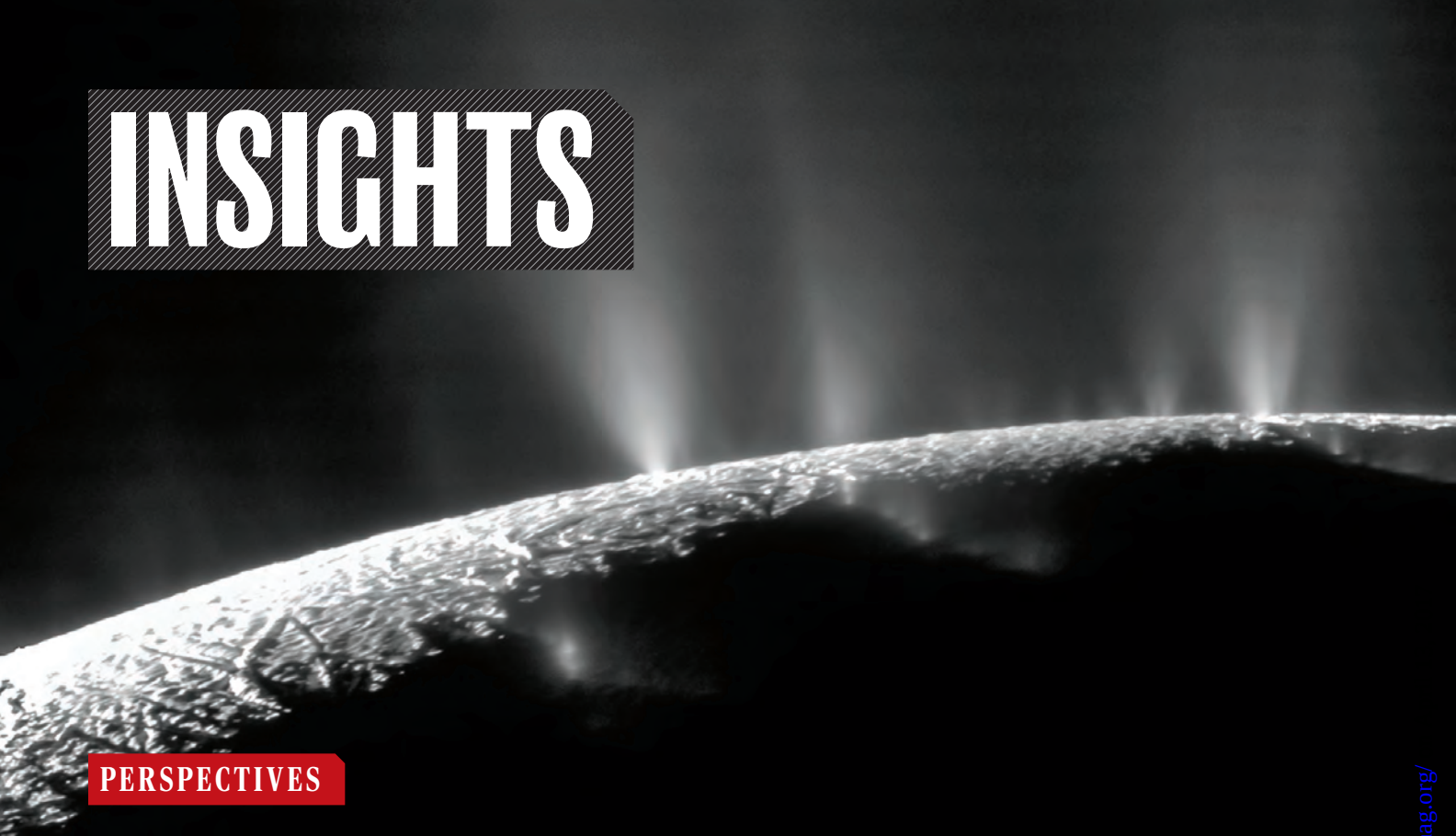

INSIGHTS

PERSPECTIVES

PLANETARY SCIENCE

Detecting molecular hydrogen on Enceladus

Cassini spacecraft detects molecular hydrogen on one of Saturn's moons

By **Jeffrey S. Seewald**

Planetary bodies with global oceans are prime targets in the search for life beyond Earth owing to the essential role of liquid water in biochemical reactions that sustain living organisms. In addition to water, life requires energy and a source of essential chemical elements (C, H, N, O, P, and S). Although there is compelling evidence for liquid water and many of the essential elements on several ice-covered planetary bodies in our solar system and beyond, direct observation of energy sources capable of fueling life has, to this point, remained elusive. On page 155 of this issue, Waite *et al.* (*1*) report that recent flybys of the ice-covered saturnian moon Enceladus by the Cassini spacecraft reveal the presence of molecular hydrogen (H_2) in jets of vapor and particles ejected from a liquid water ocean through cracks in the ice shell. The abundance of H_2 along with previously observed carbonate species suggests a state of chemical disequilibria in the Enceladus ocean that represents a chemical energy source capable of supporting life.

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Enceladus is a midsized (504-km diameter) satellite of Saturn that has an inferred rocky silicate core covered by an estimated 2- to 60-km layer of water ice (*2–4*). Evidence points to the existence of a global ocean (*3, 5*) that is likely maintained in a liquid state by heat generated during tidal deformation. The viability of life on planetary bodies such as Enceladus can be assessed through examination of biogeochemical processes on Earth. Sunlight-fueled photosynthesis is the primary source of energy at Earth's surface, but is unlikely in the outer solar system where energy from the Sun is limited, especially at depth in ice-covered oceans. In Earth's oceans, however, there are vast ecosystems where primary production is sustained in the absence of sunlight by chemical energy available from aqueous fluids venting at the seafloor. Some of the most primitive metabolic pathways utilized by microbes in these environments involve the reduction of carbon dioxide (CO_2) with H_2 to form methane (CH_4) by a process known as methanogenesis (*6*). Here lies the connection with Enceladus. By operating the Cassini onboard mass spectrometer in open-source mode during a 2015 flyby of Enceladus that intersected the vapor and particle plume, Waite *et al.* were able to minimize analytical artifacts that had compromised H_2 measurements during previous flybys. The new approach allowed them to determine that the plume gas contained 0.4 to 1.4 volume % H_2 along with 0.3 to 0.8 volume % CO_2, critical ingredients for methanogenesis.

Reconstructing the composition of the Enceladus ocean from the abundance of material in the plume is a difficult task because of unknown chemical fractionation associated with the freezing of saline ocean water in a vacuum as it is ejected through cracks in the icy shell. By making the simplifying assumption that molal abundance ratios in the Enceladus ocean are preserved in the plume, Waite *et al.* developed a geochemical model that predicts a highly alkaline (pH = 9 to 11) sub-ice ocean containing dissolved H_2 and carbonate species in a

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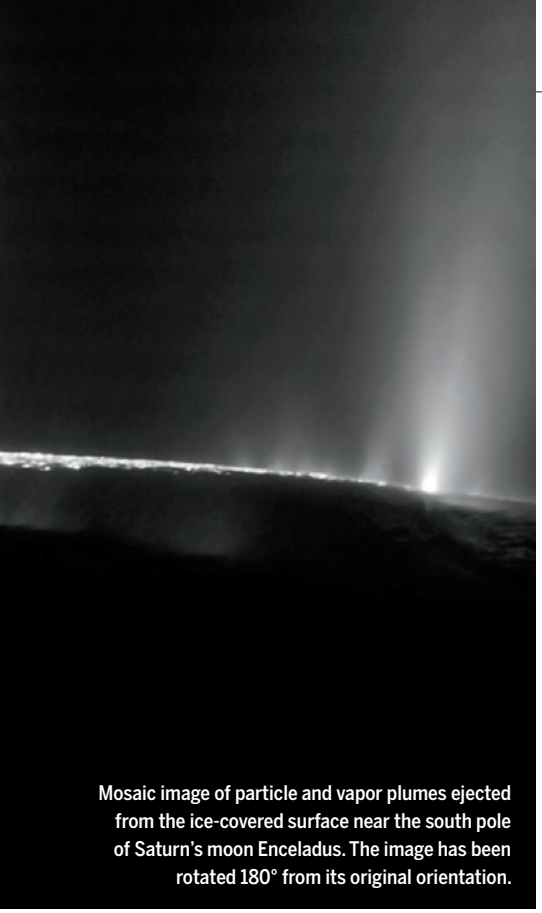

Mosaic image of particle and vapor plumes ejected from the ice-covered surface near the south pole of Saturn's moon Enceladus. The image has been rotated 180° from its original orientation.

state of chemical disequilibria. If correct, this observation has fundamental implications for the possibility of life on Enceladus; chemical disequilibrium that is known to support microbial life in Earth's deep oceans is also available to support life in the Enceladus ocean.

The detection of H_2 in Enceladus plumes represents a window into processes regulating the composition of its ocean. Although numerous processes can produce H_2 on Enceladus, Waite *et al.* present convincing arguments that point to water-rock reactions in the silicate core as the most likely source. Thus, liquid water on Enceladus is not only a requirement for life-sustaining biochemical processes, but may also be essential for geochemical processes responsible for the production of H_2. Indeed, fluid flow and associated water-rock reactions are ubiquitous on Earth in a diverse range of submarine environments (*7*) that continues to expand as we study the vast unexplored regions of our oceans. Many of these environments produce H_2 during hydrothermal alteration of rocks that contain ferrous iron and/or organic matter. The lower temperature limit for H_2 generation during fluid-rock interaction on Earth is poorly constrained, but highly relevant to assessing the viability of fluid-rock reactions as a source of H_2 on Enceladus, because the availability of heat represents a key variable that may limit the temperature of H_2 generation in the silicate core (*8*). In the context of Enceladus' geochemical evolution, the importance of water-rock reactions extends far beyond H_2 generation. As is the case on Earth, where circulation of seawater through the oceanic lithosphere regulates the chemistry of seawater, hydrothermal processing of Enceladus' silicate core has been postulated as a control on the pH, salinity, and abundance of silica in the Enceladus ocean (*9–11*).

Waite *et al.*'s results represent an important advance in assessing the habitability of Enceladus. Many questions remain, however, regarding geological processes on Enceladus that lack Earth analogs. For example, unlike Earth, where plate tectonics delivers magmatic heat and continuously supplies unaltered ultramafic rocks to near-seafloor environments readily accessed by hydrothermal fluids, there is no a priori evidence for plate tectonics or magmatic activity on Enceladus. Sustained H_2 generation on Enceladus requires that hydrothermal fluids have access to organic- and ferrous-iron–bearing rocks in the entire silicate core. What are the mechanisms for the formation of permeability and heat that allows the flow of aqueous fluids through the silicate core and back to the ocean? The accumulation of H_2 in the Enceladus ocean is conspicuous in the context of an Earth analog, where H_2 delivered to oxygenated oceans from submarine hot springs is rapidly consumed by pervasive microbial populations in seawater. Is the presence of H_2 in the Enceladus ocean an indicator for the absence of life, or is it a reflection of the very different geochemical environment and associated ecosystems on Enceladus? We still have a long way to go in our understanding of processes regulating the exchange of mass and heat across geological interfaces that define the internal structure of Enceladus and other ice-covered planetary bodies. Future missions to explore oceans beyond Earth will answer many of these questions and further constrain the possibility of life elsewhere in our solar system. ■

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10.1126/science.aan0444

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