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Subsurface Icecraft

IceMole

An Autonomous Probe for
Subsurface Ice Research

@ **Whole Earth Seminar**

University of California, Santa Cruz
14 February 2012

Bernd Dachwald
and the IceMole Team

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IceMole

Principle of Operations



IceMole

Principle of Operations



Quelle: FH Aachen/www.fichtographie.de

Extraterrestrial mission scenarios:

- In 20 – 30 years:
 - on Jupiter's moon Europa
 - on Saturn's moon Enceladus
- In 10 – 20 years:
 - on Mars' polar caps

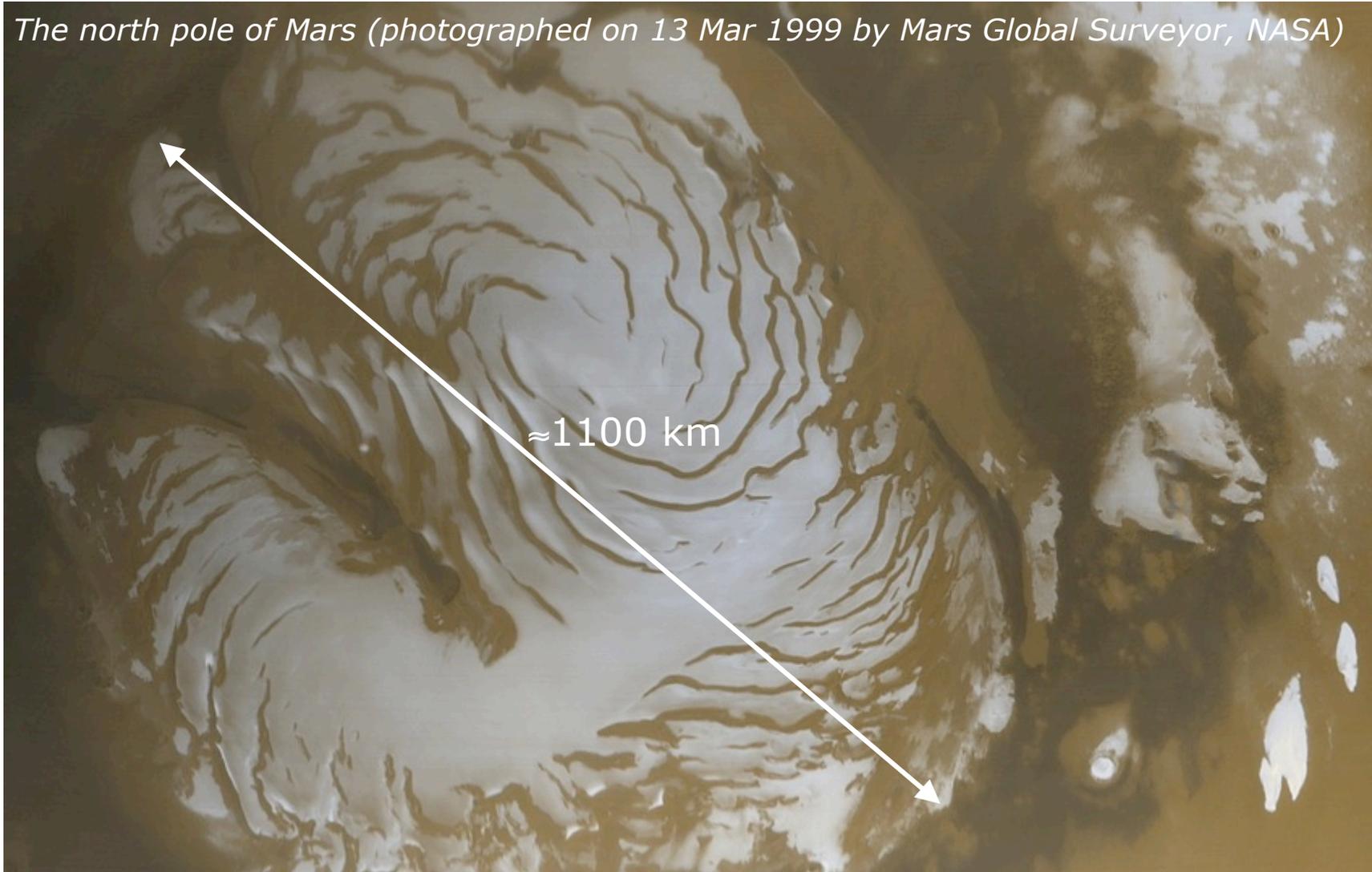
Terrestrial mission scenarios:

- In 2 – 10 years:
 - in Antarctica's ice (and eventually subglacial lakes)
- Now:
 - in glaciers and ice shields

Water Ice in the Solar System

Water Ice on Mars

The north pole of Mars (photographed on 13 Mar 1999 by Mars Global Surveyor, NASA)



Water Ice in the Solar System

Water Ice on Mars

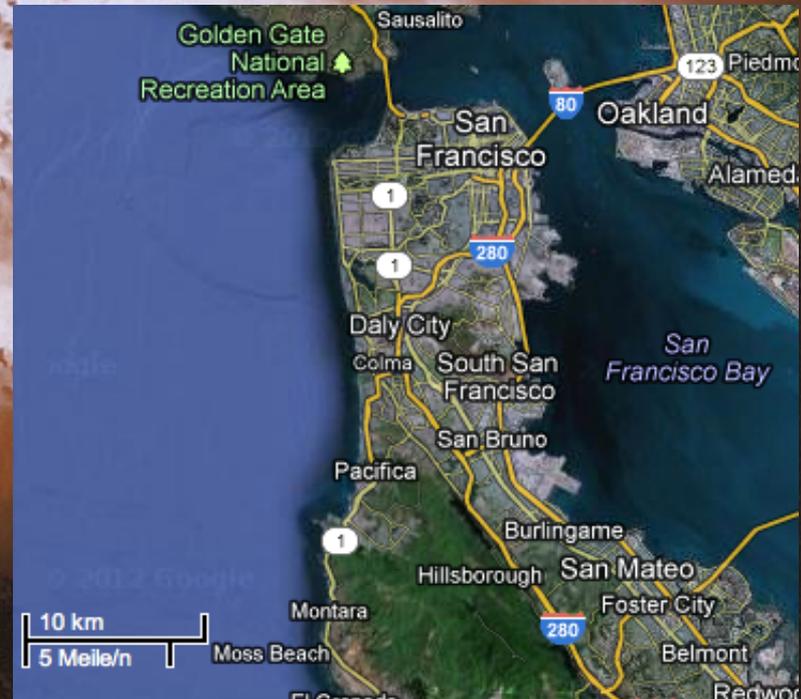
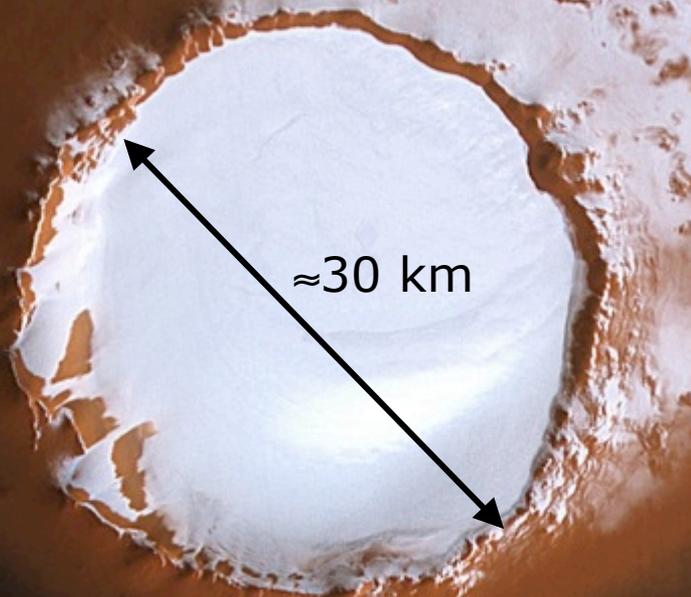
Water ice in an unnamed crater in the Vastitas Borealis (photographed on 02 Feb 2005 by Mars Express, ESA)



Water Ice in the Solar System

Water Ice on Mars

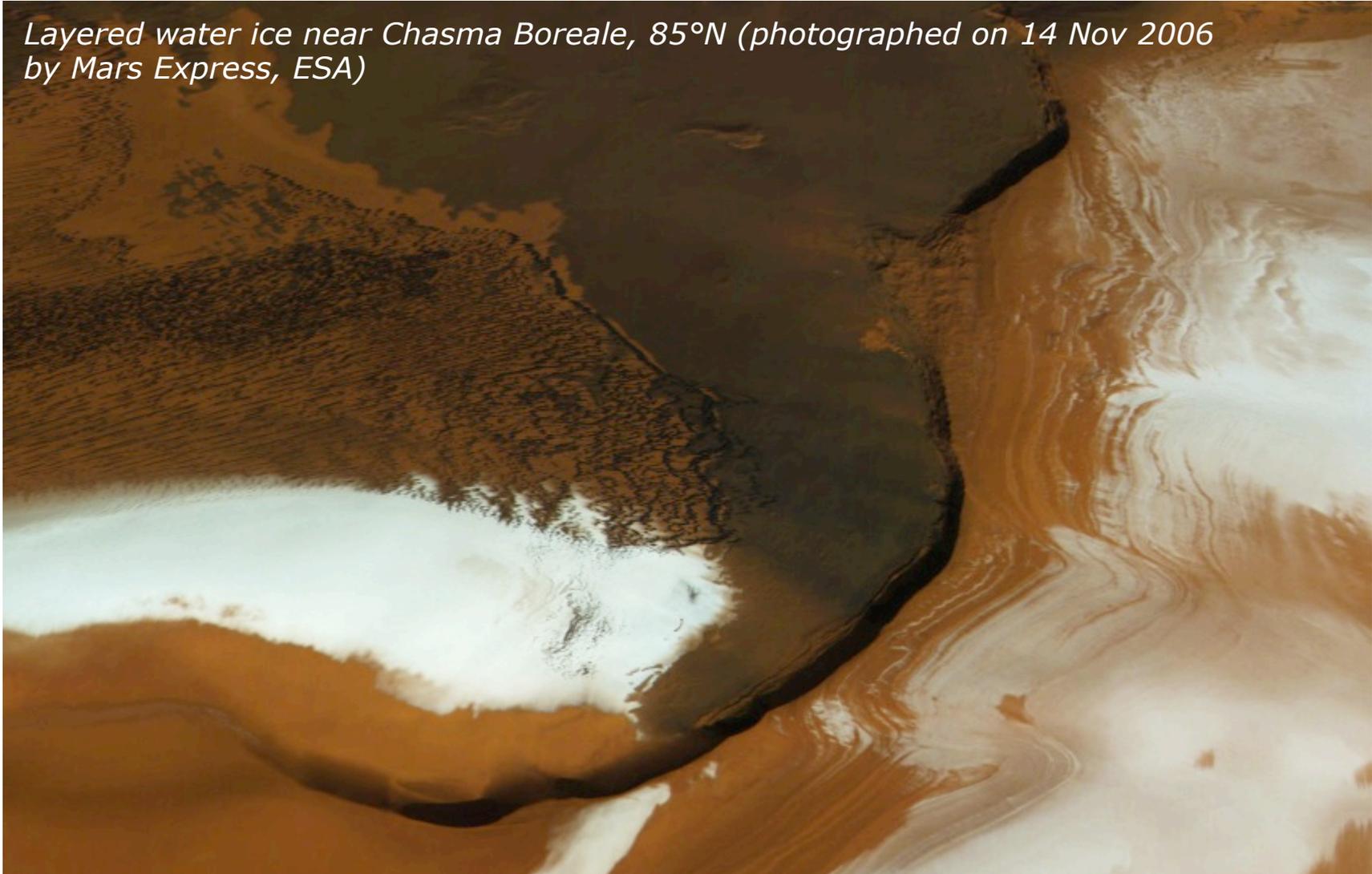
Water ice in an unnamed crater at 78°N (photographed on 23 Nov 2006 by Mars Express, ESA)



Water Ice in the Solar System

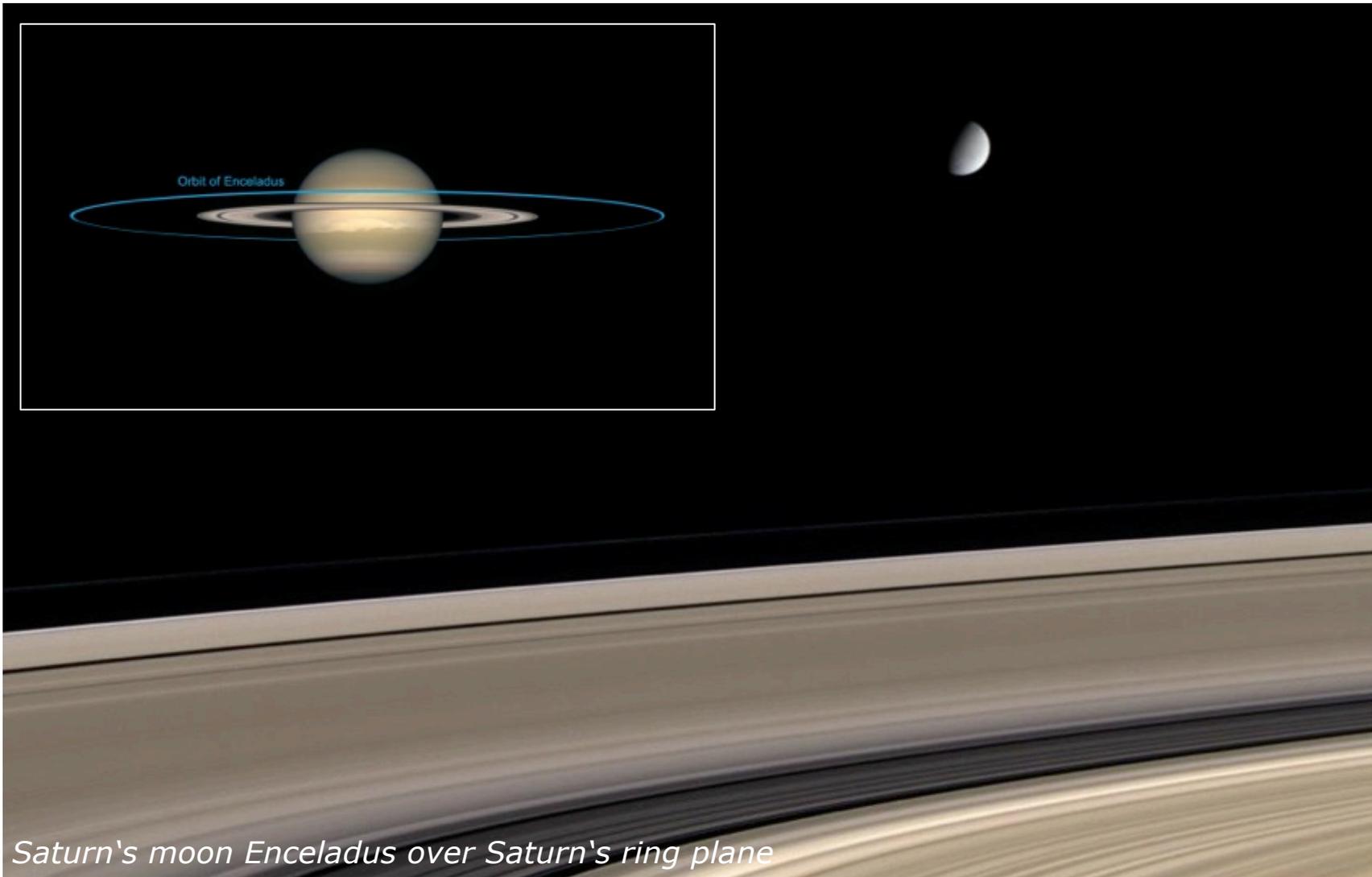
Water Ice on Mars

Layered water ice near Chasma Boreale, 85°N (photographed on 14 Nov 2006 by Mars Express, ESA)



Water Ice in the Solar System

Saturn's Moon Enceladus

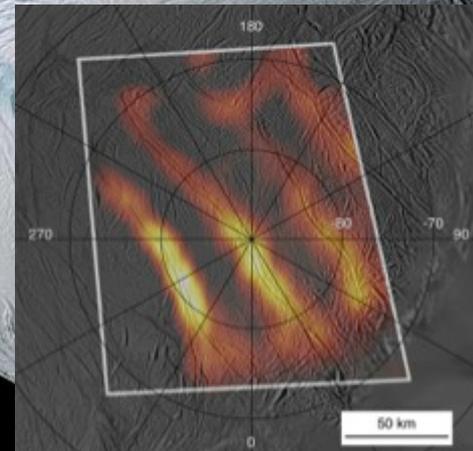
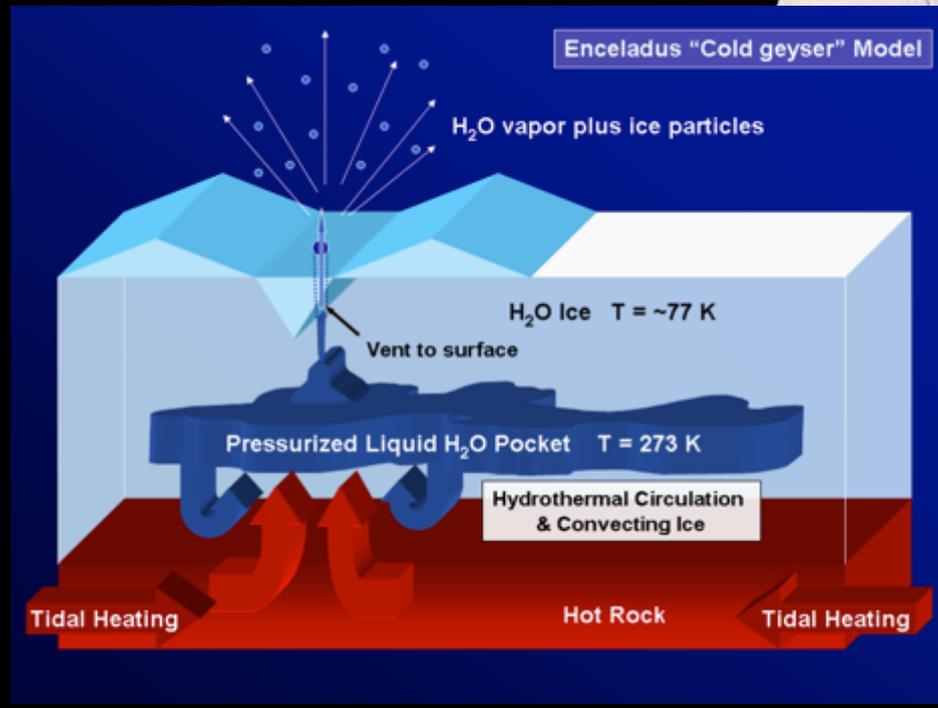


Saturn's moon Enceladus over Saturn's ring plane

Water Ice in the Solar System

Water Ice on Saturn's Moon Enceladus

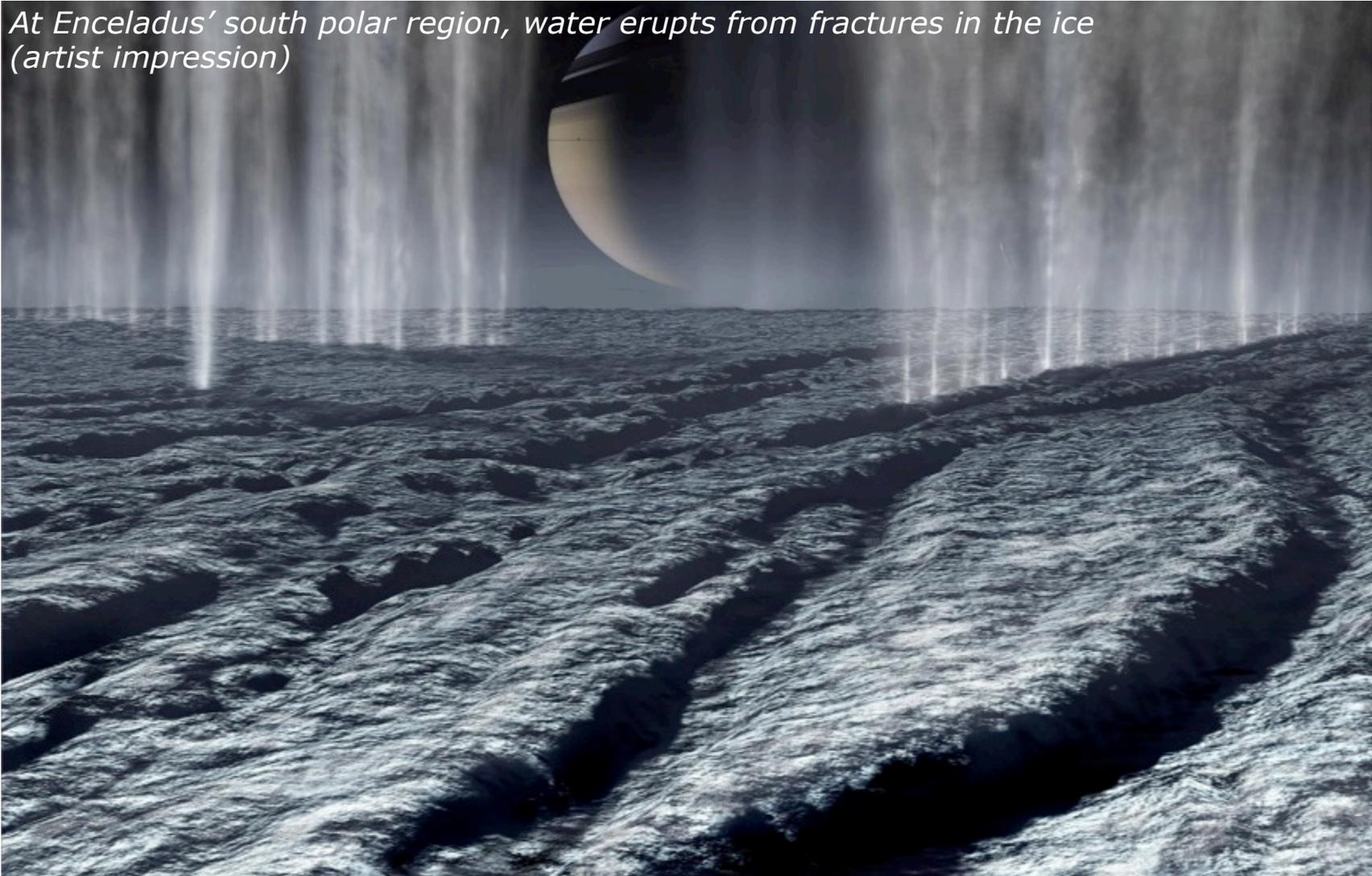
- > Some areas at the south pole (termed "Tiger Stripes" are 25 degrees warmer than can be expected
- > The underlying mechanism is largely unknown
- > Water erupts from fractures in the ice (cryovolcanism)



Water Ice in the Solar System

Water Ice on Saturn's Moon Enceladus

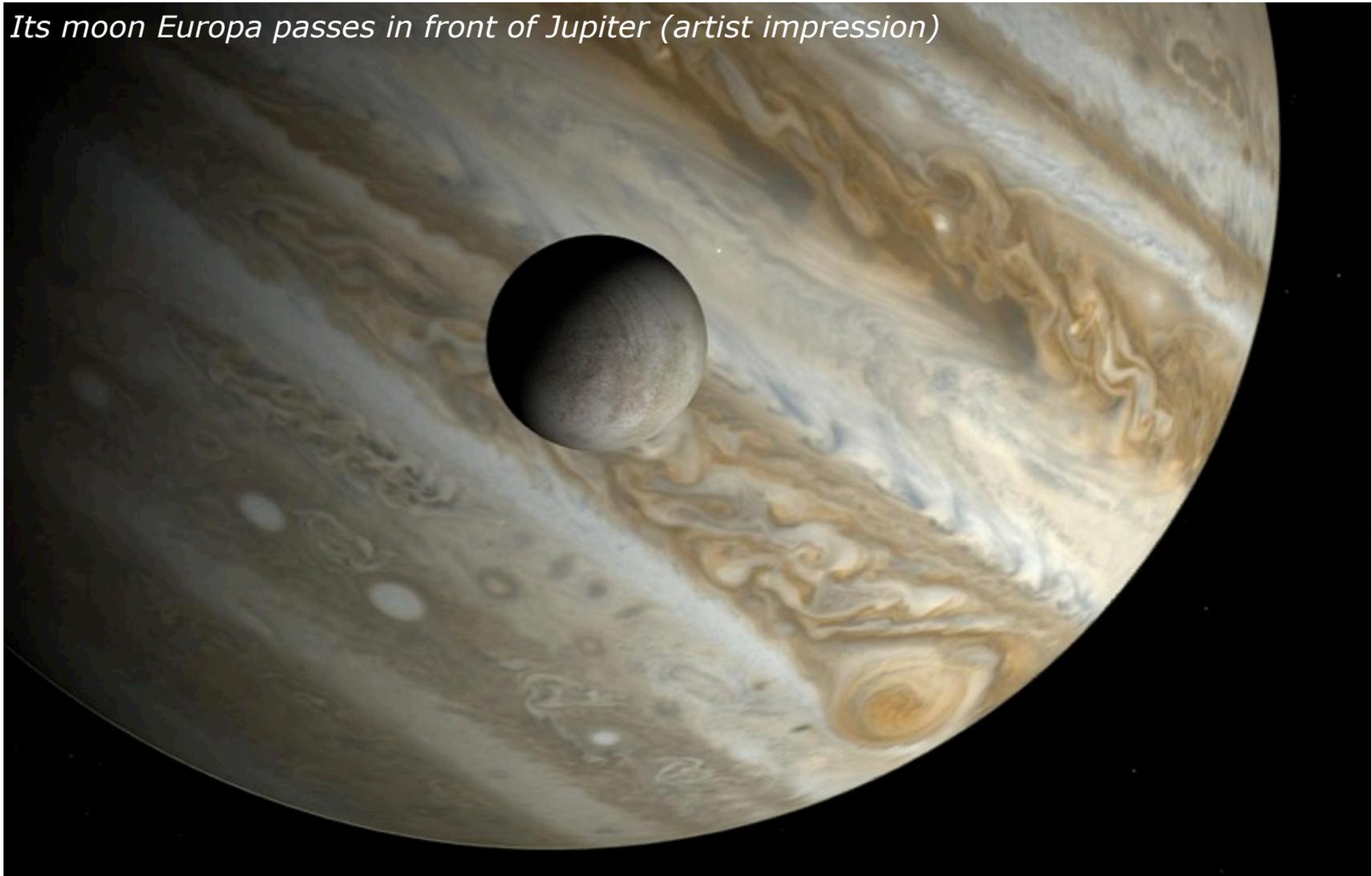
At Enceladus' south polar region, water erupts from fractures in the ice (artist impression)



Water Ice in the Solar System

Jupiter's Moon Europa

Its moon Europa passes in front of Jupiter (artist impression)



Water Ice in the Solar System

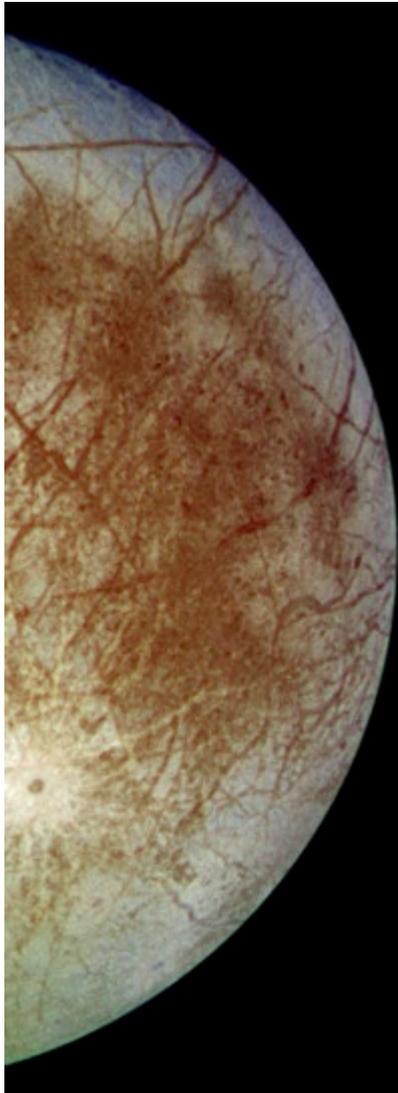
Jupiter's Moon Europa

*Potential vista onto Jupiter and its moon Io from the surface of its moon Europa
(artist impression, image courtesy: Daniel Johnson)*



Water Ice in the Solar System

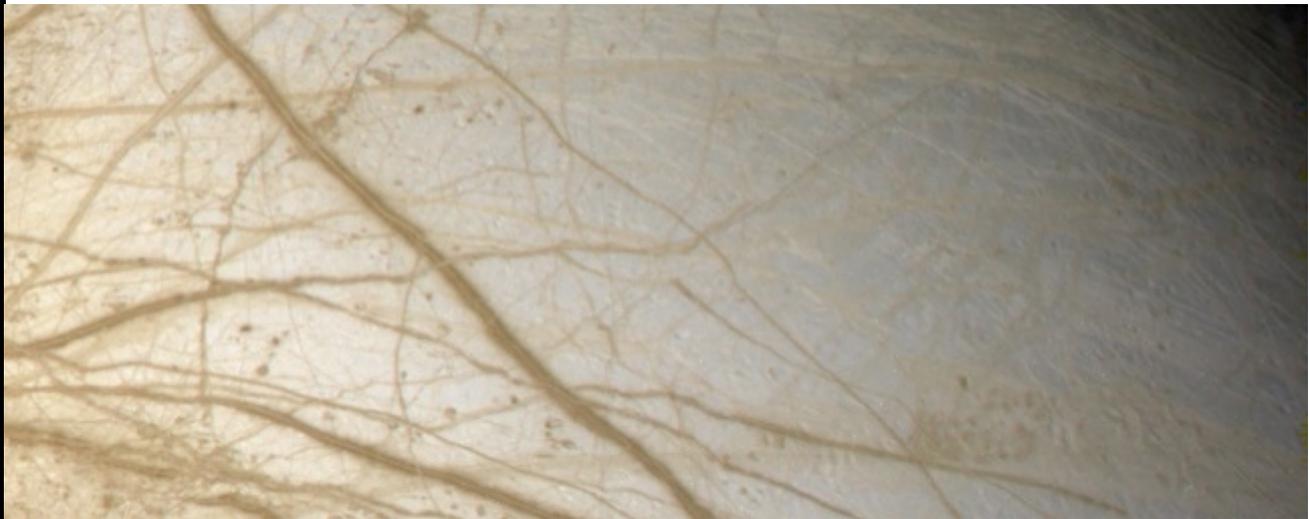
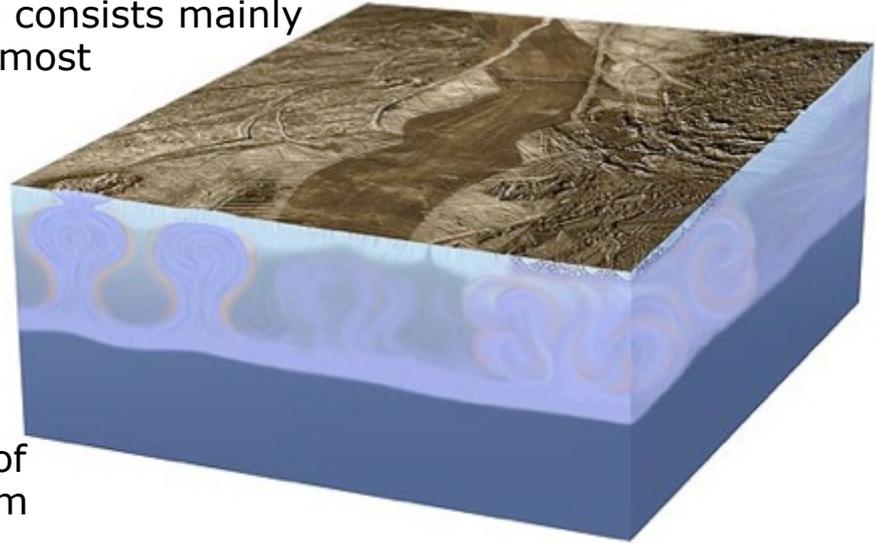
Water Ice on Jupiter's Moon Europa



The surface of Europa consists mainly of water ice and is at most 30 Mio. years old

A "warm" ocean with hydrothermal vents is expected to exist under the ice layer (depth > 50 km)

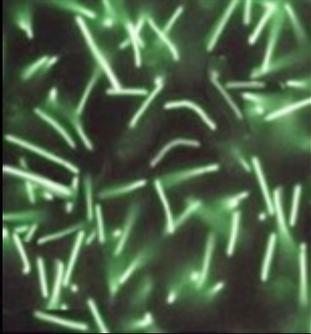
The estimated depth of the ice layer is 5-20 km



Water Ice in the Solar System

The Probable Origin of Life on Earth

Archae-,bacteria"



- > Many researchers are convinced that terrestrial life has originated around hydrothermal vents ("black smokers")
- > For most present-day life forms, this environment is extremely hostile (pressure ca. 300 bar, temperature up to 400°C)



Tube worms

Crab

Methane ice worm



Water Ice in the Solar System

Under the Ice of Europa



After having melted itself through the ice layer, a Cryobot explores Europa's ocean (artist impression)

Life in Ice

Brine Habitats for Psychrophiles in Ice

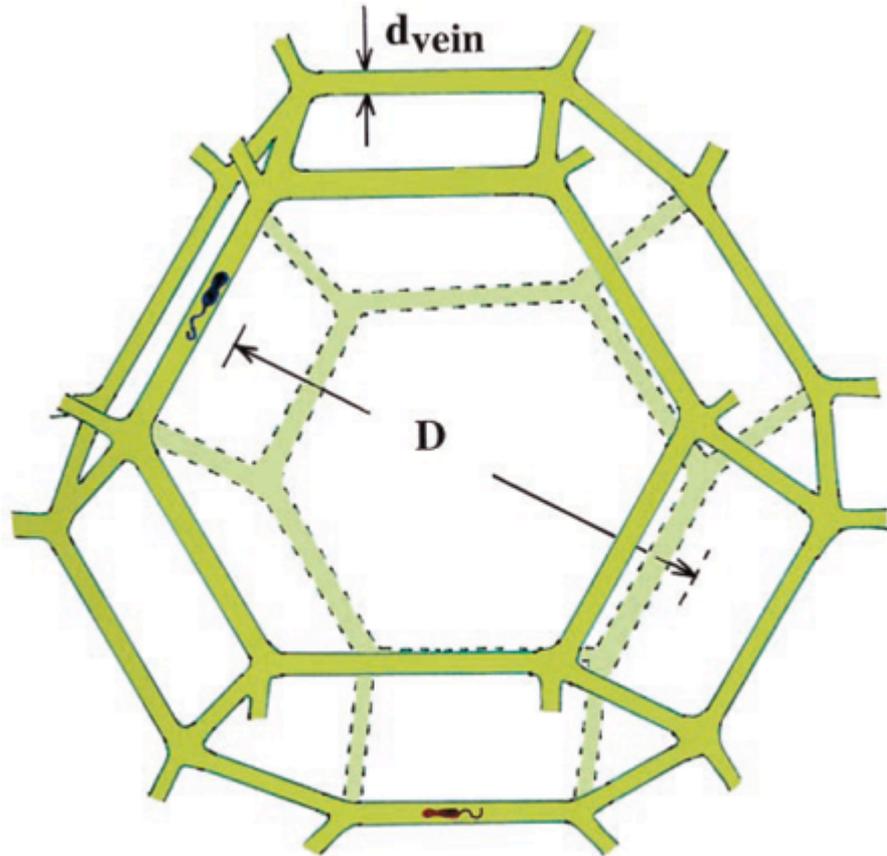
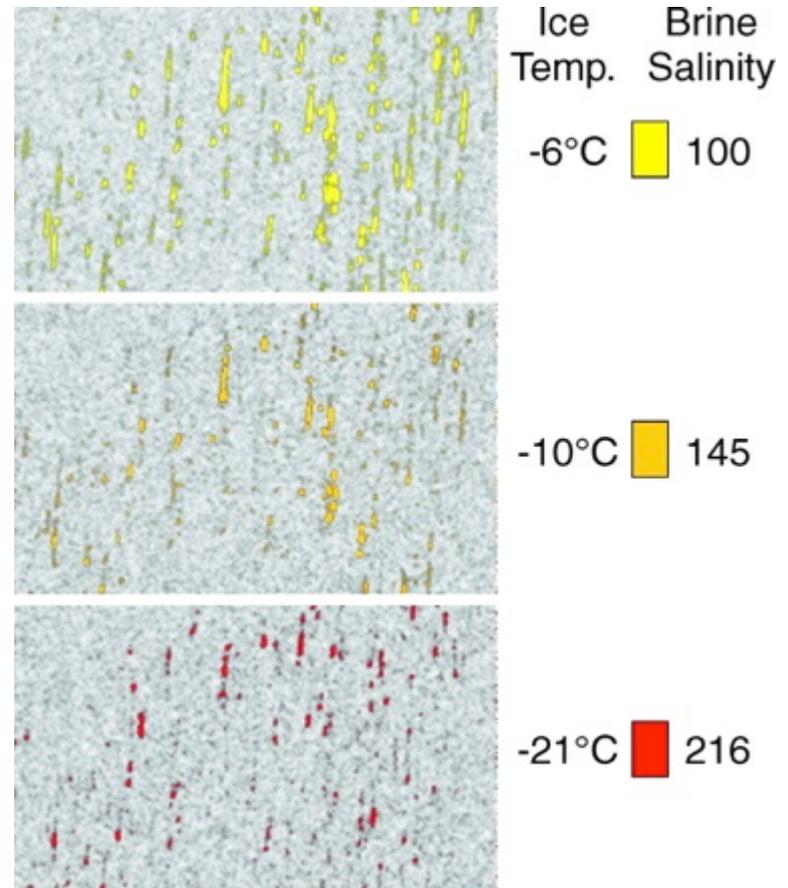


Fig. 1. Microbial habitat consisting of solid ice grains (approximated by truncated semiregular octahedra) bounded by liquid veins (not to scale). Two microbes are depicted as living in the vein of diameter d_{vein} surrounding a single grain of diameter D .

from Price: A Habitat for Psychrophiles in Deep Antarctic Ice, Proceedings of the National Academy of Sciences, 1999



5mm

Color-enhanced magnetic resonance images of the same piece of sea ice with decreasing temperature

from Thomas: Antarctic Sea Ice - a Habitat for Extremophiles, Science, 2002

Life in Ice

Brine Habitats for Psychrophiles in Ice

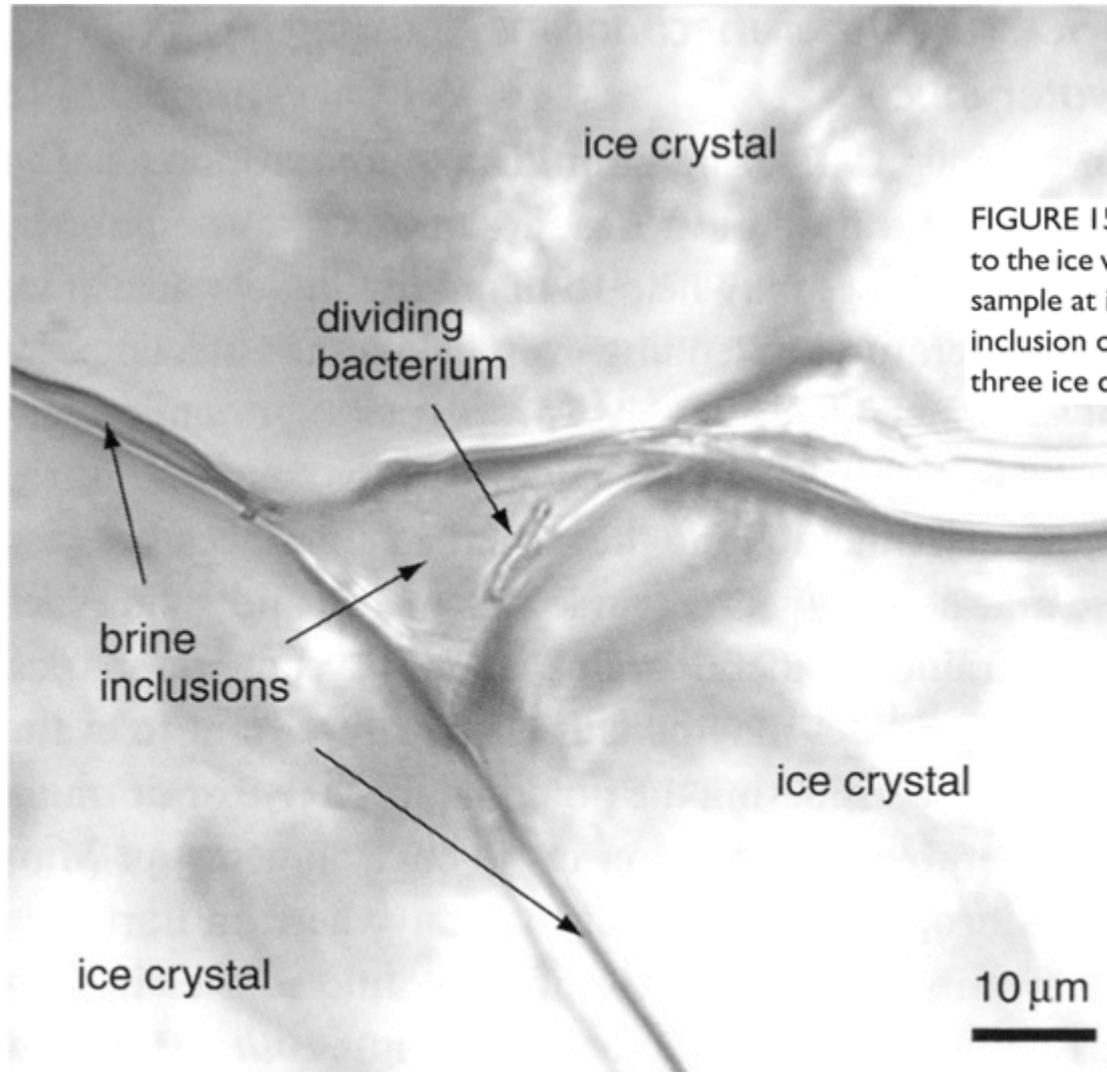


FIGURE 15.6 Microscopic image of a dividing bacterium attached to the ice wall of a brine-filled pore within an Arctic winter sea-ice sample at its *in situ* temperature of -15°C . The inhabited brine inclusion occurs at a triple juncture, formed by the conjoining of three ice crystals. (Adapted from Junge *et al.*, 2001.)

from Sullivan *et. al.* (eds.):
Planets and Life, Cambridge, 2007

Life in Ice

Bacteria in Wintertime Sea Ice Brine Channels

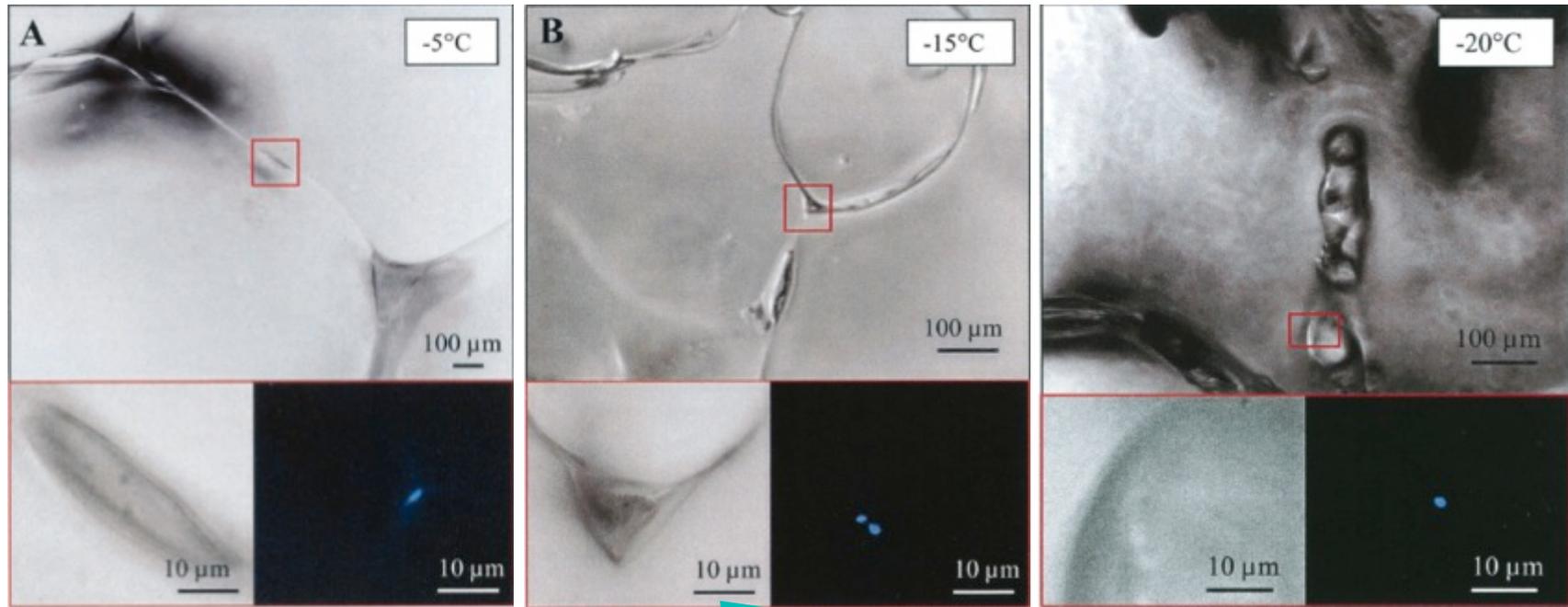


FIG. 1. Microscopic images of wintertime sea ice from the Chukchi sea near Barrow, Alaska, at -5 (A) and -15°C (B). Ice-grain boundaries and triple-point junctures (upper panels) and details of brine pockets (lower left panels, which are enlargements of the areas boxed in red in the upper panels) are visible by transmitted light. DAPI-stained bacteria (blue) attached to the wall of a brine pocket (A) or to particulate material within the pocket (B) are visible in the same fields as those shown in the lower left panels when examined by epifluorescence light (lower right panels).

FIG. 2. Microscopic images of wintertime sea ice at -20°C . The lower left panel is an enlargement of the area boxed in red in the upper panel. The images are similar to those in Fig. 1, except that a triple-point juncture is not obvious and the DAPI-stained bacterium (lower right panel) is not attached to a surface.

from Junge: Bacterial Activity at -2 to -20°C in Arctic Wintertime Sea Ice, Applied and Environmental Microbiology, 2004

Life in Ice

Bacteria and Archaea Found in -20°C Ice Samples

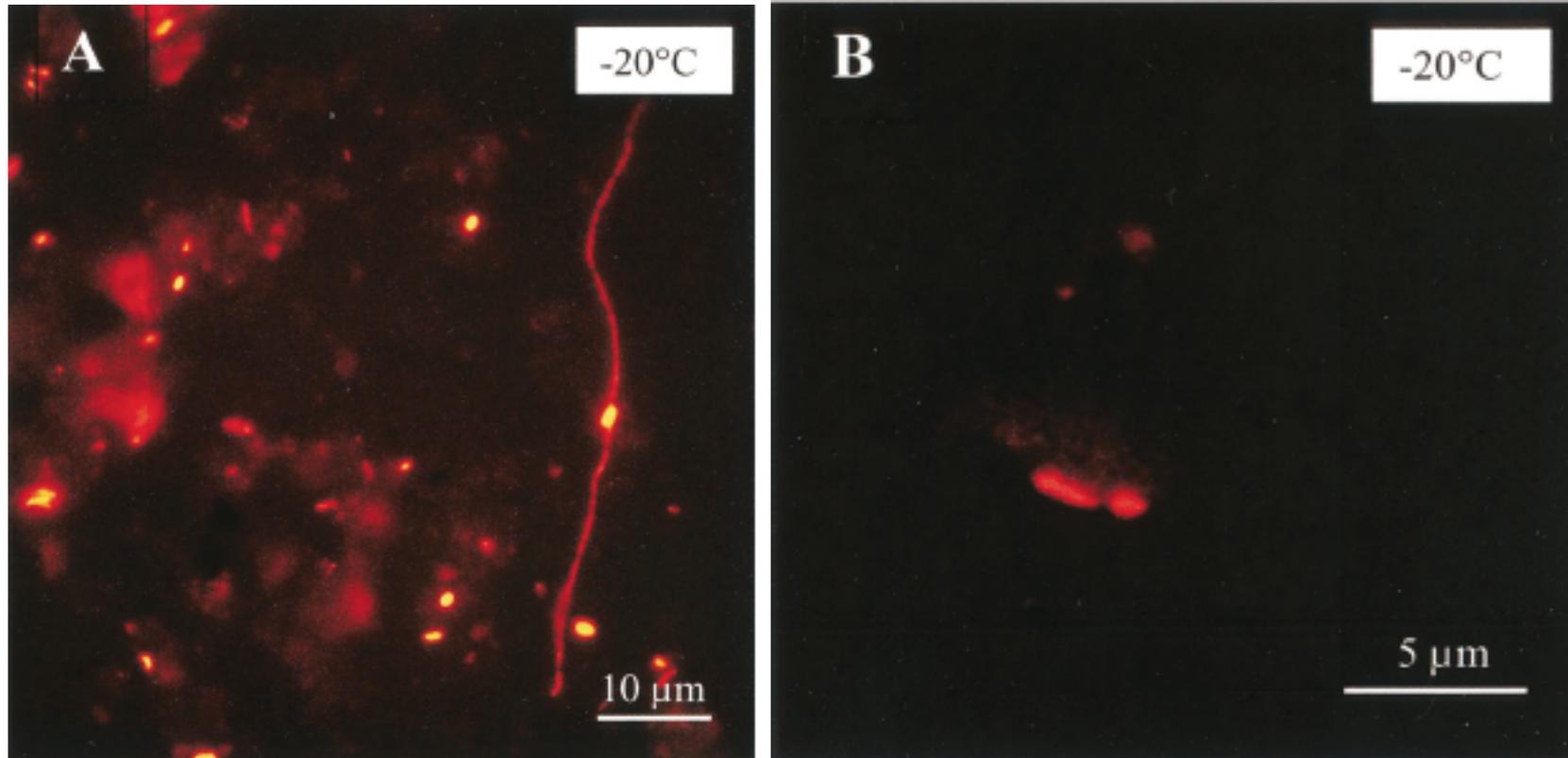


FIG. 4. Images obtained by epifluorescence microscopy of particle-associated bacteria in isohaline-isothermal-melted samples of wintertime ice from the Chukchi Sea at -20°C . Hybridization with fluorescent probes is shown for *Bacteria* (A) and *Archaea* (B).

from Junge: Bacterial Activity at -2 to -20°C in Arctic Wintertime Sea Ice, Applied and Environmental Microbiology, 2004

Life in Ice

Bacterial Abundance in Ice

Type of ice formation	Sampling location	Sample T ($^{\circ}\text{C}$)	Particle-poor ice	Particle-rich ice
Snow	South Pole	-15	$0.2-5 \times 10^3$	
Ice sheet	Over Lake Vostok (2-4 km)	-3	$0.2-8 \times 10^3$	
	Greenland (bottom of sheet)	-9		$>6 \times 10^7$
Lake ice	Lake Bonney, Antarctica	$<-5?$	5×10^3	$0.1-4 \times 10^5$
	Imikpuk Lake, Alaska	-5	7×10^4	7×10^5
Sea ice	Southern Ocean, summer	-2	$0.01-3 \times 10^6$	$0.02-2 \times 10^6$
	Southern Ocean, winter	-2	$0.2-2 \times 10^6$	1×10^7
	Arctic Ocean, summer	-2	$0.4-2 \times 10^6$	$0.05-1 \times 10^7$
	Arctic Ocean, winter	-2 to -20	$0.2-1 \times 10^5$	$0.5-3 \times 10^6$
Permafrost	Northeast Siberia	-10		$>1 \times 10^8$

$< 10^4 \text{ ml}^{-1}$

$10^4 - 10^6 \text{ ml}^{-1}$

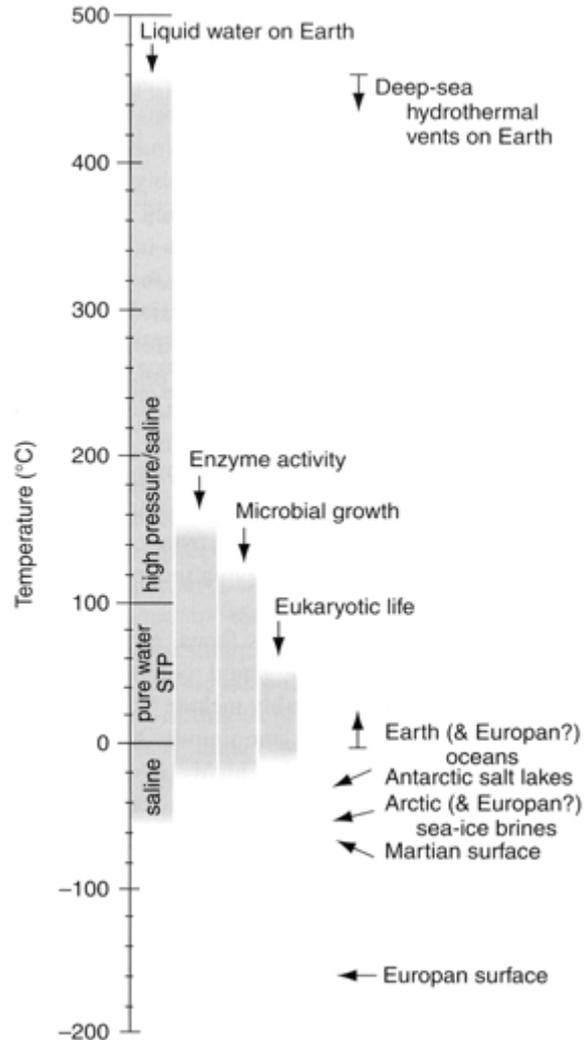
$10^5 - 10^7 \text{ ml}^{-1}$

$> 10^7 \text{ ml}^{-1}$

adapted from Sullivan et. al. (eds.): Planets and Life, Cambridge, 2007

Life in Ice

Liquid Water and Life



Temperature regime for the **presence of liquid water on Earth**:

ca. -56°C – ca. 450°C

Temperature regime for observed **enzyme activity**:

ca. -20°C – ca. 150°C

Temperature regime for **microbial growth** (Bacteria and Archaea):

ca. **-20°C** – ca. 120°C

Temperature range for **Eukaryotic life**:

ca. **-5°C** – ca. 50°C

Average surface temperature on Mars:

ca. -55°C (like in summer at Dome C)

Average surface temperature on Jupiter's moon Europa:

ca. -160°C ... and even colder on

Saturn's moon **Enceladus**

from Sullivan et. al. (eds.): Planets and Life, Cambridge, 2007

Methods of Deep Ice Research

Ice Core Drilling

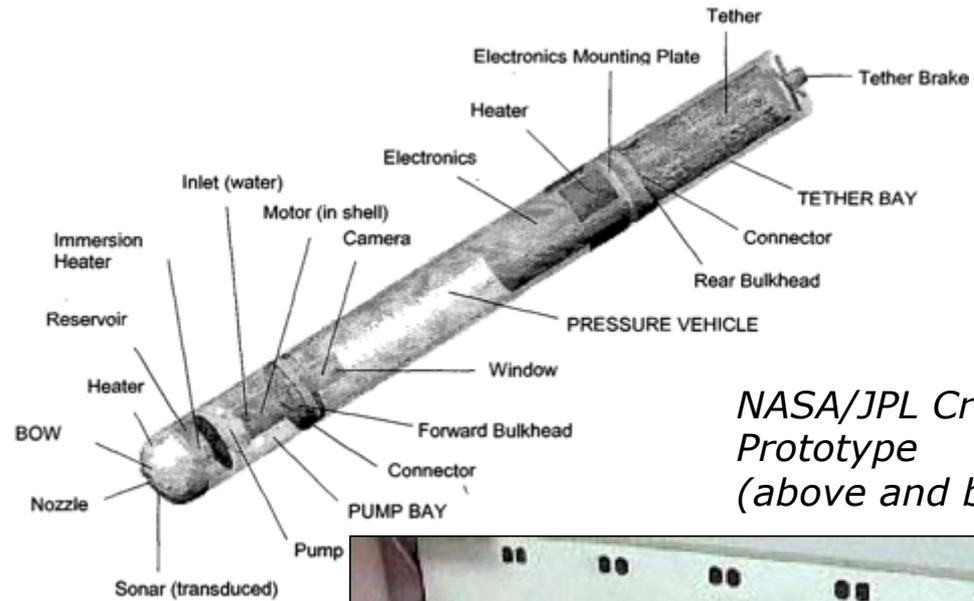


Methods of Deep Ice Research

Melting Probes



DLR Melting Probe Prototype (left)



NASA/JPL Cryobot Prototype (above and below)

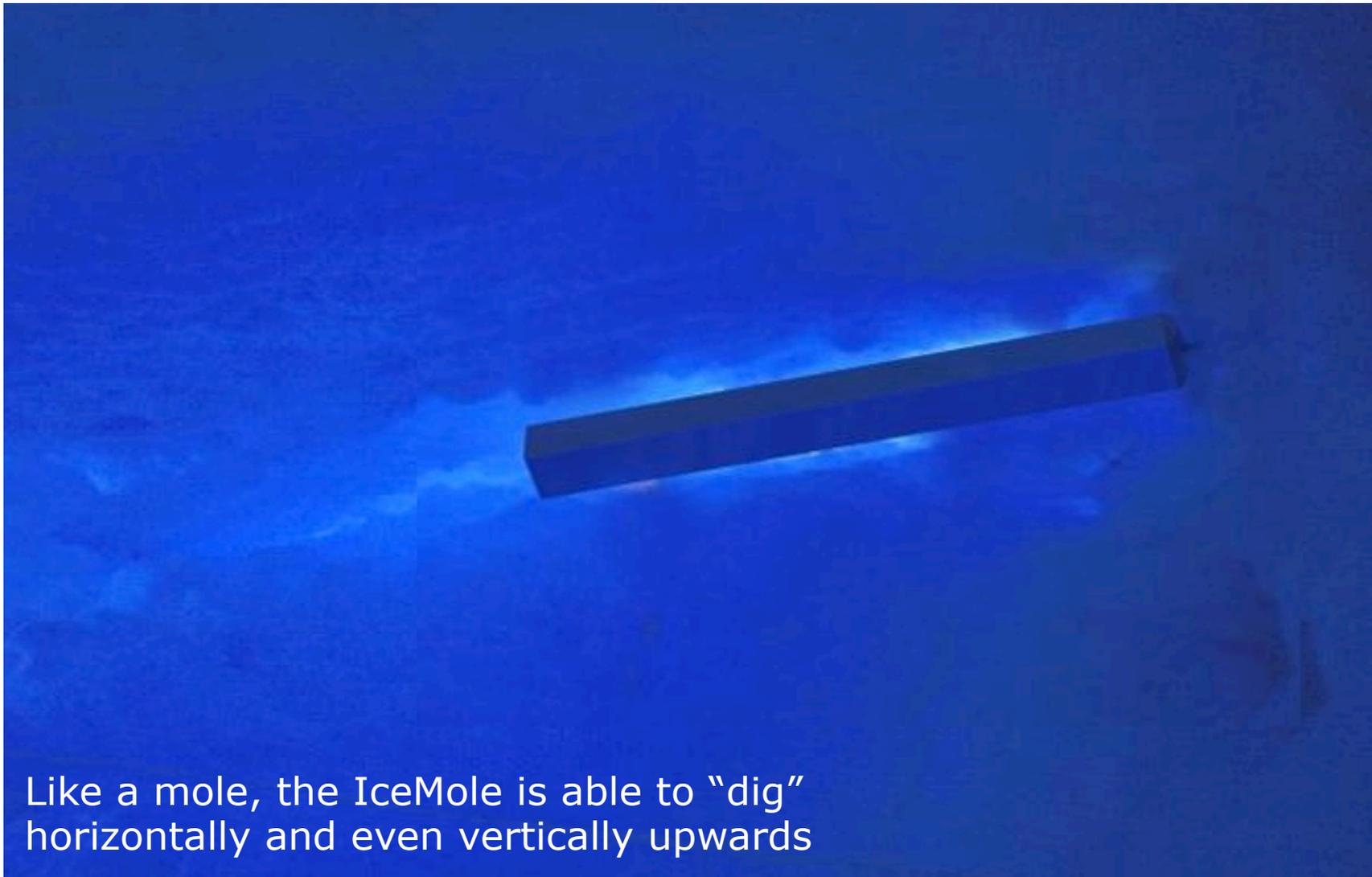


Advantages with Respect to Existing Methods

	Drill	Melting Probe	IceMole
Controllability (incl. obstacle avoidance)	↓	↓	↑
Feasibility of space-resolved in-situ profile measurements	→	→	↑
Penetration of "dirt" layers	↑	↓	↑
Recoverability	↑	→	↑
Contamination	↓	↑	↑
Autonomy (incl. weather independency)	↓	↑	↑
Feasibility for Space Applications	↓	↑	↑

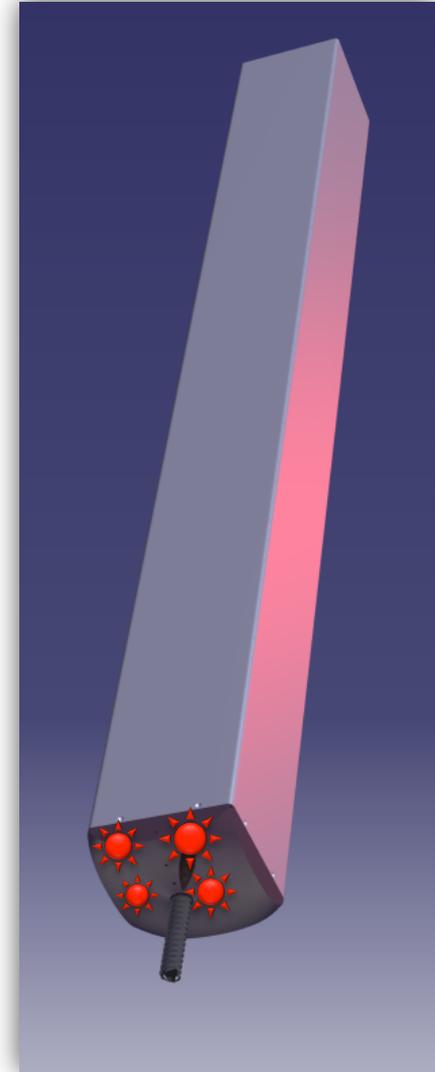
IceMole

Principle of Operations



- > Forward motion (“digging”) with combined melting head and ice screw
(The ice screw is essential for digging horizontally and vertically up against gravity)
- > Maneuverability (cornering ability) in ice by differential heating
- > Robust mechanics

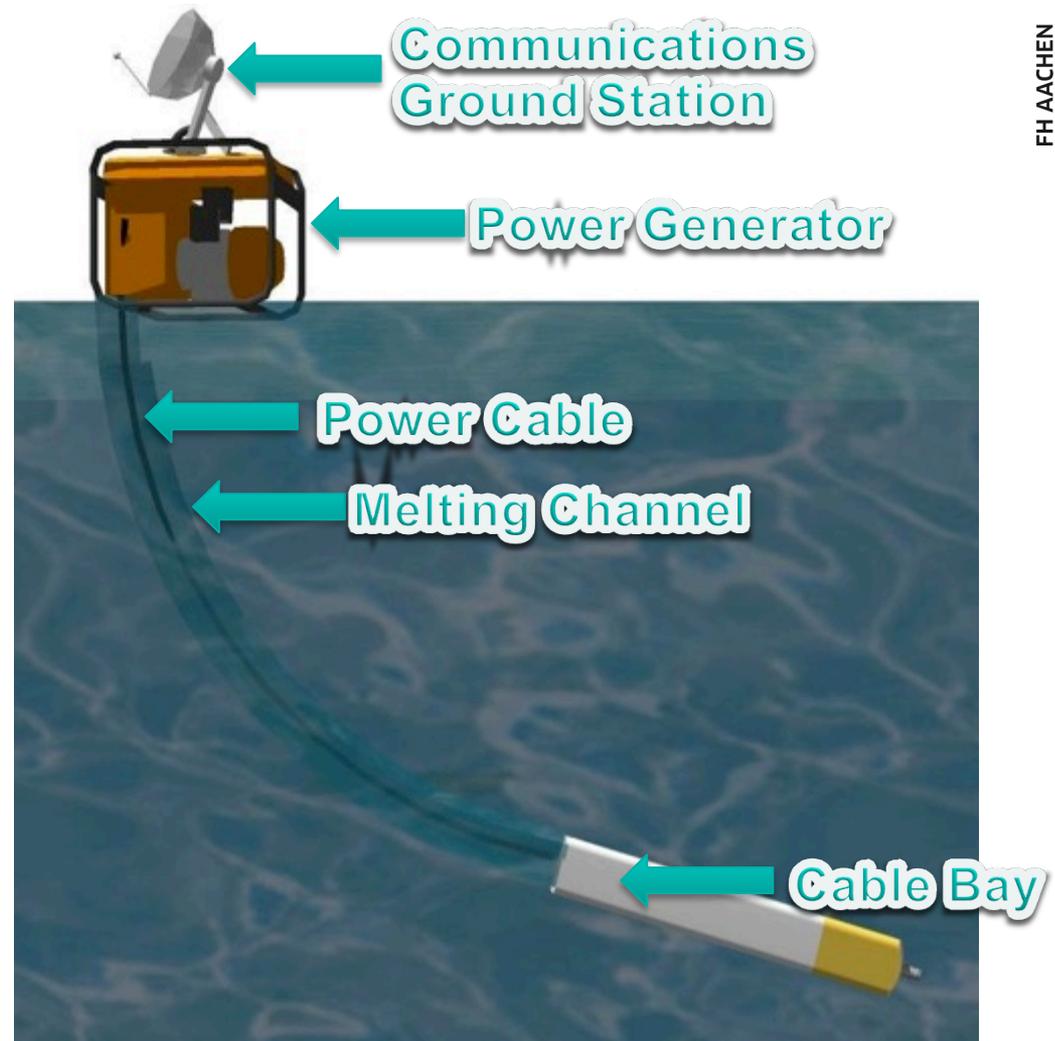
- > Continuously rotating ice screw at the melting head generates a min. driving force of 1 kN and ingests simultaneously an ice sample
- > Length of ice screw is 60 mm (thermally isolated from melting head)
- > Heaters are separately controllable:
 - > 4 heating zones at the melting head
 - > Up to 3.2 kW power at the melting head
 - > Cornering ability by differential heating
- > Melting velocity ≈ 0.3 m/h
(suboptimal, can be improved to ≈ 1 m/h)



IceMole

Power and Communications

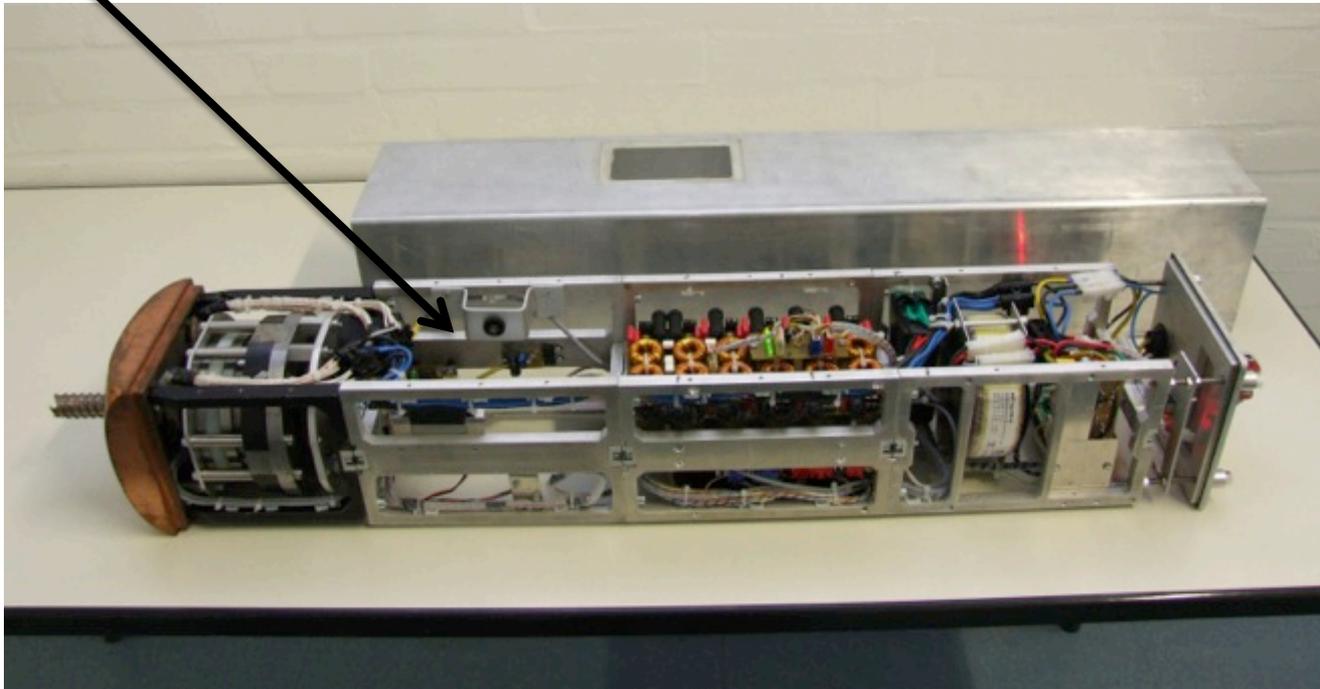
- > Power supply with generator
- > Power cable is coiled within the IceMole (it freezes behind the probe)
- > Powerline-modem transmits data between the IceMole and the ground station via the power cable
- > Ground station establishes communications with the operations team via satellite/internet



IceMole

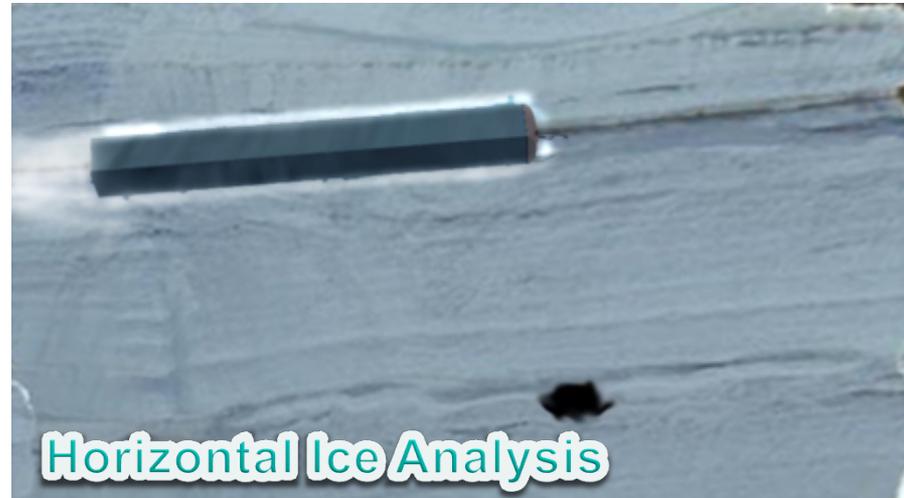
Interior View

- > Sampling of clean ice core for scientific analysis
- > No biological contamination of sampled ice
- > Variety of instrumentation options (quadratic instrument bay, 140 × 140 × tbd mm)

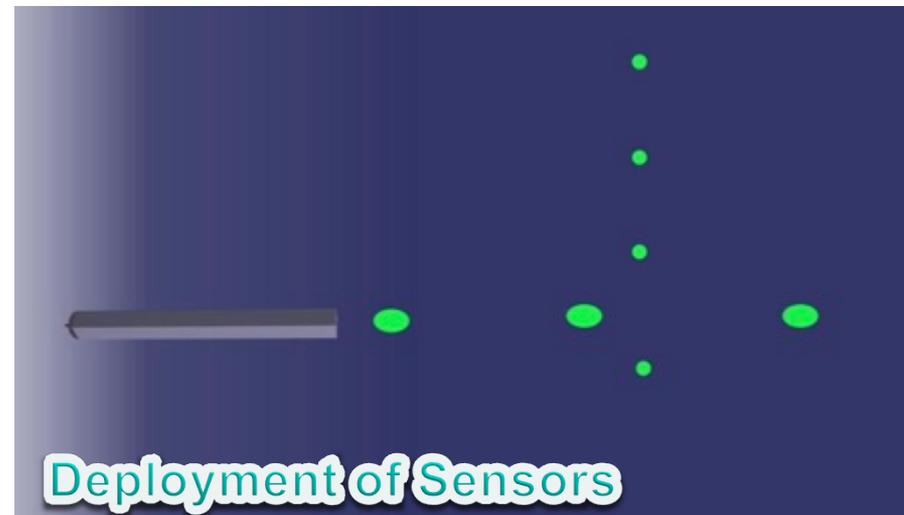


Further Application Examples

- > Controllability allows to follow interesting ice layers



- > Deployment of sensors at defined locations in the ice



IceMole

Features of the IceMole Concept

- > Compact
- > Robust
- > Mobile
- > Safe
- > Autonomous
- > Environmentally friendly (no drilling fluids)



IceMole

Field Experiments on the Morteratsch Glacier (2010)



IceMole

Field Experiments | Material Transport



Morteratsch Glazier, Switzerland

IceMole

Field Experiments | Field Camp



IceMole

Field Experiments | Field Camp



IceMole

Digging into the Morteratsch Glacier



IceMole

Field Experiments | Channel #1



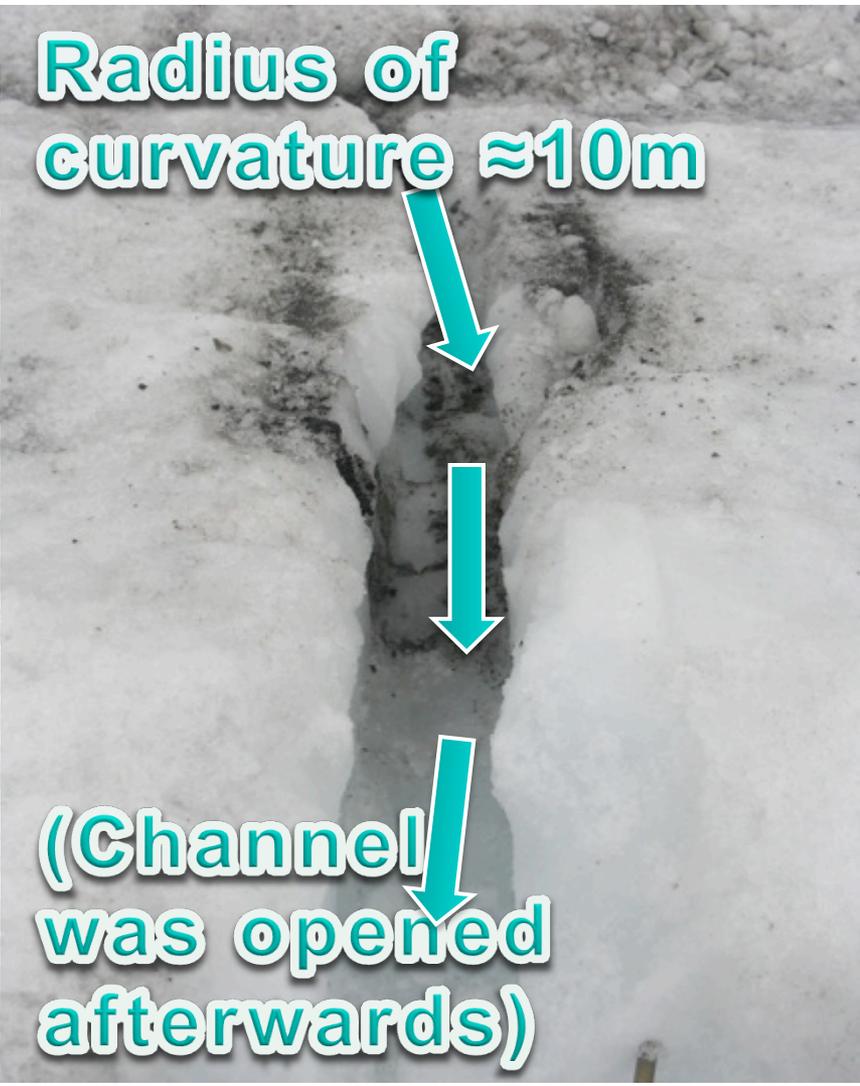
IceMole

Field Experiments | Channel #2





Penetration of $\approx 4\text{ cm}$ of “dirt”
(found on the glacier)



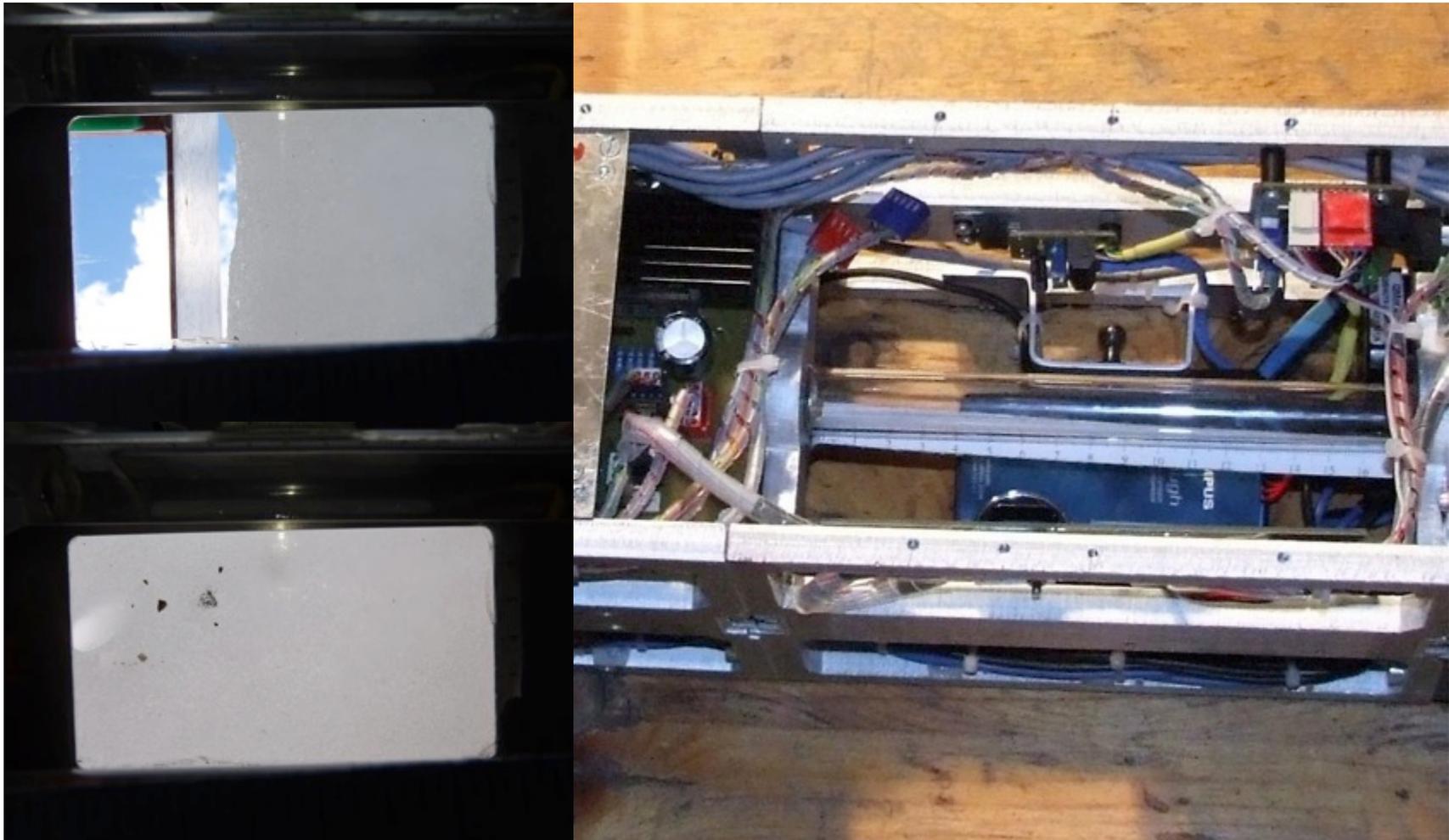
Radius of curvature $\approx 10\text{ m}$

(Channel was opened afterwards)

IceMole

Field Experiments | Payload Module

... just a cheap off-the-shelf digital camera



- > Proven feasibility of the drive concept
- > Curvature radius of about 10 meters
- > Penetration of dirt layers
- > First maneuverable melting probe
- > First probe that can melt upwards, against gravity

IceMole

Coverage in Nature News

naturenews Login

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Published online 30 April 2011 | Nature | doi:10.1038/news.2011.261

News

The IceMole cometh

Novel design could help probe explore frozen environs on Earth and beyond.

Adam Mann

Getting a probe to travel five metres might not seem like a much of a reason to celebrate. But after Bernd Dachwald and his team watched their IceMole robot autonomously drill through a small section of Morteratsch Glacier in Switzerland during the summer of 2010, they held a small party.



The IceMole team loads their hybrid probe into its launch rack.

FH Aachen / www.lichtographie.de

"This was a major milestone," says Dachwald, an aerospace engineer at Fachhochschule Aachen University of Applied Sciences in Aachen, Germany. On 27 April, Dachwald presented results from IceMole's first field test at the [2011 Antarctic Science Symposium](#) in Madison, Wisconsin. "We have proof that IceMole works not only in the lab but also in a real environment," he says.

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IceMole 2

The Next Generation

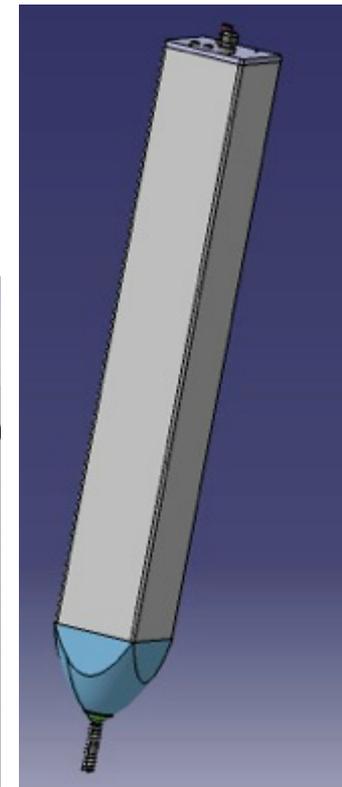
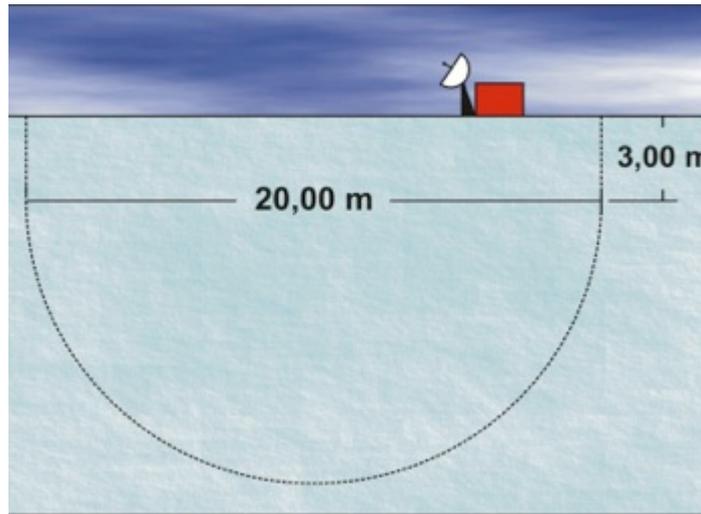
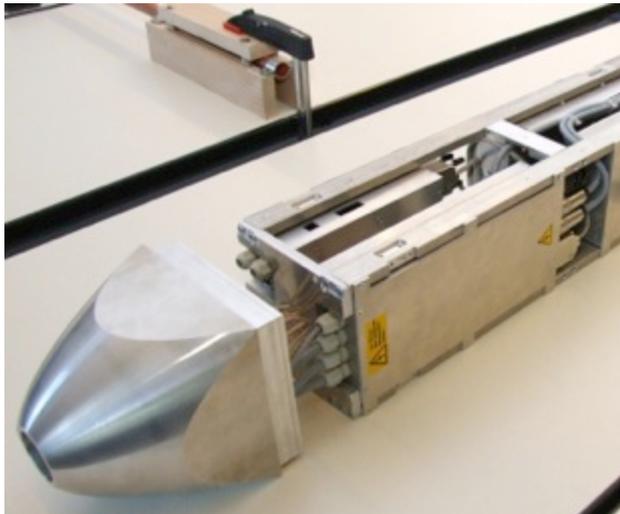
- > Heating power: max. 2.4 kW
@ melting head
max. 600 W
@ wall heaters
- > Velocity: ≈ 1 m/h
- > Power supply: 24 V DC bus voltage
- > Communication: CAN-bus (internal)
Powerline-modem
(external)
- > Payload module: Fluorescence
biosensor
- > Pressure: up to 5 bar
resistance



IceMole 2

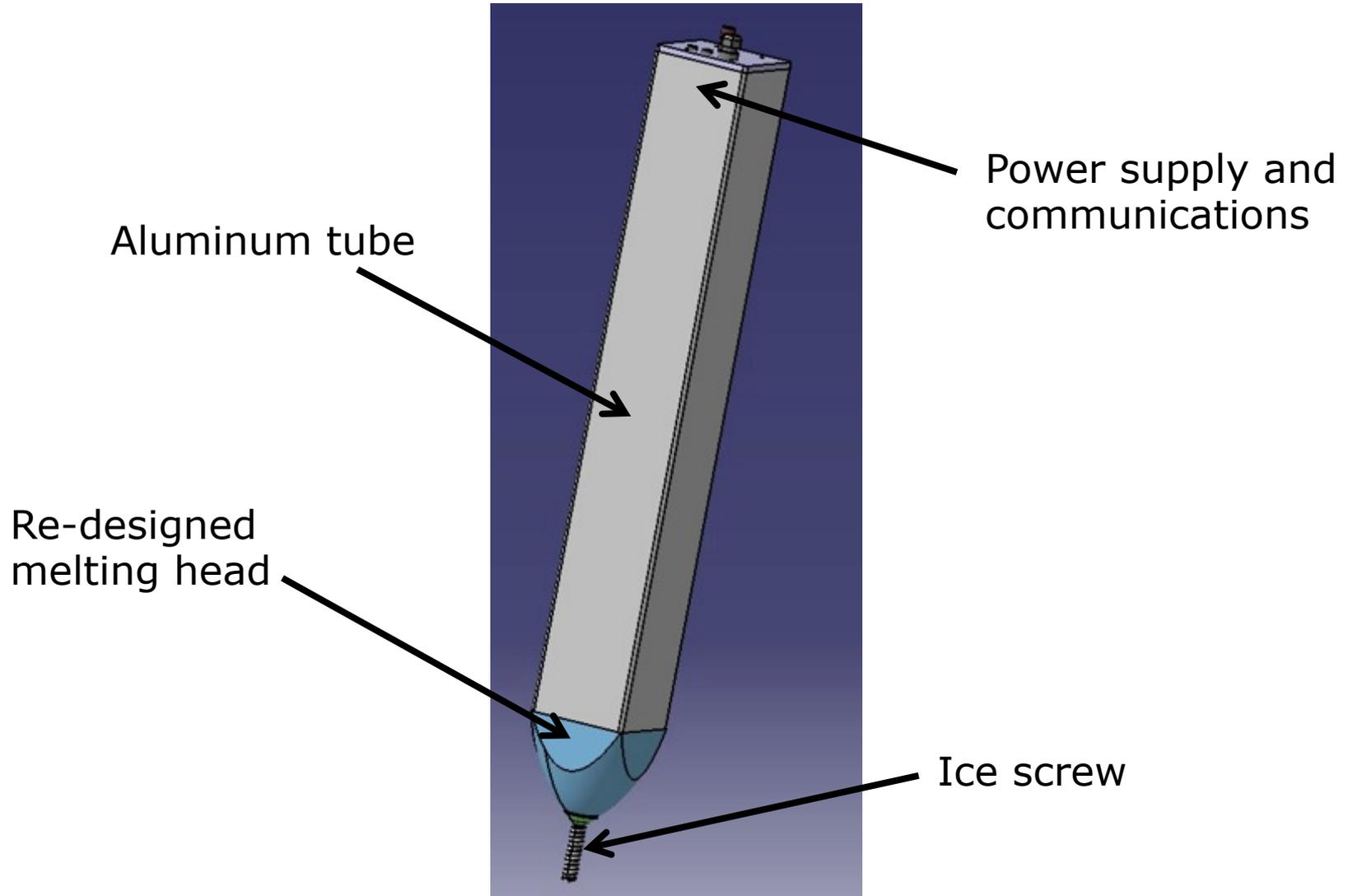
Mission Objectives for Field Test in 2012

- > Demonstrate the recoverability of IceMole and payloads
 1. Dig a horizontal "U"
 2. Dig a vertical "U"
- > Location: Hofsjökull, Iceland, Sep 2012
- > Distance: $\approx 40\text{m}$
- > Duration: 40 – 80 hours



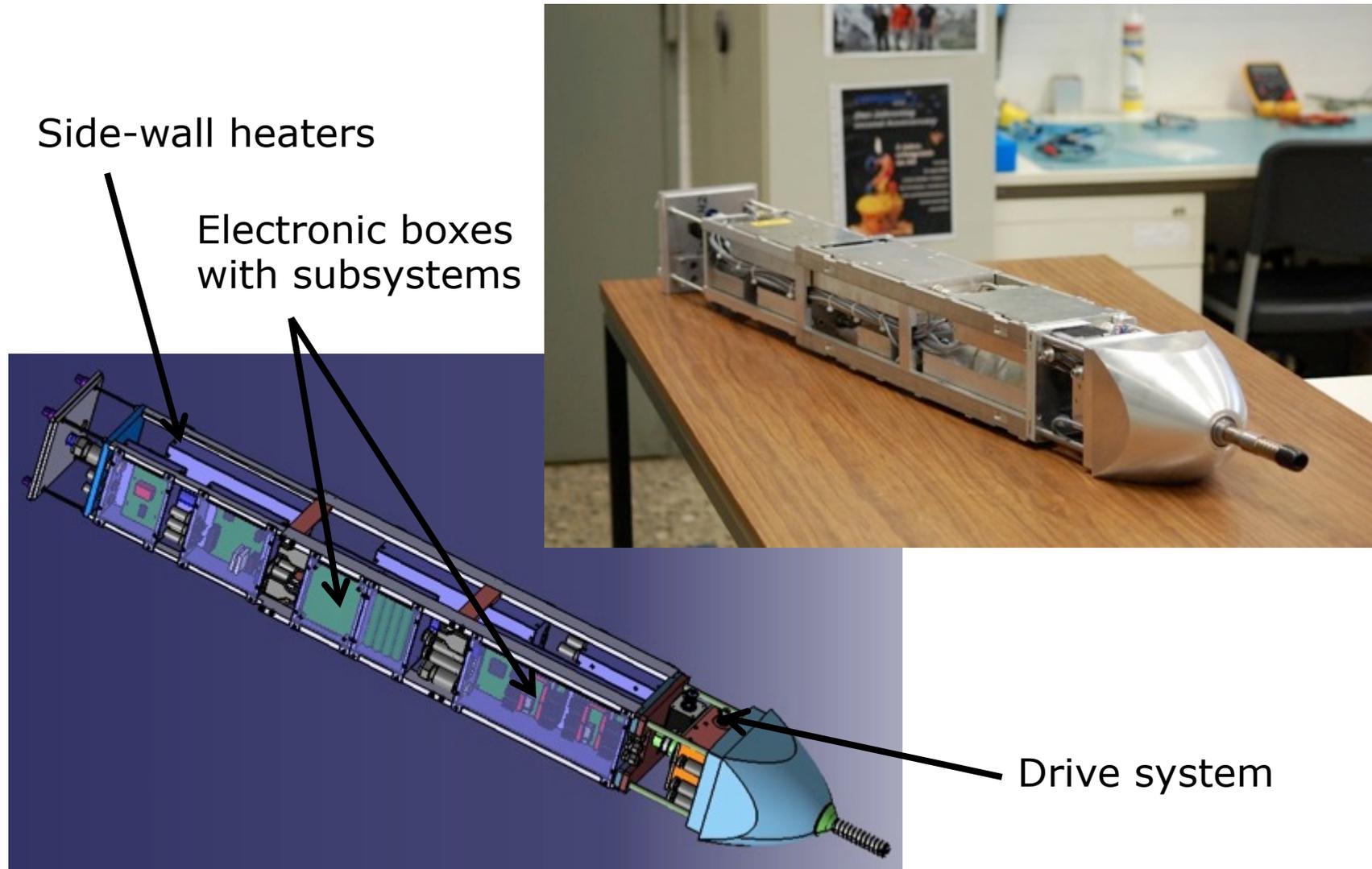
IceMole 2

External Structure



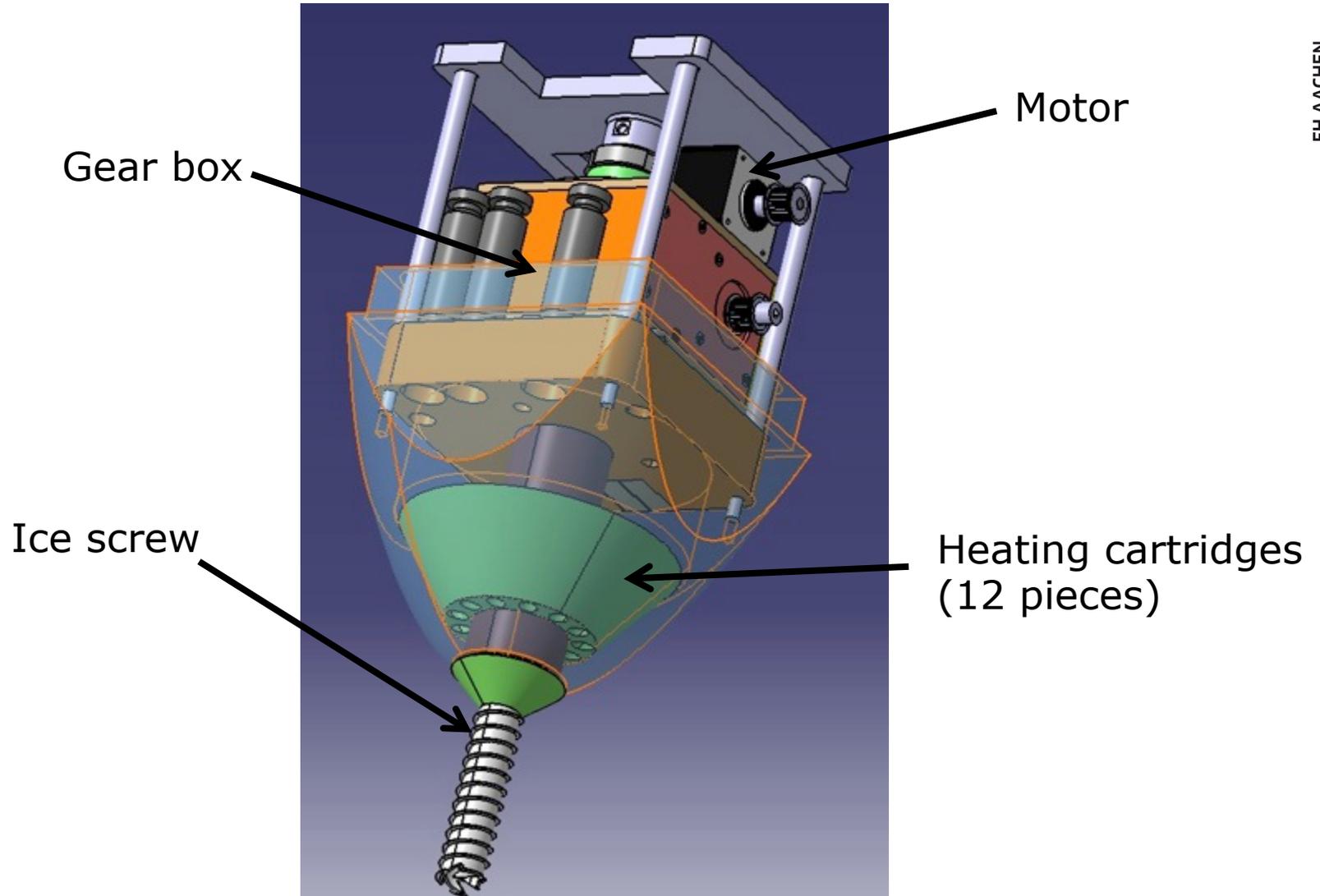
IceMole 2

Internal Structure

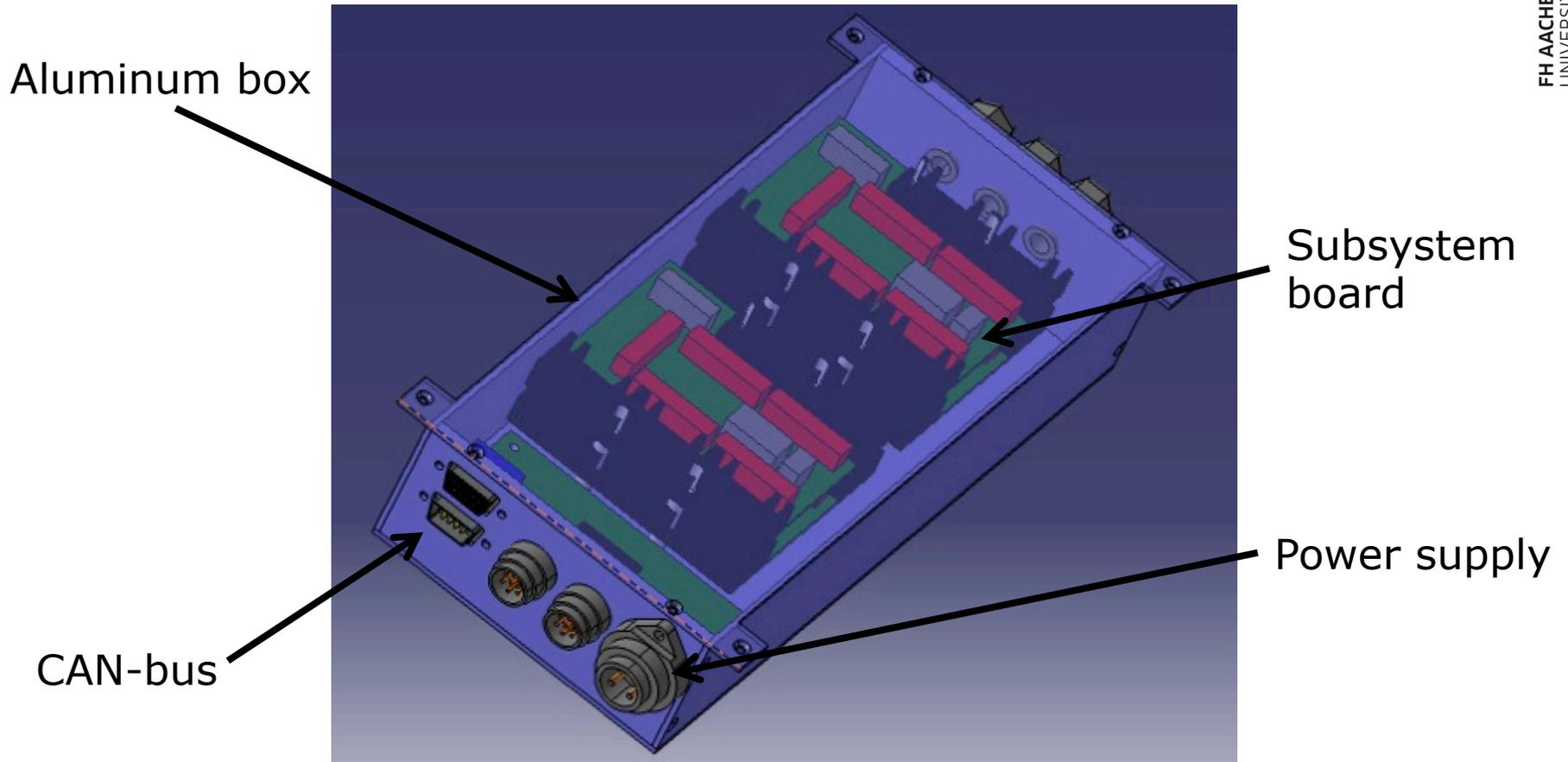


IceMole 2

Re-Designed Melting Head



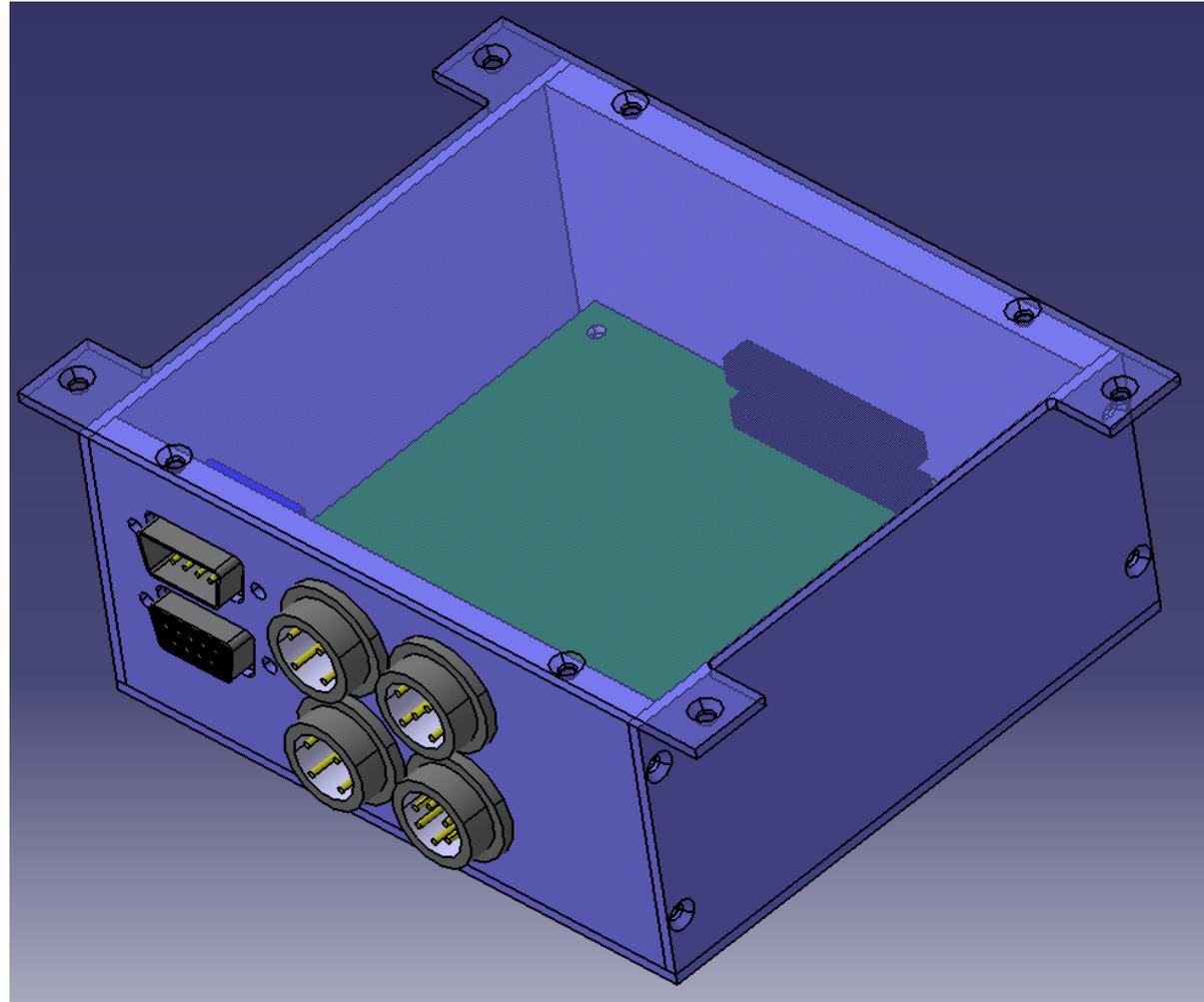
IceMole 2 Electronic Boxes



IceMole 2

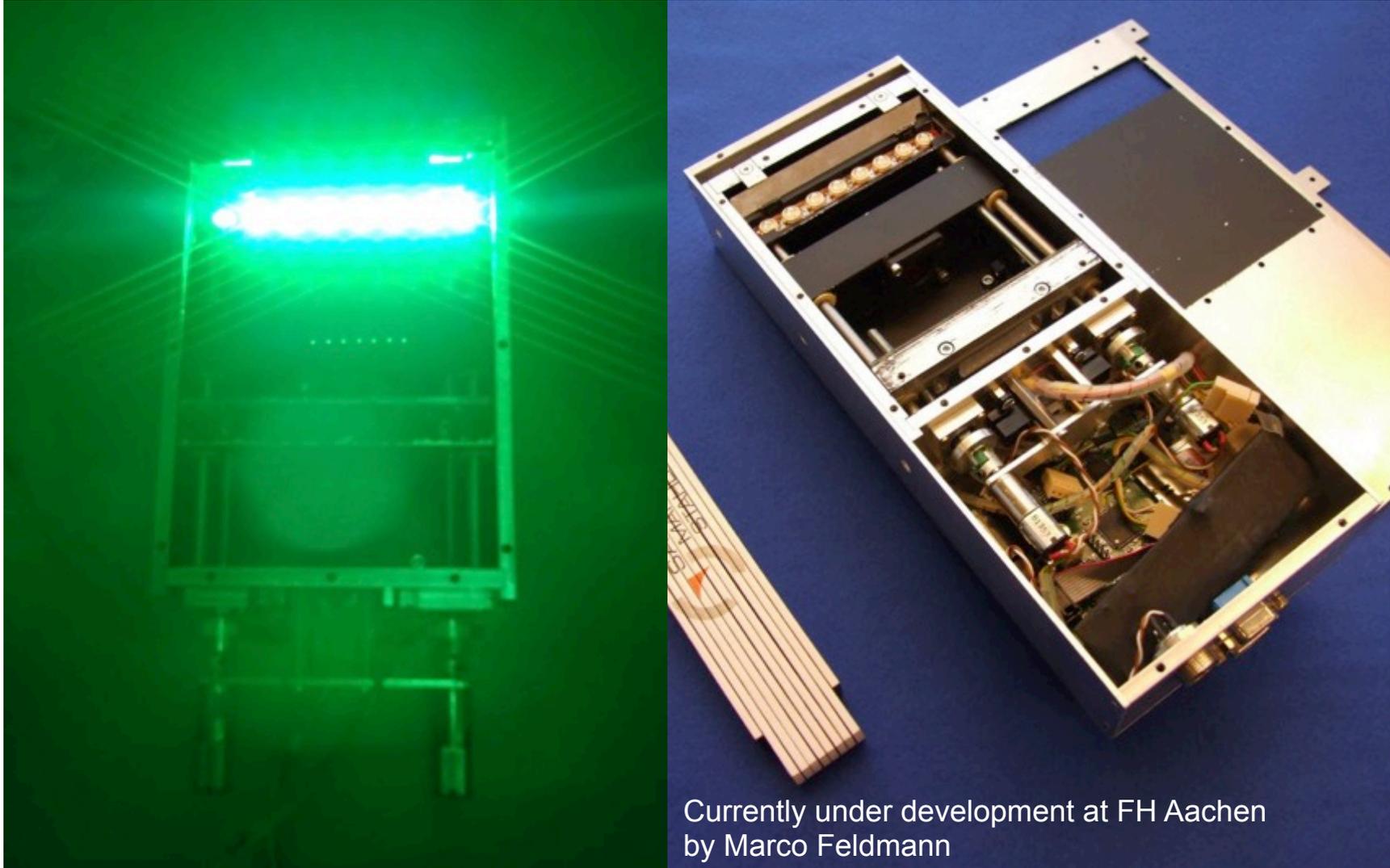
Payload Requirements

110 x 50 x tbd mm
24 V DC
CAN-Bus



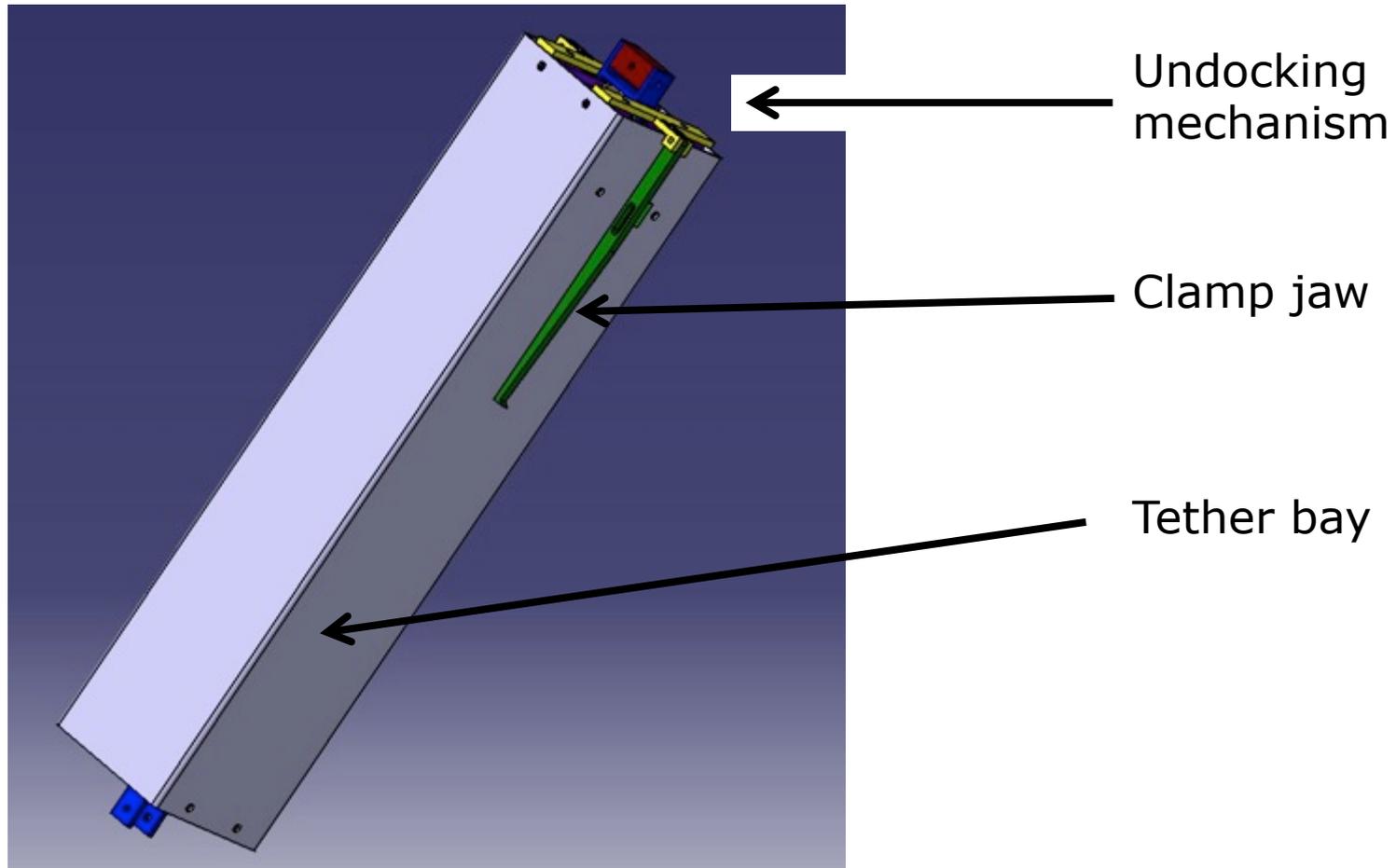
IceMole 2

Payload 2012 | "Simple" Fluorescence Biosensor



IceMole 2 Tether Container

2012 field test uses 5 containers with 10 m of tether each

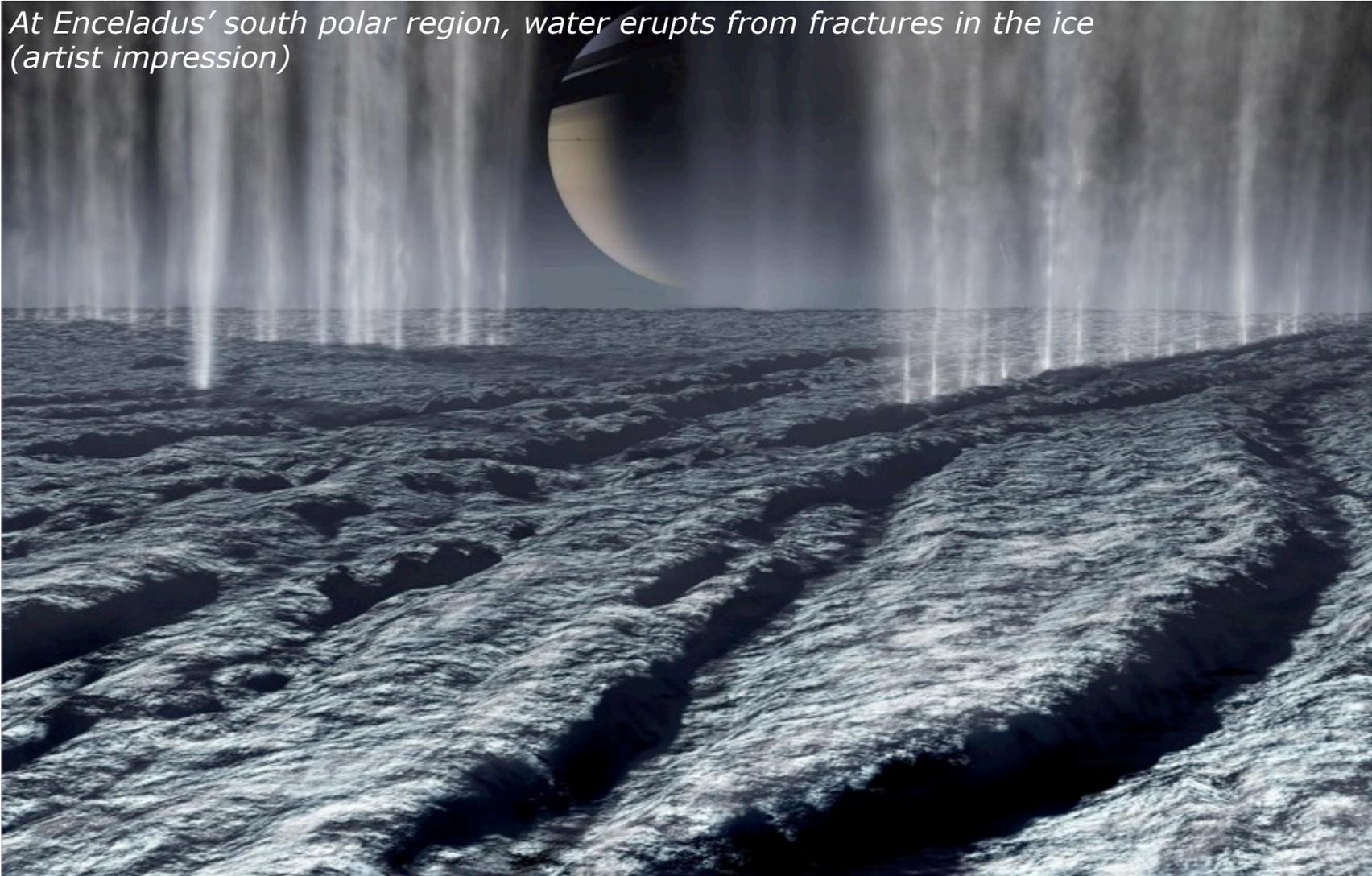


- > **Power:** transmission of several kW of power over large distances / depths
- > **Communications:** communications over the power cable
- > **Navigation:** 3D navigation under the ice
- > **Control:** autonomous and robust control
- > **Drive:** optimization of ice screw and drive mechanism
- > **Thermal Control:** optimization of cornering ability

Enceladus Explorer (EnEx)

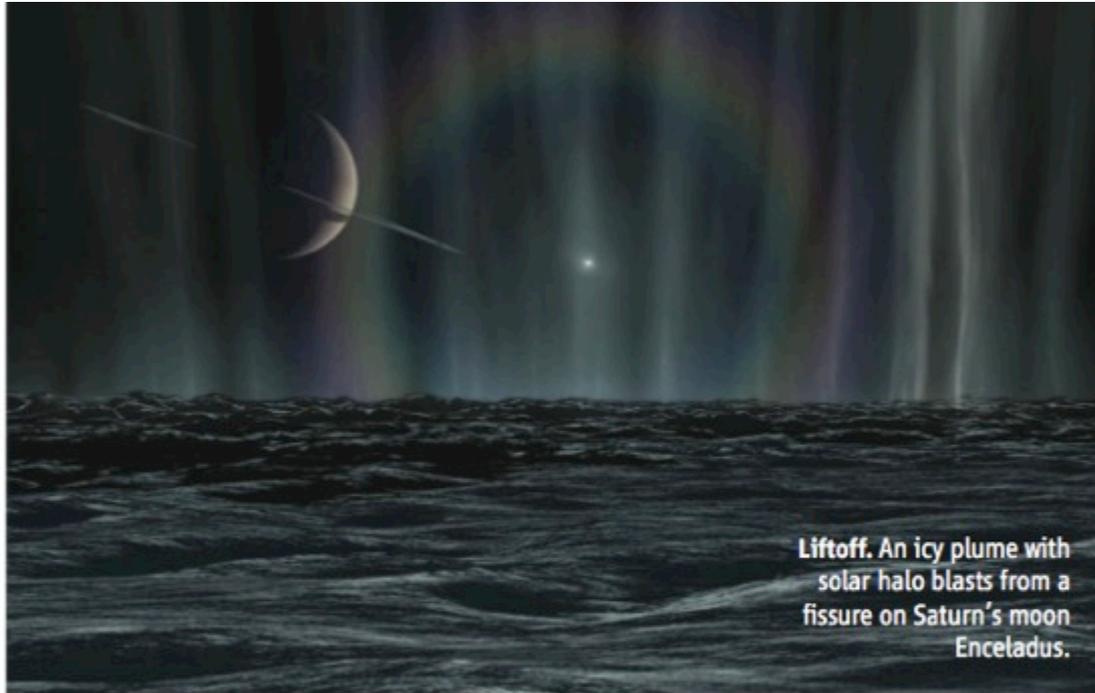
Technology Development for Enceladus Exploration

At Enceladus' south polar region, water erupts from fractures in the ice (artist impression)



Enceladus

Now a Main Target for Astrobiology Research



Liftoff. An icy plume with solar halo blasts from a fissure on Saturn's moon Enceladus.

PLANETARY SCIENCE

Enceladus Now Looks Wet, So It May Be ALIVE!

Accumulating evidence from a Saturn orbiter points to liquid water in a distant moon, but further investigation of this likely habitable zone may be out of reach

Science, Vol. 332, 2011, p. 1259

NEWSFOCUS

toward liquid water. Last March, planetary scientists Carly Howett and John Spencer of Southwest Research Institute in Boulder, Colorado, and their colleagues reported in the *Journal of Geophysical Research-Planets* that improved observations had almost doubled the best estimate of the emitted heat energy to 15.8 gigawatts. "That's quite a lot of power," Spencer says. It's enough to drive liquid-derived plumes, which require higher subsurface temperatures than clathrates do. "Once you have temperatures that high, you don't need clathrates as a driving mechanism" for the plumes, Spencer says.

The great abundance of heat energy also points to liquid water. The only known way Enceladus could generate heat is for Saturn to raise tides in solid parts of the moon the way Earth's moon raises tides in the oceans. Repeated tidal flexing of Enceladus's ice would produce heat the way repeatedly bending a paper clip makes it warm. But Enceladus's interior would be too stiff for tidal heating to work if it were solid ice throughout, notes planetary physicist David Stevenson of

LETTER

doi:10.1038/nature10175

A salt–water reservoir as the source of a compositionally stratified plume on Enceladus

F. Postberg^{1,2}, J. Schmidt³, J. Hillier⁴, S. Kempf^{2,5,6} & R. Srama^{2,7}

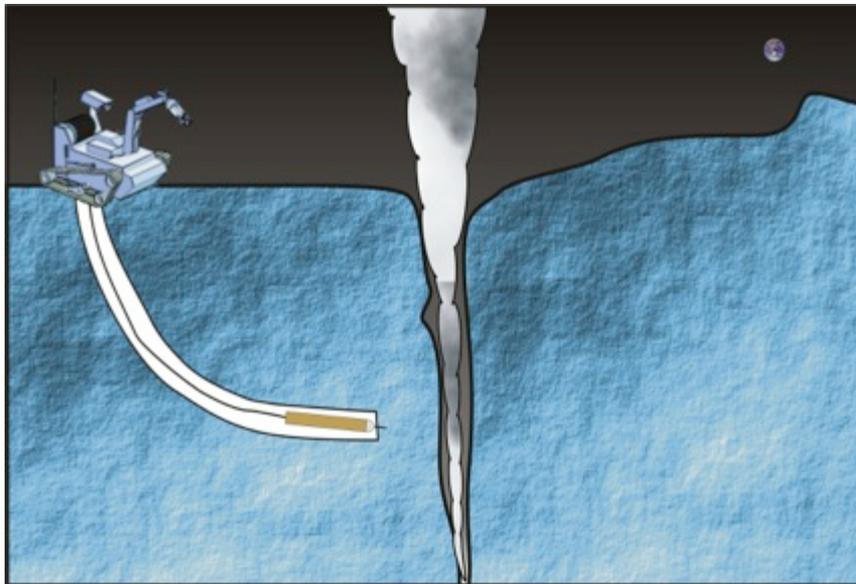
The discovery of a plume of water vapour and ice particles emerging from warm fractures (‘tiger stripes’) in Saturn’s small, icy moon Enceladus^{1–6} raised the question of whether the plume emerges from a subsurface liquid source^{6–8} or from the decomposition of ice^{9–12}. Previous compositional analyses of particles injected by the plume into Saturn’s diffuse E ring have already indicated the presence of liquid water⁸, but the mechanisms driving the plume emission are still debated¹³. Here we report an analysis of the composition of freshly ejected particles close to the sources. Salt-rich ice particles are found to dominate the total mass flux of ejected solids (more than 99 per cent) but they are depleted in the population escaping into Saturn’s E ring. Ice grains containing organic compounds are found to be more abundant in dense parts of the plume. Whereas previous Cassini observations were compatible with a variety of

terrain. Salt-poor type I grains can form by homogenous nucleation from the gas phase^{7,8}. In contrast, the salt-rich type III particles have to be formed from salt-ice condensation cores, presumably frozen spray of salt water⁸. The latter mechanism naturally forms larger grains, which then receive lower average ejection speeds for a given density and speed of the carrier gas⁷. Indeed, measurements of CDA’s High Rate Detector¹⁸ and photometry of the plume in the near-infrared¹⁹ both indicate that the grain ejection velocity decreases with size. This would lead to the compositional stratification of the plume, with an (observed) increase of the proportion of salt-rich grains close to the sources. This idea is supported by the generally larger yields of ions from impacts of salt-rich particles recorded in the E ring (Supplementary Fig. 5). Proportionally fewer of the slower (larger) salt-rich grains escape the moon’s gravity and end up in the E ring, explaining

Nature, Vol. ?, 2011, pp. ?-?

Enceladus Explorer (EnEx) Mission Objective

“Development of an
Autonomous Steerable
Subsurface Ice Probe to
Demonstrate Autonomous
Navigation in Deep Ice”
(not yet in space)



Enceladus Explorer Collaboration:

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FH Aachen University of Applied Sciences
- > **Prof. Dr. Bernd Eissfeller** and Team
Prof. Dr. Roger Förstner and Team
Univ. of the Armed Forces, Munich
- > **Prof. Dr. Kerstin Schill** and Team
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- > **Prof. Dr. Peter Hecker** and Team
Technical University Braunschweig
- > **Prof. Dr. Christopher Wiebusch** and Team
RWTH Aachen University
- > **Prof. Dr. Klaus Helbing** and Team
Bergische Univ. Wuppertal

Gefördert durch:



aufgrund eines Beschlusses
des Deutschen Bundestages



*The project Enceladus Explorer is based on an idea
and initiative of the DLR space management.*

Blood Falls, Antarctica | Enceladus on Earth

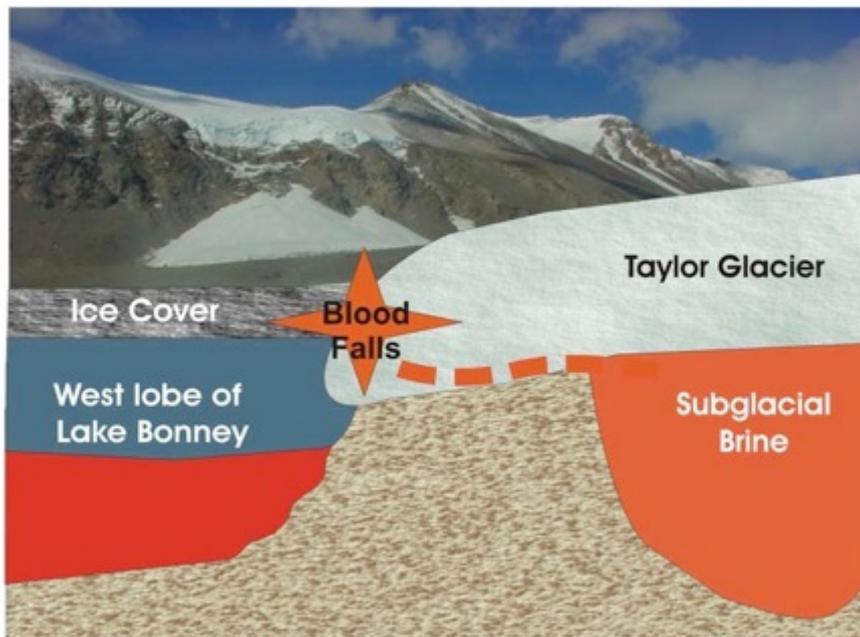
Blood Falls, Taylor Glacier, Antarctica



Blood Falls, Antarctica | Enceladus on Earth

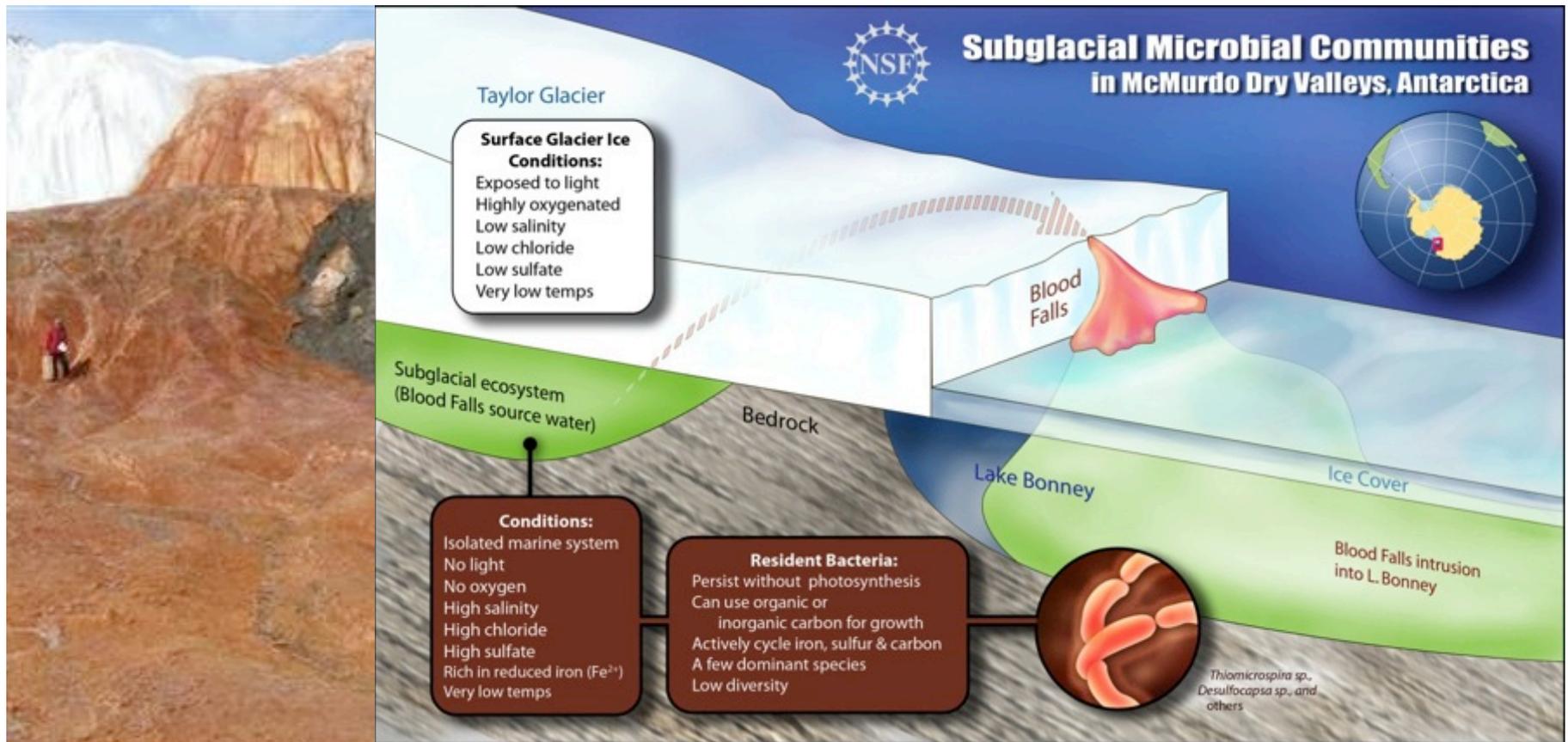
Blood Falls, Taylor Glacier, Antarctica

- > Outflow of an iron oxide-tainted plume of saltwater at the tongue of the Taylor Glacier, East Antarctica
- > Iron-rich hypersaline water emerges sporadically from small fissures in the ice
- > The source is a subglacial lake(?)



Blood Falls, Antarctica | Enceladus on Earth Subglacial Ecosystem

- > A rare subglacial ecosystem of autotrophic bacteria
- > Bacteria metabolize sulfate and ferric ions



Blood Falls, Antarctica | Enceladus on Earth

Subglacial Ecosystem

A Contemporary Microbially Maintained Subglacial Ferrous "Ocean"

Jill A. Mikucki,^{1*} Ann Pearson,¹ David T. Johnston,² Alexandra V. Turchyn,³ James Farquhar,⁴ Daniel P. Schrag,¹ Ariel D. Anbar,⁵ John C. Prisco,⁶ Peter A. Lee⁷

An active microbial assemblage cycles sulfur in a sulfate-rich, ancient marine brine beneath Taylor Glacier, an outlet glacier of the East Antarctic Ice Sheet, with Fe(III) serving as the terminal electron acceptor. Isotopic measurements of sulfate, water, carbonate, and ferrous iron and functional gene analyses of adenosine 5'-phosphosulfate reductase imply that a microbial consortium facilitates a catalytic sulfur cycle. These metabolic pathways result from a limited organic carbon supply because of the absence of contemporary photosynthesis, yielding a subglacial ferrous brine that is anoxic but not sulfidic. Coupled biogeochemical processes below the glacier enable subglacial microbes to grow in extended isolation, demonstrating how analogous organic-starved systems, such as Neoproterozoic oceans, accumulated Fe(II) despite the presence of an active sulfur cycle.

Subglacial environments represent a largely unexplored component of Earth's biosphere (1). In the McMurdo Dry Valleys, Antarctica, an iron-rich subglacial outflow (Blood Falls) flows from the Taylor Glacier (Fig. 1A), providing unique access to a subglacial ecosystem. The likely fluid source to Blood Falls is a pool of marine brine of unknown depth trapped underneath the glacier ~4 km from the glacier snout where the overlying ice is ~400 m thick (2).

present is anoxic and highly ferrous and the pH is circumneutral (Table 1), activity and DNA sequence data reveal that it supports a metabolically active, largely marine microbial assemblage (7).

Taylor Glacier is frozen to its bed, and surface-derived water does not penetrate to the base (8). Poorly understood hydrologic controls result in episodic release of brine. The data in this study are from one of these active discharge events. Salts and the iron mineral goethite rapidly

range = 20.8 to 21.7‰ for $^{34}\text{S}_{\text{SO}_4}$; 0.08‰ and range = 0.06 to 0.09‰ for $^{33}\text{S}_{\text{SO}_4}$; $n = 6$) were similar to measurements of seawater SO_4^{2-} from the past 15 My measured in marine barites (11). In contrast, values of $\delta^{18}\text{O}_{\text{SO}_4}$ (3.3‰; range = 2.7 to 4.9‰; $n = 6$) were up to 7‰ depleted compared with that of seawater $\delta^{18}\text{O}_{\text{SO}_4}$ from marine barites over the Pliocene [10.4 ± 1.6 ‰ (12)]. Because values of both $\delta^{34}\text{S}$ and $\delta^{18}\text{O}$ in SO_4^{2-} are influenced independently by microbial sulfur metabolism, including sulfate reduction, disproportionation, and reoxidation reactions (13, 14), we expect that both oxygen and sulfur isotopes would be affected. For example, dissimilatory sulfate reduction to sulfide would cause preferential enrichment of ^{34}S ($\text{SO}_4^{2-} \rightarrow \text{H}_2\text{S}$, fractionation factor (ϵ) = 20 to 40‰ for natural populations) (15) because ^{34}S -depleted S^{2-} is sequestered in iron sulfides. This would increase the $\delta^{34}\text{S}_{\text{SO}_4}$ value of the remaining sulfate pool.

Our isotope data indicate that incorporation of ^{18}O -depleted brine water oxygen into sulfate has occurred (Fig. 1B and table S3). During glacial advancement, meltwater mixing with the remaining seawater decreased the $\delta^{18}\text{O}$ value of the brine from a marine value to its current composition ($\delta^{18}\text{H}_2\text{O}_{\text{Brine}} = -39.5$ ‰; Table 1). The depleted value of $\delta^{18}\text{O}_{\text{SO}_4}$ cannot be explained by abiotic oxygen isotope exchange between SO_4^{2-} and water. Such equilibration would take tens of millions of years at subglacial temper-

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MIDGE

US Team

MIDGE: Minimally Invasive Direct Glacial Exploration

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MIDGE: Minimally Invasive Direct Glacial Exploration



“Clean sample return of subglacial water from a crevasse for life detection and analysis”

- > The melting channel intersects the crevasse 20 m below the surface

Navigation challenges:

- > Avoidance of obstacles in the ice
- > Autonomously detection of the crevasse ahead
- > Stopping before it drills into the crevasse

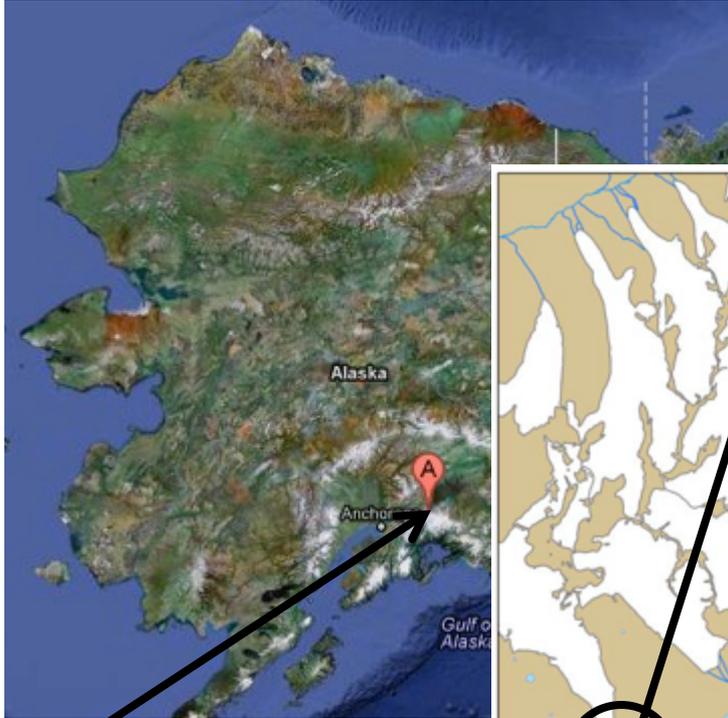
1. Detection of liquid water (target point), crevasses, and obstacles in the ice
2. Continuous measurement of the probe's attitude and position relative to the surface station and to the target point
3. Measurement of the distance to the target point
4. Autonomous optimal path determination to the target point under consideration of obstacles, available energy, and maximum range
5. Suitability of the hardware for usage in the IceMole under consideration of the constraints given by the probe and the mission scenario

- > Forward contamination of subglacial water shall not exceed the concentration of microbes in the surrounding glacial ice ($\approx 2\,000$ cells/ml; Mikucki and Priscu, AEM, 2007)

Type of ice formation	Sampling location	Sample T ($^{\circ}\text{C}$)	Particle-poor ice
Snow	South Pole	-15	$0.2-5 \times 10^3$
Ice sheet	Over Lake Vostok (2-4 km)	-3	$0.2-8 \times 10^3$

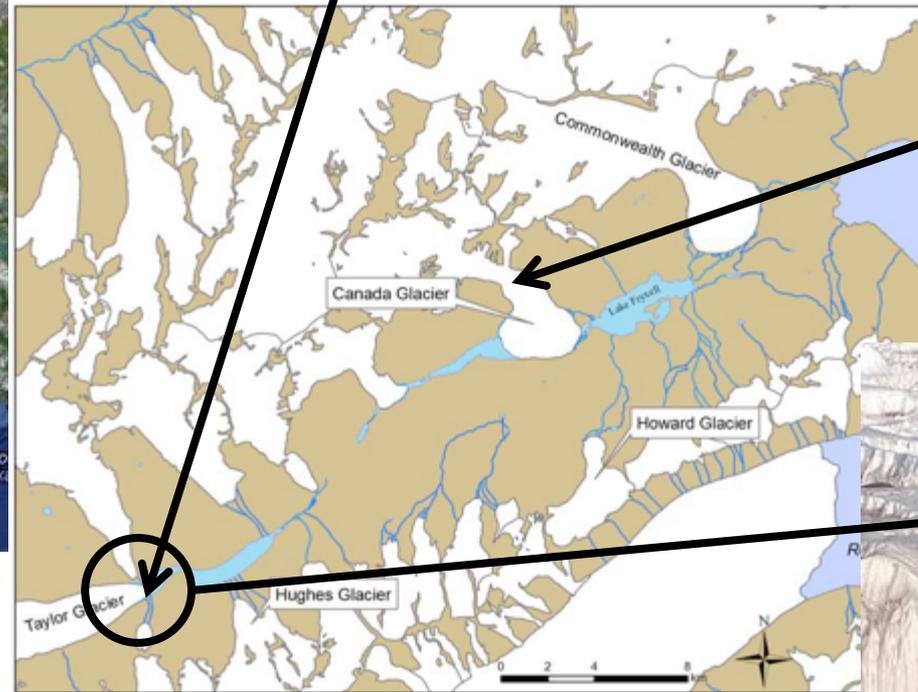
- > No cable and equipment shall be left behind
- > Decontamination via hydrogen peroxide and UV radiation

MIDGE & EnEx Field Tests



Matanuska Glacier,
Alaska
1st Test
(Summer 2013)

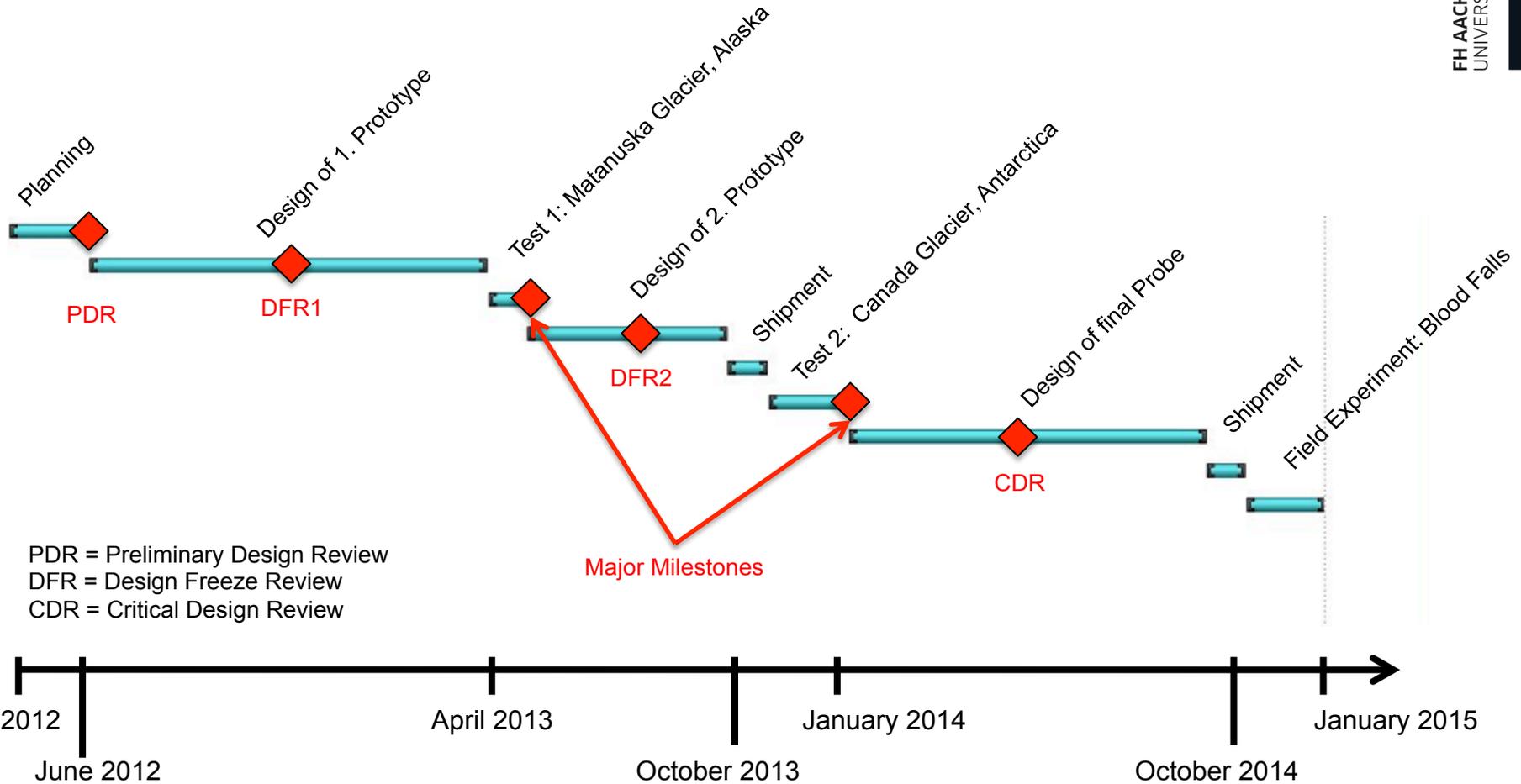
Blood Falls
Field Experiment (Winter 2014)



Canada Glacier,
Antarctica
2nd Test
(Winter 2013)



MIDGE & EnEx Timeline



- > **Navigation:** 3D navigation under the ice with ultrasound sensor head, acoustic sensors, inertial measurement unit, differential magnetometer, inclinometer, sensor fusion
- > **Contamination Control:** decontamination of the probe according to NASA planetary protection standards
- > **Control & Ops:** robust control and operations
- > **Thermal Control:** optimization of cornering ability, thermal computer simulation

*White men think of ice as frozen water,
but Inuit think of water as melted ice.
To us, ice is the natural state.*

Nuka Pinguaq, Arctic Hunter

Questions?

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Subsurface Icecraft

