Development of a Remotely Operated Underwater Vehicle for Oceanographic Access Under Ice

Presented at the 8th Annual Polar Technology Conference, 3-5 April 2012

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Johns Hopkins University
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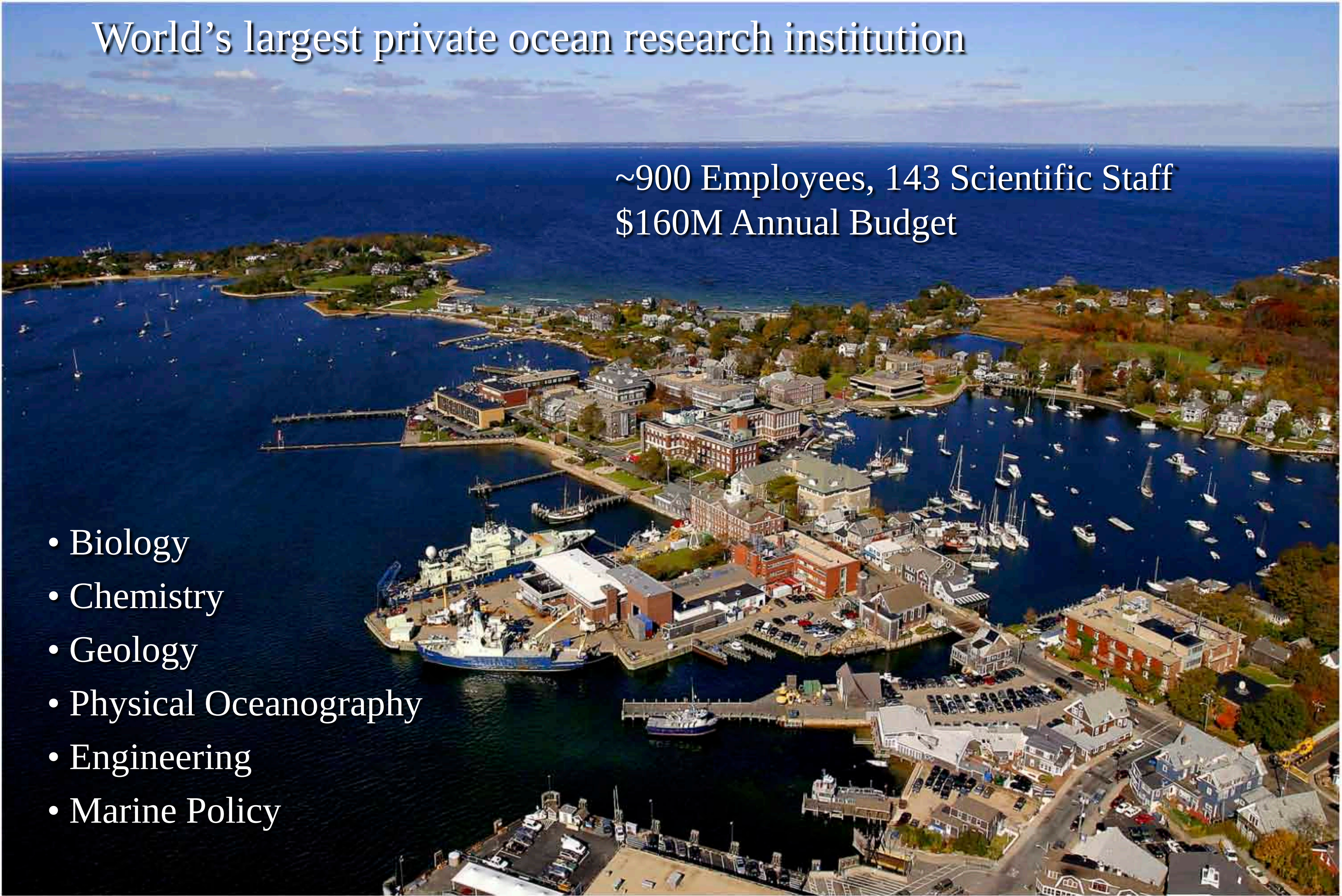
University of New Hampshire

Photo courtesy S. McPhail, NOC

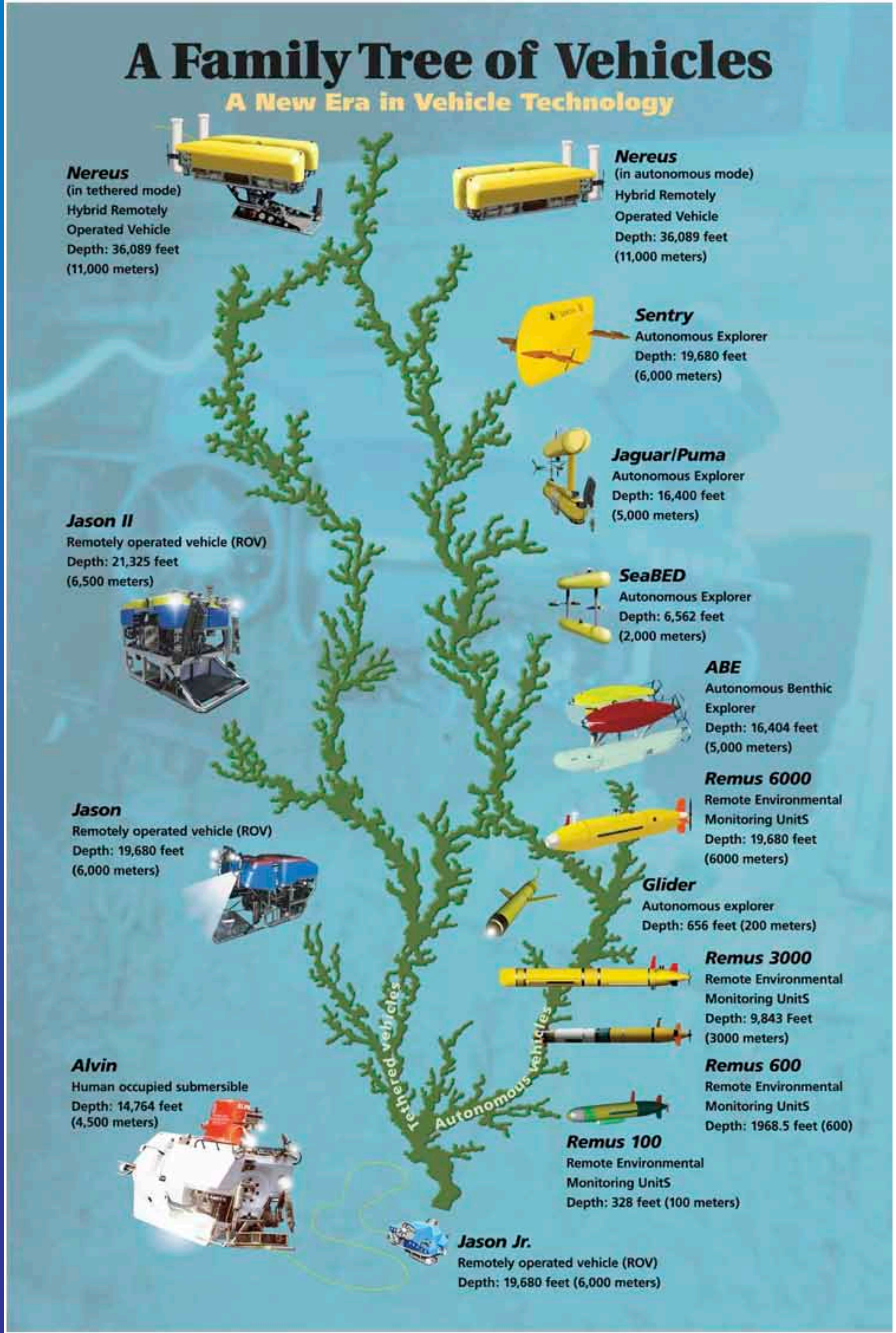
Woods Hole Oceanographic Institution



World's largest private ocean research institution

~900 Employees, 143 Scientific Staff
$160M Annual Budget

- Biology
- Chemistry
- Geology
- Physical Oceanography
- Engineering
- Marine Policy



WOODS HOLE OCEANOGRAPHIC INSTITUTION
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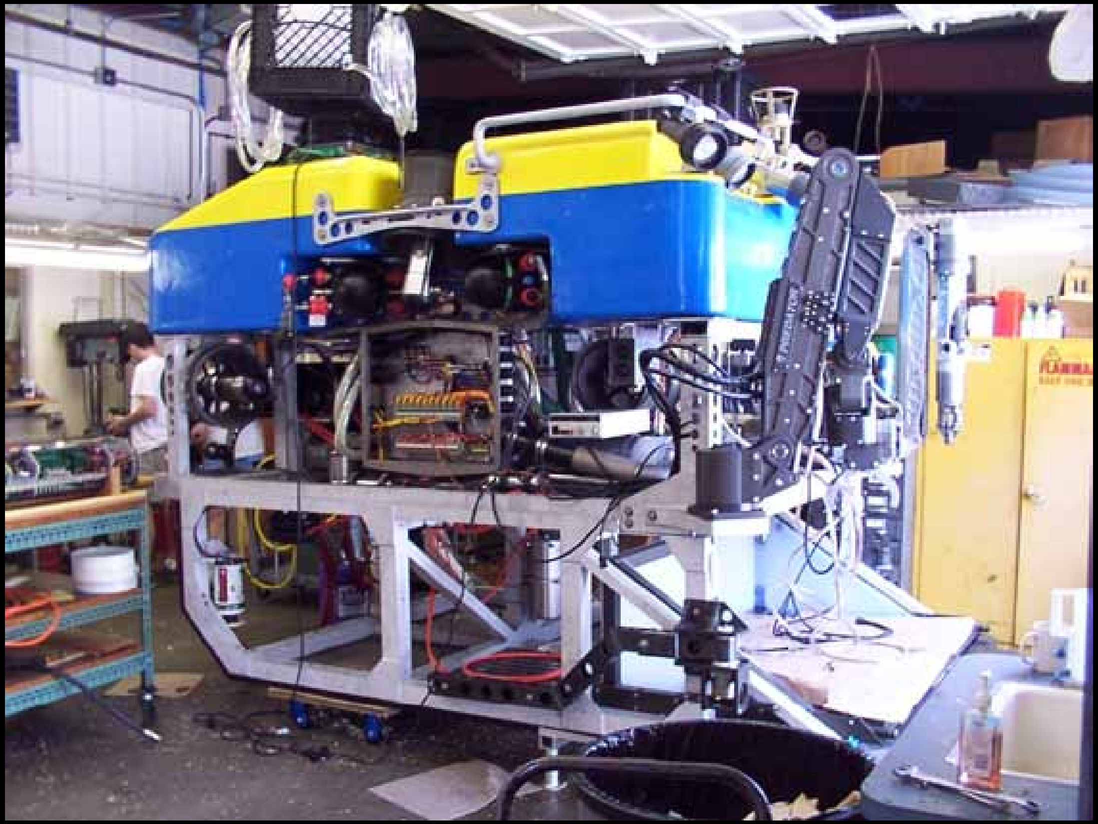
Deep Ocean Oceanography:
The *D.S.V. Alvin 4500m Submersible*

Ph.D. Student James Kinsey

Image Credit: Rod Catenach © WHOI

Crew:	3 = 1 pilot + 2 scientist
Depth:	4500m (6,500m soon)
Endurance:	6-10 Hours
Speed:	1 m/s
Mass:	7,000 Kg
Length:	7.1m
Power:	81 KWH
Life Support:	72 Hours x 3 Persons
Dives:	>4,700 (since 1964)
Passengers:	>14,000 (since 1964)

Jason II ROV



Specifications:

Size: 3.2 x 2.4 x 2.2 m

Weight 3,300 kg

Depth 6,500 m

Power 40 kW (50 Hp)

Payload: 120 Kg (1.5 Ton)

First Dive: 2002

Dives: >600

Dive Time: >12,500 Hours*

Bottom Time: >10,600 Hours*

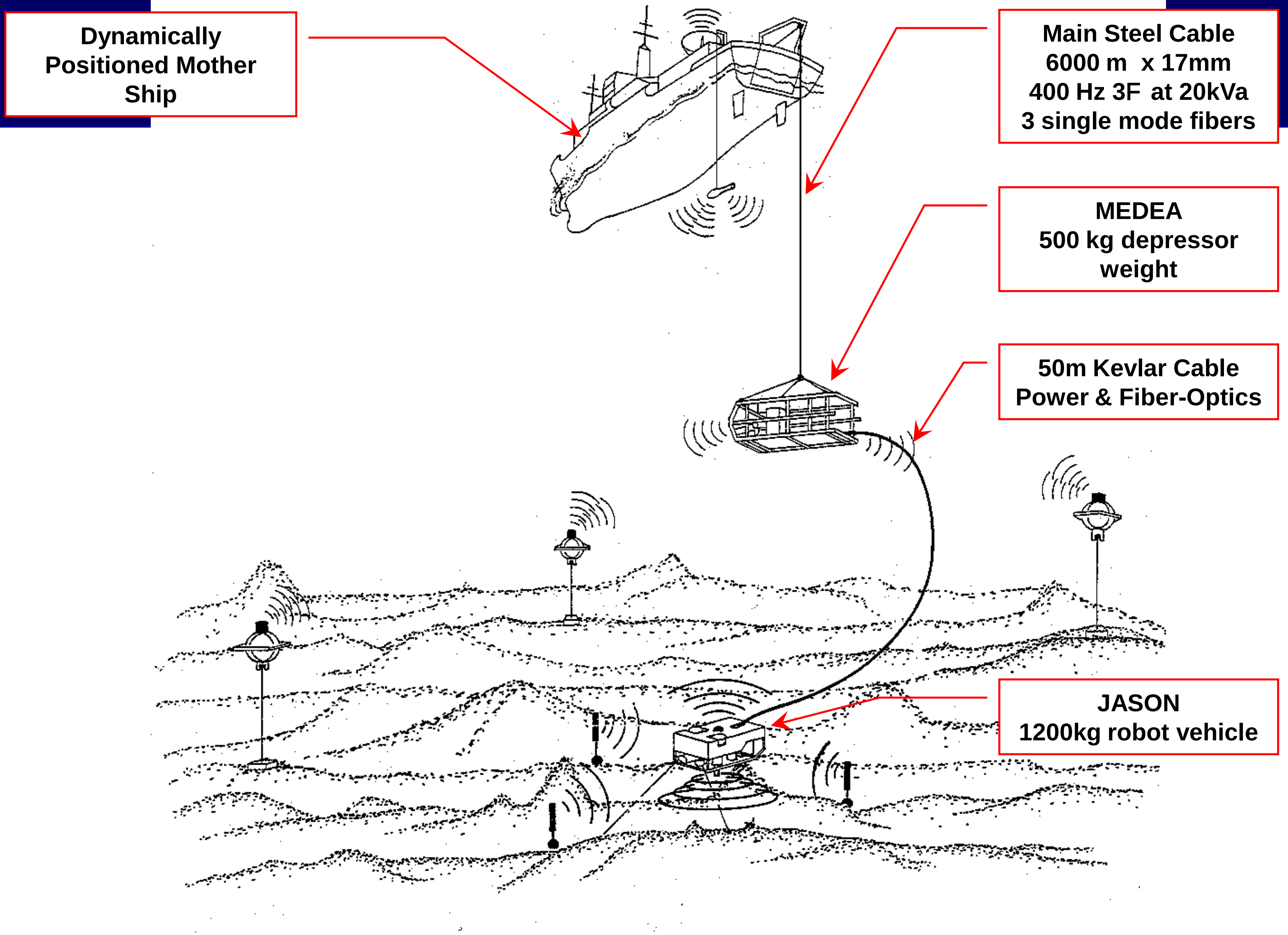
Longest Dive: 139 Hours*

Deepest Dive: 6,502 m*

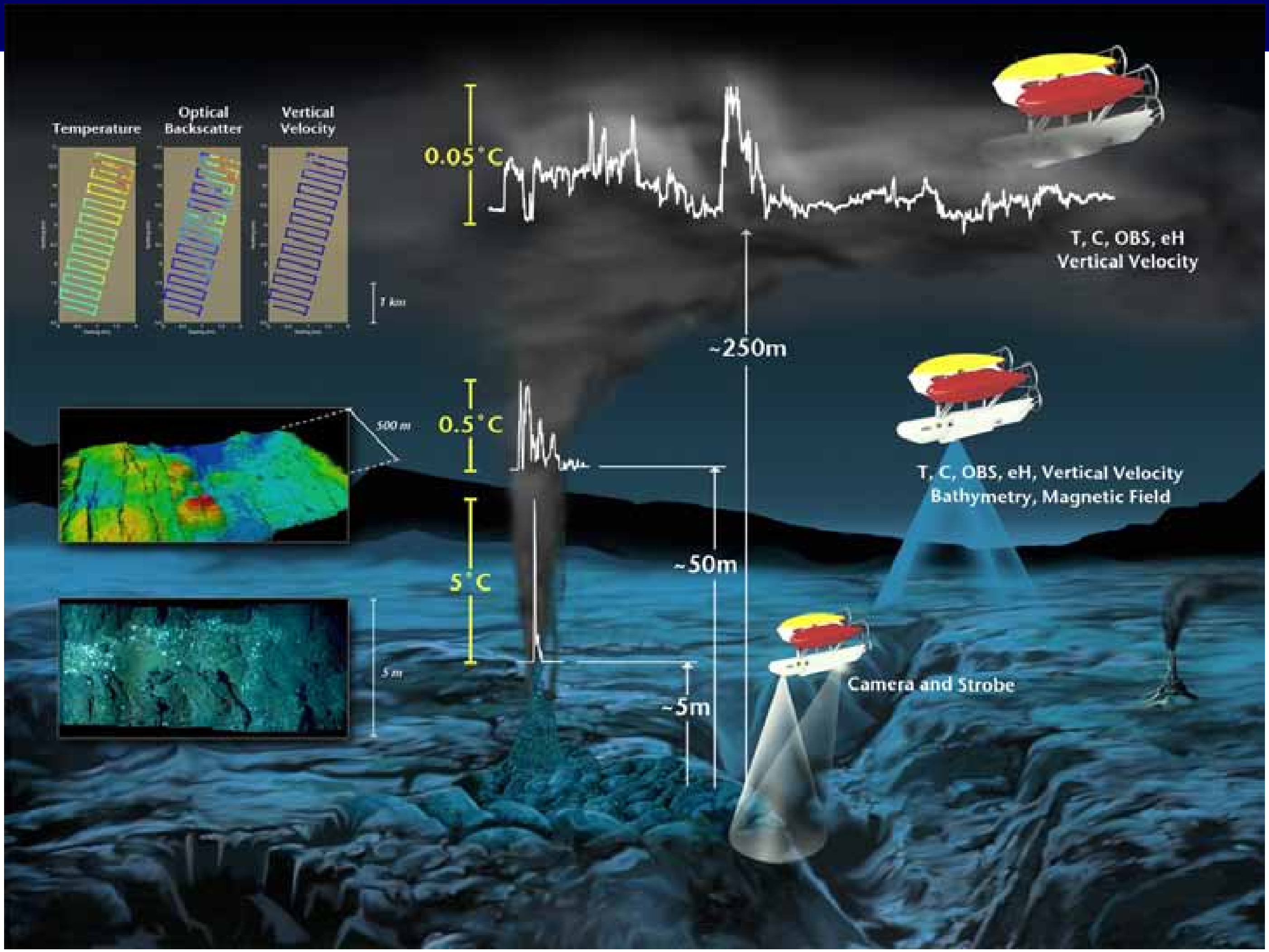
Distance: >4,800 km*

* As of Feb, 2012

Electric thrusters, twin hydraulic manipulator arms.


Dynamically Positioned Mother Ship
Main Steel Cable
6000 m x 17mm
400 Hz 3F at 20kVa
3 single mode fibers
MEDEA
500 kg depressor weight
50m Kevlar Cable
Power & Fiber-Optics
JASON
1200kg robot vehicle

The Autonomous Benthic Explorer (ABE)



Vent discoveries in the Lau Basin (near Fiji), Southern Mid-Atlantic Ridge, Southwest Indian Ridge.

(German, Yoerger, et al, 2004)

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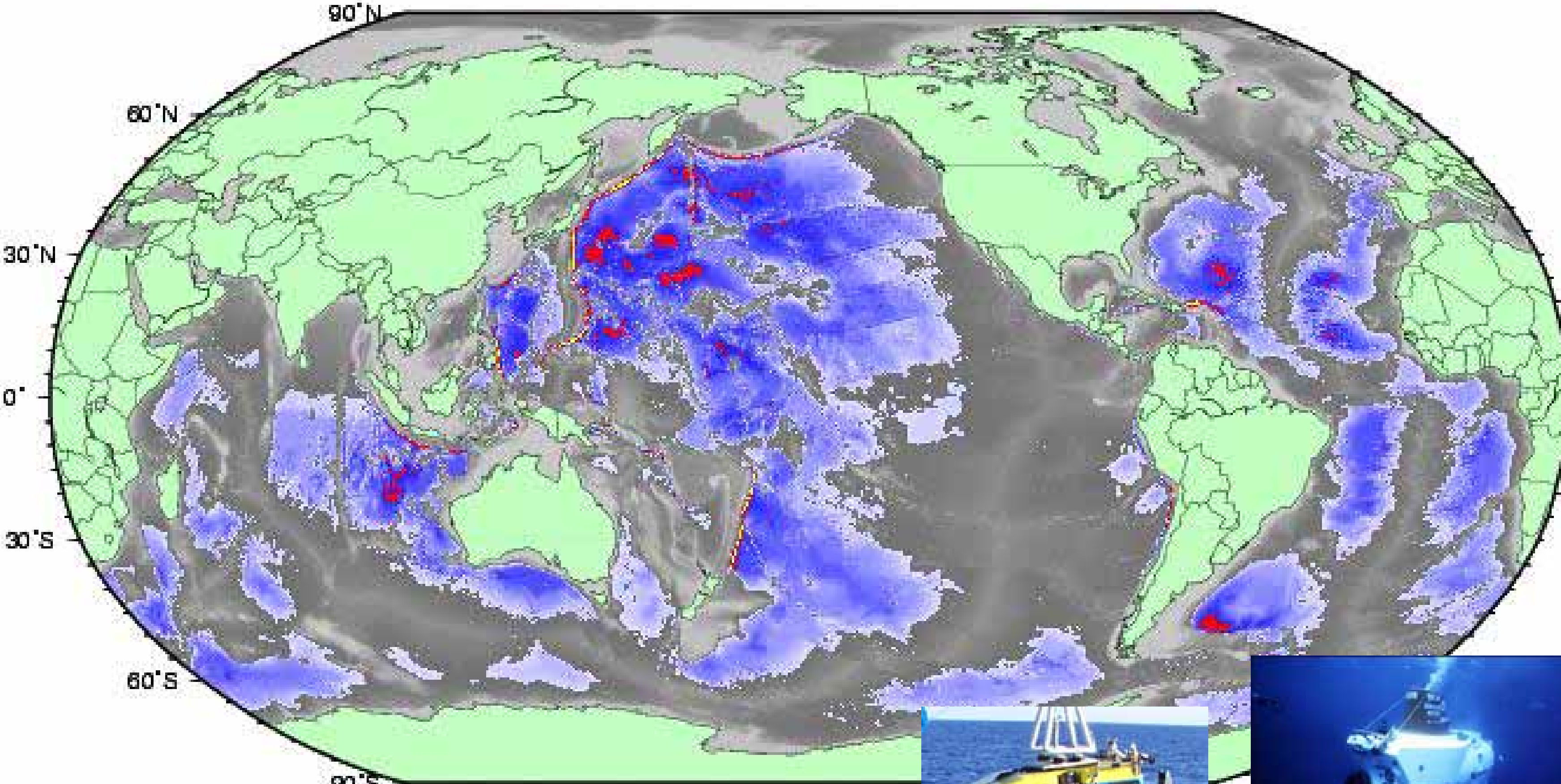
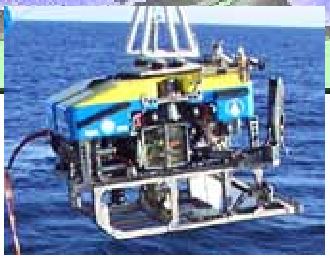
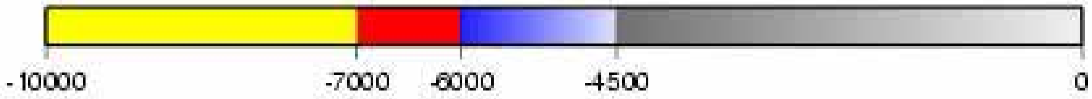
Systems Center
San Diego

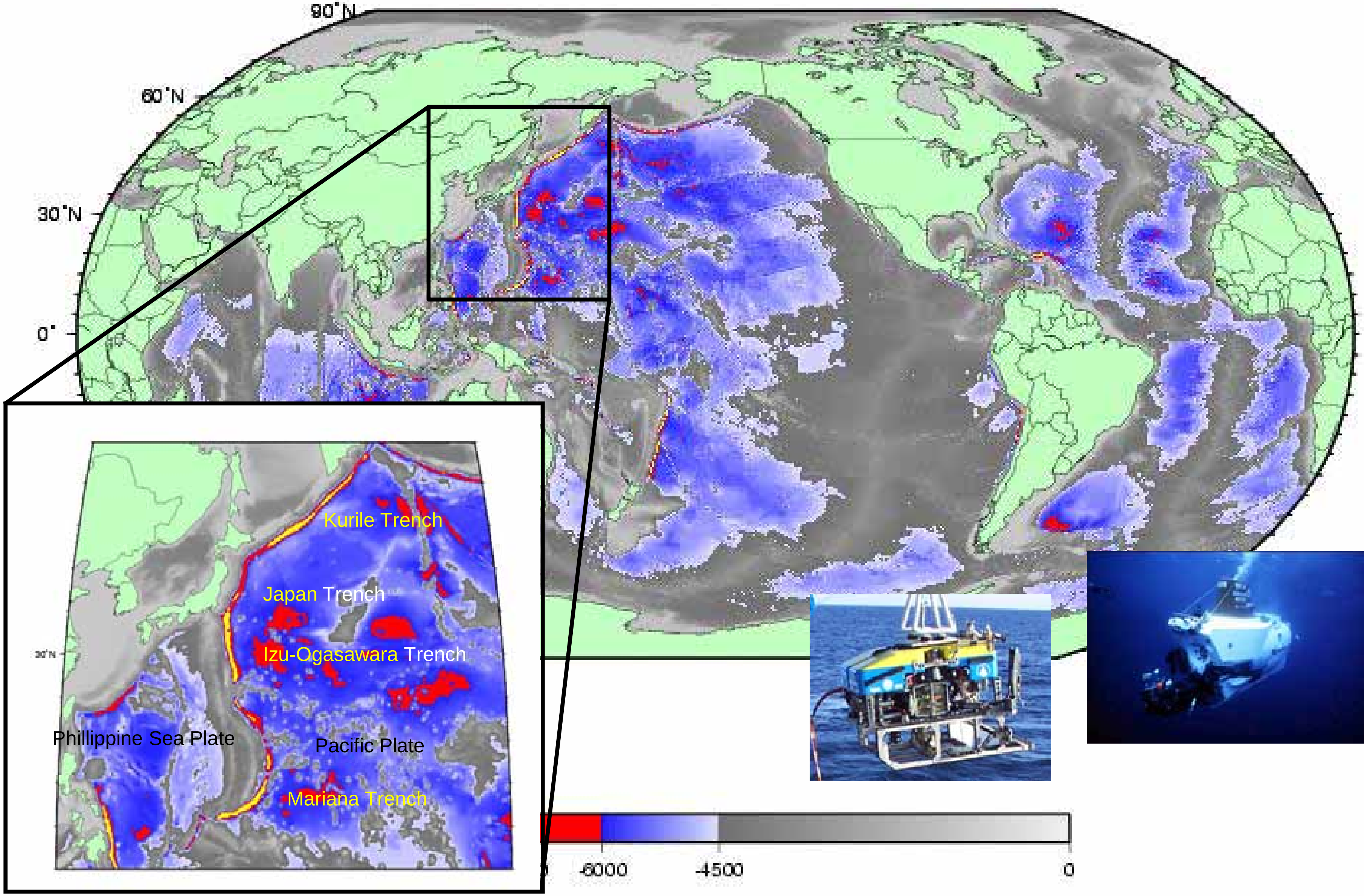




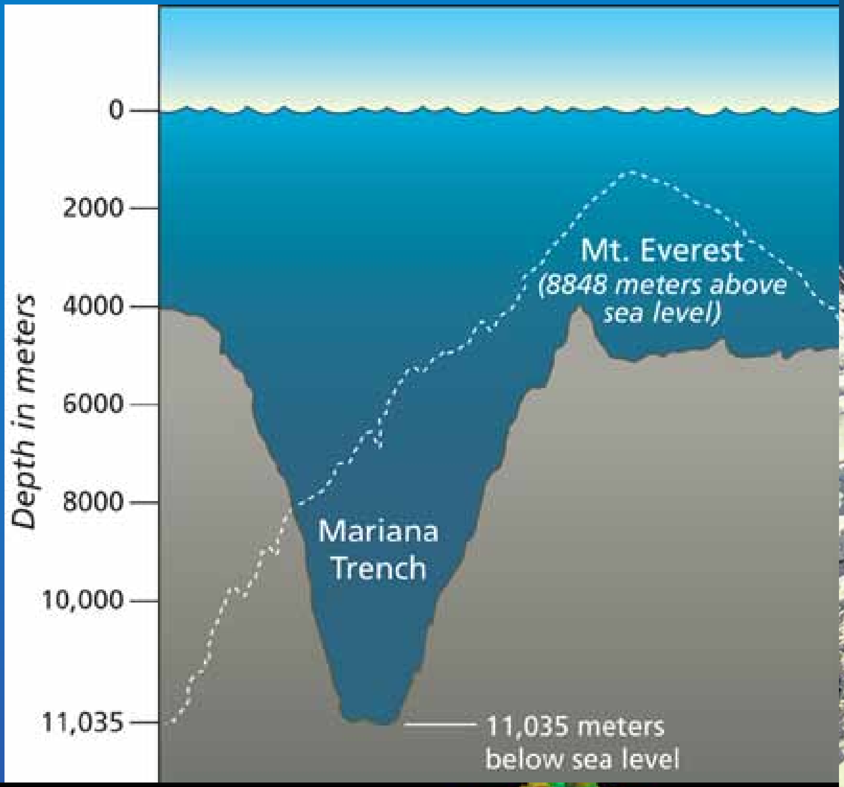
Global Ocean depth chart

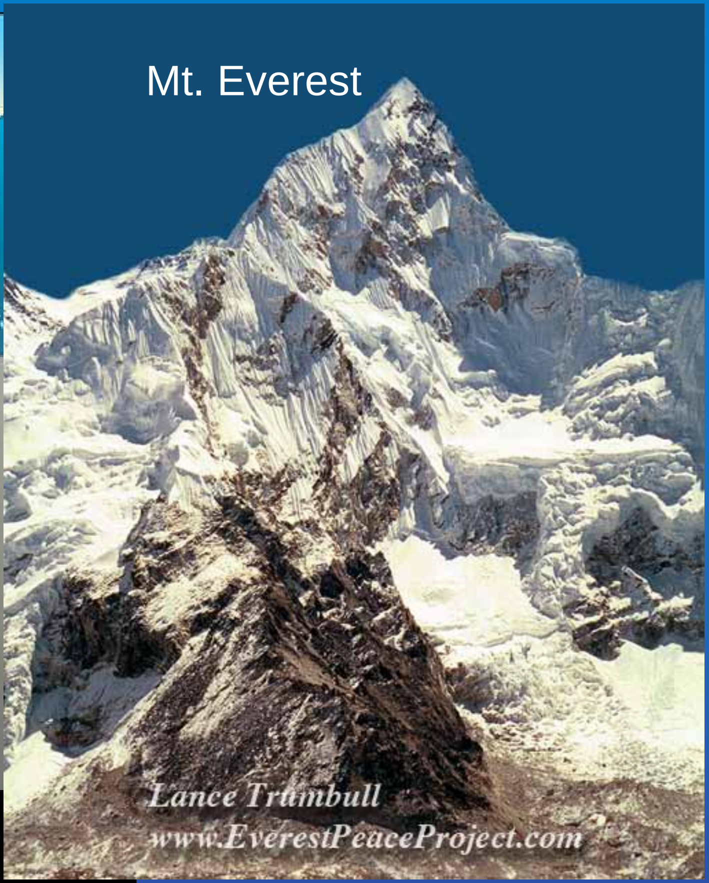
Robinson projection

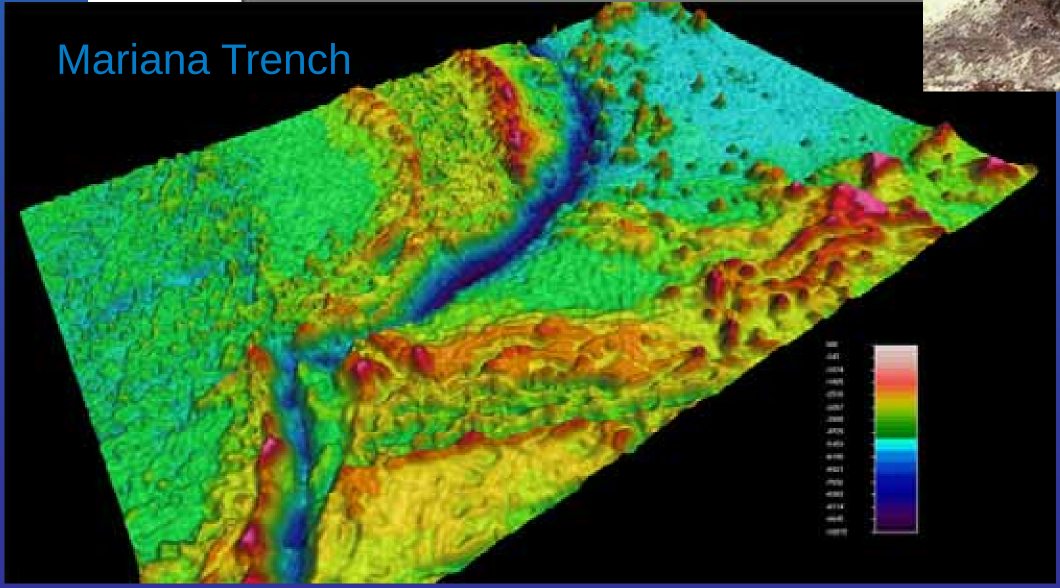




90°N
60°N
30°N
0°
Kurile Trench
Japan Trench
Izu-Ogasawara Trench
30°N
Phillippine Sea Plate
Pacific Plate
Mariana Trench
-6000
-4500
0





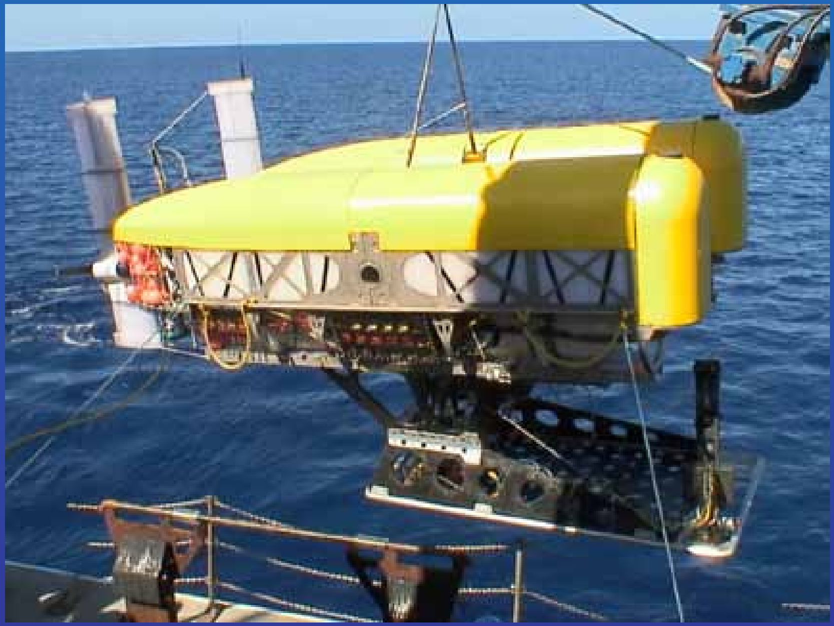


How to visit the deepest part of the ocean in a cost-effective way?

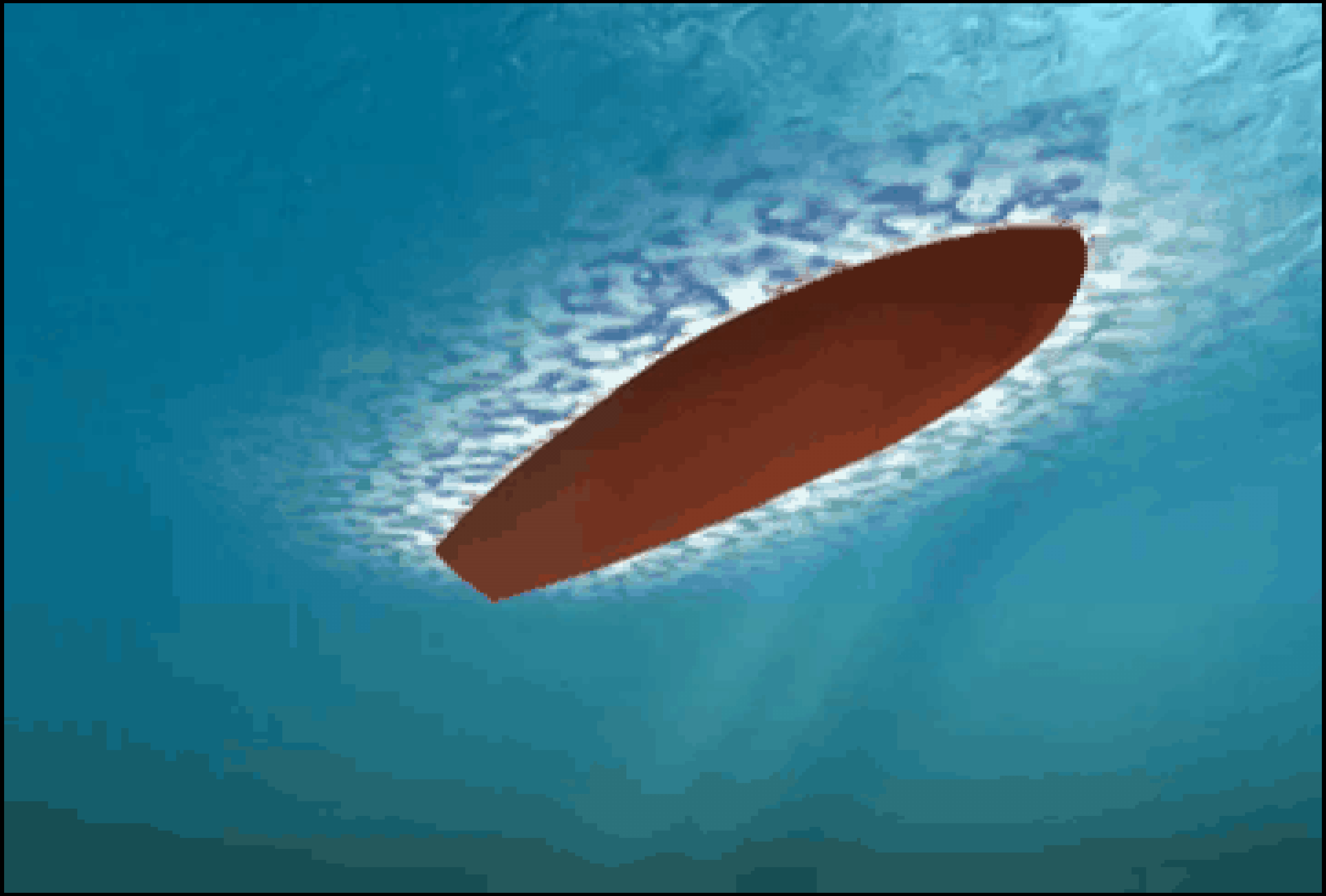
11,000 Meters an Easier Way

- A Hybrid cross between autonomous and remote-controlled undertwater vehicle
    - Untethered autonomous underwater vehicle (AUV) for mapping
    - Tethered remotely operated vehicle (ROV) for close inspection, sampling and manipulation

- New Class of vehicle intended to offer a cost effective solution for survey/sampling and direct human directed interaction with extreme environments through the use of new technologies



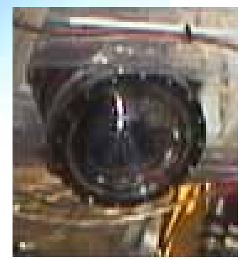
The *Nereus* Hybrid Remotely Operated Vehicle



New Technologies
Enabling the Nereus System Design

Ceramic Buoyancy
and Pressure Housings

Low Power
High Quality Imaging/Lighting



Low Power
Capable Manipulators

Micro-Fiber Tether
System

Energy
Storage

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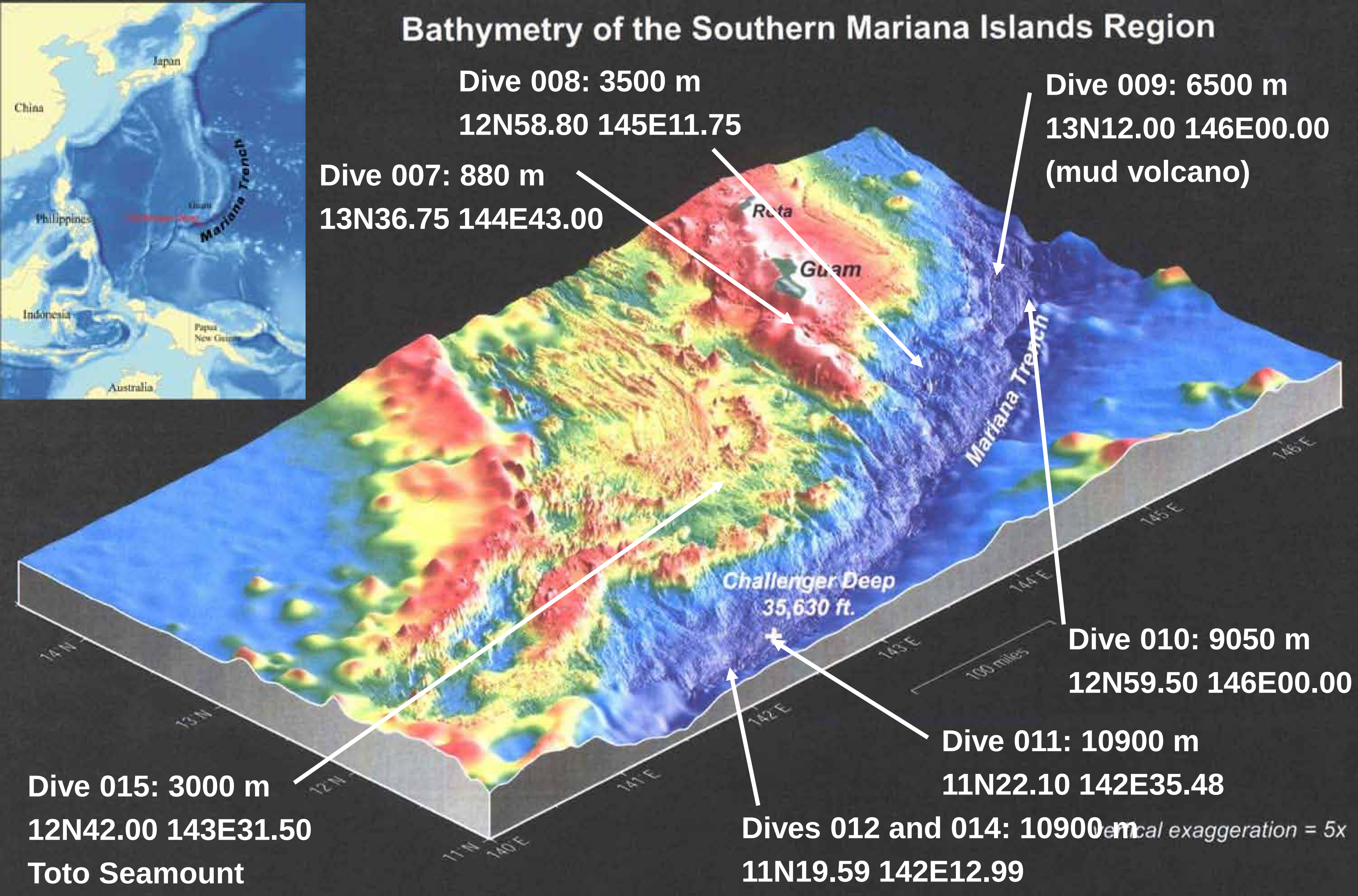
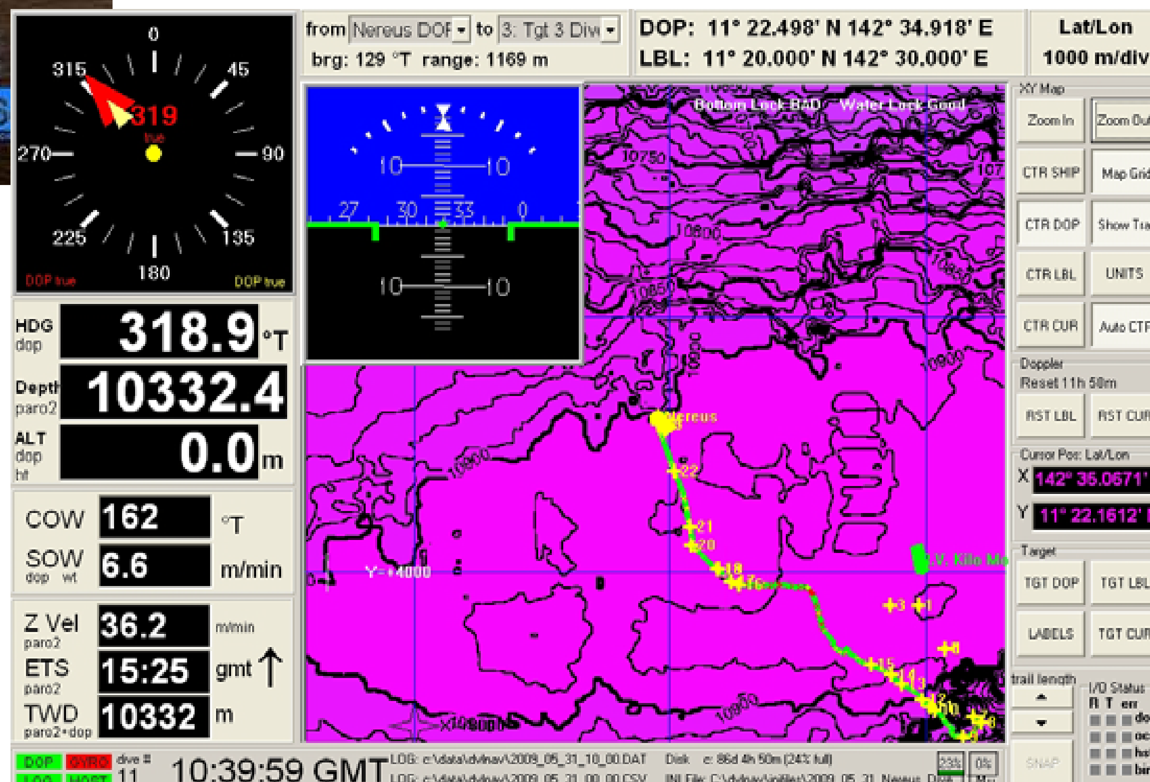
Nereus 2009 Mariana Expedition



Nereus Dive 11 to 10,903 m Depth



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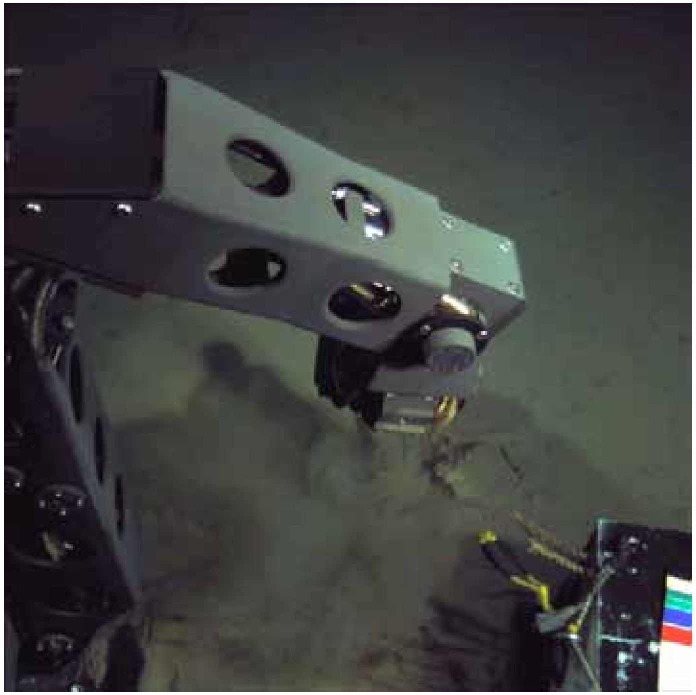
Nereus Sampling



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Nereus Sampling

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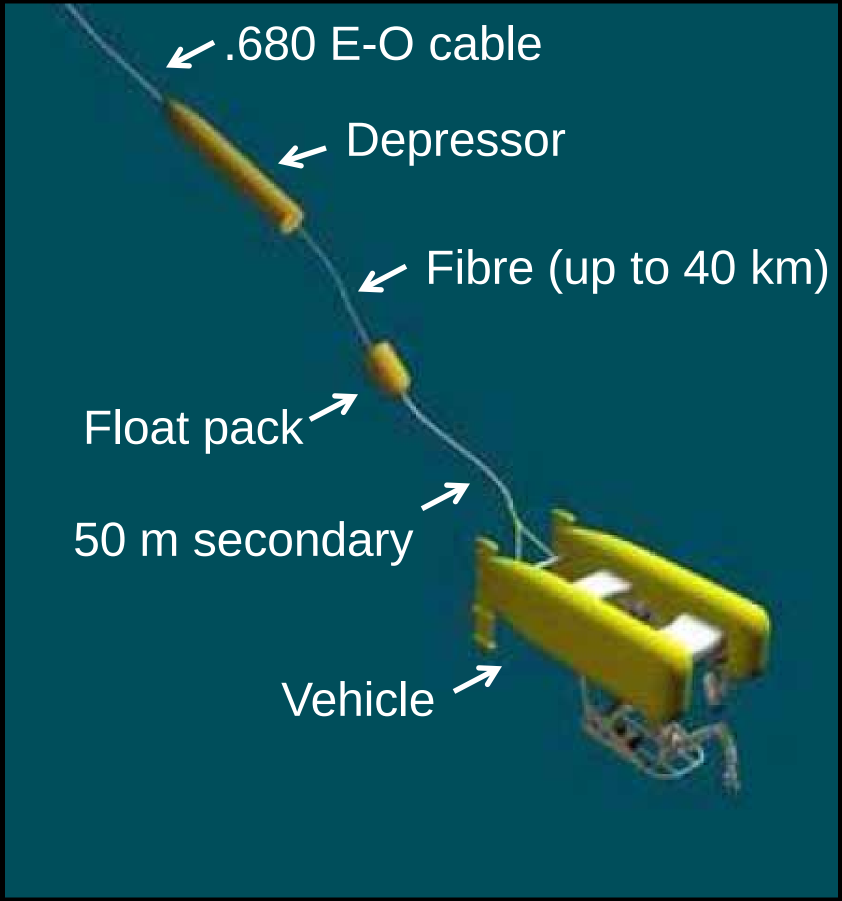
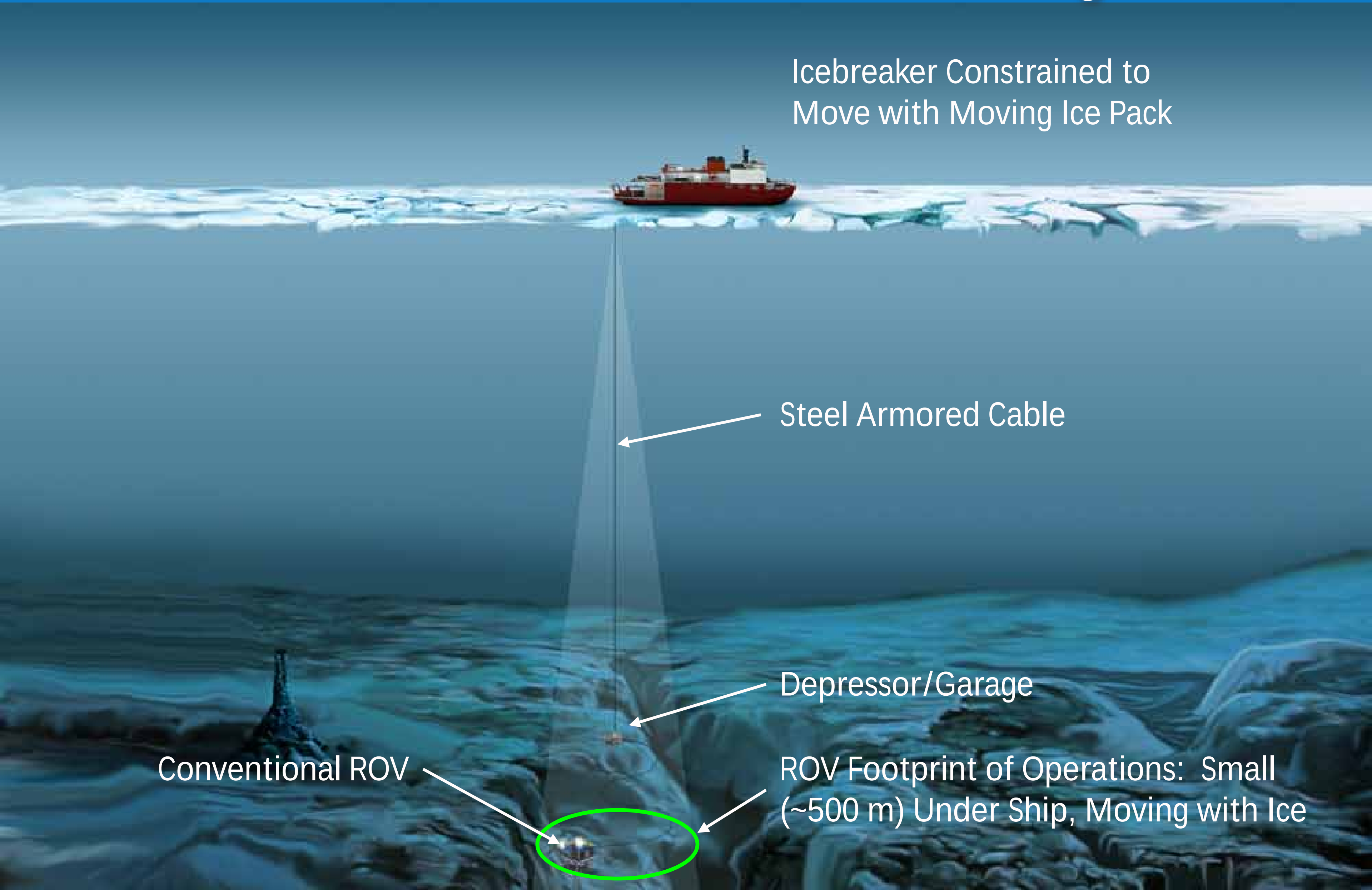
Light Fibre Tether Concept

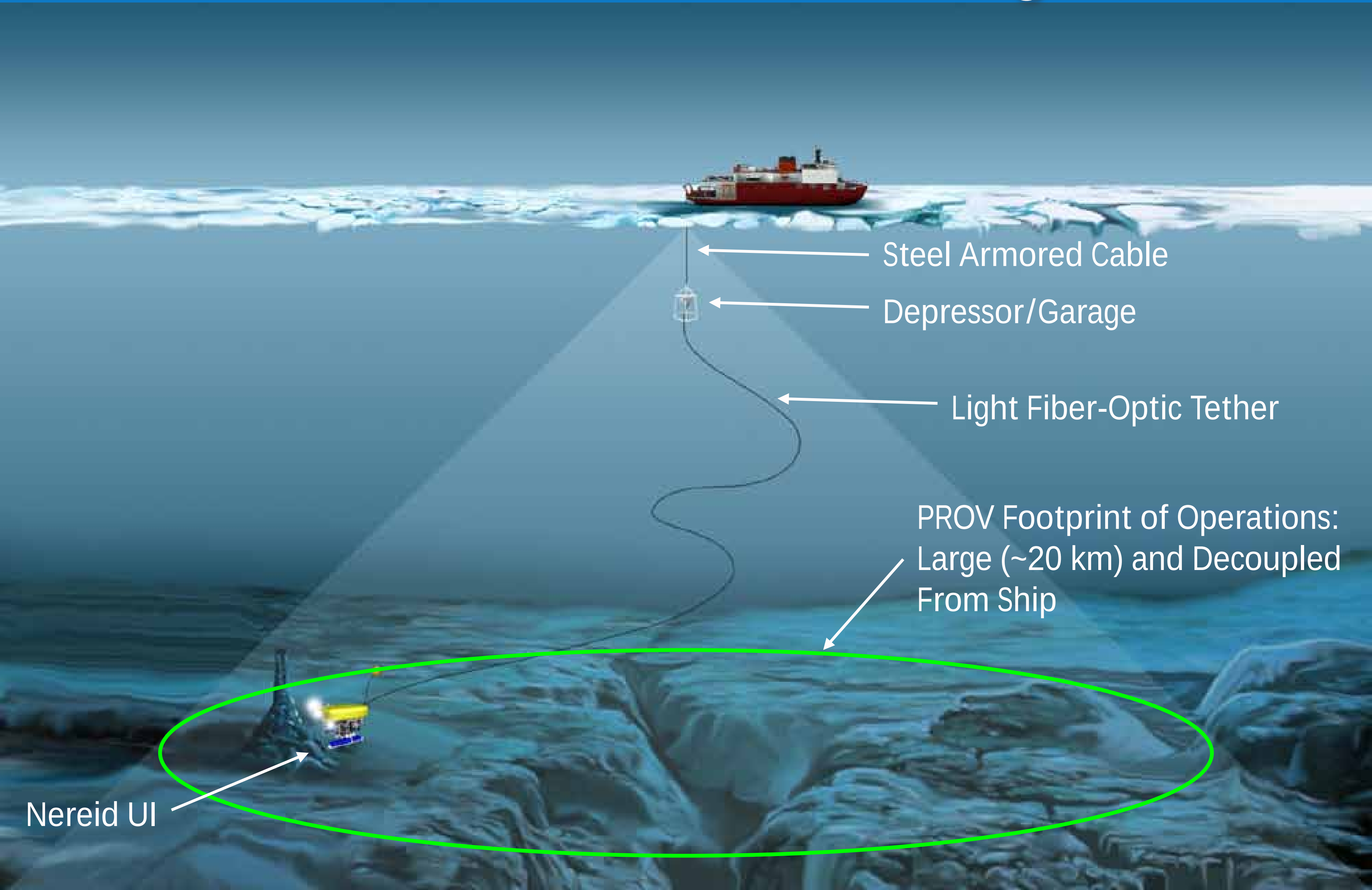


- High bandwidth (GigE) communications
- Unconstrained by surface ship
- Operable from non-DP vessels

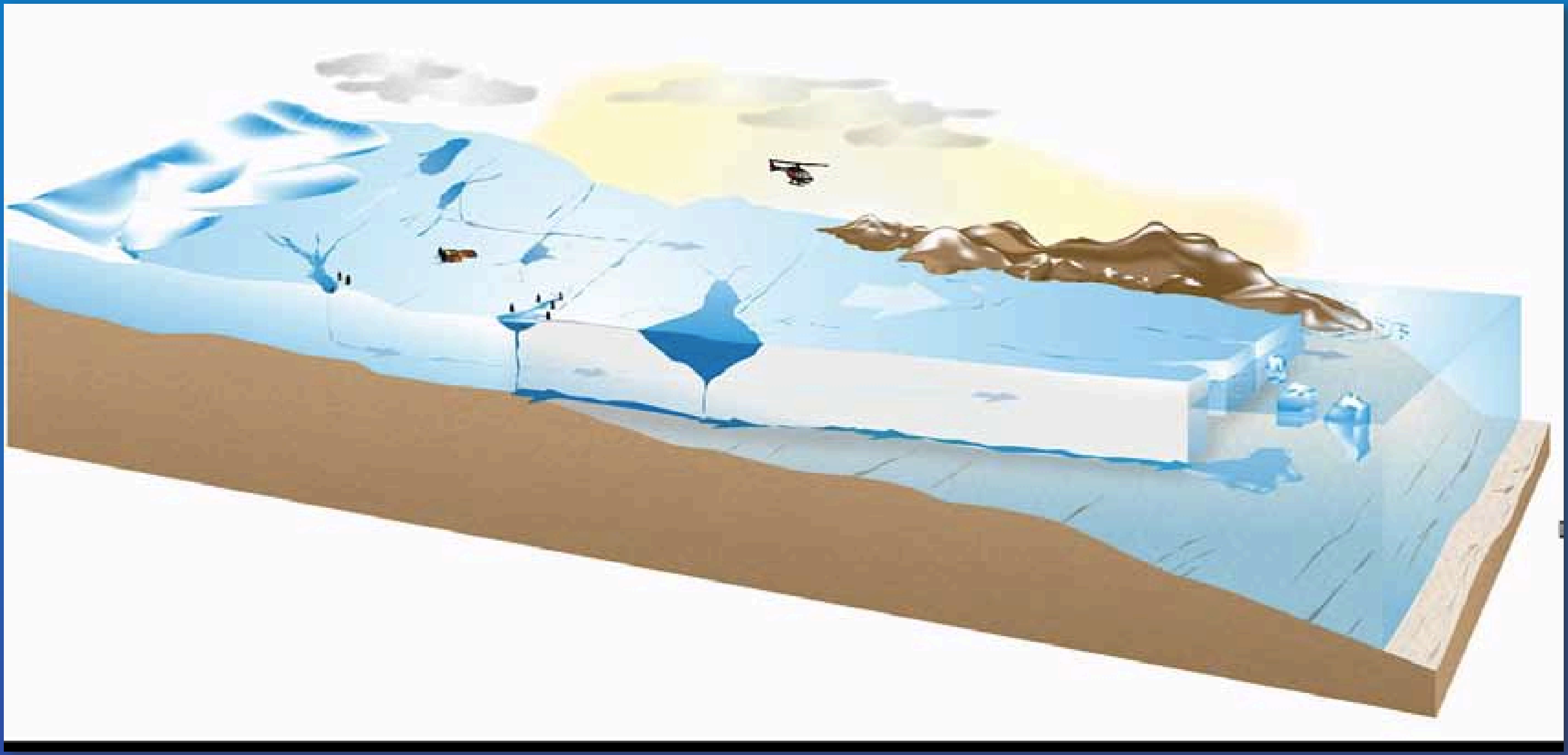
Problem: Conventionally Tethered ROV Operations from Icebreaker in Permanent Moving Ice



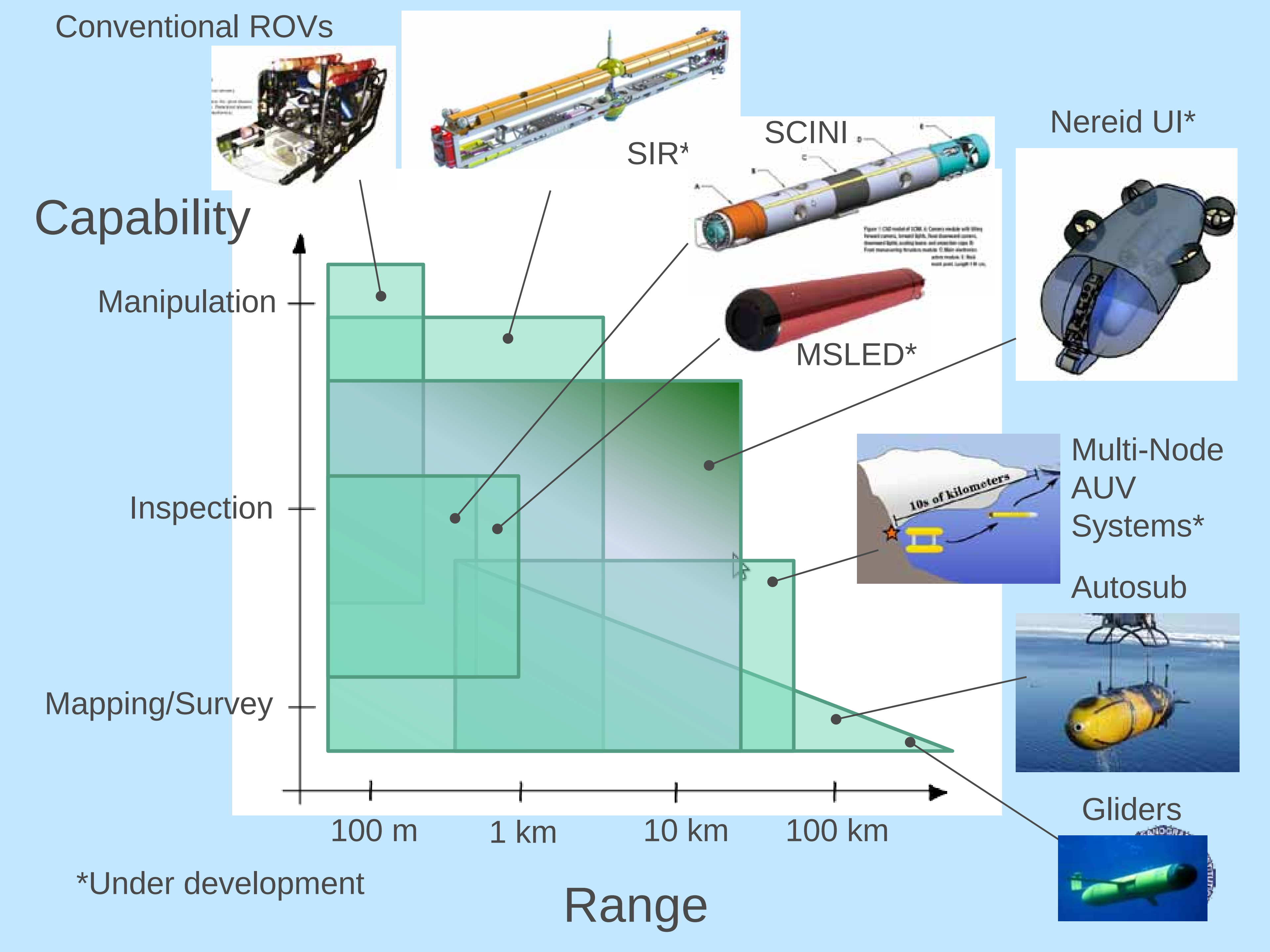
Solution: Light-Tethered Nereid Operations from Icebreaker In Permanent Moving Ice



The Under-Ice Scientific Imperative



- Near-Ice Inspection and Mapping
- Boundary Layer Investigations
- Grounding Line Inspection
- Sediment Sampling
- Ice Shelf Cavity Physical Oceanographic Mapping
- Instrument Emplacement*

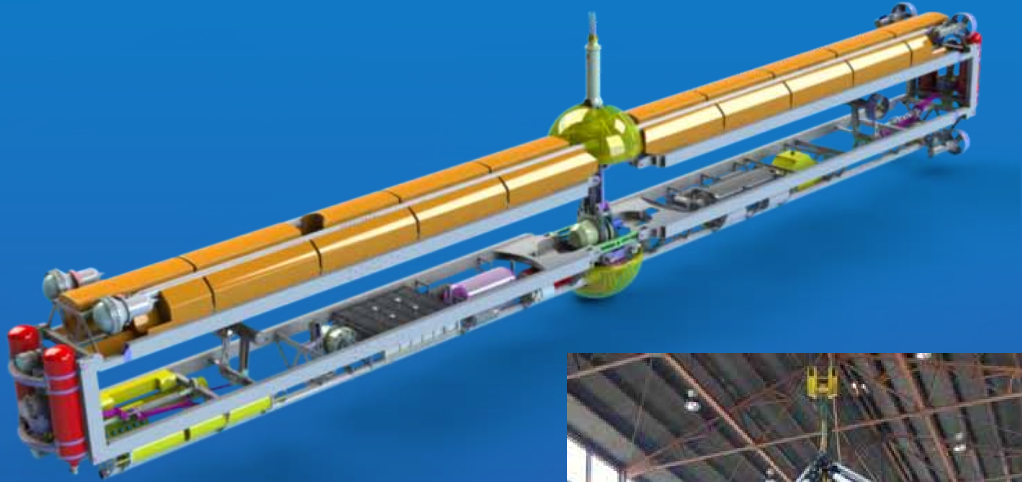


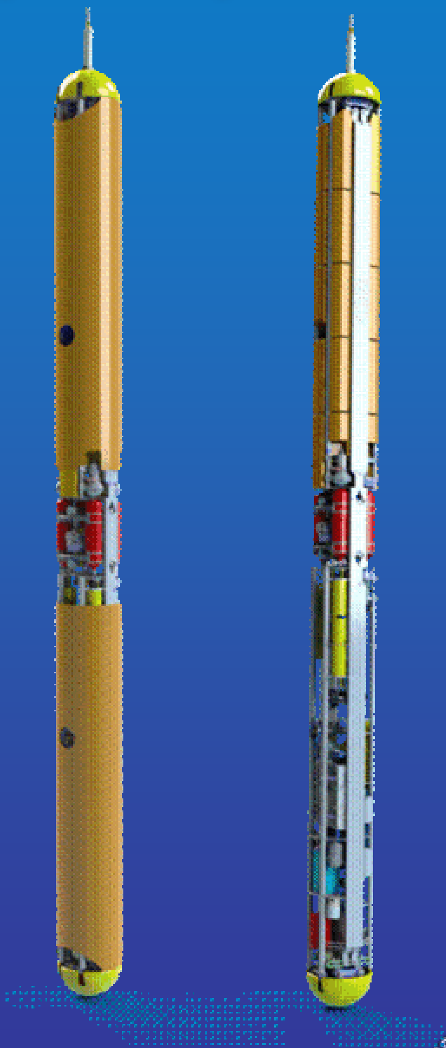
Conventional ROVs
SIR*
SCINI
Nereid UI*
MSLED*
Multi-Node AUV Systems*
10s of kilometers
Autosub
Gliders
Capability
Manipulation
Inspection
Mapping/Survey
100 m
1 km
10 km
100 km
Range
*Under development

Under-Ice Vehicle Systems

- Specialized hybrid AUV/ROV systems
- Conventional AUVs
- Conventional ROVs

Sub-Ice ROVer (SIR)

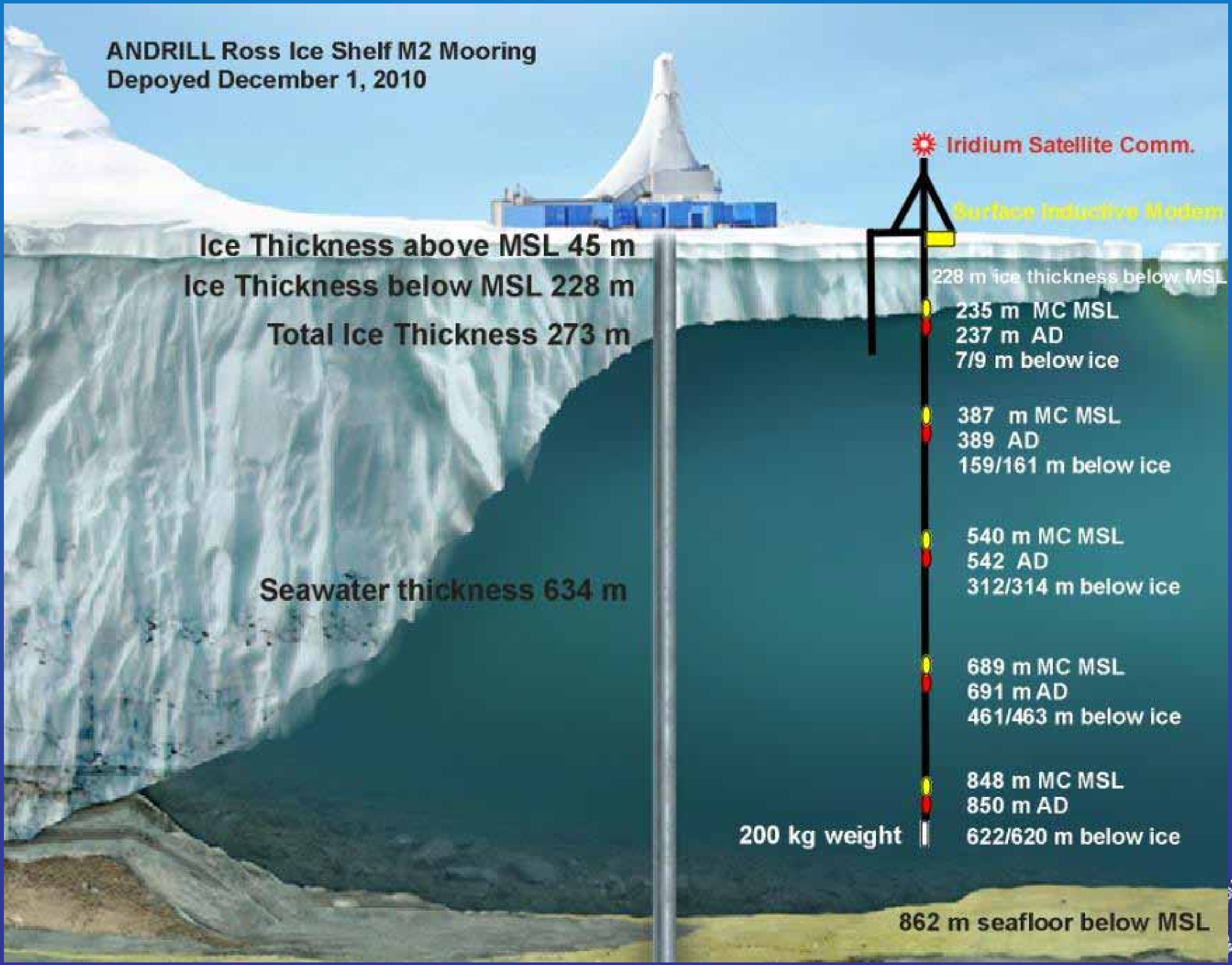




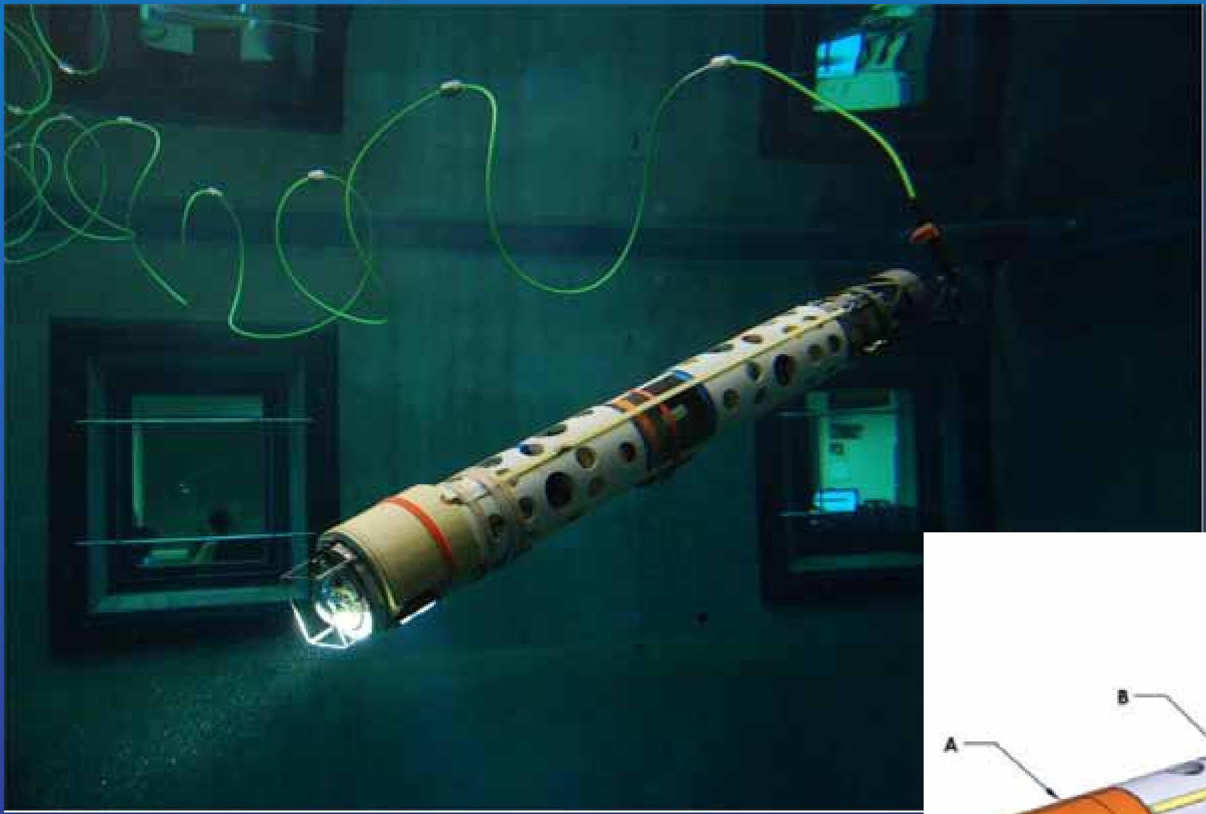
For through-ice-shelf deployment via ~70-75 cm bore holes.
Max diameter 55 cm in “folded” configuration.
Unfolds into ROV configuration.
Under development. 1500 m.
Missions: Optical imaging, acoustic imaging, PO,

Vogel et al. (2008), "Subglacial environment exploration – concept and technological challenges for the development and operation of a Sub-Ice ROVer (SIR) and advanced sub-ice instrumentation for short and long-term observations", In *Proceedings IEEE/OES Autonomous Underwater Vehicles*

SIR: Field Sites



Submersible Capable of under Ice Navigation and Imaging (SCINI)



15 cm diameter for deployment through 20 cm holes drilled in sea ice.
300 m depth rated.

Missions: Optical imaging, acoustic imaging, and PO.

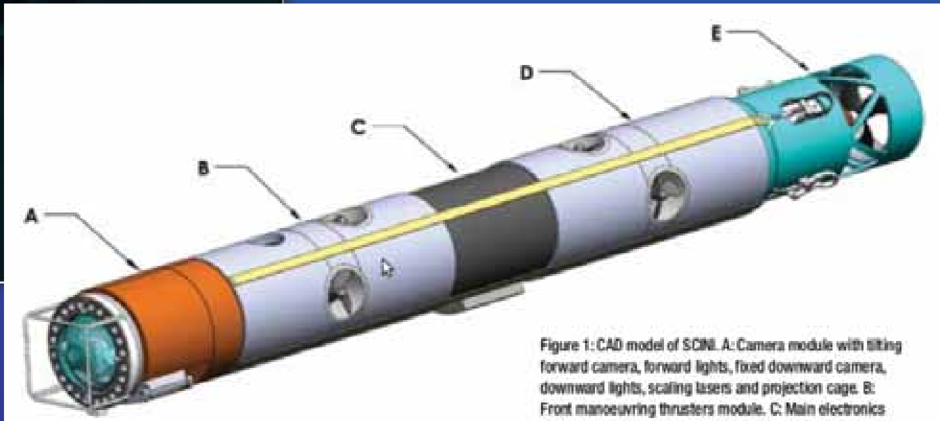


Figure 1: CAD model of SCINI. A: Camera module with tilting forward camera, forward lights, fixed downward camera, downward lights, scaling lasers and projection cage. B: Front manoeuvring thrusters module. C: Main electronics housing. D: Rear manoeuvring thrusters module. E: Main thruster module and tether attachment point. Length 140 cm, diameter 15 cm, weight 18.5 kg.

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology

SCINI: Logistics

Figure 12: Walking to the survey site from the Becker point field camp. The entire SCINI ROV setup weights less than 350 kg and can be person-hauled by three or more people, on two sledges.

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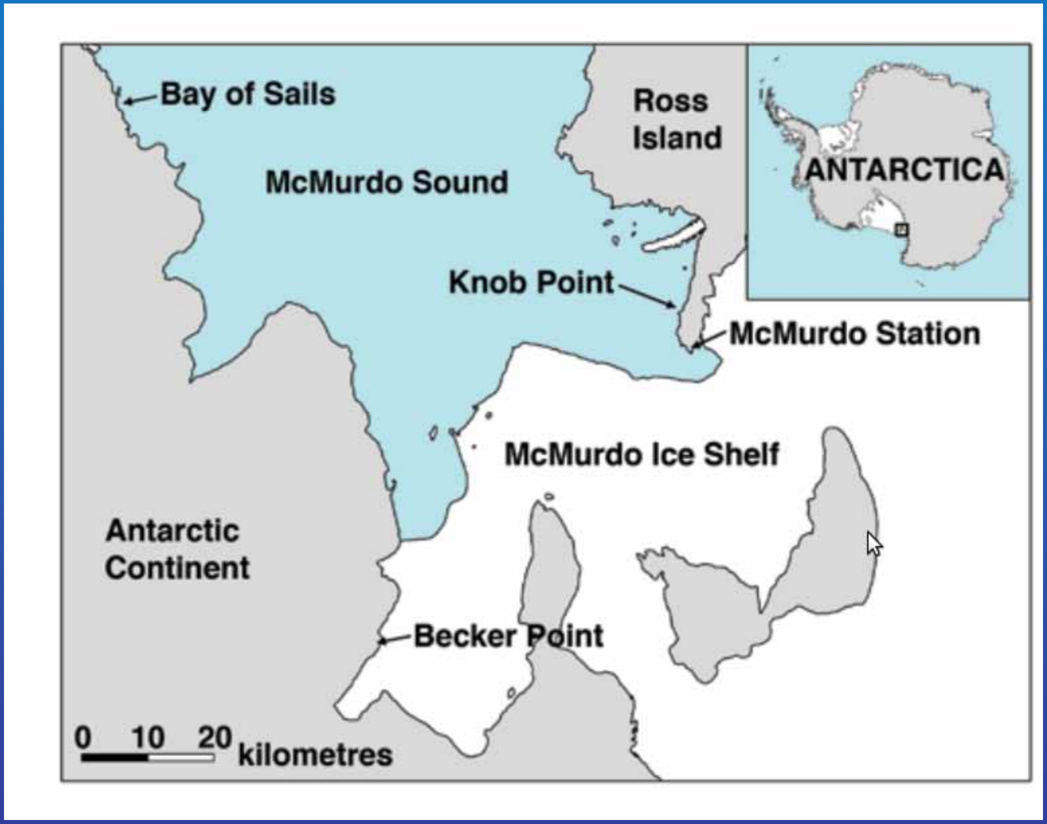
Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology

SCINI: McMurdo Sound



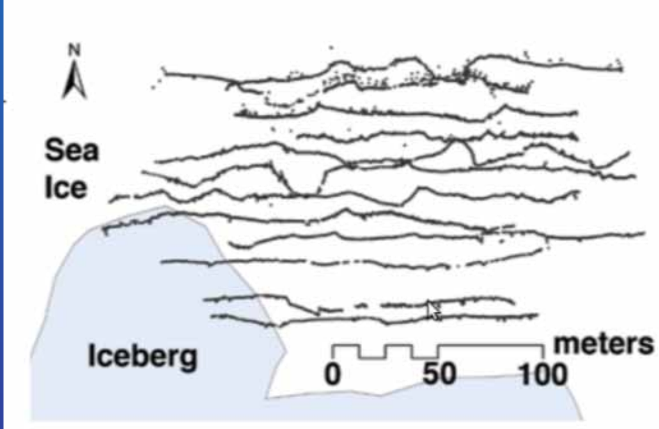
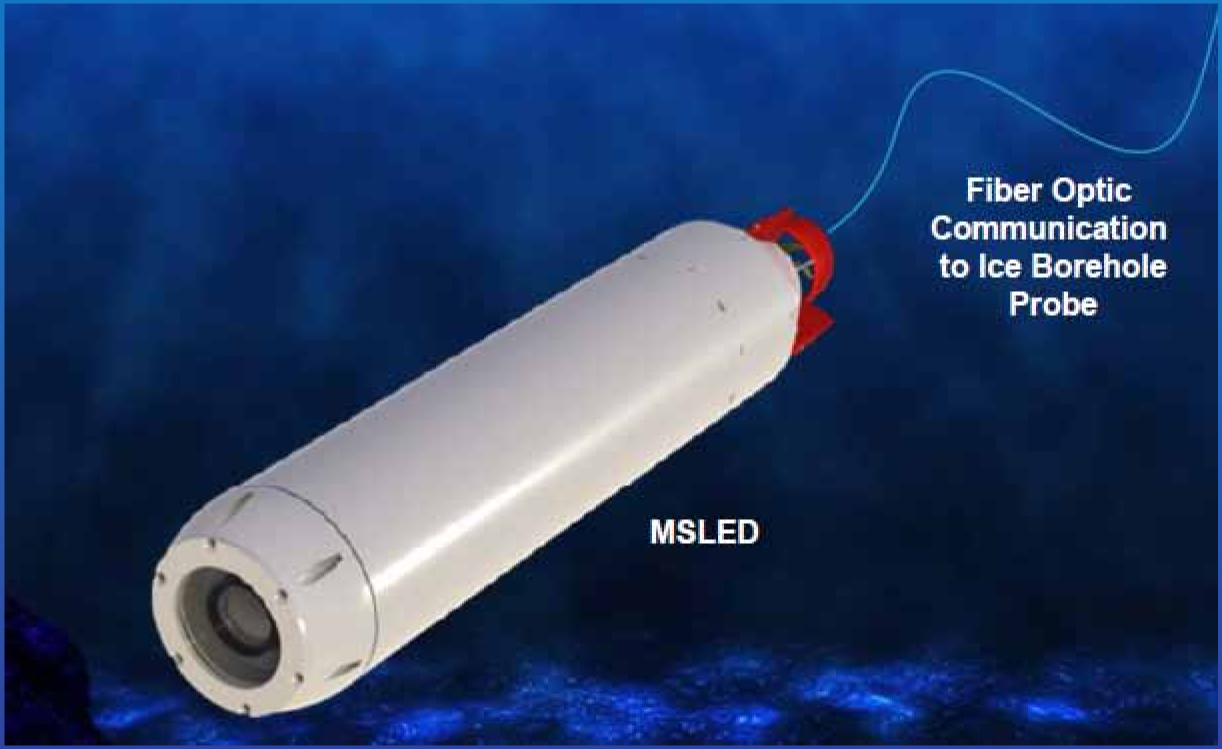


Figure 11: The ROV navigation tracklines from transects surveying the seafloor disturbance near one iceberg in Bay of Sails. Dots off the transect lines indicate bad navigation returns, demonstrating the importance of frequent returns to successfully maintain heading. Iceberg outline at sea ice level was obtained with a handheld GPS unit. The depth of the transects was between 30 m and 38 m.

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology

Micro-Subglacial Lake Exploration Device (MSLED)

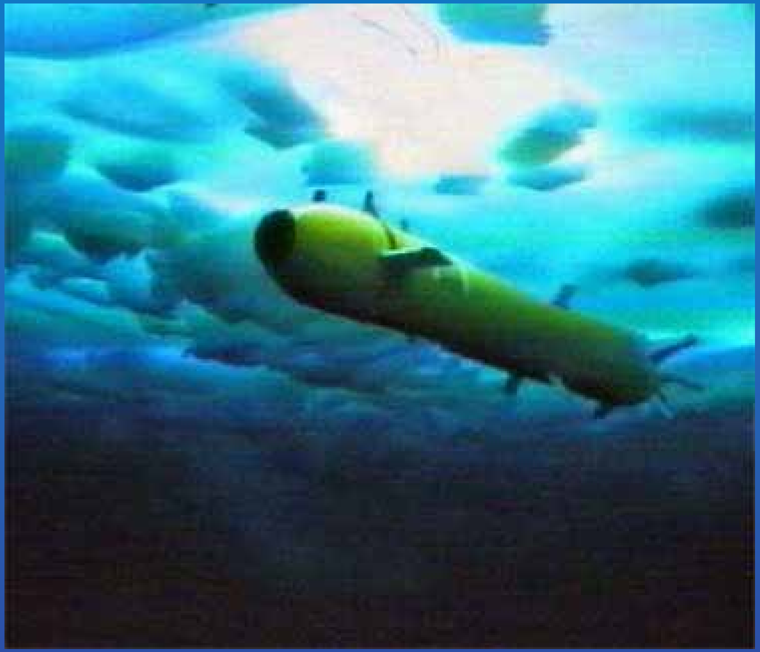


8 cm x 70 cm for deployment through bore holes drilled in ice.
1,500 m depth rated.
Camera, CTD
Fiber-optic tether
2 hour endurance

Missions: Optical imaging and PO.

A. Behar (2011) Micro Subglacial Lake Exploration Device (MSLED). Eighteenth Annual West Antartic Ice Sheet Initiative (WAIS) Workshop, 2011

Theseus AUV



1.27 m x 10 m for long-endurance fiber-optic cable deployment.
8,000 kg
1,300+ km range
2,000 m depth rated.

Fiber-optic tether deployment.

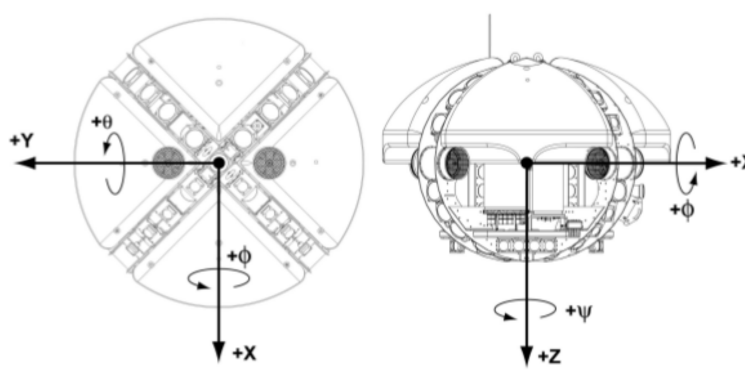
More recent versions of Theseus developed by ISE for Canadian UNCLOS Arctic bathymetric survey operations.

J. Ferguson et. Al. (1999), Theseus AUV-two record breaking mission, Sea Technology (40)2:65-70, 1999.

Stone Aerospace *Endurance*

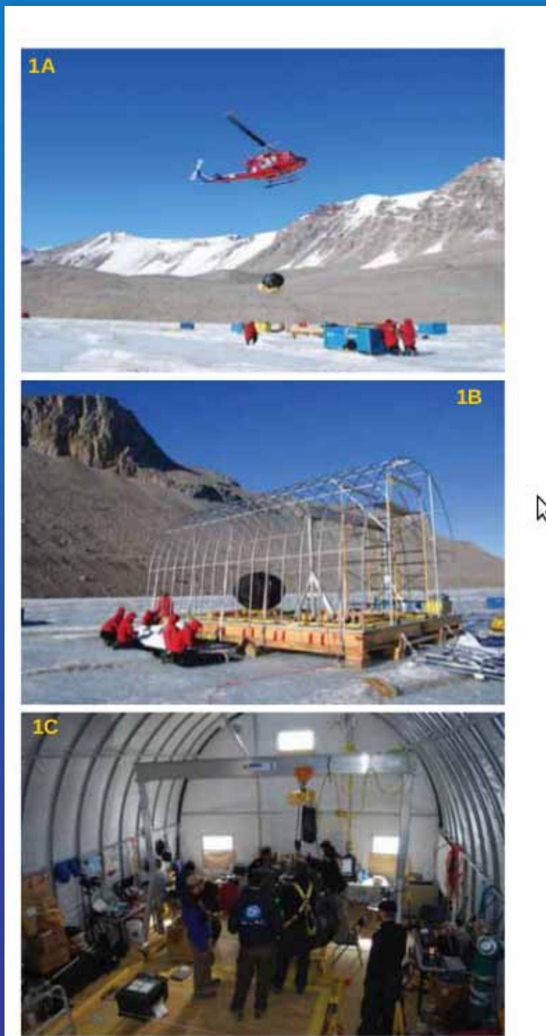
Table 1: ENDURANCE vehicle specifications

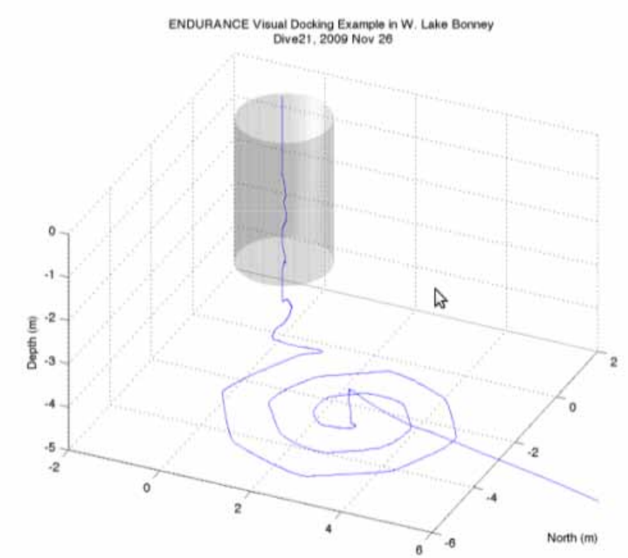
Dimensions	Ellipsoid major axis (diameter): 2.13 m Ellipsoid minor axis (height): 1.52 m
Mass	1.3 t including science payload
Depth rating	1000 m (excluding payload)
Onboard power	2 × 2.5 kW h lithium-ion rechargeable battery packs
Thrust	6 electric thrusters @ 110 N nominal thrust
Service range	5 km
Maximum transit speed	0.3 m/s
Cruise speed	0.24 m/s
Onboard instrumentation	Honeywell inertial measurement unit (IMU) RDI Doppler velocity log (DVL) 2 Paroscientific pressure depth sensors 32 Imagenex 100 m sonars 24 Imagenex 200 m sonars Imagenex DeltaT multi-beam sonar Sonardyne inverted ultra-short baseline (USBL) transceiver

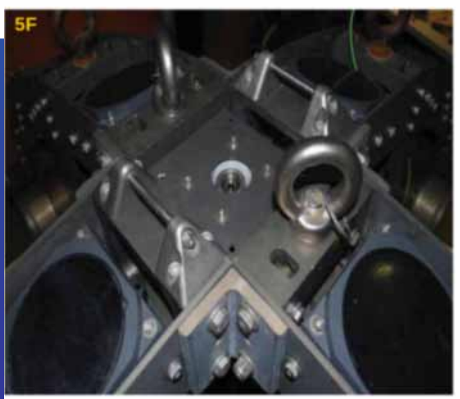


Richmond et al. (2011), “Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project”, UUST’11

Stone Aerospace *Endurance*



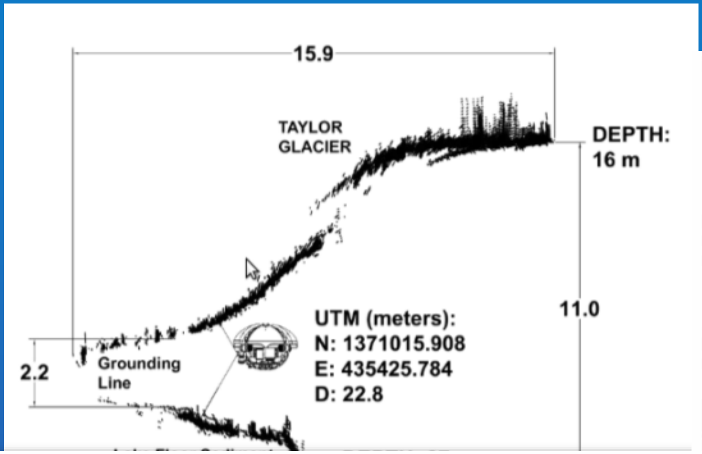


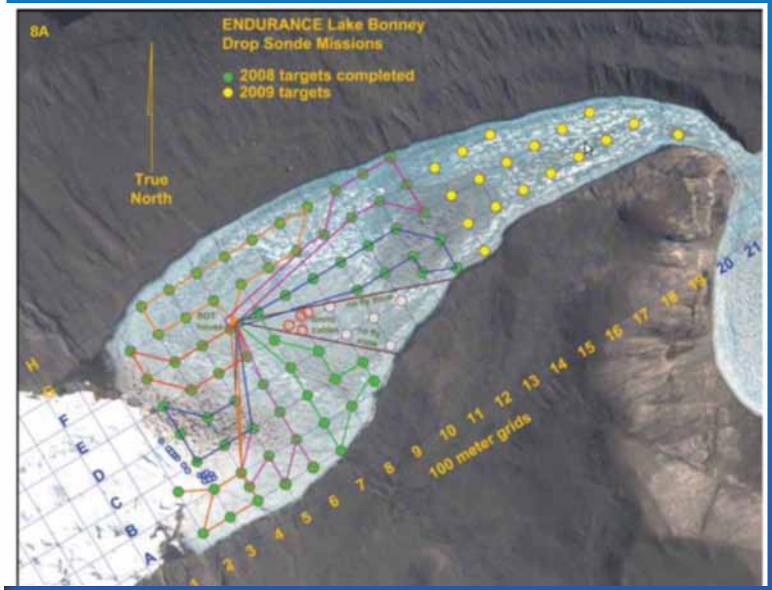


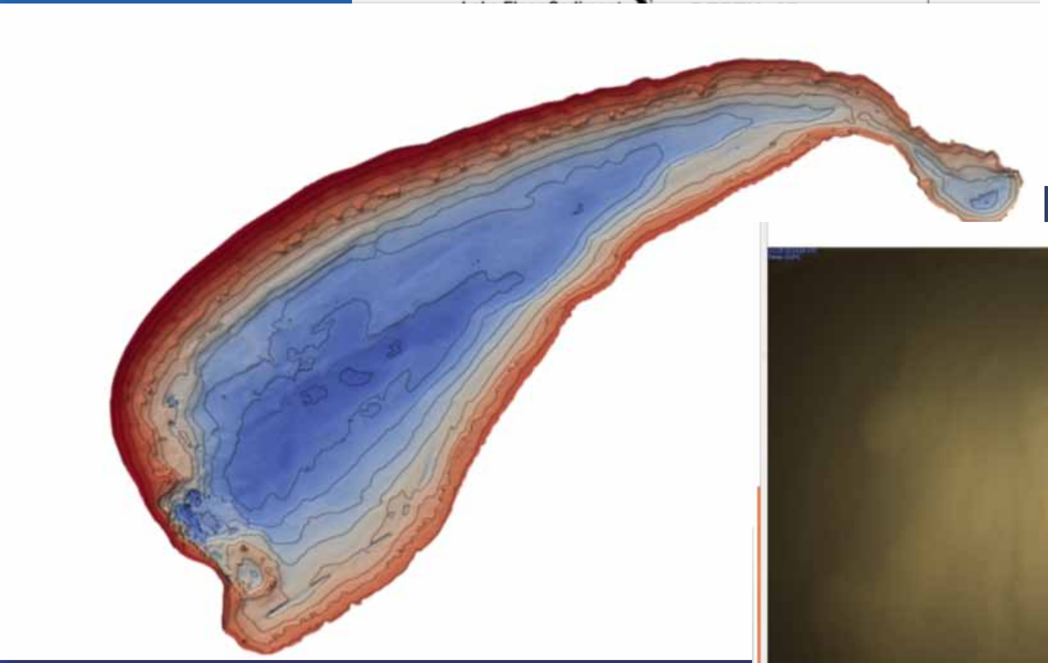
Stone et al. (2009), "Sub-ice exploration of West Lake Bonney: Endurance 2008 mission," In Proceedings UUST'09.

Richmond et al. (2011), “Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project”, UUST’11,.

Stone Aerospace *Endurance*







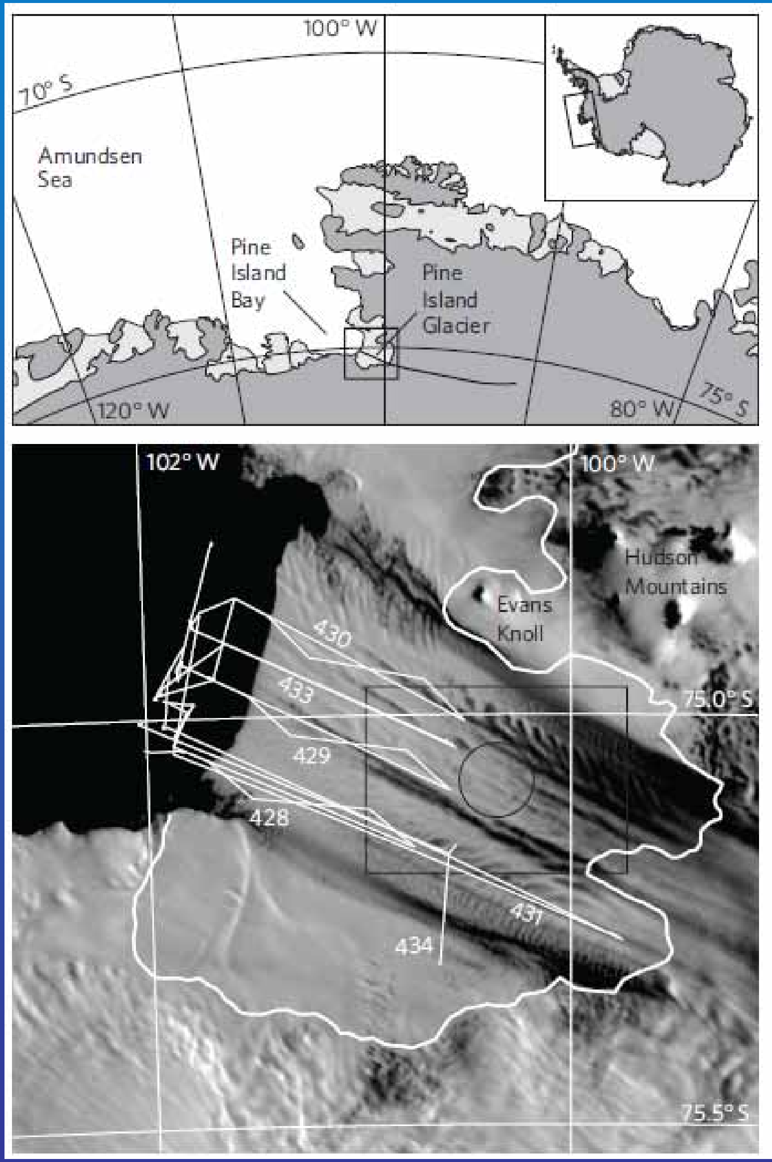
Richmond et al. (2011), "Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project", UUST'11.

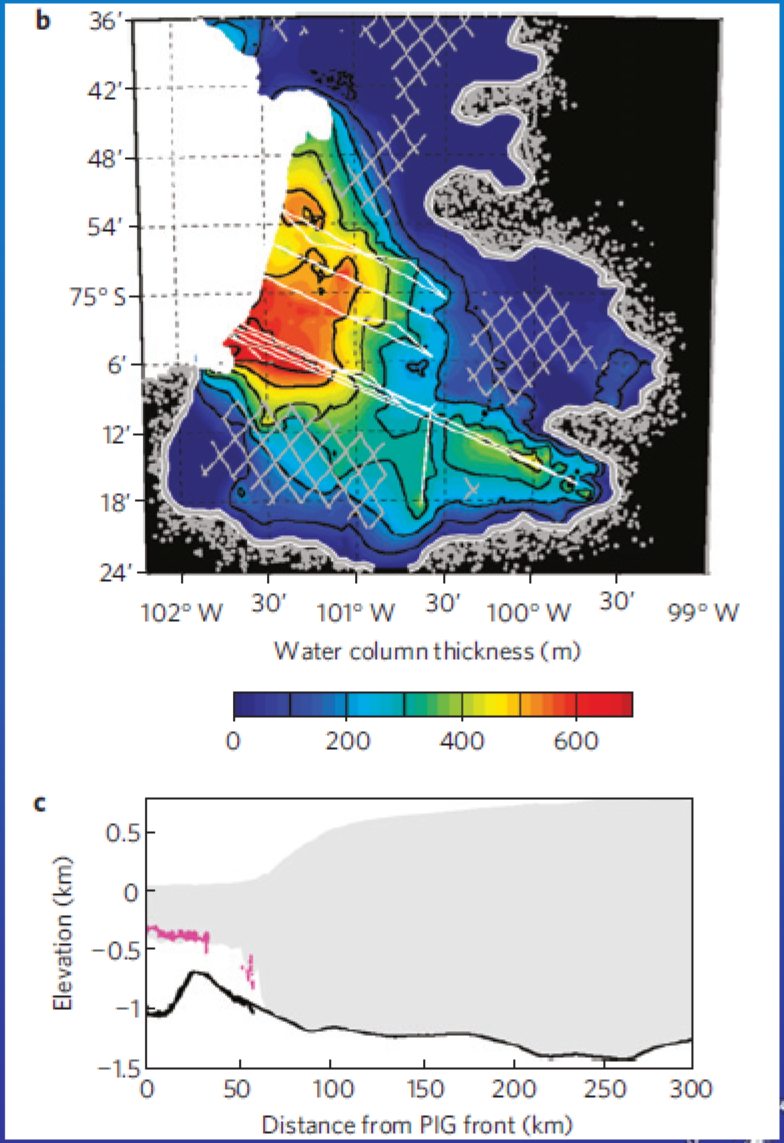
Autosub 3

400 km range
1,600 m depth
7 m x 1 m
3000 kg
Missions: Acoustic survey and PO survey.

Jenkens et al. (2010), “Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat”, Nature Geoscience, June 2010.

Autosub 3





Jenkens et al. (2010), “Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat”, Nature Geoscience, June 2010. (Results of January 2009 operations from R/V N. B. Palmer)

Ice Cold Unit for Biological Exploration (IceCube) ROV

Modified Deep Ocean Engineering Phantom S2 – 450 m depth rated, 100 kg

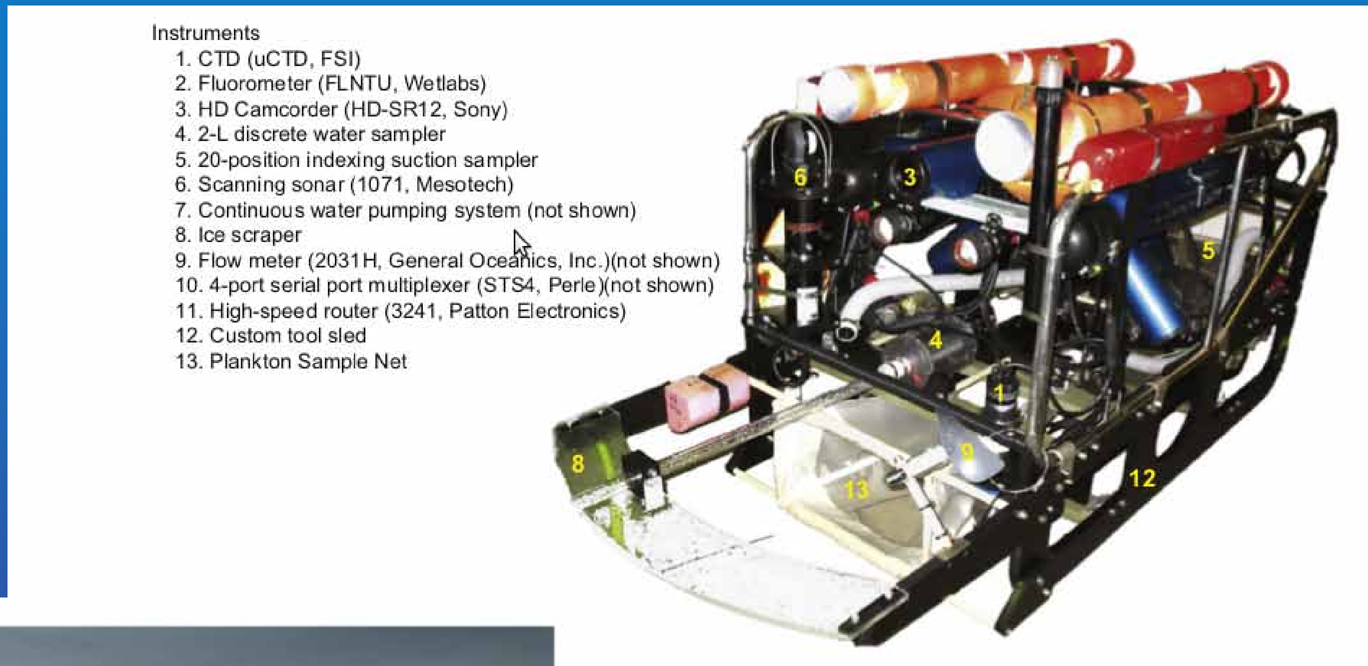


Fig. 2. Partial view of the tabular iceberg C-18a investigated by the ROV in 2009. Photo credit: Rob Sherlock.

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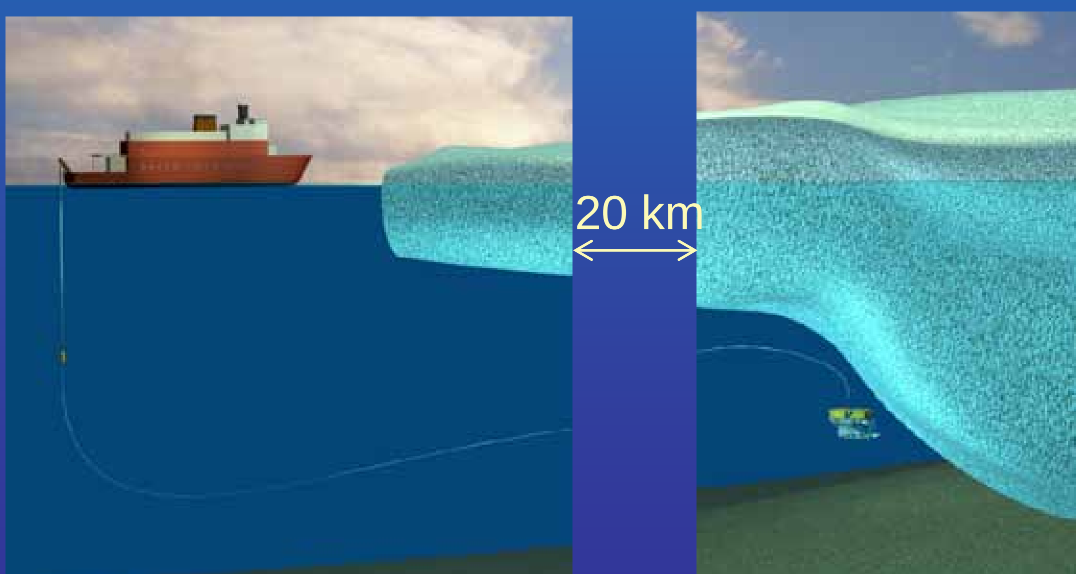
PROV Concept of Operations

Mission:

• Penetrate under **fixed ice** up to 20 km as a tethered vehicle while supporting sensing and sampling in close proximity to the under-ice surface

• Return safely to the ship



Notional Concept of Operations:

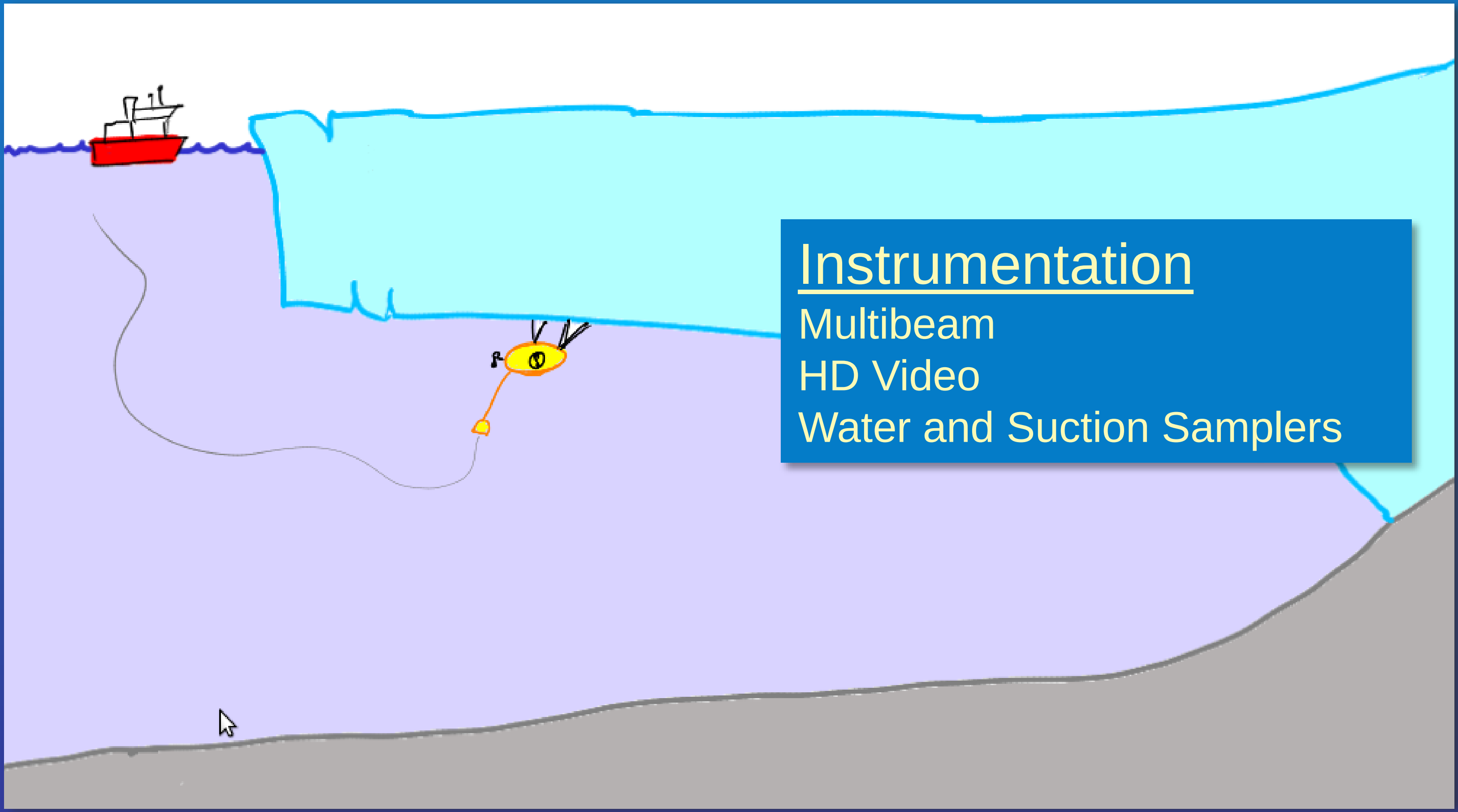
• Install acoustic Nav/Comms as required near ice-edge

• Deploy from vessel at ice edge as tethered system

• Transit to ice-edge and begin survey activities under-ice to the maximum range of the tether.

• Complete mission and return to the vessel as an AUV and recover onboard in open water

Use Case 1: Near-Ice Inspection and Mapping



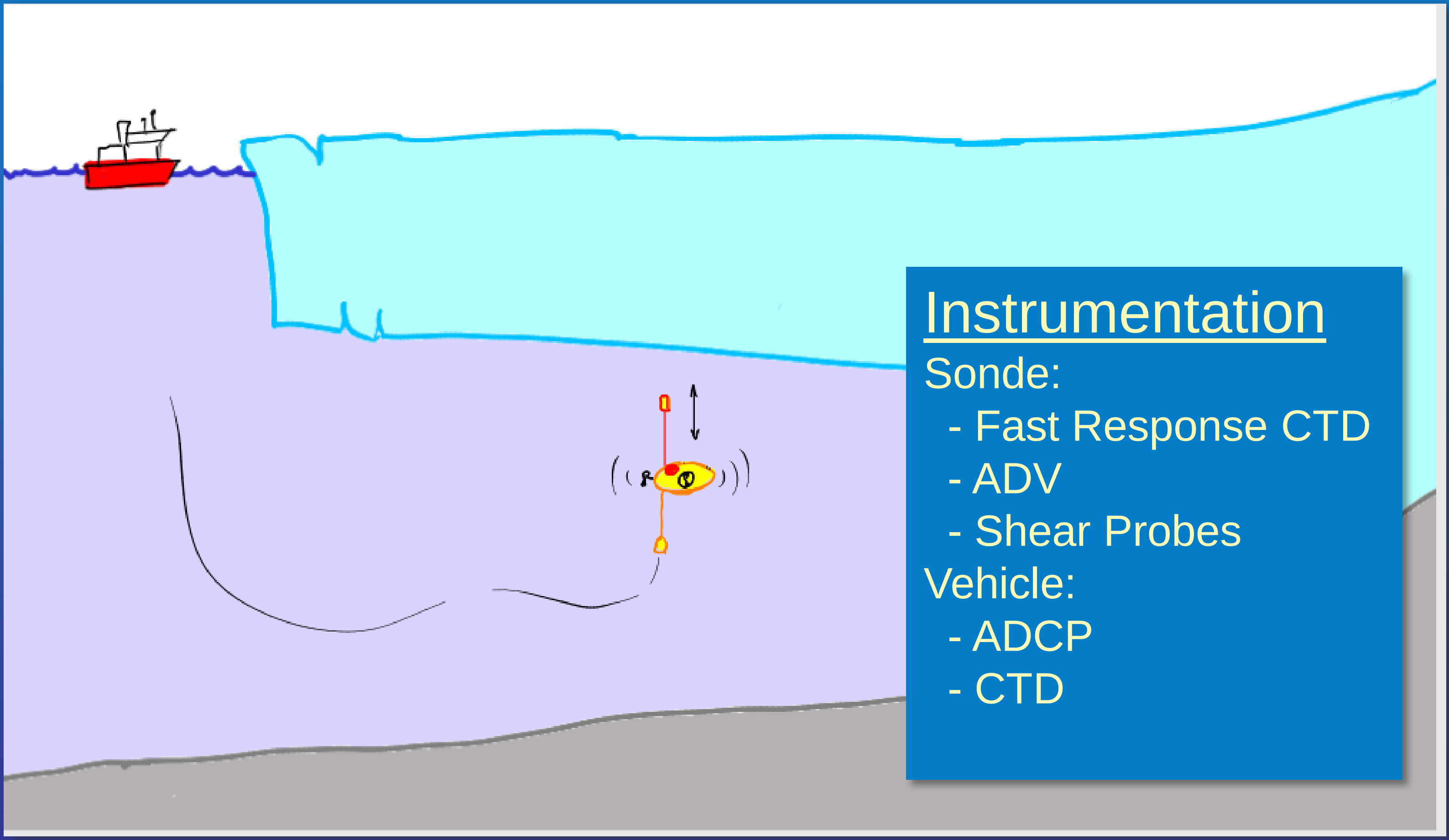
Instrumentation

Multibeam

HD Video

Water and Suction Samplers

Use Case 2: Boundary Layer Investigations

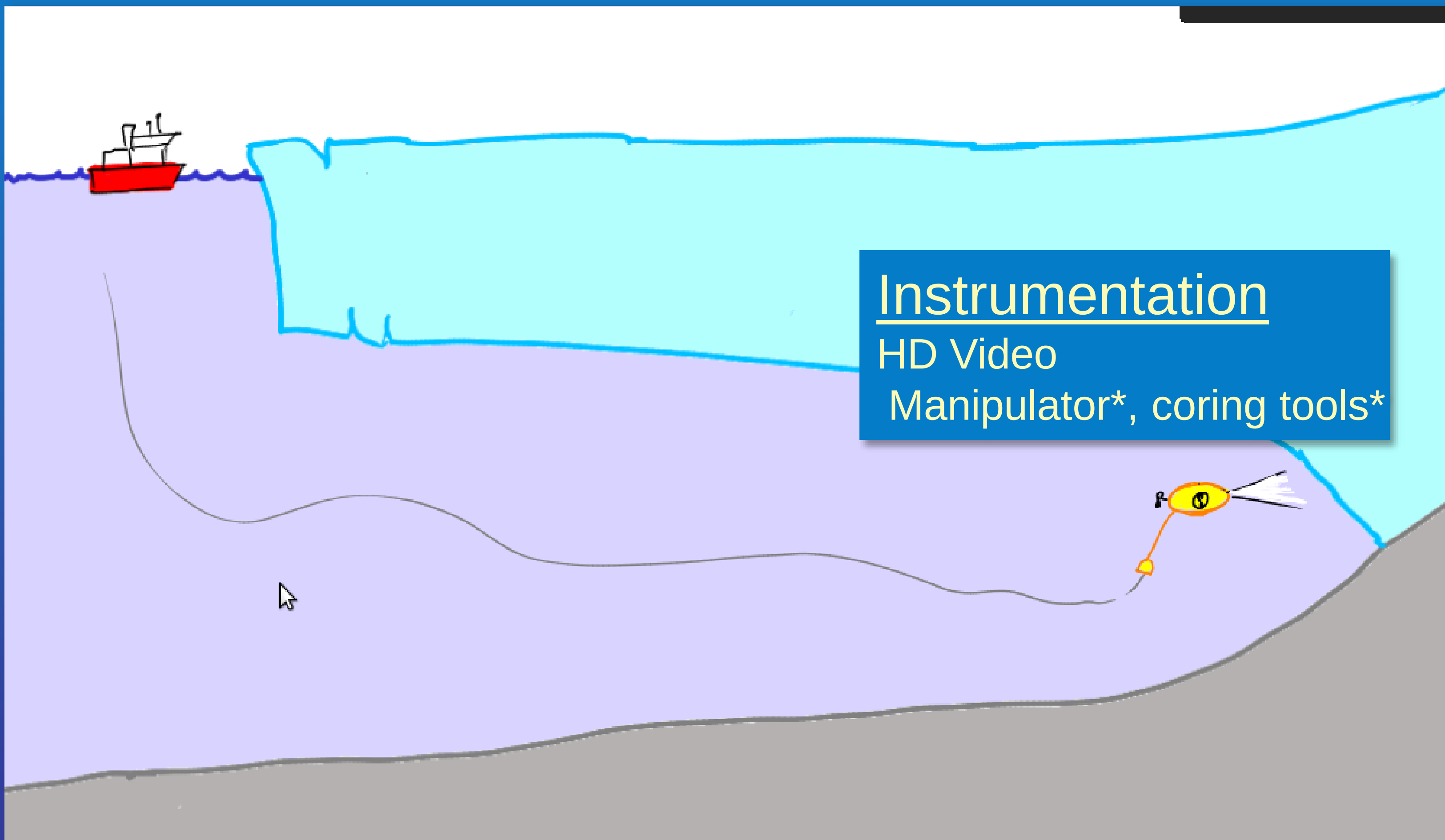


Instrumentation

Sonde:
- Fast Response CTD
- ADV
- Shear Probes

Vehicle:
- ADCP
- CTD

Use Case 3: Grounding Line Inspection

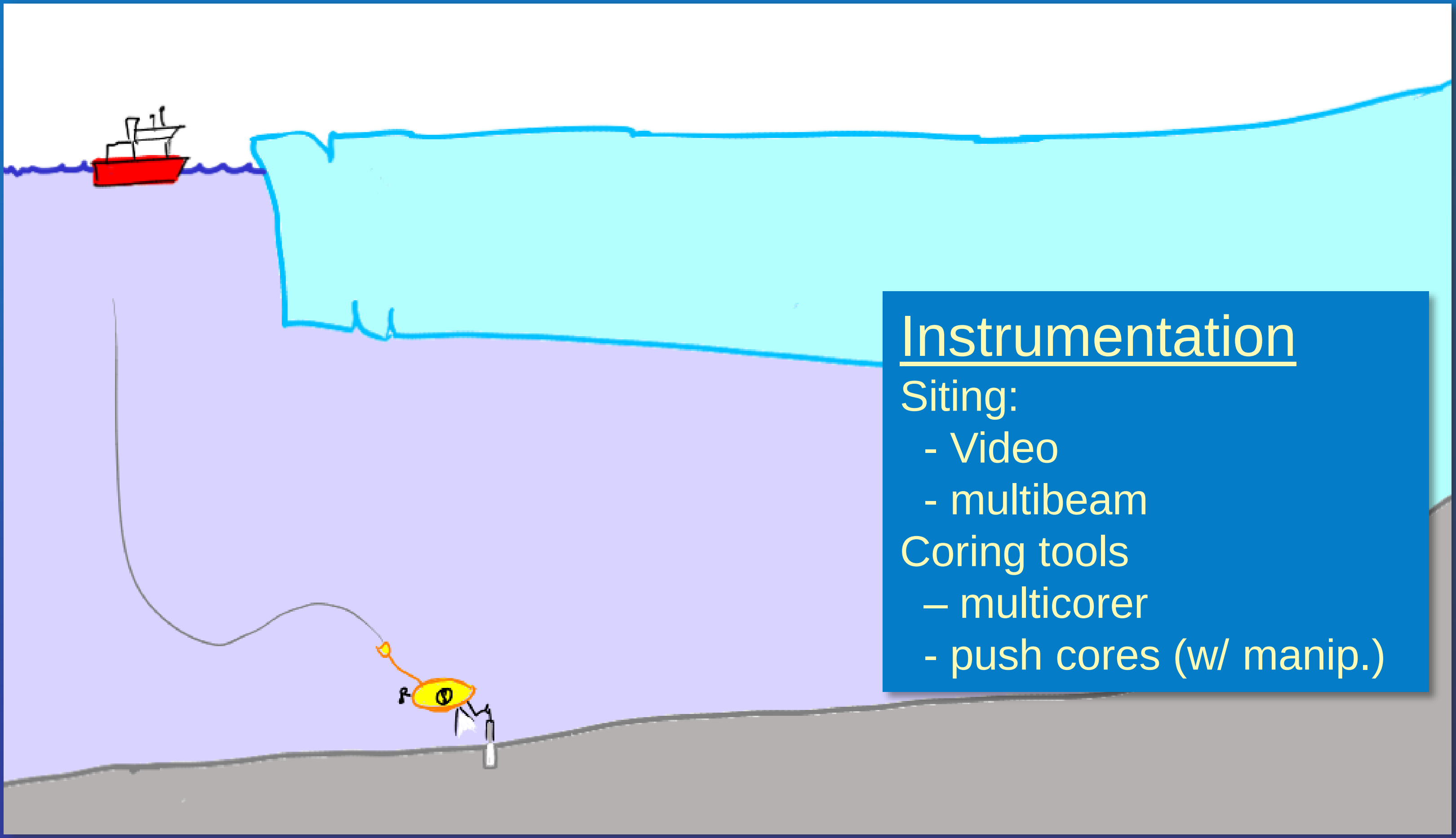


Instrumentation

HD Video

Manipulator*, coring tools*

Use Case 4: Sediment Sampling



<u>Instrumentation</u>

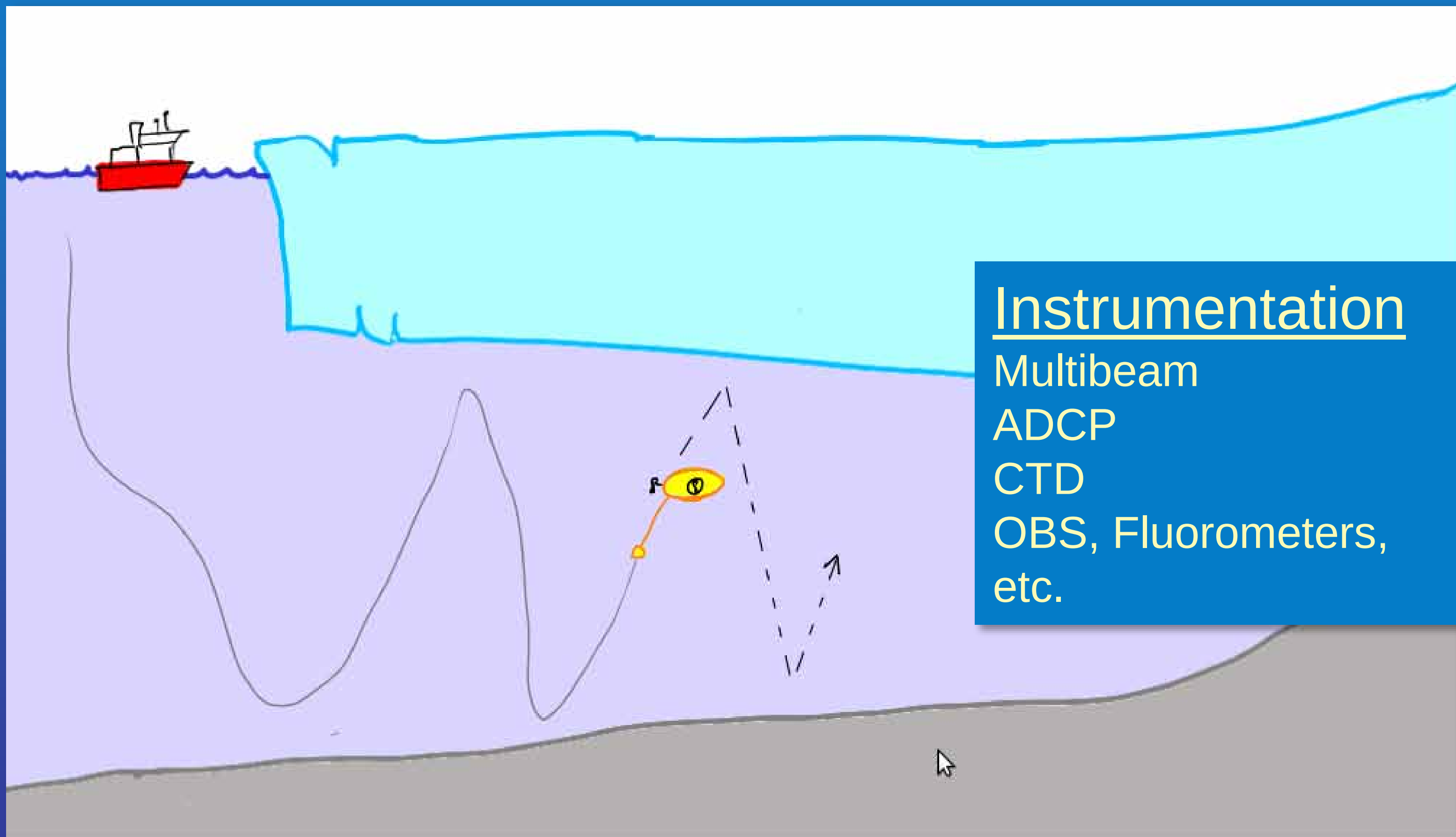
Siting:

- Video
- multibeam

Coring tools

- multicorer
- push cores (w/ manip.)

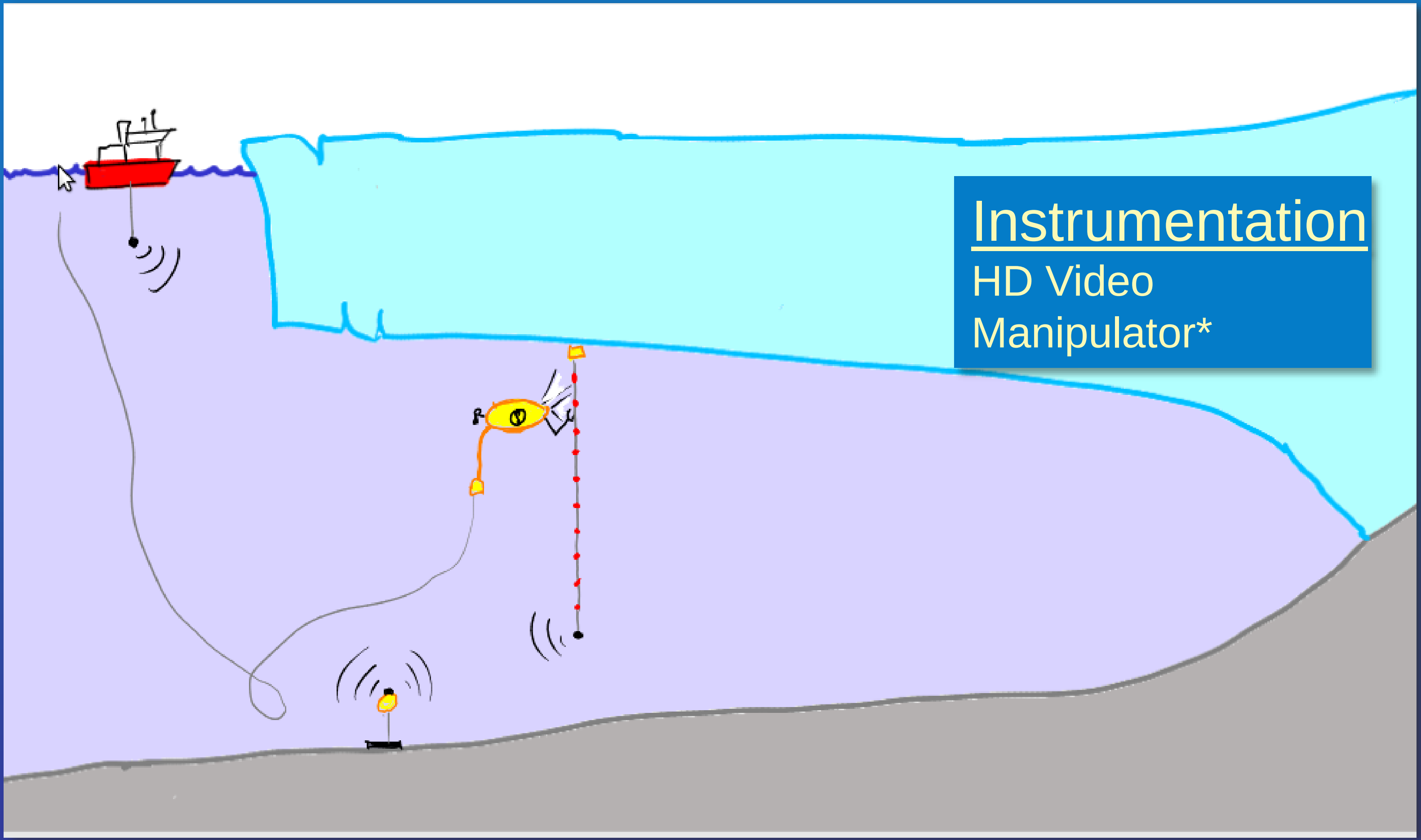
Use Case 5: Ice Shelf Cavity Physical Oceanographic Mapping



<u>Instrumentation</u>

Multibeam
ADCP
CTD
OBS, Fluorometers,
etc.

Use Case 6: InstrumentDeployment/Recovery *



Design Parameters

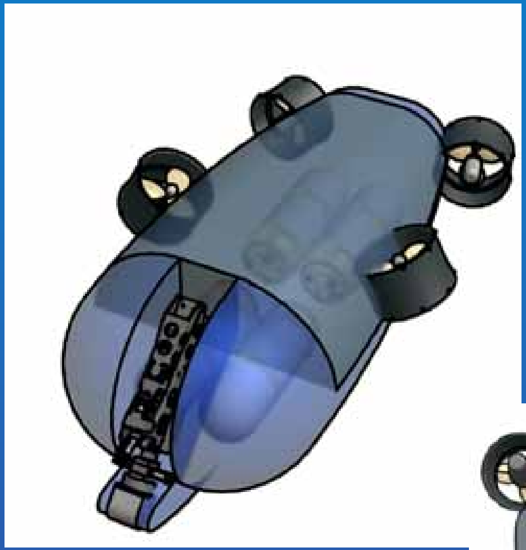
- Bathymetry -> Depth rating
- Ice Draft -> Maneuverability/Sensing
- Water column structure -> Need for, and capacity of VBS
- Circulation and Tides -> Minimum speed
- Sea-Ice and Sea State -> LaRS complexity
- Phenomena -> Special design considerations
- State of Knowledge -> Conservatism in design
- Logistics -> Special design considerations, field-planning

- Regions Studied:
  Antarctic Ice Shelves
  Greenland Glaciers
- Assumptions:
  Ship-based, open-water launch/recovery, sub-type for through-ice deployment

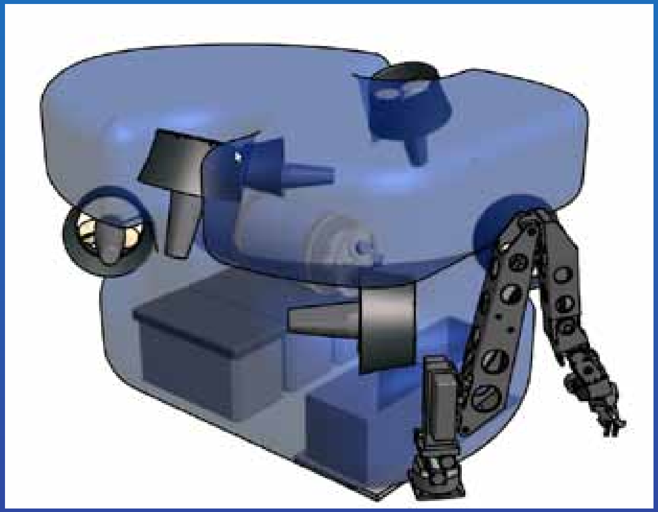
Design Constraints: Antarctica

- Bathymetry -> Depth rating: 2000 m
- Ice Draft -> Maneuverability/Sensing: mission-driven/??
- Water column structure -> Need for, and capacity of VBS: mission-driven, potential for creative solutions
- Circulation and Tides -> Minimum speed: 0.5 m/s
- Sea-Ice and Sea State -> LaRS complexity: simple, AUV-like
- Phenomena -> Special design considerations: minimize entrained volume, thermally couple as much as possible, detect ?, pre-launch washdown
- State of Knowledge -> Conservatism in design: reliability-driven
- Logistics -> Special design considerations: What can be learned from small, proxy vehicles?

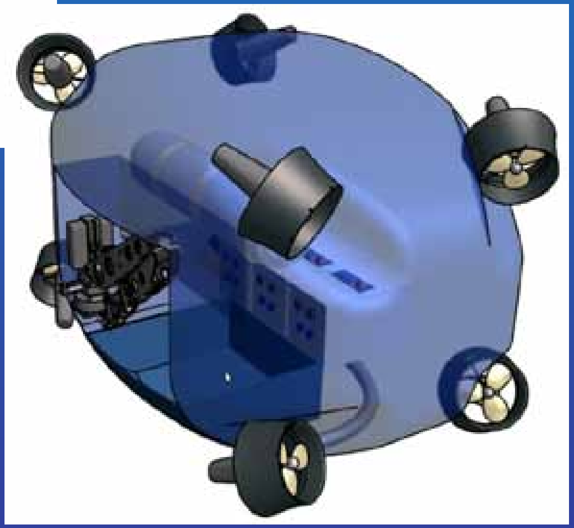
Concepts



Flatfish



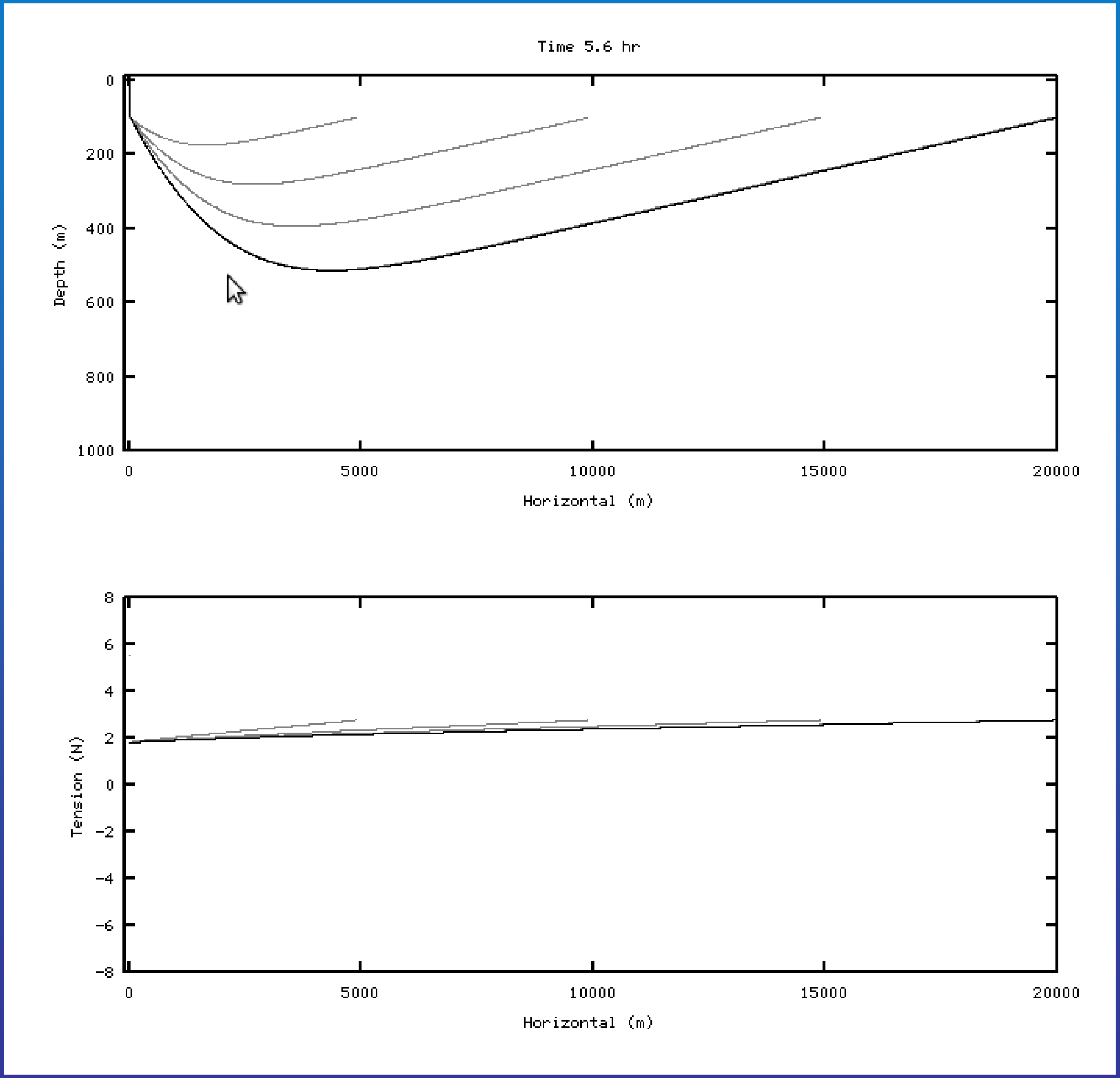
Conventional



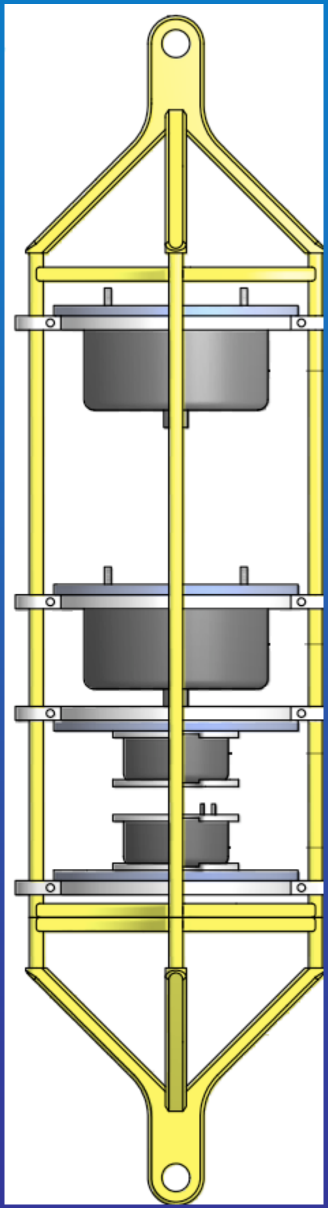
Crab

Specifications	Range	20 km horizontal excursion
	Air Weight	1800 kg
	Depth Rating	1000 m
	Battery	16 kWhr lithium-ion
Navigation	Inertial	Phins INS
	Acoustic	LF 1000 m range up/down altimetry; up/down ADCP/DVL; LF (3.5 kHz) homing; imaging sonar for obstacle avoidance
Communication	Tether	Fiber-optic Gb Ethernet, 20 km
	Acoustic	LF (3 kHz) 20-300 bps for ship to vehicle; HF (10-30 kHz) 300 bps for vehicle to sensor; vehicle to vehicle
Imaging	Acoustic	Reson 725 multibeam or Mesotech 675 profiling (upward-looking)
	Optical	Real-time color HD video; high resolution digital camera; LED lighting
Chemical/Physical Sensors		Seabird CTD; pH; micro-structure probes on deployable sonde
Biological Sensors		Optical backscatter; Photosynthetically Active Radiation (PAR); Chlorophyll; Turbidity; Dissolved Oxygen
Auxiliary payload allowance		20 kg; 500 Wh

Fiber Tether Sink-rate Simulation



Acoustic Communications and Navigation

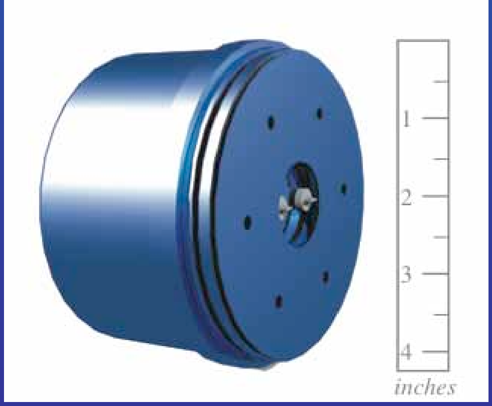


Short range, 10 kHz

- ITC 3013 (hemispherical coverage)
- Use for 5-8 km horizontal and similar for slant range in deep water, depending on propagation conditions.
- Data rate/efficiency 100-1000 bps, 4-40 bits per joule.

Long range, 3 kHz

- ITC 2002 (slight toroidal beam-pattern)
- Use for up to ~20 km, path dependent performance.
- Data rate/efficiency: ~50-100 bps, 2-4 bits per joule.



Supercooled Water and Frazil Ice

- Formed in supercooled water, 0.01-0.03 C below freezing: polynyas, water-layer interfaces, glacial interfaces, brinicles

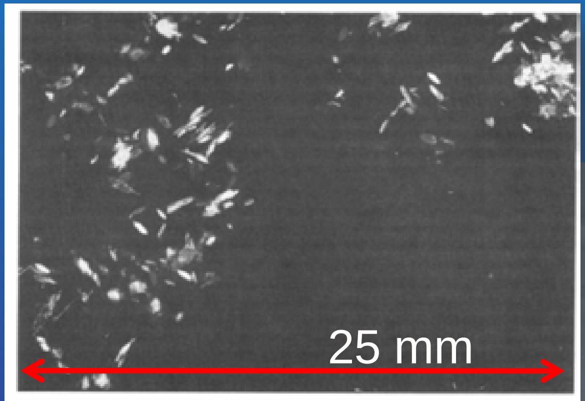


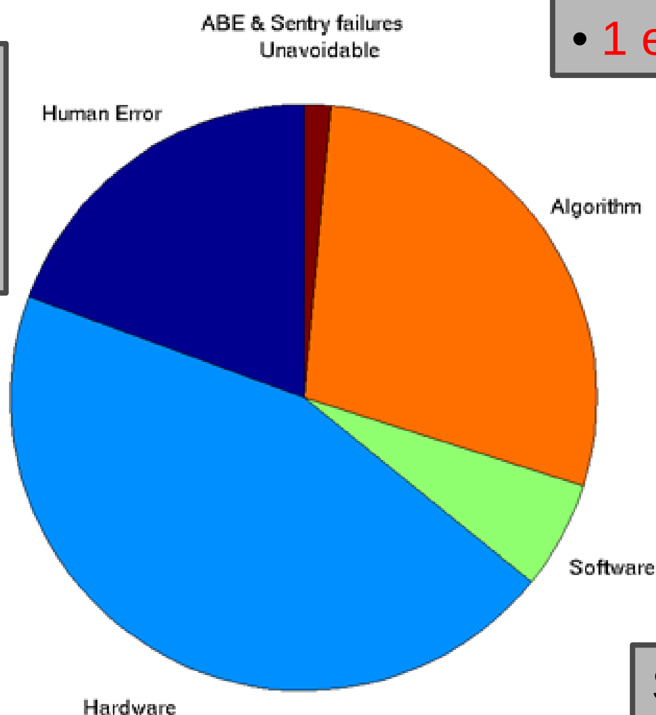
Figure 1 Photograph through crossed polaroids of a suspended solution of frazil-ice crystals; the photograph covers 25 mm in the vertical (from Martin & Kauffman 1981).

http://www.bbc.co.uk/nature/15835017

Design for Reliability/ Fault-Tolerant Control/Design

Photo courtesy S. McPhail, NOC

ABE and Sentry failures in 350 dives



Unavoidable
- 1 entanglement

Human error
- 3 setup
- 7 mission programming
- 2 incorrect ballast

Algorithm
- 5 bottom-following
- 9 abort process
- 5 lbl

Software
- 2 inadequately tested change
- 2 programming blunder

Hardware
- 4 lbl elec/acoustics
- 2 connector failure
- 2 faulty battery
- 7 release failure
- 13 (4) Thruster elec/mechanical
- 1 computer failure

23 FATAL UNDER ICE

Mobility/Autonomy Core

Nereid UI

Core

Auxiliary

Battery

Battery

Battery

Light-Tethered ROV

Core

Auxiliary

Battery

(trickle-charged)

Inspection-Class HROV

Core

Battery

. . .

Come-Home Capability

- Act upon loss of tether
- Timeout before Bailout
- Standown
- Home Acoustically
- Breadcrumbs
- Deadman Initiation
- Constant Depth
- Top-Follow
- Bottom-Follow
- Visualize Bailout
- Recall Election

Nereus References

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Conclusions

- More detailed exploration under permanent fixed ice will be enhanced by the Nereid Under Ice vehicle and lead to important new knowledge difficult to gather with autonomous systems having limited bandwidth communications
- Both operational and scientific techniques developed during this project should be of interest to those contemplating missions on other planets
- Teaming of human explorers to robotic tools over high bandwidth links promises most efficient of resources