Enceladus as revealed by the Cassini-Huygens mission. J. Hunter Waite[1], Chris Glein[1], Frank Postberg[2], and Jonathan Lunine[3], [1]Southwest Research Institute, San Antonio, Texas, hwaite@swri.edu, cglein@swri.edu, [2]Freie Universitat Berlin, Berlin, Germany, frank.postberg@fu-berline.de, and [3]Cornell University, Ithaca, New York, jil45@cornell.edu.

Introduction: The present geological activity of Enceladus is arguably the greatest discovery of the Cassini-Huygens mission. This small icy satellite in the Saturn system is only 504 km in diameter. Yet, buried beneath its icy surface lies a global ocean with a pH of ~9-11 (compared with an Earth seawater value of ~8.1), an ionic strength of ~0.1-0.2 (compared to a seawater value of 0.72), and a volume 1.7-2.4 x 10^7 km^3 (compared with an Earth ocean volume of 1.3 x 10^9 km^3 [1].

Tidal interactions in the Saturn system not only maintain a global liquid water ocean, but they appear to generate sufficient energy dissipation within an unconsolidated water-filled porous core of Enceladus that is in good agreement with the gravity field measurements and that allows foe efficient long term heating that produces a hydrothermal system deep below the south pole [2,3]. The presence of the hydrothermal system is independently supported by observations of SiO_2 nanograins [4] in the Saturnian dust environment and through the existence of H_2 gas in the plume gases that are emitted through vaporization of the internal ocean [5] when exposed to the vacuum environment of space. (see Figure 1.)

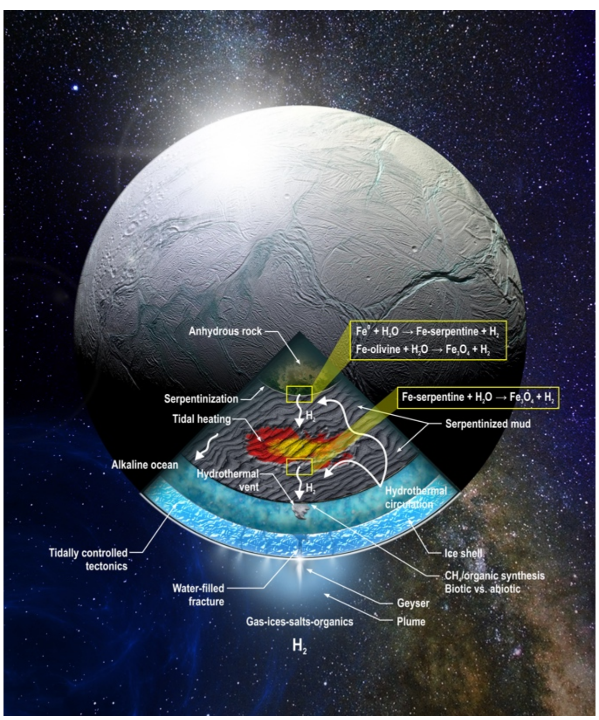

Figure 1: Water-rock reactions are capable of forming H_2 in a hydrothermal system in Enceladus' south polar region.

Observations and Findings: Measurements by the suite of instruments onboard the Cassini spacecraft have vastly increased our understanding of Enceladus. We summarize some of the most important observations and implications below.

Existence of an internal ocean. Geophysical data from both the Cassini Radio Subsystem (RSS) and the Imaging SubSystem (ISS) have been used to constrain the characteristics of the internal ocean. The coherent picture that emerges from the combination of gravity, topography, rotation and microwave measurements [3,6,7,8] are enumerated as follows:

1. Core density: 2300-2500 kg/m^3
2. Core radius: 190-200 km
3. Liquid water + ice mantle: 50-60 km thick
4. Ice shell thickness: 20-25 km (from librations), thinning out to 2-5 km in the southern polar region
5. Thickness of global ocean: 25-30 km (+10 km at the south pole)

Composition of ice grains and gases. The plume emitted from the south polar region contains both micron-sized ice grains and volatile gases. The largest class of ice grains provide compositional information on the salt concentrations [9] in units of mol/kg H_2O:

NaCl	**0.05-0.2**
$NaHCO_3$ + Na_2CO_3	0.01-0.1
KCl	~0.001

The primary exsolved gases found in the plume are water-dominated [4] with the following molar percentages:

H_2O	**~98**

CO_2	0.3-0.8
CH_4	0.1-0.3
NH_3	0.4-1.3
H_2	0.4-1.4

In addition to the primary salts and gases shown above, the plume contains ambiguously identified evidence for a host of organic chemical compounds including gases such as formaldehyde, C2, C3, and C4 hydrocarbons, methanol, as well as nitrogen-bearing organics [10]. Most surprisingly, some of the ice grains showed strong evidence for very large organic compounds greater than mass 1000 u [11]. These unexpected heavy organics are the subject of continued study and are of primary importance in the future exploration of Enceladus.

Habitability. NASA has established a checklist for determining the habitability of a planetary body. The criteria include:

1. Extended regions of liquid water
2. The presence of organic molecules and the associated biogenic elements CHONPS
3. Energy sources that can be harnessed to sustain metabolism

The existence of a global ocean and the composition of the ice grains and gases clearly establish that Enceladus satisfies criteria 1 and 2 (with the exception of any detection of phosphate). Most importantly, the gas composition of the plume can be used to quantify the chemical affinity state of the ocean with regard to the methanogenic metabolic reaction:

$4H_2+CO_2 \rightarrow CH_4+2H_2O$ with an inferred chemical affinity of 40 to 130 kJ/mole CH_4 [4].

The large positive chemical affinity of this reaction satisfies habitability criteria 3 and establishes Enceladus as the best *known* body in the solar system outside of Earth to look for microbial life. Figure 2 provides a graphical summary of the geochemical parameters that quantify the chemical affinity.

Conclusion: Cassini found that a global ocean exists below the ice surface on a small icy satellite of the Saturnian system, Enceladus. Plumes composed of gases and entrained ice grains provide a port for sampling the chemical characteristics of the internal ocean. This sampling allows us to infer that hydrothermal processes at the base of the interior ocean create a source of molecular hydrogen, which can serve as a nutrient source for microbial life forms. This potential for microbial metabolism taken together with the existence of unidentified complex organics in the ice grains provides an imperative for a return mission to further explore the potential for life at Enceladus.

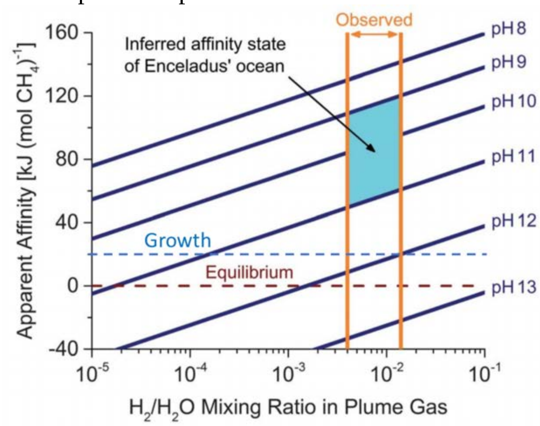

Figure 2: Methanogenic chemical affinity from H_2 as a function of the ocean pH. Modified from [4].

References:

[1] Glein C. R. et al. (2018) *Enceladus and the icy moons of Saturn, The University of Arizona Press,* 39-56. [2] Choblet G. et al. (2017) *Nature Astron., 1,* 841-847. [3] Iess L. et al., (2014) *Science, 344,*78-80. [4] Hsu H-w et al. (1996) *Nature, 519,* 201-210. [5] Waite J. H. at al. (2017) *Science 356,* 155-159. [6] Thomas P. C. et al. (2016) *Icarus, 264,* 37-47. [7] Cadek O. et al. (2016) *Geophys. Res. Lett., 43,* 5653-5660. [8] Le Gall A. et al (2017) Nature Astron., 1, 1-5. [9] Postberg F. et al. (2009) *Nature, 459,* 1098-1101. [10] Waite et al. (2009) Nature, 460, 487-490. [11] Postberg F. et al. (2018) *Nature, 558,* 564-568.