide and 25-80 km long ridges, in addition to smaller ridges and troughs similar to features observed in THT but with less continuity. Its central unit characterized by ropy and interlaced ridges suggests that the LHT might correspond to a relict SPT.

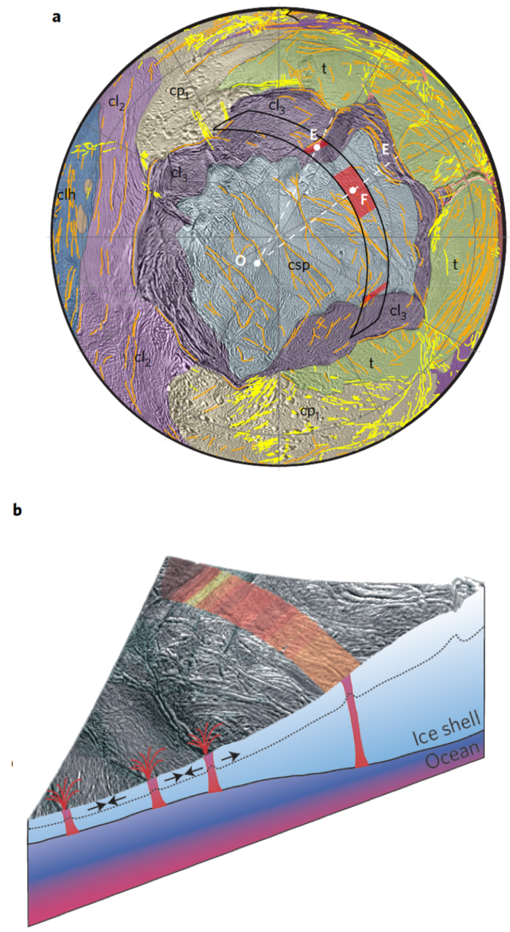

Figure 2.3.2: *a) Orthographic projection of the SPT with the structural units as mapped by Crow-Willard and Pappalardo (2015) superimposed, b) An illustrative slice through Enceladus SPT subsurface with the microwave-derived heat excess superimposed (Le Gall et al. 2017).*

Finally, the cratered plains of Enceladus that surround the LHT, THT and SPT record the earliest stages of geologic activity on the satellite presenting heavily cratered terrain, including subducted material and shallow craters (Crow-Willard and Pappalardo, 2015). The unit also bears morphologically fresh narrow-troughs crosscutting larger craters and in some places merging pit chains that suggest a recent incipient extension. Despite the wealth of information obtained by Cassini, many fundamental questions remain. How old is the oldest terrain on Enceladus? Since when has the moon been active? Has the location of this activity varied over time? What is the fundamental cause of deformation that created the tectonized regions?

Key observations to address these include measurements from orbit such as thermal emission, topography, InSAR, ice-penetrating radar; stereo-imaging and compositional mapping. Complementary constraints such as seismic and heat flow measurements, could be gathered from the ground by a lander.

2.3.3 What processes control the plume eruption and for how long has it been active ?

The Enceladus plume is formed by gas and icy grains expelled through cracks in the South Polar Terrain of the moon. A small fraction of the icy grains escapes Enceladus' gravity and feeds the E rings (Fig. 2.3.3, Kempf et al. 2005), while most of the icy grains fall back on the surface (Schenk et al. 2011). Approximately one hundred jet sources have been identified based on Cassini ISS observations using triangulation techniques (Porco et al. 2014). The distribution of jet sources appears consistent with CIRS temperatures (Howett et al. 2011) and with localized hotspots seen in high-resolution Cassini VIMS observations (Goguen et al. 2013, Goldstein et al. 2018). However, as pointed out by Spitale et al. (2015), some jet-like feature (Figure 2.3.3) may be just visual artifacts due to the view angle relative to the fracture geometry. This suggests that the eruption may be continous all along the tiger stripes, rather than associated with localized discrete sources. A few high-resolution images suggests that the eruption source are associated with localized geological features, supporting the view that certain jet-like features are real physical jets (Helfenstein and Porco 2015). But a detailed analysis of jet sources and morphologic features is still lacking, and cannot be achieved using only the Cassini observations.

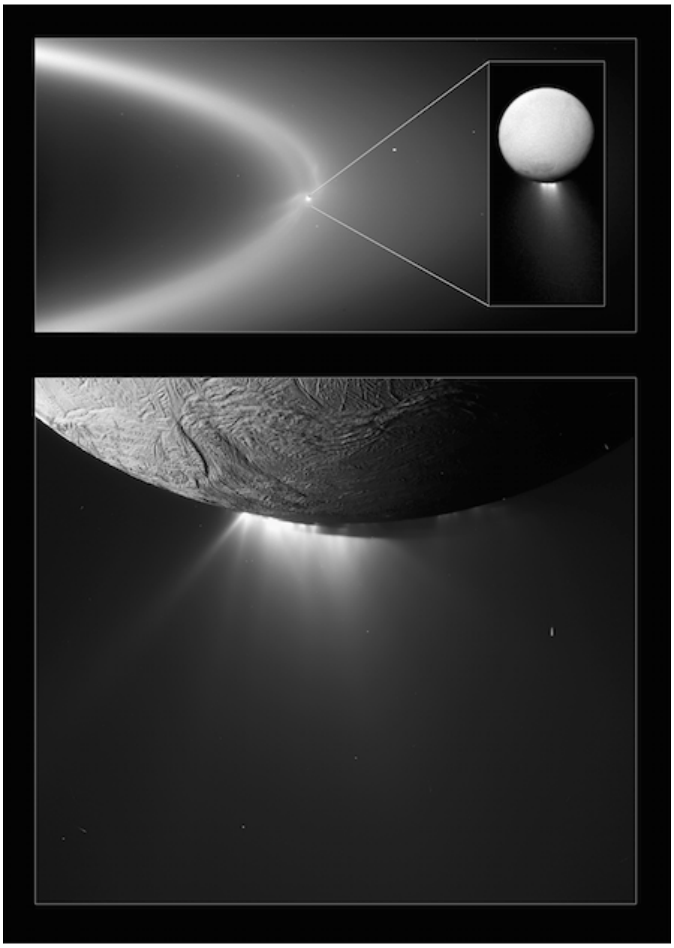

Figure 2.3.3: *Cassini ISS images of Enceladus' eruption activity from different distances, illustrating that the ejected icy particles feed the E-Ring (top) Credits : NASA/JPL/SSI.*

The physical mechanism at the origin of the jet eruption also needs to be confirmed. The consensus post-Cassini view is that the jetting activity is directly associated with liquid water into cracks at shallow depths (Spencer et al. 2018, Goldstein et al. 2018). Adopting a thickness of the south polar ice crust of 3-10 km (e.g. Thomas et al. 2016; Čadek et al. 2016; Beuthe et al. 2016 ; Le Gall et al., 2017), one expects that there exists a table of liquid water in the cracks, only about 0.3-1 km below the surface, from which most of the plume materials must disperse (cf. Fig. 2.4.1). Accelerated by the pressure drop to vacuum, the mixture of gas and particles is vented to the surface. The emission varies with location and time, so the dynamics and exchange processes from the subsurface to the vents cannot be uniform and constant. Detailed high-resolution mapping of the jet source in both the visible and the infra-red combined with subsurface radar sounding and InSAR by a future orbiter will be essential to identify precisely the jet sources and their subusurface reservoir and to monitor the temporal and spatial variations of their activity.

Data from the Cassini mission showed that the plume composition is dominated by water, amounting to more than 96% for the neutral gas (Waite et al. 2017) and 99% for the particles on average (Postberg et al. 2018b). The most abundant volatiles (Waite et al. 2017) are ammonia, molecular hydrogen, carbon dioxide, and organic gases, in mixing ratios of fractions of a percent, with upper limits of H_2 and NH_3 slightly above 1% (Waite et al. 2017). Methane (≈ 0.2%) is the most abundant organic compound in the gas phase with less abundant C_2 and maybe C_3 species (Magee and Waite 2017). In the solid phase the main non-icy compounds are sodium salts and organic material on the percent level, with three main ice grain populations (Postberg et al. 2009a, 2011a, 2018a). As noted above (see e.g. section 2.2.3), SiO_2 is another important constituent in plume particles (> 100 ppm, Hsu et al. 2011, 2015). O- and N-bearing organic species might be present in neutral gas (Magee and Waite 2017) and have been positively identified in a fraction of organic-bearing ice grains (Khawaja et al. 2019). Cassini data clearly indicates the presence of other volatile and organic species in the plume material (Waite and Magee 2017, Postberg et al. 2018b), but these remain unspecified due to the low sensitivity and low mass resolution of Cassini's in-situ instruments.

The apparent heterogeneity of the ice grains' composition strongly argues for different grain formation mechanisms (Fig. 2.4.1-d). Salty ice grains are thought to be frozen spray from oceanic water injected in the icy cracks, whereas the salt poor and most of the likewise salt poor but organic-bearing grains are thought to condense from supersaturated vapor inside (Schmidt et al. 2008, Postberg et al. 2009) and above (Yeoh et al. 2015) the ice vents. Some of the organic-bearing grains show spectral features indicative of the presence of highly refractory and complex organic material in much higher concentration than in those grains carrying volatile organics. Postberg et al. (2018a) postulated that this insoluble and probably hydrophobic material originates from an organic film near the oceanic surface disrupted during water eruption processes (Fig. 2.4.2). The compositional diversity among the various types of grains indicates that conditions for grain formation probably vary in both space and time (Postberg et al. 2018b). However, details are unclear on how these different grain populations form and what they tell us about the physical-chemical state of the plume sources.

Evidence for systematic spatial variations in plume properties across Enceladus' South Polar Terrain can also be found directly in the Cassini data. The fraction of organic-bearing grains is higher over Damascus and Baghdad sulci than over Cairo and Alexandria sulci (Postberg et al. 2011), which is consistent with variations in the strength of organic spectral signatures observed in the surface deposits around these fissures (Brown et al. 2006). Examinations of high-resolution plume observations (Dhingra et al. 2017) indicate variations in the particle size distributions, with Cairo material having distinctly different spectral properties from material erupting from Baghdad and Damascus. These variations may be related to the changes in the apparent particle size of the surface deposits around these fissures (Jaumann et al. 2008). Comparisons of data obtained by multiple instruments revealed that the dust-to-gas ratio in the plume is higher above Baghdad and Damascus than it is above Cairo and Alexandria (Hedman et al. 2018). These systematic spatial variations in source properties across Enceladus' South Polar Terrain likely reflect trends in the source material for the plumes and/or the plumbing connecting these reservoirs to the surface, which still need to be understood.

The total particle flux from the surface systematically varies by over a factor of four as the moon moves around its eccentric orbit (Hedman et al. 2013, Nimmo et al. 2014, Ingersoll and Ewald 2017). Variations in the gas flux on similar timescales have been reported by some researchers, while others find that the gas flux does not vary much as the moon moves around Saturn (Saur et al. 2008, Smith et al. 2010, Perry et al. 2015, Hansen et al. 2017). The changes in the particle flux are most easily interpreted as the result of changing tidal stresses allowing more or less material to escape from the moon (Hurford et al. 2007, Nimmo et al. 2007, Smith-Konter and Pappalardo 2008, Behounkova et al. 2015, 2017). However, simple tidal models fail to explain the observed trends, suggesting that the tidally-controlled eruption mechanism is more complex than anticipated (Nimmo et al. 2014, Hurford et al. 2015, Behounkova et al. 2015, Kite et al. 2016, Ingersoll & Ewald 2017).

Analyzing the Enceladus plume allows one to directly put constraints on the interior composition and the subsurface physical conditions. The plume discovery was probably the biggest surprise of the

Cassini mission. But clearly, the Cassini instruments were not designed for this investigation. Studying the plume and the distribution of its fallback material on the surface with a dedicated suite of in-situ and remote sensing instruments will offer a unique opportunity to sample fresh materials coming from a possibly inhabited ocean and to better understand the processes controlling the eruption of these oceanic materials to space.

SECTION SUMMARY: Monitoring the present-day plume activity and identifying the sources and geological processes at their origin are essential to understand how such activity initiated and for how long it has been active. While part of the science goals may be achieved by a multiple flybys approach, detailed surface and subsurface mapping as well as temporal monitoring of plume activity require a dedicated Enceladus orbiter. A lander in the SPT would also provide detailed local contraints on the tidally-induced eruption and faulting activity.

2.4 ENCELADUS' PLUME MATERIAL AS A WINDOW ON THE ORIGIN OF LIFE

Although future spacecraft exploration of Enceladus shall not be restricted to this single question, an overarching goal for any attempt at better characterizing this specific moon is to illuminate its astrobiological potential. First, deciphering the plume composition involves a better understanding of chemical transport in the ocean (2.4.1). Moreover, we argue here that because Enceladus can be used to test the hydrothermal hypothesis for the origin of life (2.4.2), specific groups of life signatures shall be envisioned in practice (2.4.3).

2.4.1 How efficient is the transport of hydrothermal materials from seafloor to the plume source? Is the plume composition representative of the hydrothermal fluids at the seafloor?

In the "hot vibrating core" model (Choblet et al., 2017), besides heat, seafloor hotspots are expected to deliver the products of hot water-rock reactions occurring in the core, into the ocean. Characterizing the fate of such hydrothermal products still involves modelling efforts: first-order scaling relationships suggest that, especially at high latitudes, rotationally confined hydrothermal plumes within the ocean (see e.g. Vance and Goodman, 2009) would deliver excess heat to the ice-ocean interface and lead locally to thinning of the ice shell by melting of the ice shell (see Cadek et al., 2019 and 2.3.1). Such ocean plumes would also transport the chemical products of water-rock interaction occurring in the core to the plume feeding-zone. Typical speeds of centimetres per year (Choblet et al., 2017) are predicted, consistent with the appropriate growth-rate for nano-silica grains (Hsu et al. 2015). If the existence of such confined oceanic plumes controlled by seafloor hydrothermal activity is confirmed, it will indicate that the plume composition is a relatively good proxy of chemical processes occuring in the hydrothermal vents.

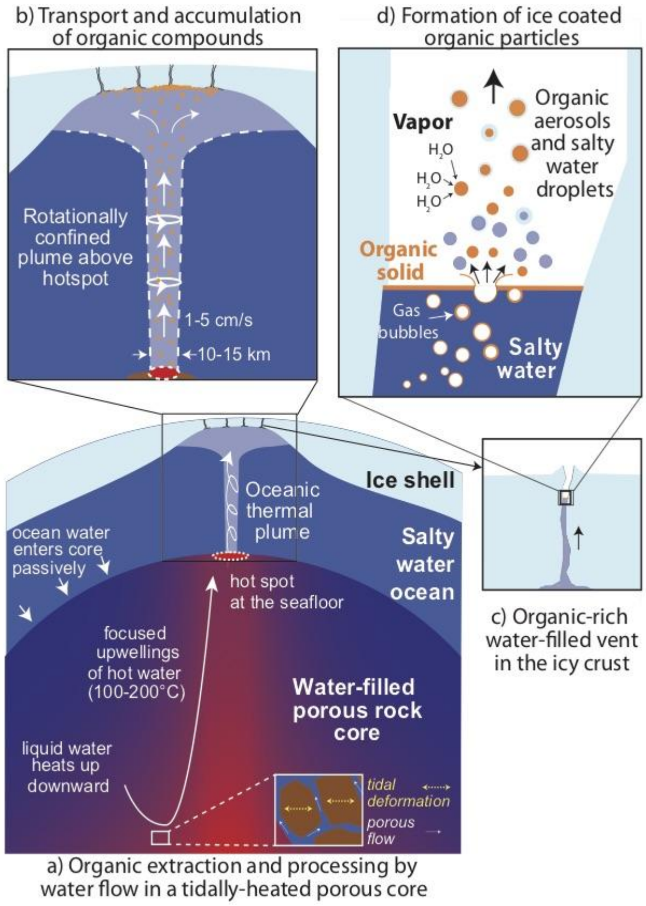

Figure 2.4.1: *Proposed transport of hydrothermal organics from the deep core through the ocean and incorporation into ice grains emitted by the plume (after Choblet et al. 2017 and Postberg et al. 2018).*

The seafloor signal could however be blurred by specific dynamics of global scale rotating convection in the ocean, which may limit the efficiency of chemical transport from the seafloor to the bottom of the ice shell. Preliminary simulations (Bouffard et al., 2018) show that this is probably not the case under the poles: while powerful zonal jets shall be expected at low latitudes bounded by the tangent cylinder, the strong heat flux heterogeneity prescribed at the seafloor always leads to polar upwellings in the ocean flow. However, such numerical simulations are far from the real dynamical regime of Enceladus' ocean. Observational constraints on the oceanic flow and associated heat flux are required in order to quantify the coupling between oceanic thermal plumes and global ocean dynamics. In addition to convection, mechanical forcing must be considered for Enceladus' ocean.

Another key aspect relates to the active effect of non-water compounds (essentially salts and organics with a wide mass range, cf. 2.1.3) on ocean dynamics and the evolution of its composition. Although possibly not as pronounced as in the case of Earth's oceanography, the effects of chemical gradients on Enceladus's ocean flow might involve alteration of the main aspects discussed above and lead locally to stratification or double-diffusive convection phenomena. Beginning to understand both the chemical evolution of the ocean and the role of compositional buoyancy will necessitate modelling efforts, but only additional constraints from further observation at Enceladus will enable us to decipher this complex environment: in addition to electromagnetic sounding mentioned above that relies on salinity (or ocean conductivity) as one of the basic ingredients to interpret measurements, a refined in-situ compositional characterization of plume materials either directly within the plume, in the E ring or by a ground analysis of particles redeposited at the surface, will provide selection criteria among plausible chemical evolution scenarios.

2.4.2 Can we use Enceladus to test the hydrothermal hypothesis for the origin of life?

In-situ analysis of Enceladus' plume during closes flybys of Cassini has revealed the presence of water, ammonia, molecular hydrogen and nitrogen, possibly sulphur, and simple as well as complex organic compounds (Waite et al. 2017; Postberg et al. 2018). On Earth, hydrogen and carbon dioxide form a spontaneous redox couple, which can be utilised by specific microorganisms for example, methanogens (which produce methane) or acetogens (which produce acetate), to support growth. All of the key elements that are required for life (CHNOPS) have either been detected in the plumes or are expected to be present due to the water-rock interactions at the sea-floor (McKay et al., 2014, 2018). Furthermore, the predicted conditions within the subsurface oceans are not deemed extreme for microbial life, for example, a predicted pH of between 8.5 and 12 (e.g. Postberg et al. 2009; Hsu et al. 2015; Glein et al. 2015), salinity between 0.5 and 2 % (Postberg et al., 2009, 2011), and varying temperatures between -0.15 °C (Glein et al., 2015) and 100 °C (and possibly more) at localised areas of hydrothermal activity (Sekine et al. 2015, Choblet et al. 2017). Although these conditions may be considered habitable, there is yet no evidence that life actually emerged within these oceans.

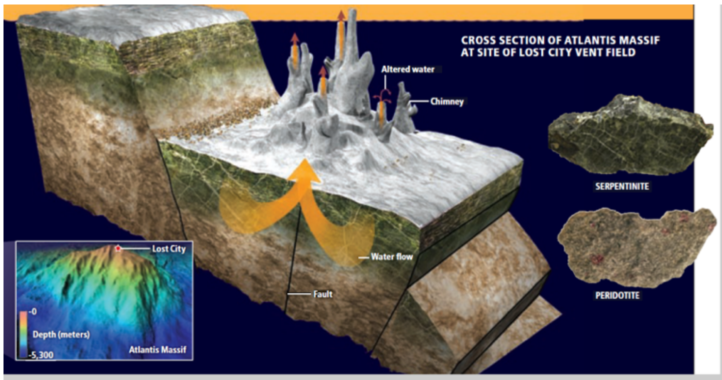

Figure 2.4.2: *Schematic representation of the fluid circulation in the vent and the serpentinization process leading the formation of the alkaline hydrothermal vents of Lost City (Bradley 2009), considered to be good analogues to those occurring at Enceladus seafloor (Hsu et al. 2015, Sekine et al. 2015, Tobie 2015).*

If life did exist on Enceladus, questions would need to be asked regarding its origin. At present there are two broad hypotheses for the origin of life in the Solar System. Firstly, that there is a local origin of life event, from which we know virtually nothing, and secondly that life is transferred (panspermia) from one place to another (McKay et al. 2018). Research regarding the origin of life is predominantly focused on the hypothesis that life emerged on Earth rather than elsewhere in the Solar System, since it is virtually impossible to accurately estimate the ancient geological conditions of other planetesimals, a challenging enough feat when dealing with Earth (Westall et al. 2018).

However, the actual origin of life is highly debated with two contrasting theories; 1) that life originated at Hadean alkaline hydrothermal vents (Martin and Russell, 2007; Russell et al., 2014; Sojo et al., 2016), or 2) that life originated on surficial volcanic/hydrothermal shallow ponds, by using UV radiation and wet-dry cycles as driving force (Powner et al. 2009; Deamer and Georgiou 2015). However, whichever way life evolved, the distance between the Earth and Enceladus would mean that the probability of material being transferred between the two is low (Worth et al., 2013). Therefore, Enceladus as an astrobiology target is compelling, because life there would most probably represent a second genesis, and could be used to better test the hypotheses of the emergence of life.

Of particular relevance to Enceladus is the hypothesis that life on Earth originated in a Hadean alkaline hydrothermal vent similar to the Lost City system, which is situated at the intersection between the Mid Atlantic Ridge and the Atlantis Transform Fault (Kelley et al., 2001; Russell, 2007; Russell et al., 2014). This system is formed due to serpentinization occurring in the ocean floor (hydrothermal activity alters the olivine ocean crust), which abiotically yields methane and hydrogen, molecules which are fundamental for life on Earth (Figure 2.4.2); such molecules have also been found in the plumes of Enceladus (see section 2.3.3 and Fig. 2.4.1). Due to the lack of requirement for active plate tectonics or magmatic heating for these systems to persist, these hydrothermal systems are most likely present on Enceladus (Barge et al., 2017). Therefore, if life had emerged on Earth in these alkaline hydrothermal vents, it is conceivable it may also have evolved in a similar manner on Enceladus. Nevertheless, it is possible that the scarcity of high potential electron acceptors (Russell et al., 2014) in Enceladus' oceans has heavily limited the energy available which life there could feed upon. In any case, a future mission to Enceladus to investigate life may result in a second data point for life, which would provide a fundamental test regarding the origins of life and may perhaps enable the long-sought after comprehensive and universal theory for the emergence of life, on Earth and elsewhere (Lazcano and Hand 2015; McKay et al. 2018).

2.4.3 Are there signs of extant or extinct life in Enceladus' plume materials?

Multiple lines of chemical and physical evidence obtained by both orbital and remote sensing support the conclusion that the subsurface ocean of Enceladus satisfies the basic requirements for habitability (Postberg et al. 2018, Glein et al. 2018, McKay et al. 2018, see 2.4.2). Because the plumes are likely sourced from the subsurface ocean that has both organics and the potential for energy-producing pathways, the search for life at Enceladus is compelling. However, an unknown remains on how the material might be modified between synthesis and measurement, *e.g.* how the different mechanisms interplay and affect the ejected material that could be measured by an Enceladus plume-science or lander analysis.

The initial assessment of potential signatures of life features several measurements but including all is likely beyond a single reasonable mission. The aim will thus be to group potential life signature measurements to maximize the likelihood of life detection. The measurements in each set should be the most agnostic possible. Signatures that are of particular interest in the context of Enceladus plume material (gas or ice grains in the plume, or sedimented at the surface of the satellite) can be divided in three main types:

- Organic molecular signatures: Any selectivity in organic molecules can be used as a potential identification of biological activity (McKay 2004, McKay et al. 2018). For instance, the presence of a large enantiomeric excess in chiral molecules would be a significant finding towards the biological origin of those molecules. The presence of monomers of the same handedness in a biological polymer is a requirement for stability, and thus should be universal in any type of complex molecules used by life. In addition, life will use preferentially certain types of molecules and functional groups, different from the statistical distribution that can be found in abiotically-synthesized compounds and from the bias towards simple molecules. The presence of such a deviation from statistics is evidence towards a system beyond chemistry-only (e.g. McKay 2004). Lastly, patterns in molecules, or repetition of a specific suite can also be used to detect polymeric chains characteristic of complex molecules created by living organisms (e.g. Dorn et al. 2011). Organic molecular signatures have the advantage of targeting both extinct and extant life.

- Structural indicators of microbial life: cells are the basic structural units of life, the containers of biochemistry. The ability to detect not just the chemical signature of cell membranes and walls, but also verify their shape and that they contain important polymeric biomolecules would be extremely important for any claim at finding life (e. g. Lindensmith et al. 2016).

- Biological activity signatures and impact on the environment: minerals like SiO_2 and carbonates may be produced biotically on Earth and therefore may strengthen the case for past biological activity in the system. In addition, living systems have a preference to incorporate lighter isotopes. Those are examples of additional signatures that would add up to the other multiple lines of evidence, to be able to claim confidently the detection of life in an ocean world such as Enceladus.

The astrobiology community has long recognized that life detection cannot be dissociated from environmental parameters that provide essential context for both a positive and a negative result. The challenge will thus be to associate precise instruments and methodologies allowing a robust and synergetic detection of biosignatures, but also to maximize the contextual science of the samples without requiring significant additional payload.

SECTION SUMMARY: Determining if Enceladus' deep habitable environments have been suitable for the emergence of life requires finding direct and indirect evidence for biological activity. Searching for chemical biosignatures in plume materials can be achieved by flythrough approaches but will be limited to tiny icy grains. Landing near an active jet source will give access to coarser icy samples potentially providing direct evidence for microbial life and contraints on the environmental context.

3. SCIENTIFIC INVESTIGATIONS AND MISSION CONCEPTS

Cassini's major discoveries at Enceladus demonstrated that great science can be achieved by a flyby mission. Cassini investigations provided first insights on the plume structure, the composition of the vapor and icy grain components (also called the dust in the following), their mass ratio, the speed and size distributions of the constituents, and the interaction with the saturnian corotational plasma, as well as on the replenishment of the magnetosphere and E-ring region with fresh plasma and dust particles. However, Cassini's instruments were not optimized to perform detailed investigations of the « unexpected » plume. In addition, the geometry of the flybys and the intervals between successive observations resulted in limited spatial and temporal coverage, essential for complete surface mapping, geophysical investigations and temporal monitoring of the plume activity.

Reevaluation of the plume and endogenic activity with improved spatial and temporal coverage, combined with detailed chemical analysis of ejected plume materials, using up-to-date dedicated instruments, are the ambition and challenges of the next generation of missions to Enceladus.

3.1 Science investigations from icy samples:

Enceladus offers the **unique opportunity to interrogate the subsurface ocean without drilling**. The plumes deliver both vapor and grains to space, with heavier particles falling back down to the surface. Therefore, any future Enceladus mission whose scientific goals include characterizing the ocean must be capable of sampling plume ejecta (orbiter or flyby) or fallout (lander). How sample is collected and at what volume will be an important trade, as each approach has pros and cons.

Sampling the plume material using a fly-through approach ensures direct analysis of freshly erupted materials. This was impressively demonstrated by Cassini's in situ detectors (e.g. Waite et al, 2017, Postbeg et al. 2011, 2018). Fly-throughs may be targeted at different altitudes, different times in the orbital period, or over different tiger stripes (e.g. MacKenzie et al. 2016). The importance of the latter was recently further demonstrated by Hedman et al. (2018) who used data from Cassini UVIS and VIMS to show that the dust/gas ratio varies between tiger stripes. These results suggest heterogeneity in the subsurface conditions across the south pole. However, if the spacecraft velocity is above about 8 km/s, large organic molecules break apart, as shown by the Cassini INMS and CDA measurements (Waite et al. 2017, Postberg et al. 2018), which increases the difficulty of identifying complex molecules and biosignatures, if no low speed flybys are considered. Lab experiments are currently underway to elucidate the effects of high-velocity measurements in preparation for the next mission to Enceladus (Klenner et al. 2019, Bonaccorsi et al. 2019, Seaton et al. 2019, Waller et al. 2019).

Where plume falls back to the surface of Enceladus depends on the eruption style at the vent. Recently, however, Southworth et al. (2019) generated maps of surface deposition for different models using the latest maps of jet and/or curtain locations from

Cassini data, facilitating the identification of compelling and safe landing sites for an Enceladus lander. Evidence for buried craters (Kirchoff and Schenk, 2009) and pit chains (Martin et al., 2017) point to a much thicker regolith in some aereas than predicted by models of plume-sourced regolith deposition. Because we have to be careful not to land in a place where the thickness of the deposits from plume fallback and E-ring is too large, detailed mapping of a few regions of interest before landing site will have to be performed.

Landed architectures could catch samples from the plume fallout and/or scoop samples from the surface. The latter may have been altered by space environments (e.g. Lunine et al. 2018) and may therefore be less interesting as a primary target for biosignatures. However, sampling modified material to determine the processes responsible for modification of Enceladus' surface would provide highly useful context. Once the samples are collected, be that in flight or on the ground, a suite of chemical and optical analyses are possible for searching for biosignatures in the plumes and determining the habitability of the subsurface ocean by characterizing its chemical and physical state.

High–resolution mass spectrometry can be used to identify the chemical composition of gases and icy grains and therefore identify organic molecular signatures directly in the plume, as well as on the surface by collecting fallout erupted materials. Specific targets could include biologically relevant molecules like amino acids, nucleic bases, lipids, or sugars. Chirality of amino acids or sugars may also be explored with the addition of gas and liquid chromatography. Structural evidence may be detectable via the identification of chemical compounds used in cell walls in the mass spectra, while biological activity signatures would be detectable in isotoptic abundances (eg. Reh et al. 2016).

Additionally, new assays are being developed to facilitate the **identification of biomolecules**. This includes techniques like microfluidic capillary electrophoresis (e.g. Mathies et al. 2018), laser-induced fluorescence (e.g. Skelley et al. 2005; Mathies et al. 2018), fluorescent antibody assays (e.g. Parro et al. 2011), and nanopore sequencing (e.g. Pontefract et al. 2018; Carr et al. 2019).

Optical imaging of samples can be used to identify cells, which, if life is present, are estimated to be within the plumes at concentrations ~10^4-10^8 cells/mL (Steel et al. 2017; Porco et al. 2017). Atomic force miscroscopy could resolve ice grains and has been demonstrated on Rosetta (Bentley et al. 2016), but new techniques are also in development. Digital holographic microscopy, for example, can discern between mineral and cells of similar morphologies and can detect motion (Nadeau et al. 2016, 2018; Bedrossian et al. 2018).

Characterizing the habitability of the subsurface ocean will rely on measuring the presence and abundance of certain molecular compounds through some form of mass spectrometry. This includes identifying potential redox pairs and their availability as a chemical energy source (Glein et al. 2018). The abundances of micronutrients like phosphate, sulfate, and iron salts demonstrates availability (Lingam and Loeb, 2018). Ocean temperature can be derived from D/H and ethylene/ethane ratios while pH can be inferred from the abundance of CO_2, bicarbonate, or carbonate (Glein et al. 2018).

Instead of sending a suite of complex instruments to Enceladus to characterize life signatures, another option is to bring Enceladus' icy samples to Earth. **Returning samples from Enceladus** (presumably of ejected ocean material) would uniquely enable investigations that are exquisitely sensitive, path-dependent, and that leverage improvements in measurement capabilities for decades to come. These are essential qualities in the search for life, for which previous attempts such as the Viking missions have taught us to expect the unexpected. They would also provide definitive answers regarding the chemistry and synthesis conditions of the samples. A stand-alone mission dedicated to sample return would by design make little contextual measurements, which would have to be carried out by a separate mission. Alternatively, a sample return element would be highly complementary to the science of an *in situ* mission. Such an element would be a clean interface for an international contribution. International contributions have enhanced essentially every large robotic planetary mission.

3.2 Remote-sensing and geophysical investigations from the orbit:

In addition to fly-through sampling, **the orbiter architecture provides opportunities for critical contextual measurements.** These geophysical and remote-sensing measurements can provide the data necessary to characterize the modern subsurface ocean, its longevity, and how it is vented into space.

Global topography (via radar and/or laser altimetry and stereoimaging) and **high-resolution imaging** can provide new insights into the resurfacing rate and therefore the longevity of the plume activity at the SPT. Identifying active features would be facilitated by topography in conjunction with monitoring the **thermal emission and surfaced displacements with InSar** (Vance et al. 2019). Furthermore, geomorphological and compositional mapping with these data can inform the surface history (e.g. Crow-Willard and Pappalardo 2015) and properties of the regolith and ice shell (e.g. Bland et al. 2012; Martin et al. 2017). **Targeted high-resolution optical and InSAR imaging together with accurate altimetry and ice-penetrating radar of the vent sources** in the SPT will provide crucial constraints on the vent dynamics and the connection with subsurface water reservoirs.

High-fidelity measurements of Enceladus' gravity field and global shape, would allow direct detection of the tidal deformation, providing constraints on the global Love numbers k_2 and h_2 (e.g. Hussmann et al. 2011) as well as on the regional enhancement of **tidal deformation** in the SPT (by monitoring changes in local gravity, tilt and strain at the surface). This would yield further insights on the local ice shell structure and fault geometry (Soucek et al. 2017, 2019). These data combined with accurate libration measurements could also potentially reveal the mechanical properties of the rock core and confirm if it is highly dissipative at present (Choblet et al. 2017, Vance et al. 2019). Such measurements will be key for understanding the likelihood of hydrothermal activity.

In contrast to Jupiter, Saturn's magnetic field does not possess any known deviations from azimuthal symmetry (Dougherty et al. 2018). Therefore, no prominent time-periodic field is available to perform electromagnetic induction studies to probe the electrical conductivity of a subsurface ocean similar to the studies at Europa or Ganymede (Kivelson et al 2004). Sources for time-variability at Enceladus are the time-variable plumes, which generates time-variable magnetic field and the time-variable magnetospheric properties (e.g. Gurnett et al. 2007, Saur et al. 2010). These fields can in principle be used to probe Enceladus' interior, but they require a sufficient temporal coverage of the **magnetic field measurements**. Such a coverage can be obtained by a low orbiting spacecraft, ideally complemented by an array of magnetometers on the surface of Enceladus (Saur et al. 2010). These observations should be supplemented with **plasma measurements and simultaneous observations of the plume properties and time variability**.

3.2 Geophysical investigations from landing platform(s):

In addition to **sampling plume fallout via catching plume fallout or scooping surface deposits**, landed architectures are well suited to conducting *in situ* **contextual science and geophysical investigations.**

Seismology would be the best technique for resolving the interior structure of Enceladus, including variations in composition and thermal properties with depth. These aspects are essential for further assessing the habitability of Enceladus' ocean and seafloor and for understanding the context allowing to interpret any candidate biosignatures. Seismic investigations would also be **complementary to orbit-based geophysical measurements**, thanks to their ability to measure the moon's dynamics on time scales that are not resolvable from orbit and providing locally a « ground (and underground) truth ». There is a trade-space for any such mission between the number of seismic nodes, seismometer sensitivity, and mission duration needed to characterize the thickness and dynamics of the ice, any fluid layers therein; the thickness, heterogeneity, and dynamics of the ocean; and the nature of the underlying rocky interior (Vance et al. 2018a,b; Panning et al. 2018; Stähler et al. 2018). The small size of Enceladus means that a single seismometer has a strong likelihood of detecting signals originating anywhere on or within the moon, while the significant observed plume activity indicates ample seismicity for passive seismic techniques. However, the strong variations in ice shell thickness may make the seismic signal interpretation challenging. Complementary with orbital measurements will be essential to solve that issue and provide **a realistic 3D representation of Enceladus' dynamic interior.**

Geodetic measurements from the surface alone, or in partnership with an orbiting element, would improve the use of gravity and topography measurements as independent means for constraining the ice thickness and transport properties. Using a radio transponder, a lander would provide position knowledge for an orbiter, which would improve the interpretation of orbital geodesy. A landed mission would permit experiments measuring the **local deformation of the surface** of Enceladus by monitoring the tilt of the spacecraft. Simulations (Vance et al. 2019) indicate a required sensitivity of better than 2 µrad, which would not be achievable only from orbiting radio science or other surface measurements (e.g., stereo topography or radar).

3.4 Mission concepts and architectures:

The above science investigations can be achieved using different mission architectures which may partly or totally address the four main science questions presented in section 2. Table 1 presents a preliminary assessment of the ability for each mission concept to achieve the four main science objectives we identified. Hereafter we briefly review the pros and cons of each type of mission profiles and the possible opportunity to achieve such a mission in the framework of the future ESA programme.

Multiple flyby mission: Such a mission concept is the simplest one and has the advantage to perform several plume flythrough trajectories, at different altitudes, positions relative to the main faults and differerent times in the orbital periods, as well as potential flybys of other moons and E ring crossing for comparative studies. The geophysical investigations as well as temporal monitoring of plume and fault activity are, however, strongly limited. The relative high velocity of plume crossing will also limit the capabilities to identify complex molecules and biosignatures. Several projects using such a mission concept have been proposed to NASA as Discovery (Sotin et al. 2011, Tsou et al. 2012, Lunine et al. 2015) and New Frontiers, and to ESA in L-class (Coustenis et al. 2009, Tobie et al. 2014) and M-Class (Mitri et al. 2018) categories. While a M-class mission cannot be excluded if a reduced payload is considered (Mitri et al. 2018), a ESA-led L-class mission appears the optimal category for such a mission concept.

Enceladus orbiter: This mission concept is a further level up in complexity and hence cost. Orbit insertion around Enceladus will require several orbits around Saturn with potential flybys of other moons to lower spacecraft orbit. Therefore, such a mission concept in addition to providing detailed investigations of Enceladus will offer the opportunity to study the Saturnian system and acquire comparative observations at other moons. An Enceladus orbiter is the ideal configuration to perform geophysical investigations, surface mapping and plume activity surveys. However, because of the small gravity and the proximity to Saturn, polar orbits would be unstable, so that plume crossing and SPT imaging at high resolution can be performed only during brief excursions from stable low latitude orbit or during low-speed flybys before insertion (Spencer et al. 2010, Lunine et al 2018). A detailed mission concept study of Enceladus orbtier was performed by Spencer et al. (2010) for the NASA Planetary Science Decadal Survey. Such a mission would be comparable to the JUICE mission in terms of payload and operations, with a preliminary tour around Saturn followed by an Enceladus orbital phase.

Lander(s): Landing on Enceladus near a vent source is probably the best way to collect fresh oceanic materials potentially containing biosignatures. However, owing to its rugged topography, possibly unconsolidated icy powder surface and its low gravity, landing is a real challenge (e.g. Lunine et al. 2018). Reducing the risk necessitates a detailed mapping and characterization of the landing zone, which requires a preliminary reconnaissance mission (either multiple flyby mission or orbiter mission).

Detailed studies to date of concepts for surface missions on icy moons demonstrate the plausibility of autonomous laboratory operations for biosignature characterization and geophysics (Konstantinidis et al. 2015, Hand et al. 2017). For biosignature investigations, a single lander suitably located in a freshly erupted area may fully address the astrobiological questions. A mobile lander sampling several areas would increase the probability of successful detection. A lander could also use passive seismic and electromagnetic measurements to monitor the activity of the plumes and fault activity and to get crucial informations on the subsurface structure. A second geophysical lander located outside the SPT, in the equatorial region or in the northern hemisphere, would allow a more complete characterization of the interior structure and core activity. Such a lander configuration combined with an orbiter, which will act as a relay in addition of providing a full coverage, will be the ideal configuration to address most of the science questions.

Such an ambitious mission architecture combining orbiter and lander(s) would not be possible in an ESA-stand alone mission, but can be achieved in the framework of international partnerships with other agencies (NASA, JAXA etc.), either as ESA-led L-mission orbtier mission complemented with partner lander(s) or as an orbiter mission led by a partner agency with a M-class lander provided by ESA, in the same spirit as the Cassini-Huygens mission and TSSM mission concept.

Sample return: The only architecture reported in the literature is a stand-alone, multi-flyby mission with elements derived from NASA's Stardust mission (Tsou et al. 2012). However, other options exist. As for *in situ* missions, sample return is much facilitated by Enceladus' low gravity (e.g. relative to Mars sample return), which allows for sampling of its extended plume through flybys and hovering above the plumes or landing from orbit at a relatively low ΔV expense. The measurements to be carried out on Earth dictate the mass and state of samples that must be returned. These, in turn, drive the choice of possible mission architectures. Sampling directly from the plume simplifies operations. Cassini operations have shown that repeated flybys are possible at a ≈3-week cadence, allowing dozens of flybys within a collection time that remains short compared to the roundtrip time of 13+ years (Tsou et al. 2012). This can offset limited collector sizes and the tenuous plume density, which limit the mass that can be collected per flyby. The collected mass can be accumulated much faster by orbiting Enceladus, hovering over the plumes, or landing on the SPT and collecting surface or infalling plume material. The added advantage is that of lower sampling velocity, i.e. less sample modification upon collection.

Critical issues and technology developments: Beyond Jupiter, the most critical issue concerns the power source. At Saturn, solar power is very low and a long-term exploration mission with an orbiter and/or lander as proposed here requires the use of radioisotope power sources. Solar power only may be envisionned for small spacecraft performing reduced and limited operations (Lunine et al. 2012, Mitri et al. 2018), but will have a limited science return. In previous mission concepts to Saturn such as TSSM, MMRTGs or ASRGs using ^{238}Pu were considered and were to be provided by NASA. The developments of ASRGs have now been abandoned by NASA and the amount of available ^{238}Pu is now reduced. Within Europe, the radioisotope ^{241}Am is considered a feasible alternative to ^{238}Pu and can provide a heat source for small-scale radioisotope thermoelectric generators (RTGs) and radioisotope heating units (RHUs) (Tinsley et al., 2011). About 1000 kg of ^{241}Am exists in an isotopically pure state within stored civil plutonium at reprocessing sites within the UK and France. Studies has been performed to design a process that will chemically separate ^{241}Am (Tinsley et al. 2019). Prototypes for both radioactive heater units (warming the spacecraft) and thermoelectric generators (providing spacecraft power) have been demonstrated, and the first ^{241}Am-based RTGs at high TRL may be available in less than a decade. In order for ESA to send ambitious missions beyond Jupiter, it is essential to ensure the development of an independent European power source.

Landing and possible displacement at the surface in case of a mobile lander will require the development of an autonomous guidance, navigation and control (GNC) system surface of Enceladus. Radio tracking (essential for achieving the geophysical requirements) and data downlink will be greatly improved by the development of ESA ground-stations with state-of-the-art Ka-band technology, comparable to NASA's Deep Space Network capabilities.

Sampling of icy materials from the orbit and from the ground for direct analysis and/or sample return will also require developments of specific collecting devices and new generation of instruments (icy grain analyzer, high-resolution mass spectrometer) of detecting complex macromolecular organics and biomolecules. Collection technologies have been flown for sample return missions such as NASA's Stardust, Genesis, OSIRIS-REX as well as JAXA's Hayabusa (-2) but need to be tailored to the specific needs of Enceladus plume sampling. Other focus areas are means to check that enough sample has been collected, and to preserve the sample through the return journey (most crucially during reentry heating if the sample is to be kept cryogenic). Finally, the implementation of back planetary protection requirements (Cat. V – Restricted in the COSPAR policy) has yet to be defined, although options have been discussed (Takano et al. 2014). There are likely synergies with Mars sample return efforts.

	Multiple flybys		Enceladus orbiter	Lander(s)		Sample return	Enceladus orbiter	
				single	multi		Lander(s)	Sample R
1-Origin in the Saturn system	M-class	L-class	Saturn tour				Saturn tour	Saturn tour
2-Hydrothermal context								
3- From ocean to space				SPT landing				
4- Biosignatures in plume materials								
Mission profiles	*ESA-led M- or L-mission*		*ESA-led L-mission*	*- ESA-led L mission - ESA M-Mission + int. partner*		*ESA M-mission + int. partner*	*- ESA-led L mission + int. partner contr. - Int. partner-led mission + ESA M-class mission*	

Relevant for science questions : Not Partly Mostly Fully

Table 1 : Synthesis of the different mission concepts that could address the main science questions about Enceladus and how they could be achieved in the framework of the ESA Voyage 2050 programme.

MISSION CONCEPT SUMMARY: Preliminary assessment indicates that the **optimal mission concept** to address the four main science questions identified in this white paper would consist of **an Enceladus orbiter and at least one lander in the south polar region**. Such an ambitious mission architecture can be achieved in the framework of international partnerships with other agencies (NASA, JAXA etc.), either as ESA-led L-mission orbiter mission complemented with partner lander(s) or as an orbiter mission led by a partner agency with a M-class lander provided by ESA, in the same spirit as the Cassini-Huygens mission and TSSM mission concept. This large mission could be preceded by a smaller reconnaissance mission (M-Class) performing multiple flybys and plume flythrough analyzes that will bring first hints about the astrobiological potential of Enceladus and will help defining the instrument requirements and specifities for more in-depth characterization. **A detailed CDF study in association with potential partner agencies would be required to further assess these mission concepts and determine the optimal partnership scheme.**

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