Nuclear waste in the abyssal Atlantic

Deep ocean robots to investigate anthropic impacts

J. Escartín
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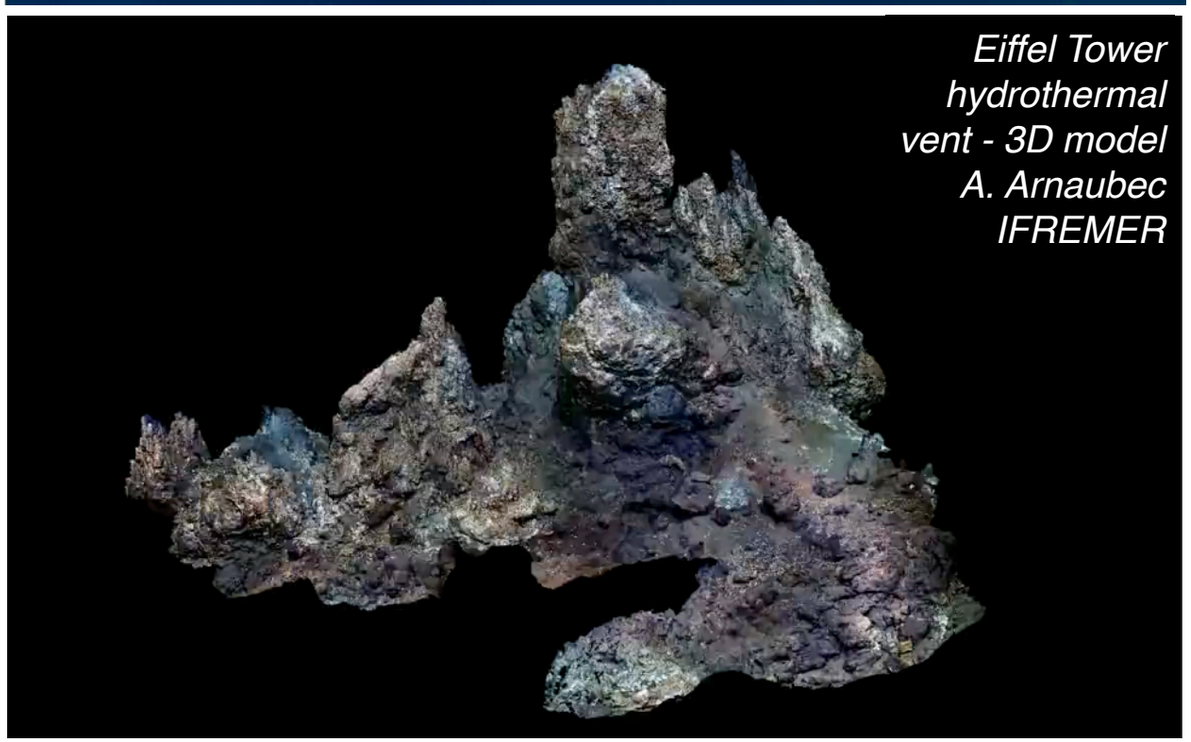
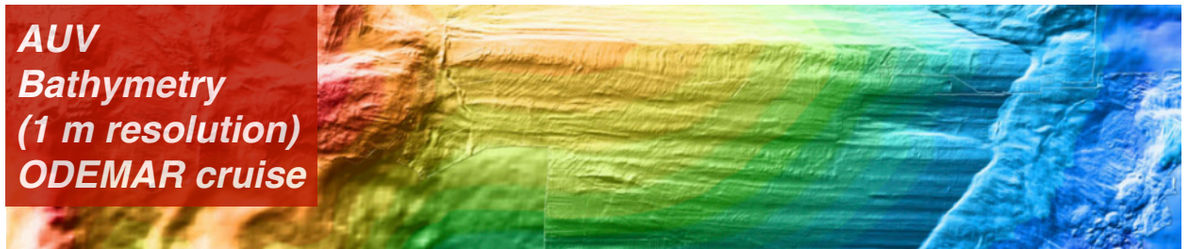
NODSSUM Project: IN2P3+INSU, IFREMER
co-PI: P. Chardon (IN2P3)

ROV VICTOR6000 IFREMER

AUV Ulyx6000 IFREMER



Eiffel Tower hydrothermal vent - 3D model A. Arnaubec IFREMER



AUV Bathymetry (1 m resolution) ODEMAR cruise

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Context on nuclear waste dump in the ocean

Knowledge gaps: need of deep-sea surveying

Status of seafloor mapping and imaging

Tools and capacities for deep-sea exploration

NODSSUM project

Scientific questions and objectives

Planned implementationioactive waste dump

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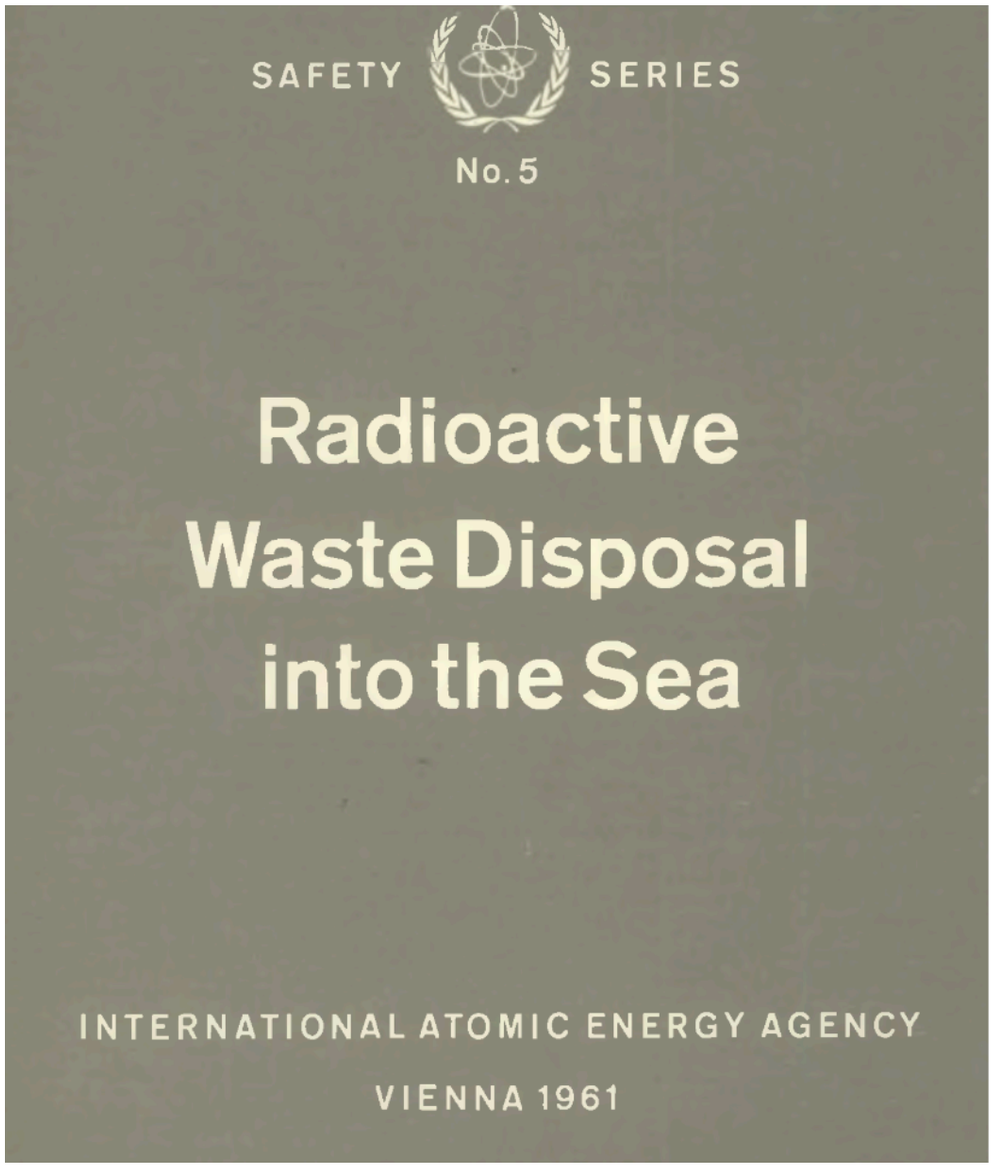
How to dispose of radioative waste?

The ocean as a long-term repository …

primarily for medium & low-level radioactive materials

Approach to a solution of the radioactive waste disposal problem

IAEA 1961 Report



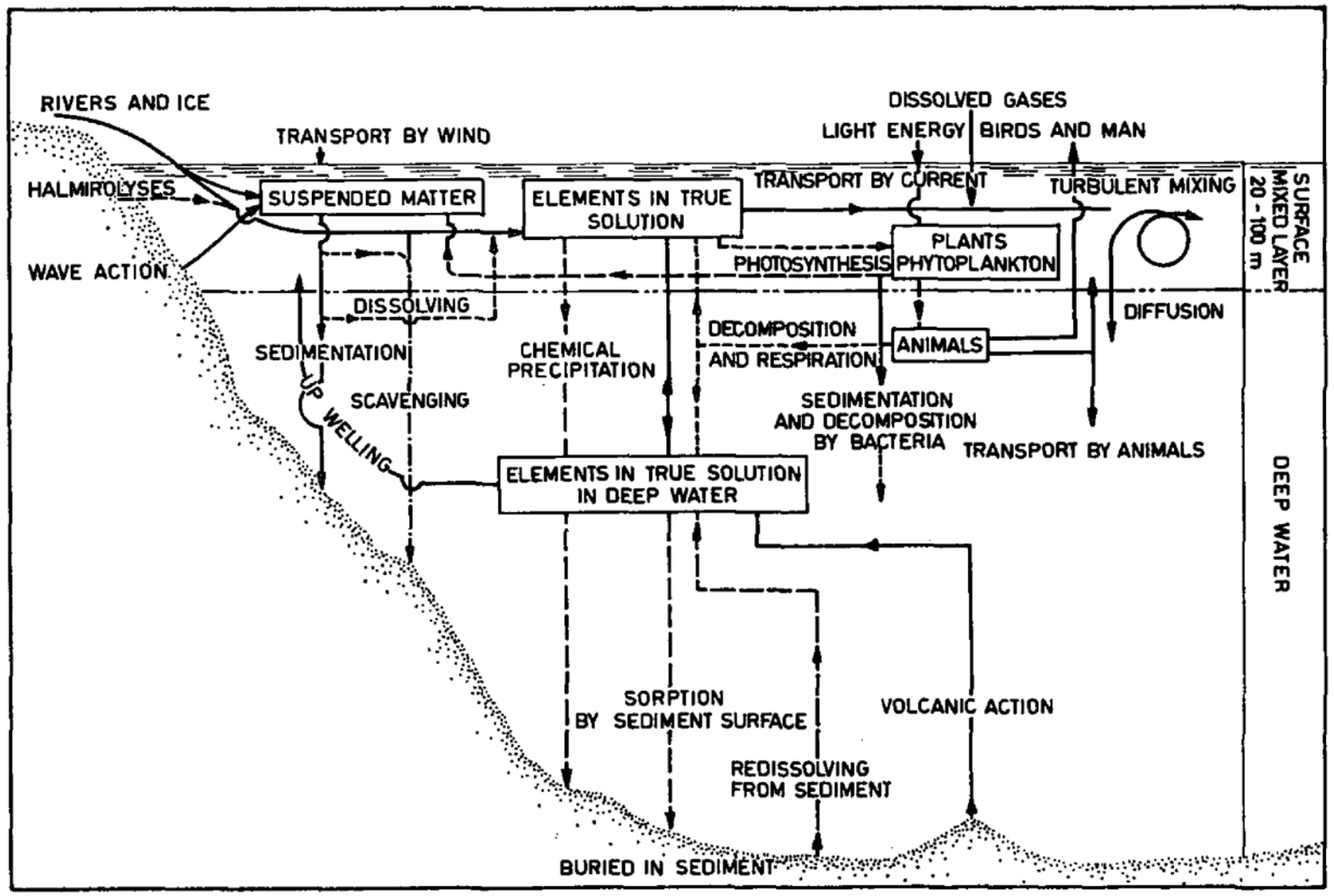


Fig. 3
Scheme of major physical and geological processes in the sea

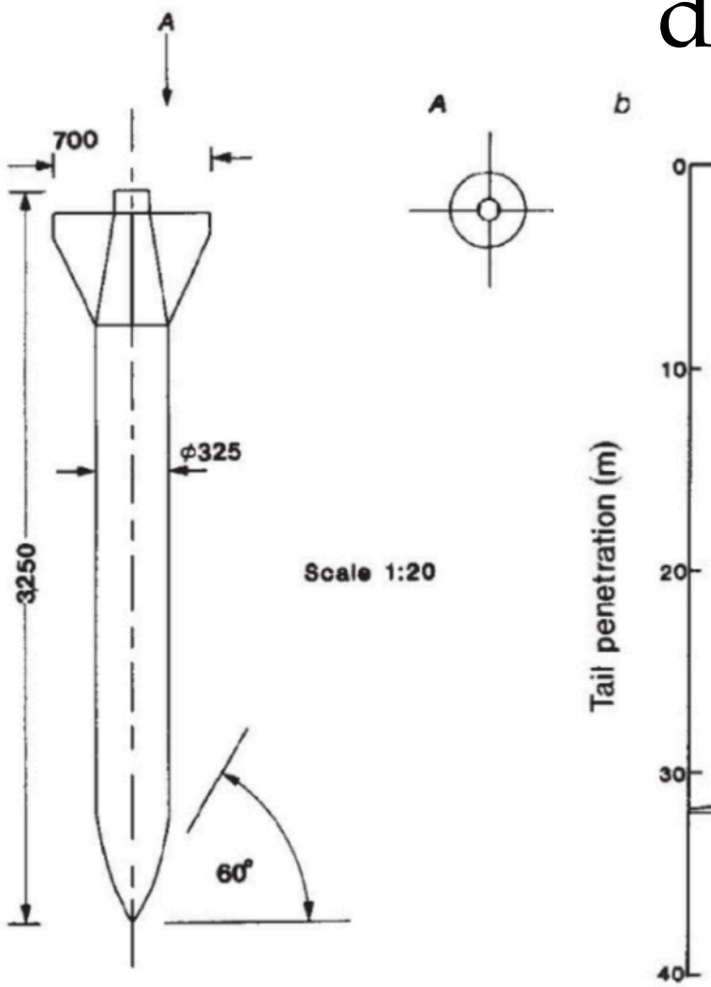
Physical (mainly dynamic) processes
Chemical processes
Biological processes
Combined processes

Science-based approach to evaluate risks and safety issues in the environment

Limited by understanding of processes (geological, chemical, biological) in the ocean

Basic lack of information about the deep ocean

Early years: ideas for radioactive waste disposal in deep ocean sediments



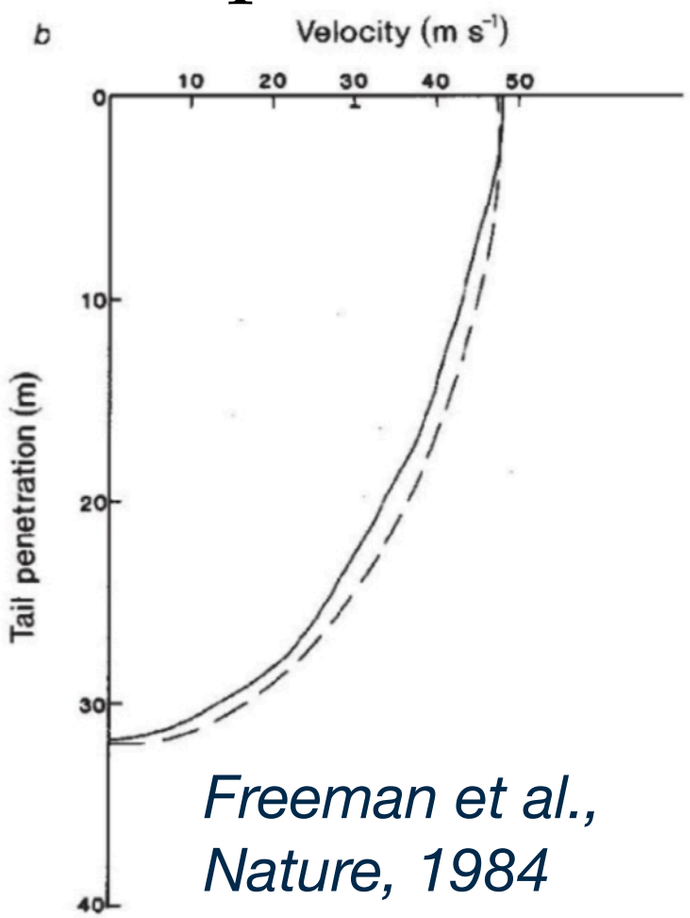
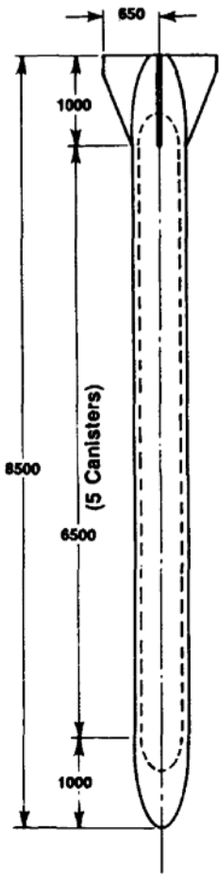
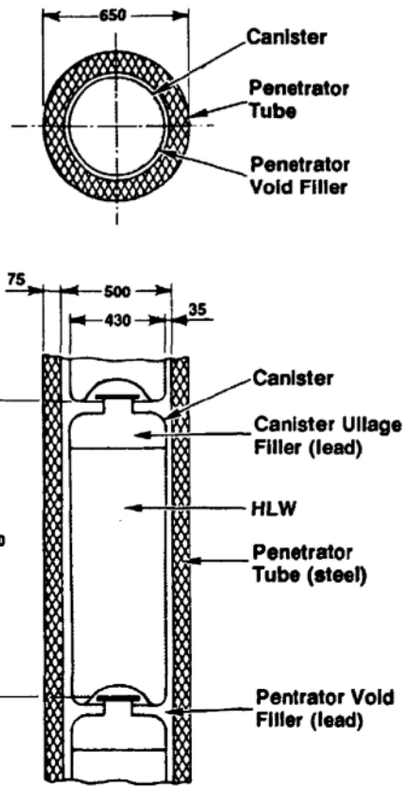


Fig. 2 The model penetrator used in the experiments.

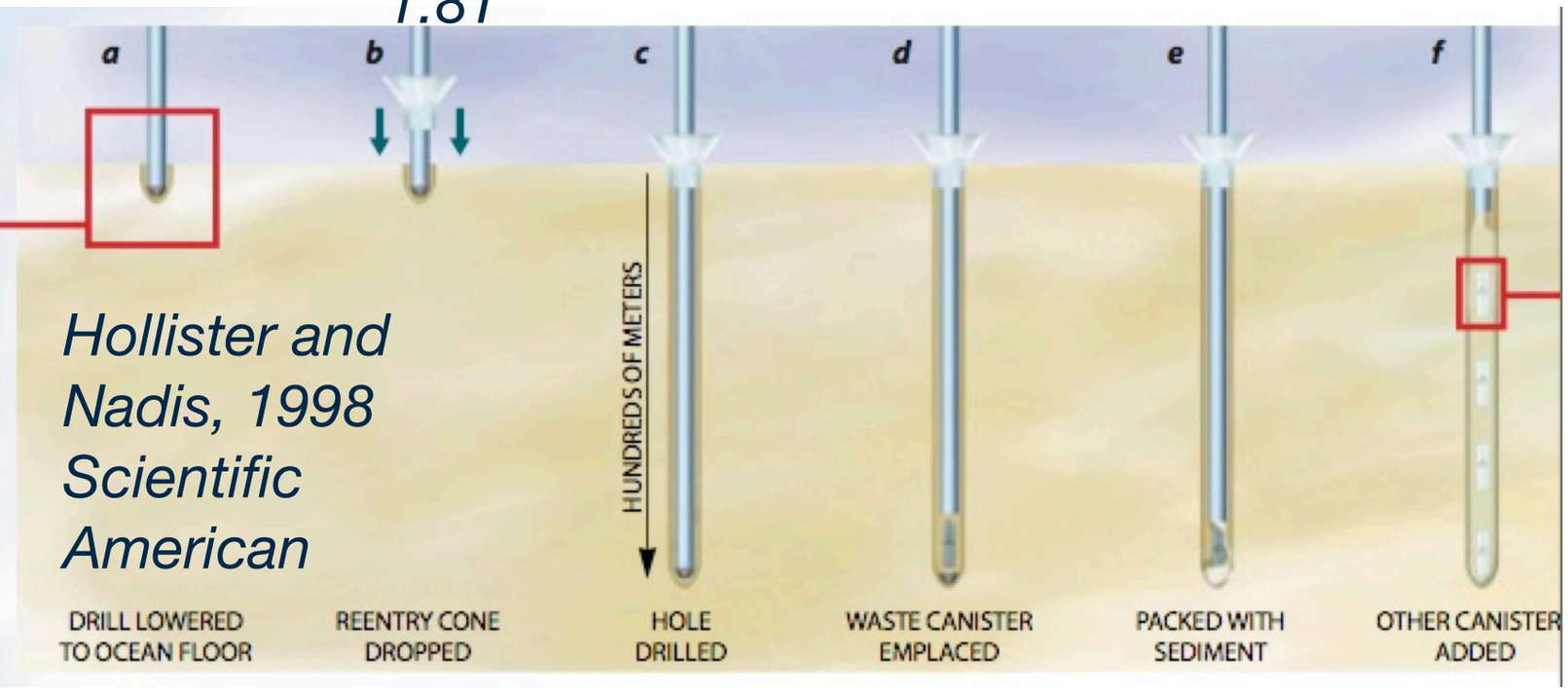
Freeman et al., Nature, 1984





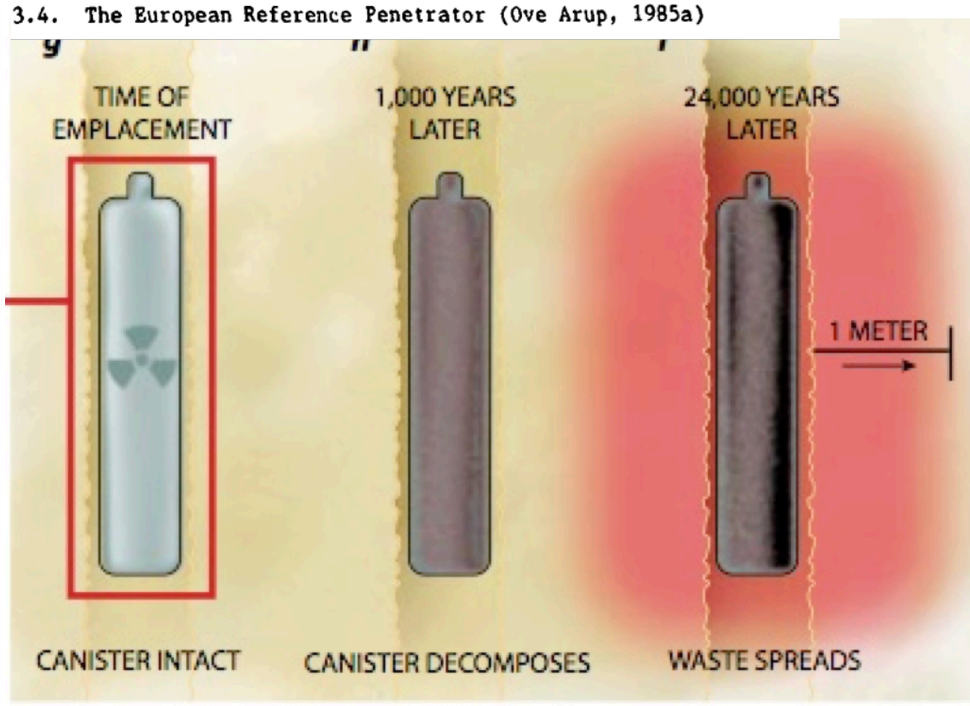
Total Weight = 18t
(Dimensions in mm)

1.8T

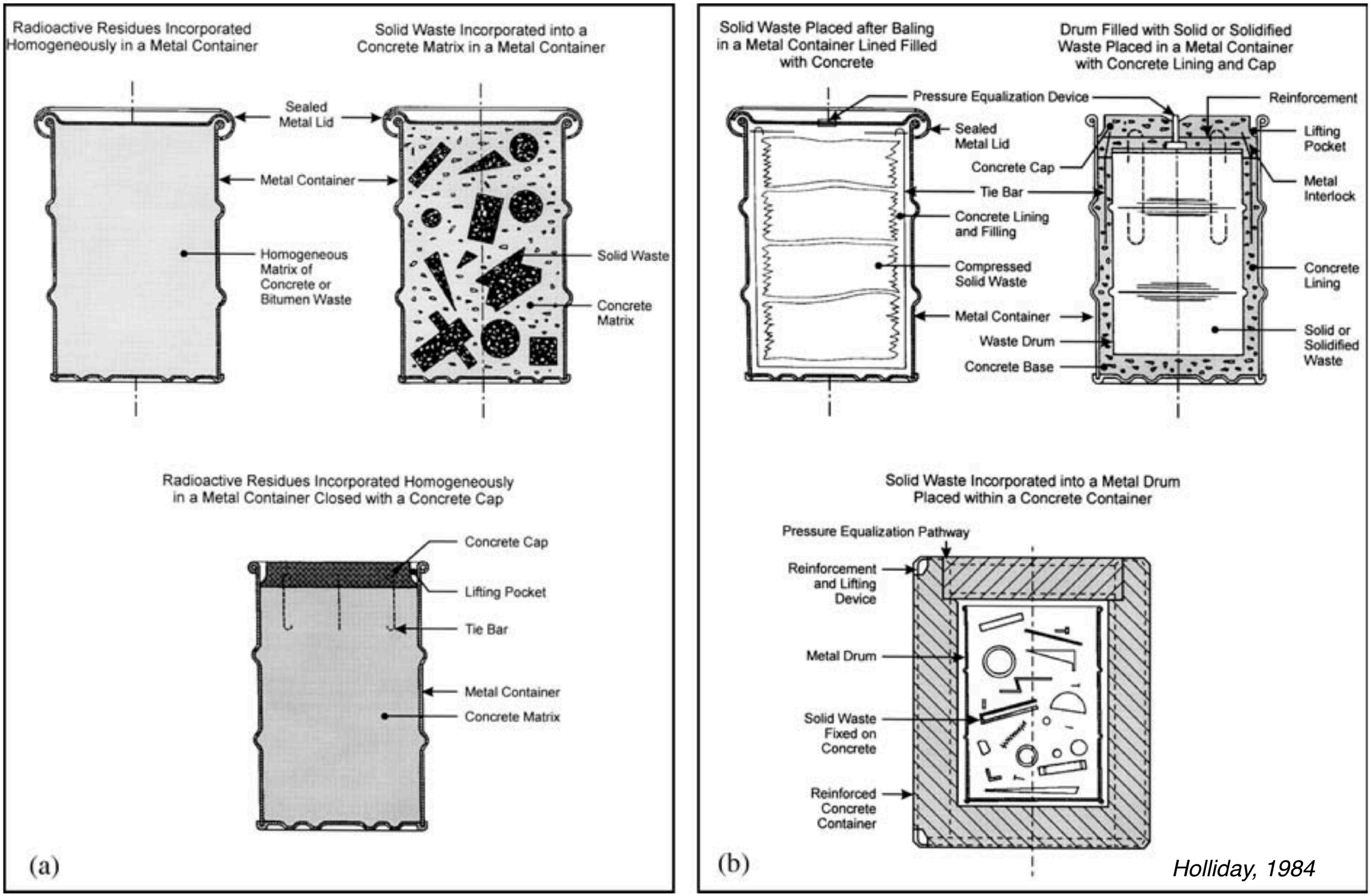


Hollister and Nadis, 1998 Scientific American

3.4. The European Reference Penetrator (Ove Arup, 1985a)

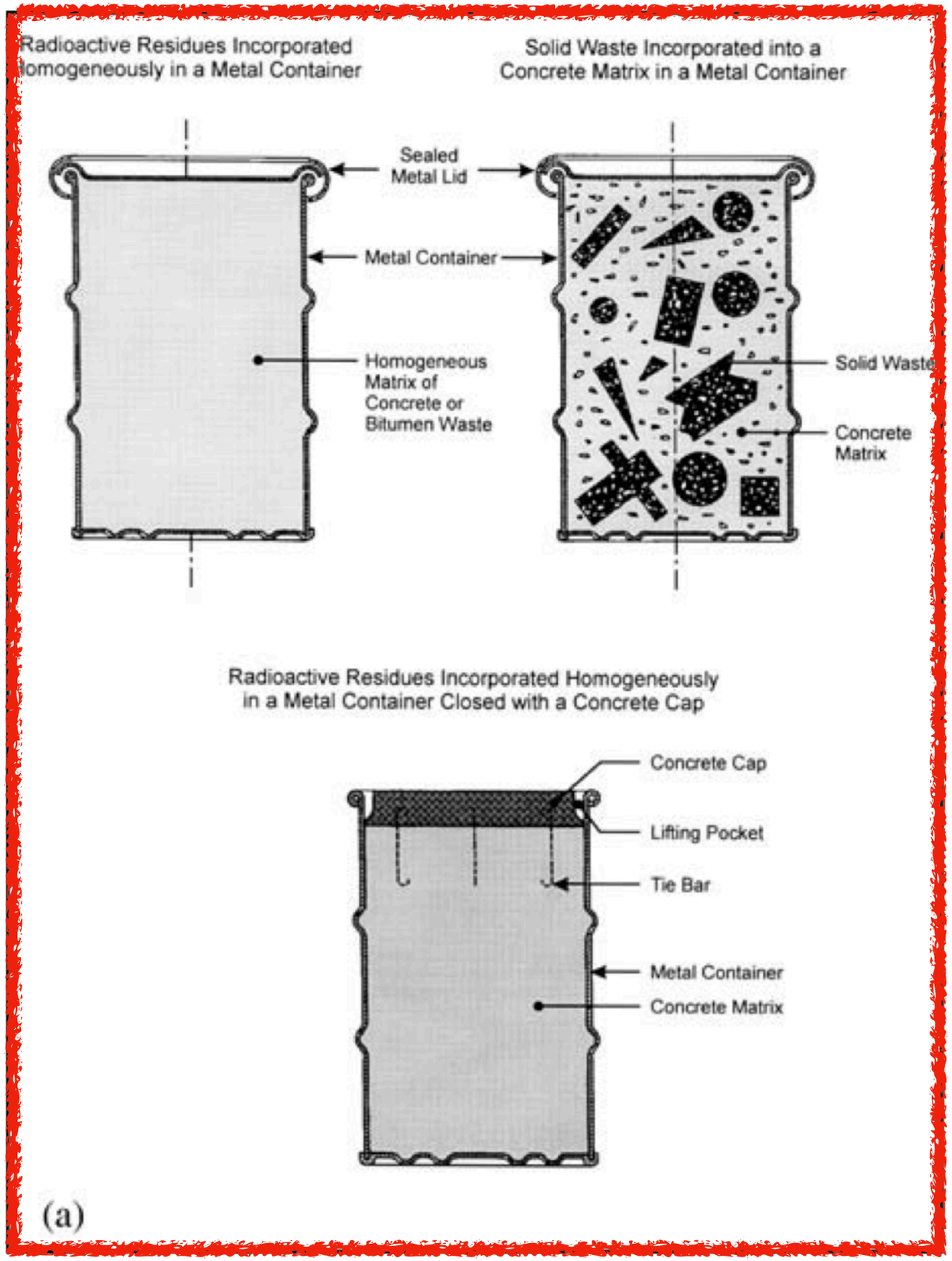


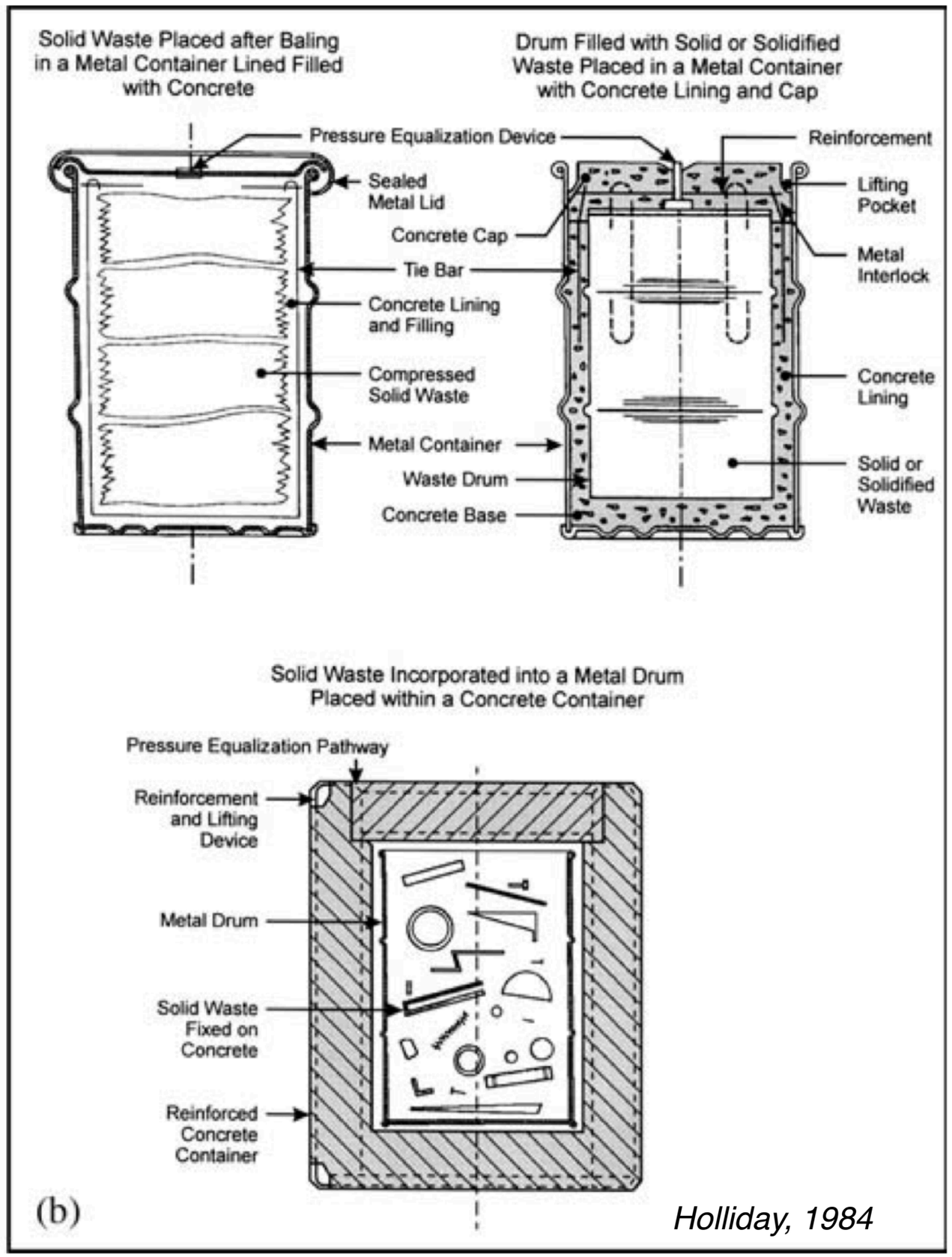
Nuclear waste containment



Monolithic (concrete - left) and void (right) packages for nuclear waste containers

Nuclear waste containment





Holliday, 1984

Monolithic (concrete - left) and void (right) packages for nuclear waste containers

Ocean dumping of radioactive waste: the cheap & efficient approach

Oceans used as dumpsite of radioactive waste from ~1946 (US), till banning of activities in 1994

Waste conditionned in barrels

Considered that abyssal plains off-limits and without potential human impact

https://www.youtube.com/watch?v=2bd8cOllXjo

https://www.youtube.com/watch?v=kn93mQ27aso

Ocean dumping of nuclear waste

Dumping in all oceans but concentrated in Atlantic and Arctic

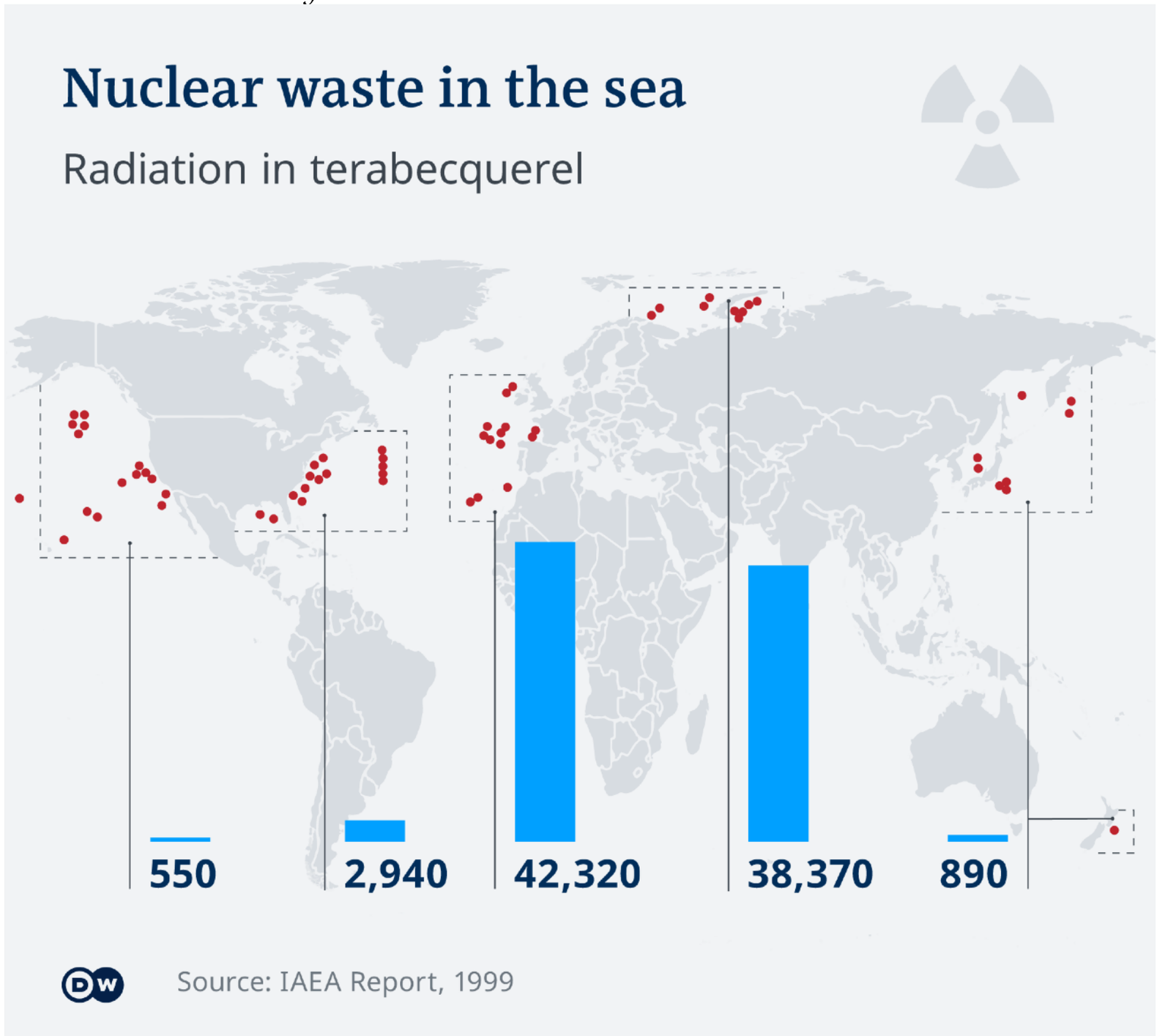
Nuclear waste:

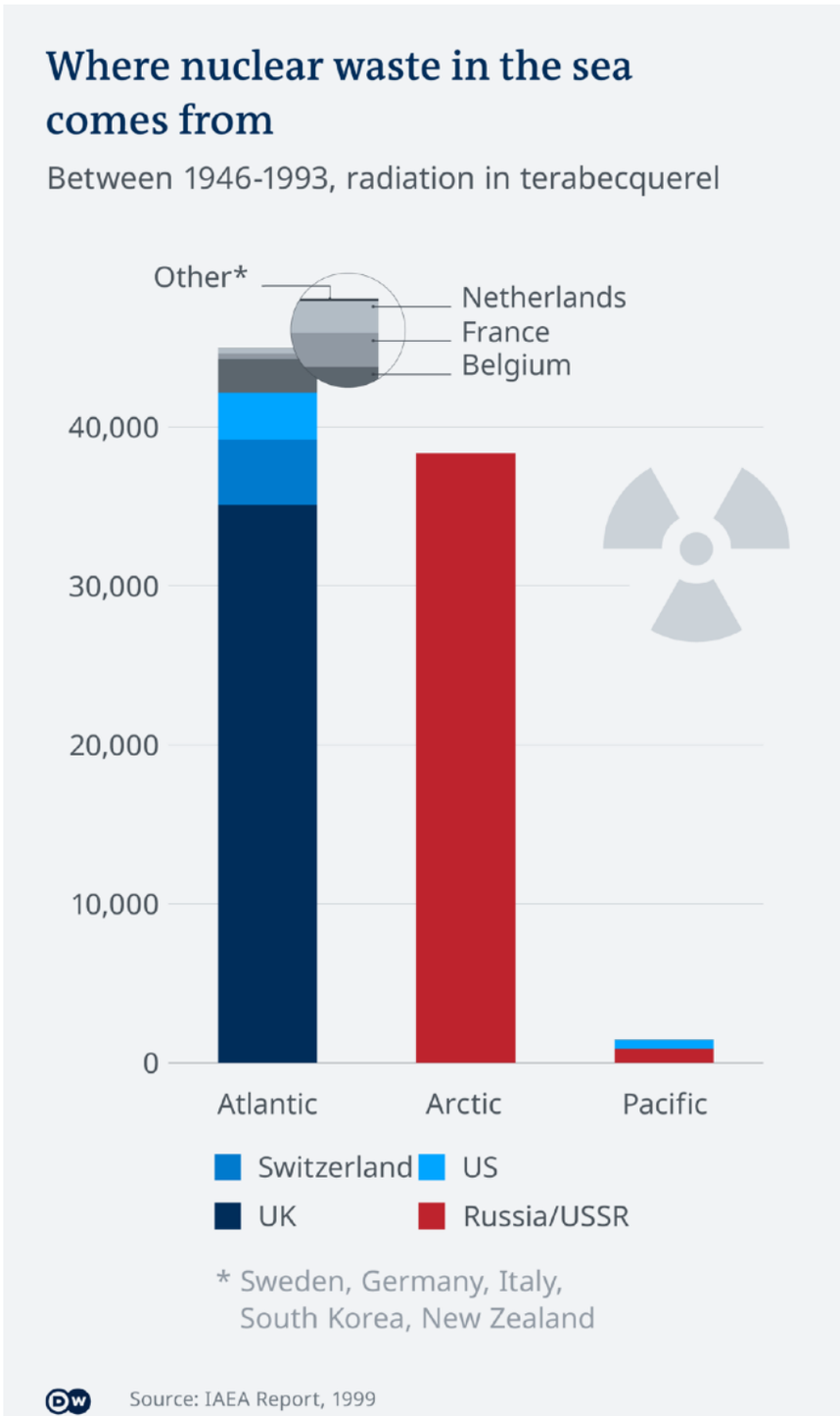
Reported to and coordinated by the International Atomic Energy Agency (IAEA.org)

… except USSR/Russia (late declaration of dumped materials)

Main sources: UK, USSR (nuclear energy)

Military nuclear waste: 6 nuclear submarines + atomic warheads (3 USSR, 3 USA)





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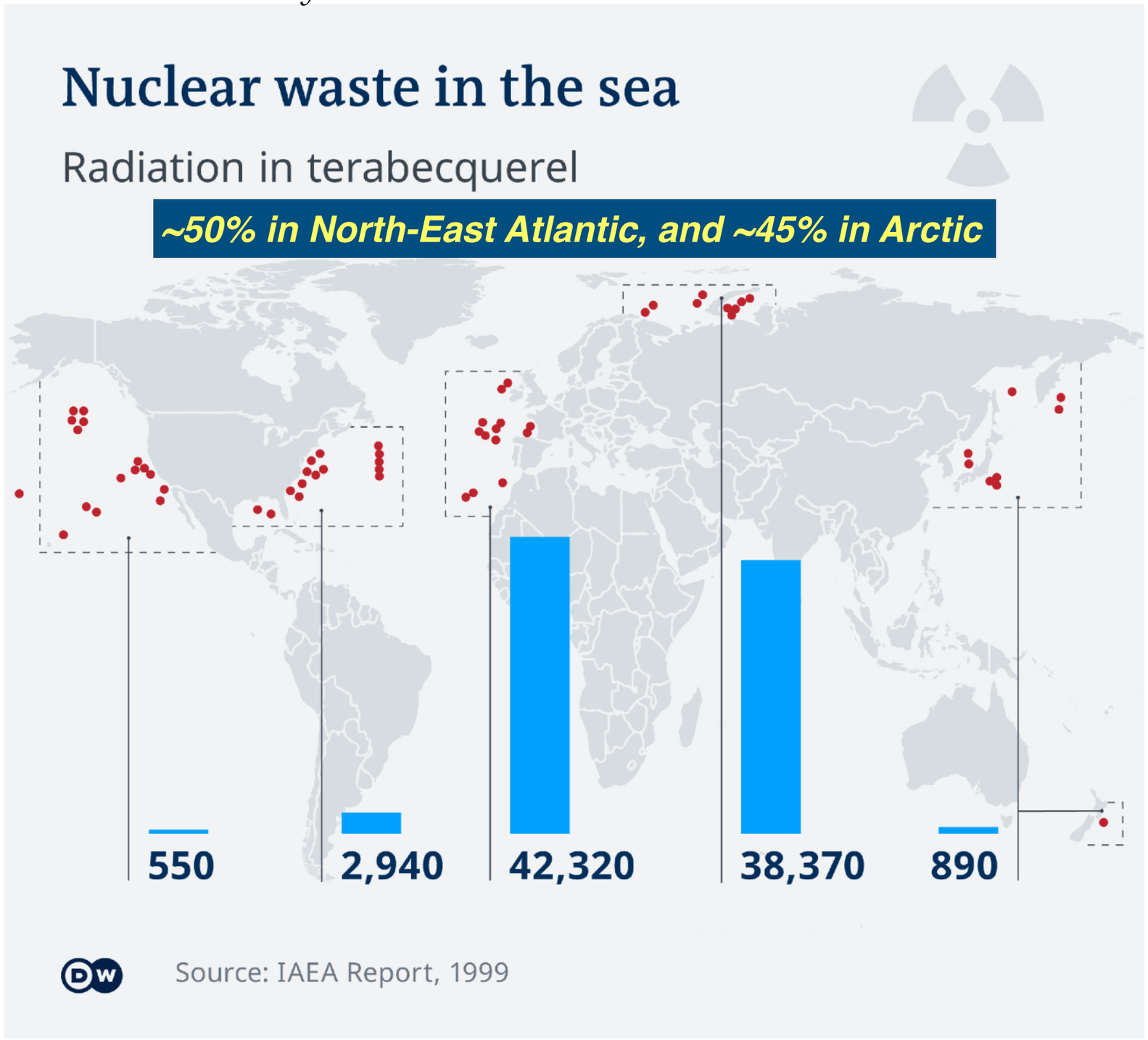
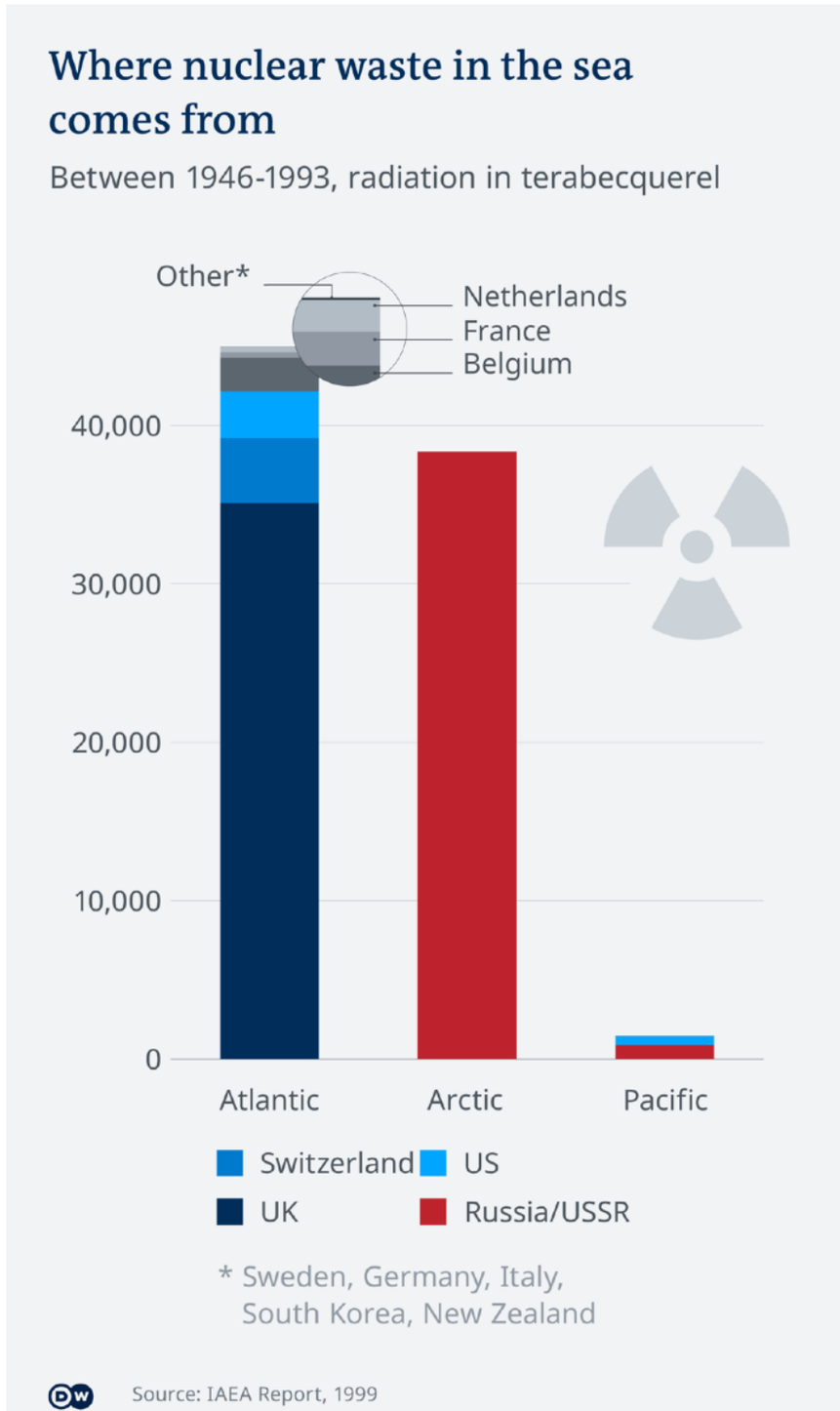
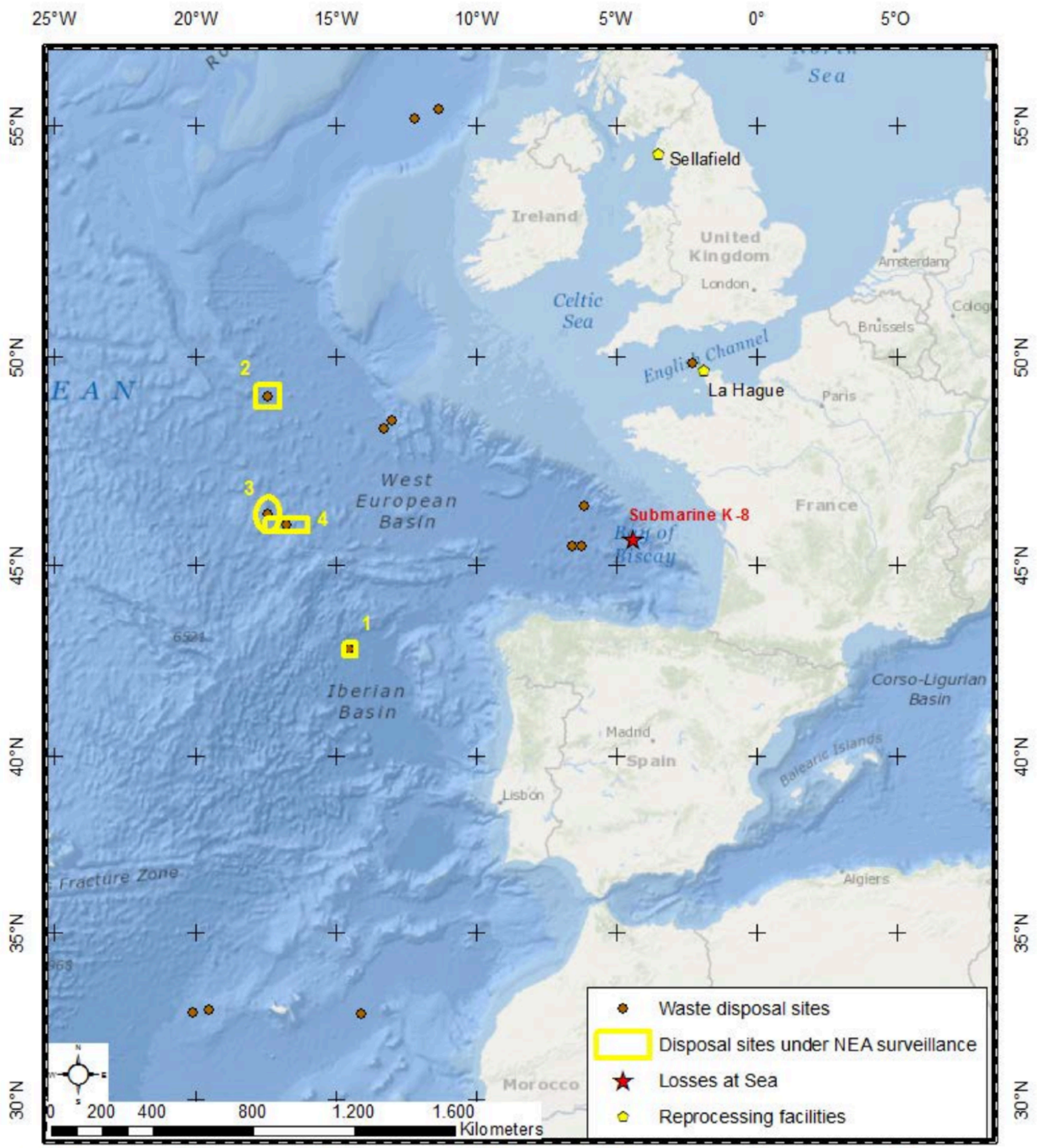




North East Atlantic dump sites



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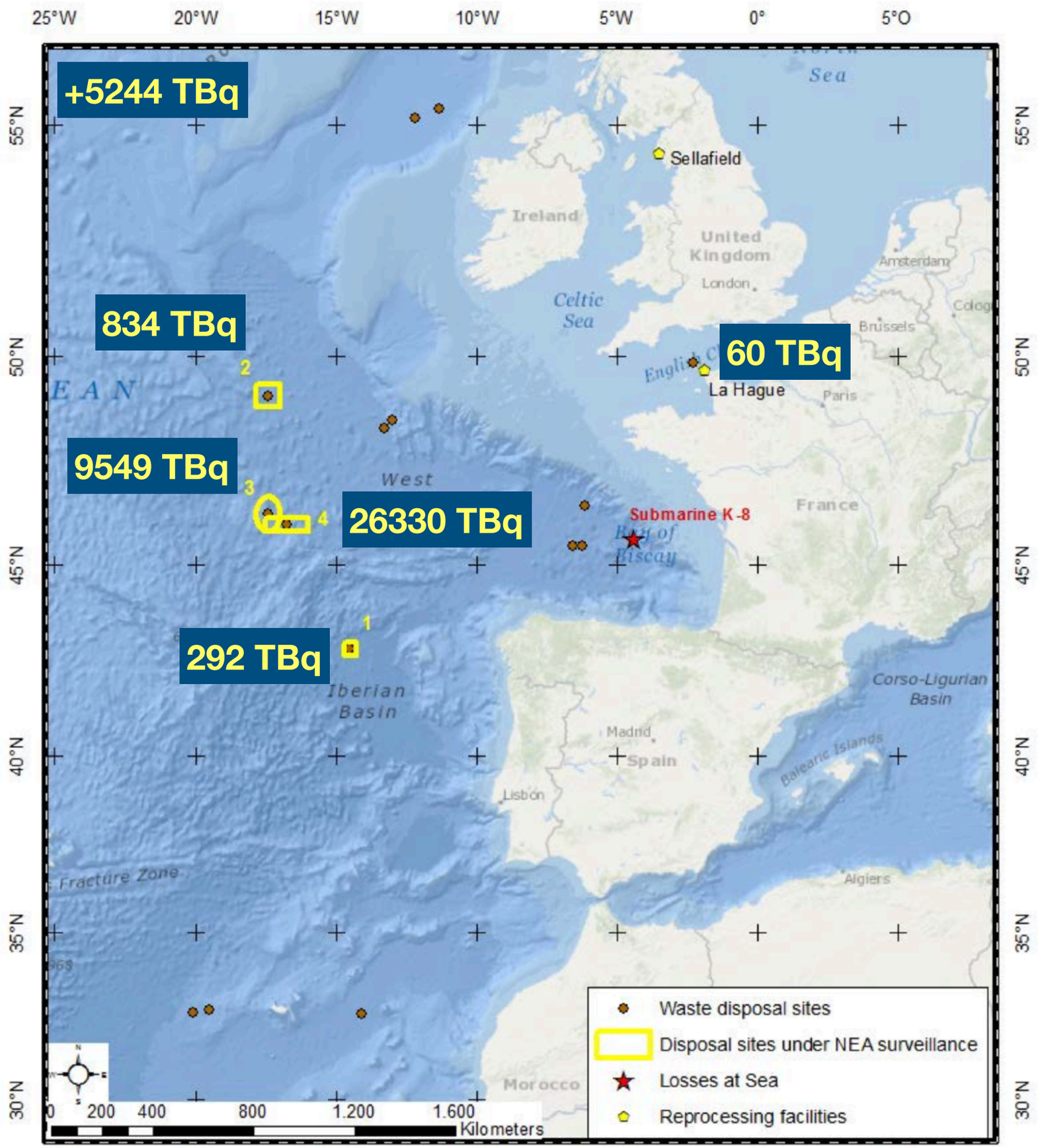

Timeline

1946: Start of dumping at sea (USA, Pacific)

1957: IAEA -> Advisory group on Ocean Radioactive Waste Disposal

1958: UNCLOS I Conference

1972: London Convention to prevent marine polution by dumping wastes adopted

1975: London Convention impemented, prohibition of high level waste dump

1983: Moratorium on low level waste dumping

1988: Impact assessment - CRESP Program

1993: Russia discloses high level nuclear waste dump (including fuel)

1994: Total prohibition of radioactive waste dump

1995: CRESP Assessment program

1996: London Protocole signed -> all ocean dumping forbidden (with exception)

2019: Mandated assessment (London Convention) - not realized

Preconized: follow up of the dump areas for environmental monitoring/assessment

Containment in barrels designed for ~25 years (plus resistance to impact)

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London Protocol - Principles

Principles

- "..shall prohibit the dumping of any wastes or other matter with the exception of those listed in Annex 1" ("reverse-list")
- Dumping of materials listed in Annex 1 requires a **permit**, which must be issued in accordance with provisions of Annex 2

Annex 1: Waste or other matter that may be considered for dumping

1. dredged material
2. sewage sludge
3. fish wastes
4. vessels and platforms
5. inert, inorganic geological material
6. organic material of natural origin
7. bulky items primarily comprising iron, steel and concrete
8. carbon dioxide streams from carbon dioxide capture processes for sequestration.

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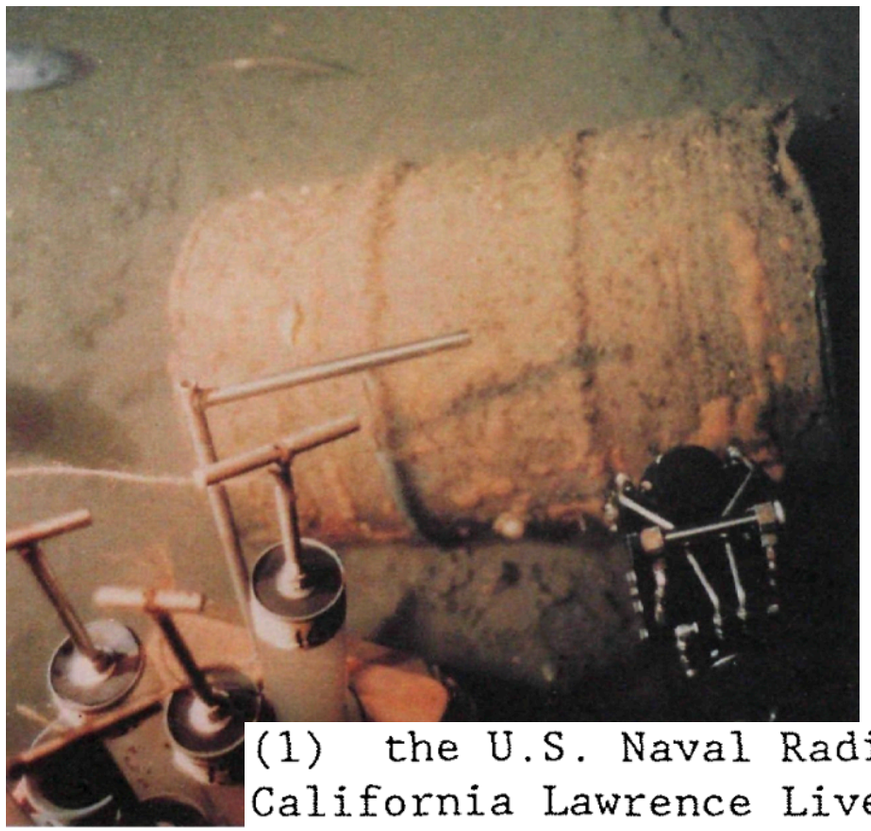
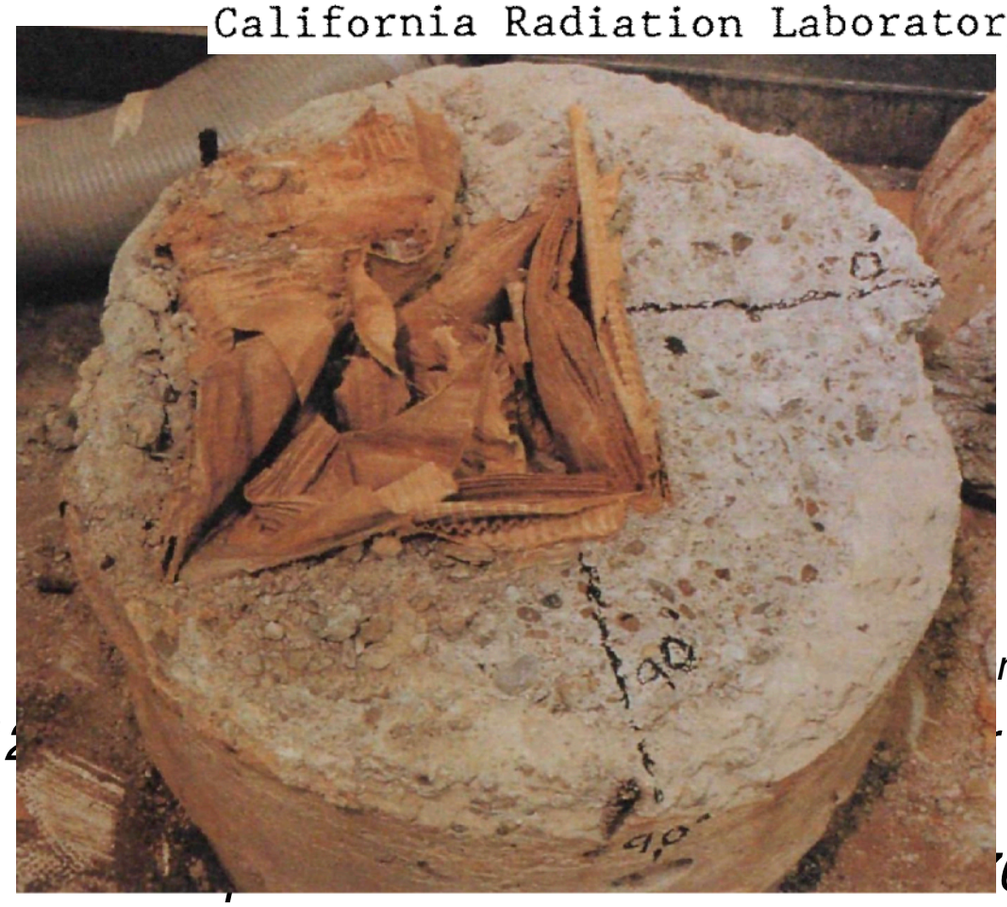
What is the legacy of 40-80 years of waste dumping?

Nuclear waste containment

Pacific dump site (USA). 900m. 1946 & 1954-1965. Waste: a cardboard box. Corrosion of metal.

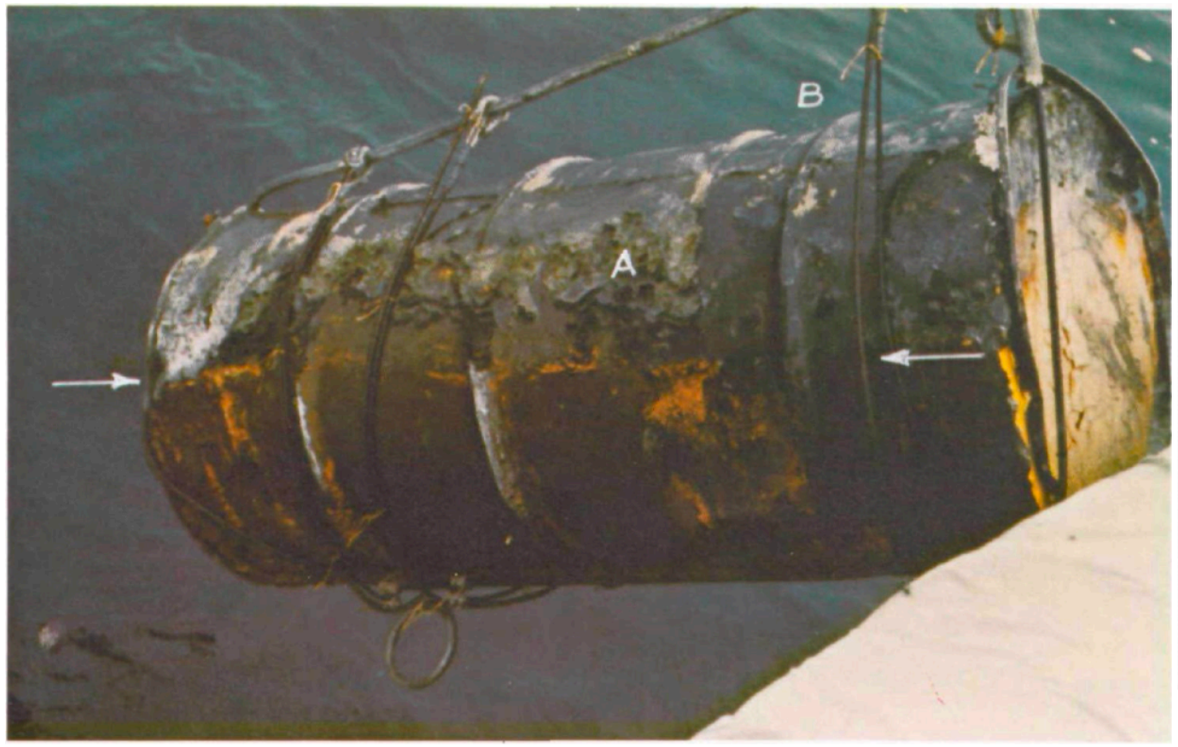


(1) the U.S. Naval Radiological Defense Laboratory, (2) the University of California Lawrence Livermore Radiation Laboratory, and (3) the University of California Radiation Laboratory at Berkeley.



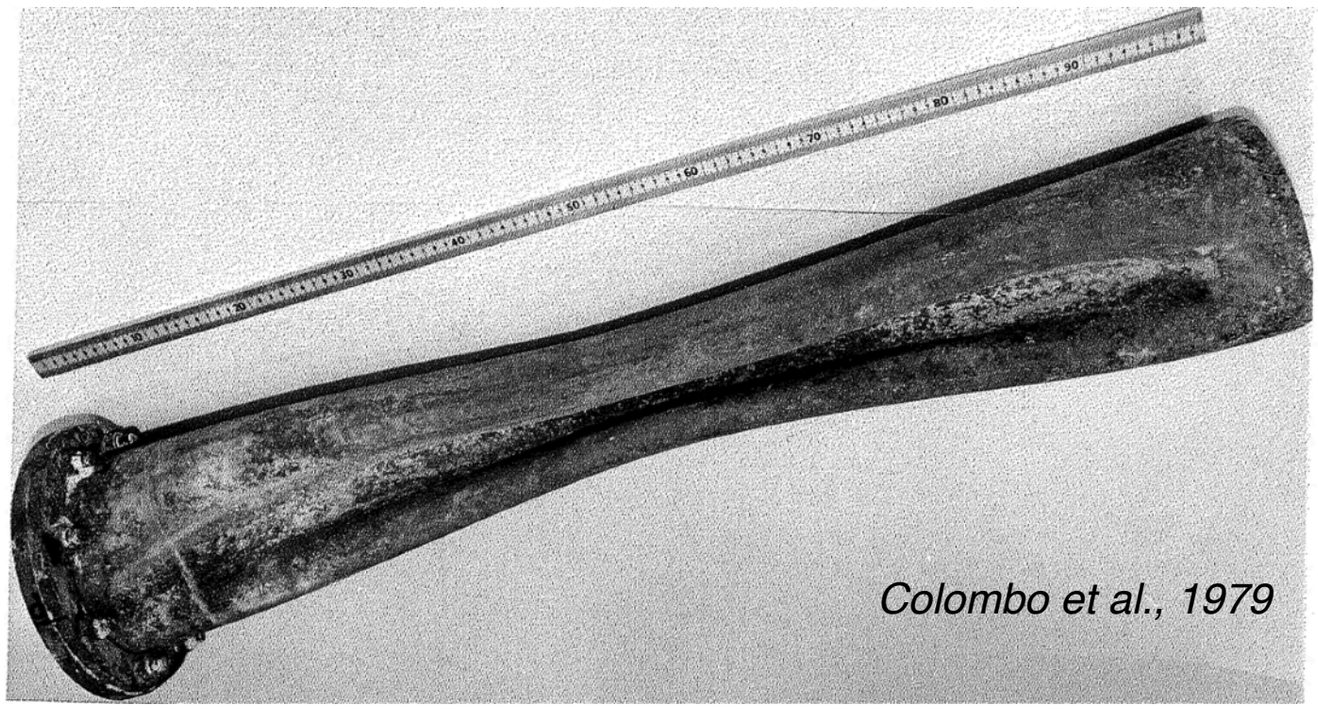
Colombo & Kendig, 1993

Nuclear waste containment



120 miles E of Delaware/Maryland Border (USA)
2873 m waterdepth
Dumped in 1961 - Recovered in 1976

Concrete container



Inner metal container: sealed liquid+filter assemblies

cesium-137, cesium-134 and cobalt-60 in both the concrete matrix and the inner vessel

Ocean dumping of radioactive waste: the cheap & efficient approach

What is the legacy of 40-80 years of waste dumping?

Need environmental impact assessment in the deep ocean

https://www.youtube.com/watch?v=2bd8cOllXjo

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What do we know about the ocean seafloor?

What do we know about the ocean seafloor?

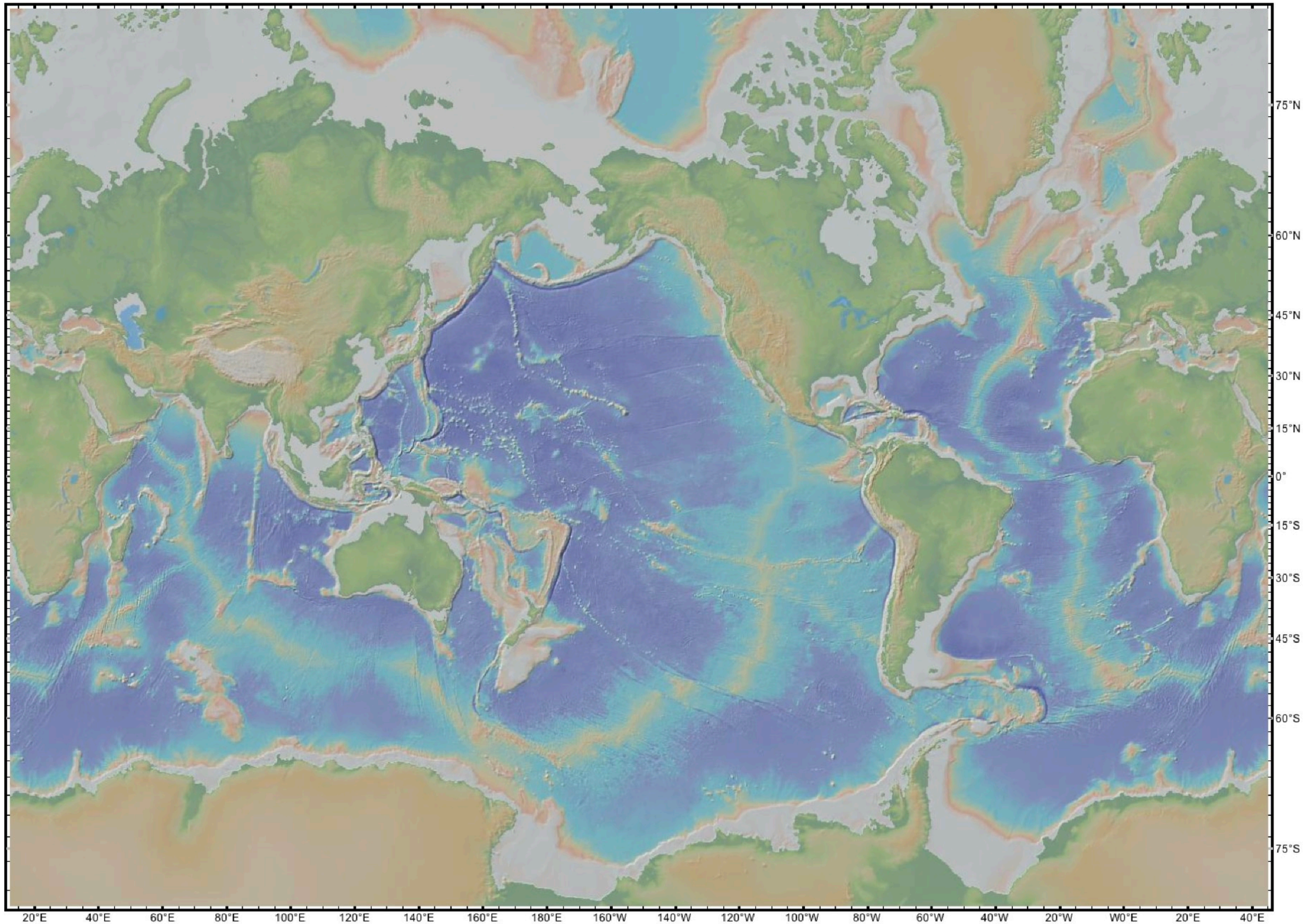
Bathymetry reveals the structure of the oceanic lithosphere over ~70% of the Earth's surface

Marie Tharp's extraordinary physiographic maps (50's to late 60's)

Seafloor role: Chemical exchange ocean/solid Earth, C sink/source, ecosystems, interaction with currents…

What do we know about the ocean seafloor?

and the view with the help of satellites (90's to date), coupled with ages… but…

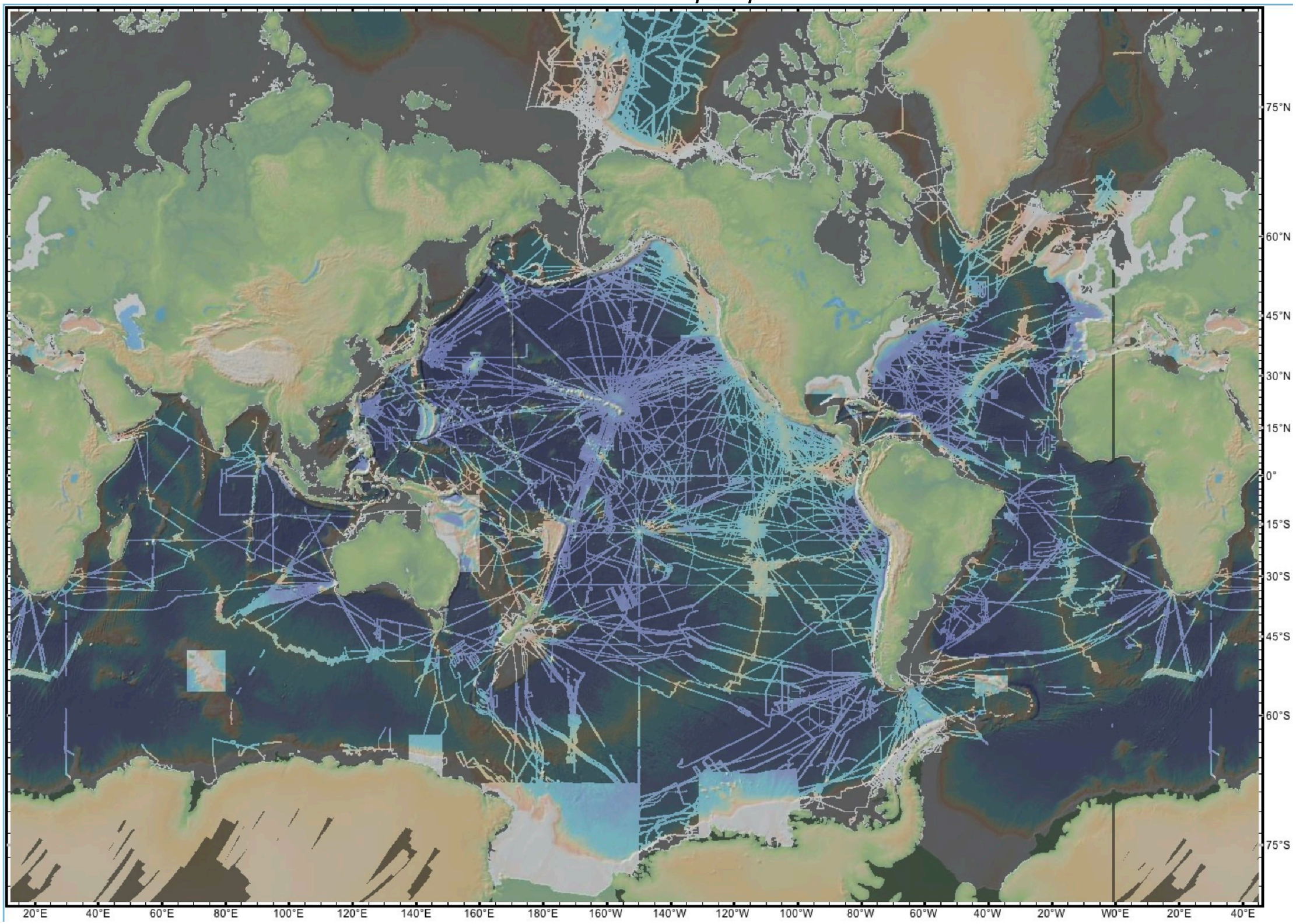


www.gmrt.org

What do we know about the ocean seafloor?

multibeam bathymetry only available for ~25% of the seafloor

Resolution ~100 m per pixel



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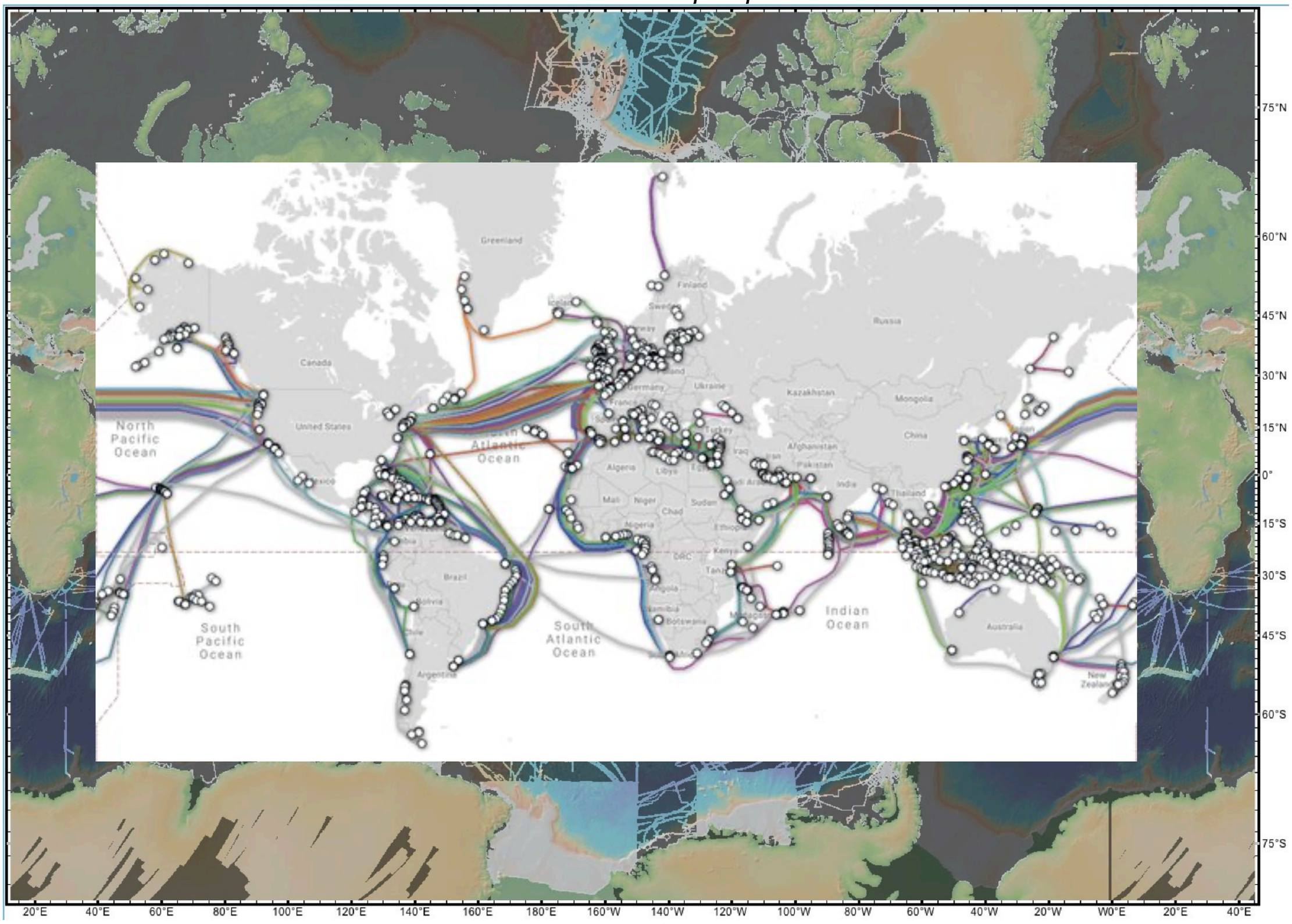

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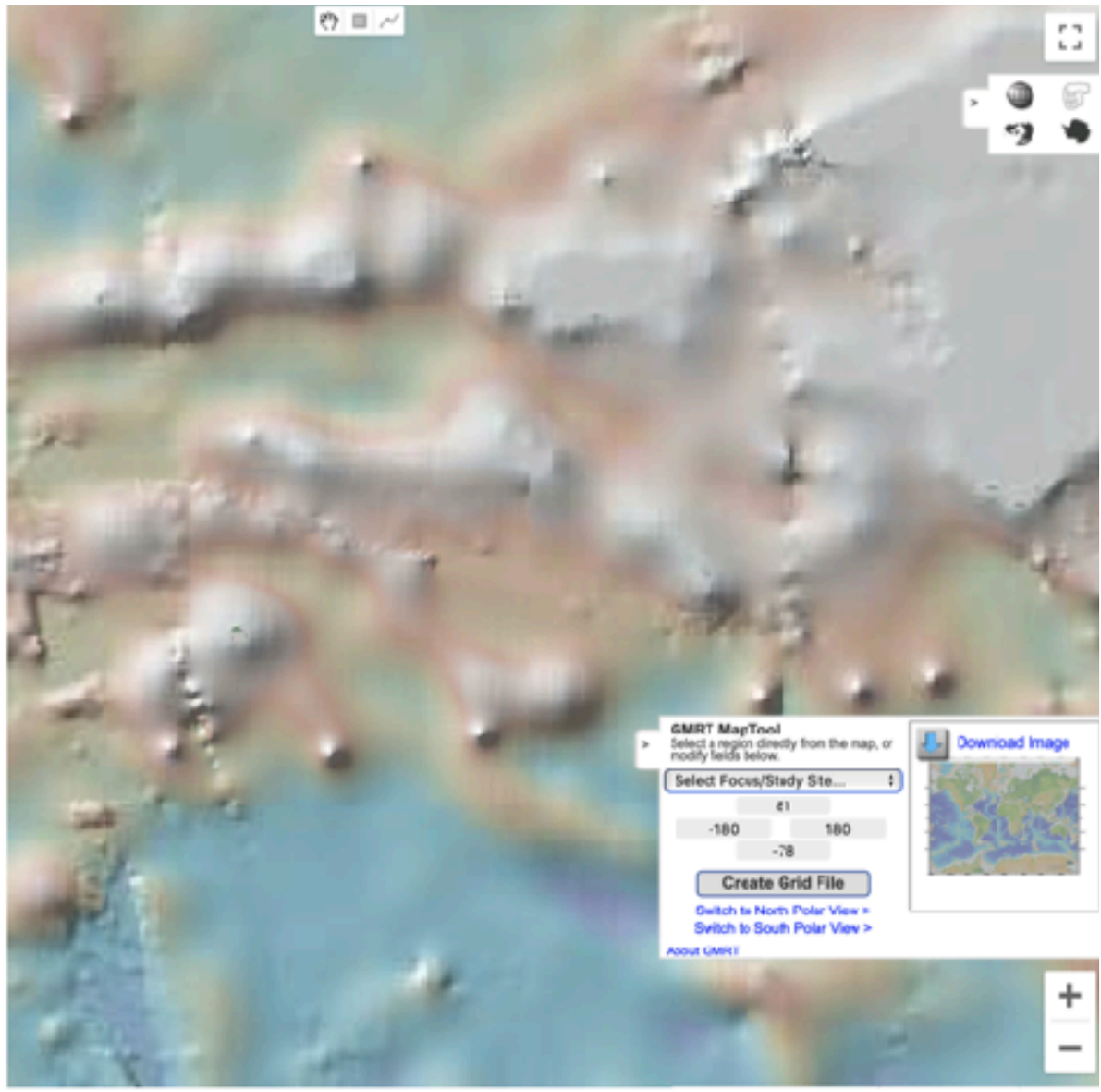
2005 collision USS San Francisco
Uncharged waters



1 casualty, 1b$ in damages -> NASA/NAVY projet for new generation of satellite altimetry sensors

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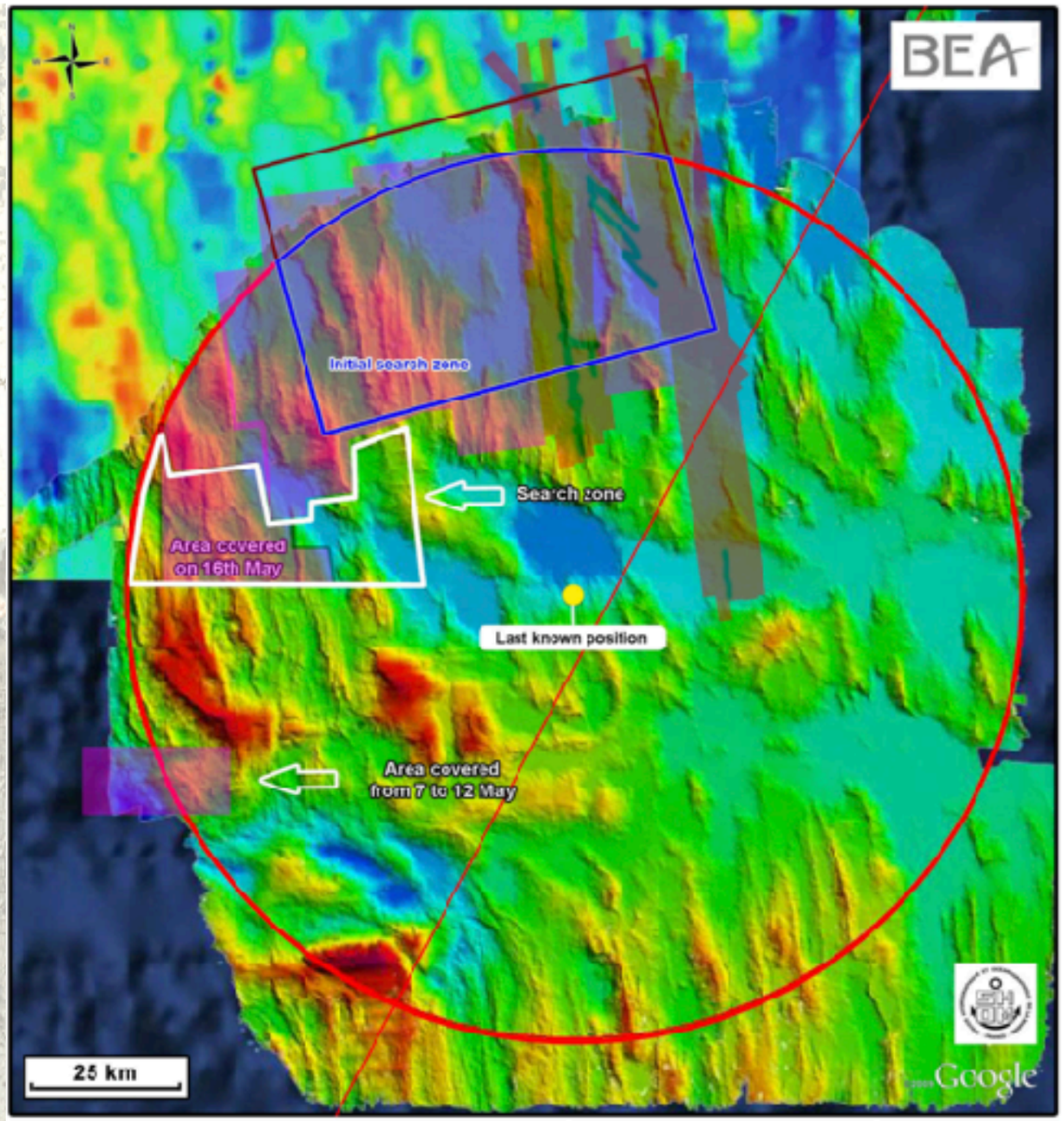
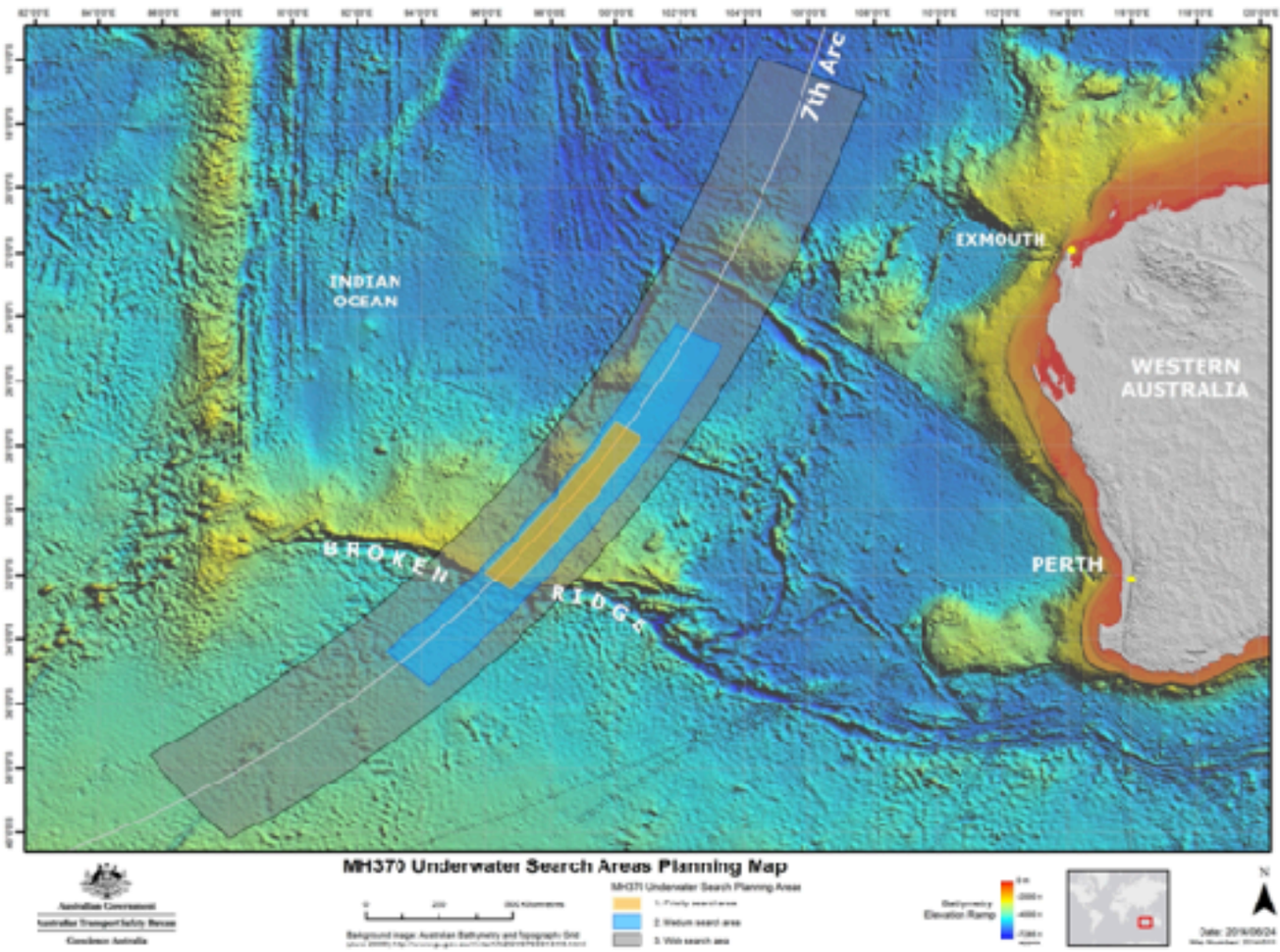
www.gmrt.org

Coupling AUV mapping and ROV observations



Paris-Rio AF 447 Airbus search
1/2009 Crash
Recovered 5/2011



Malaysian Airlines MH370
3/2014 Crash
Not found after intensive searches

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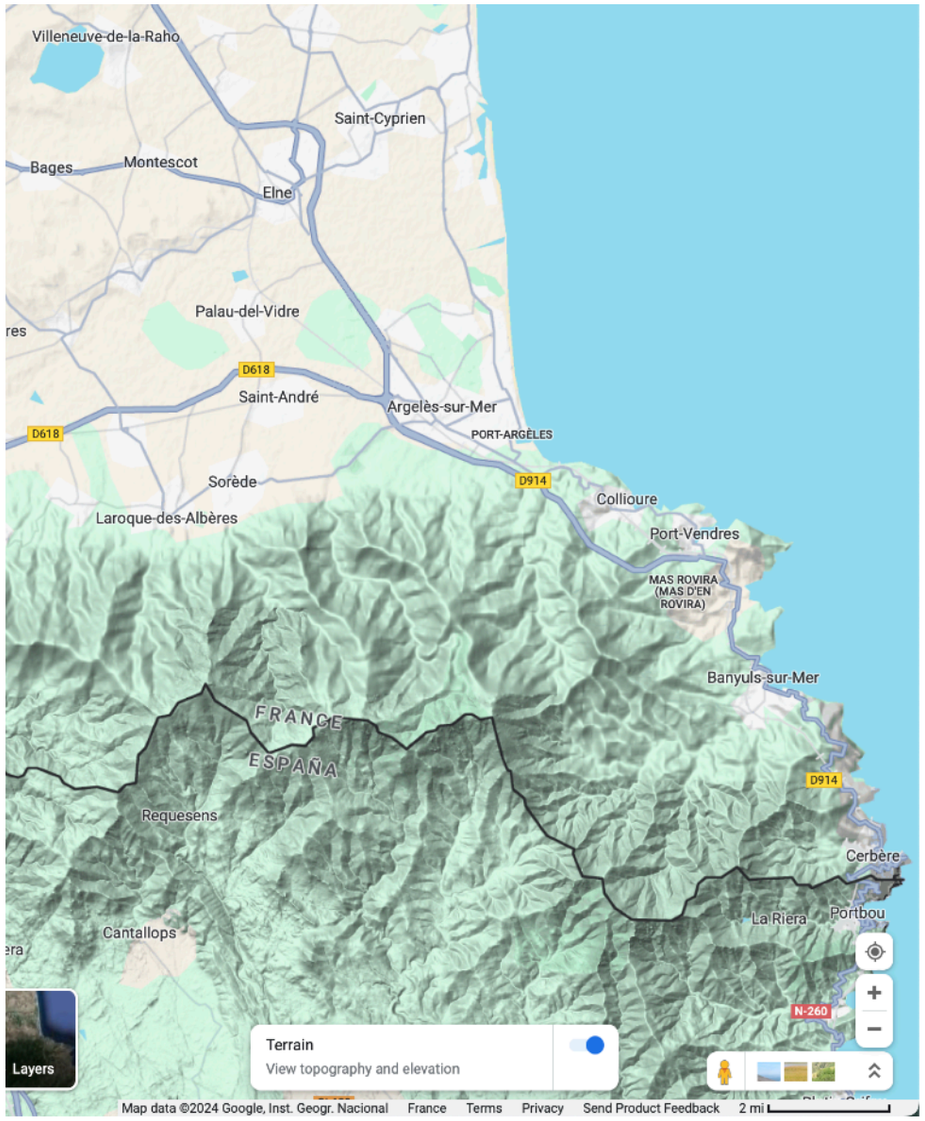
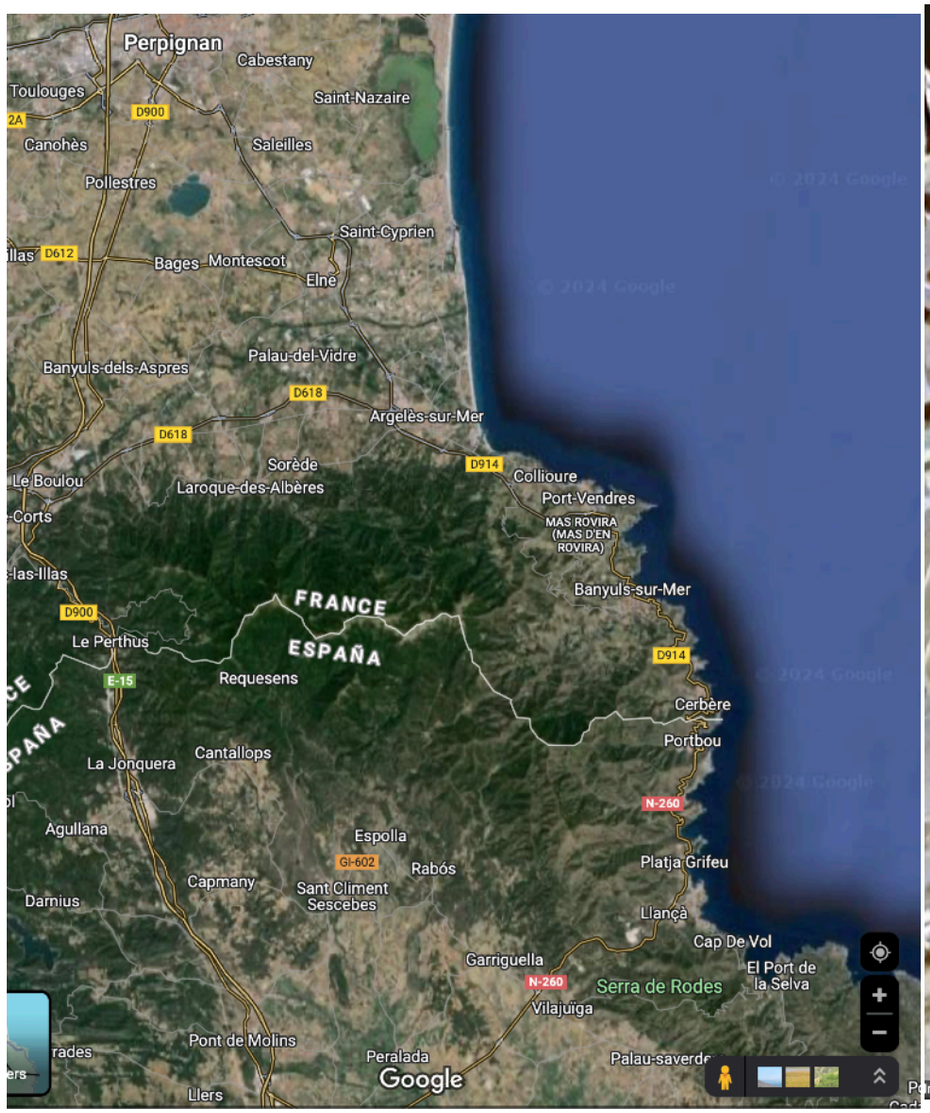


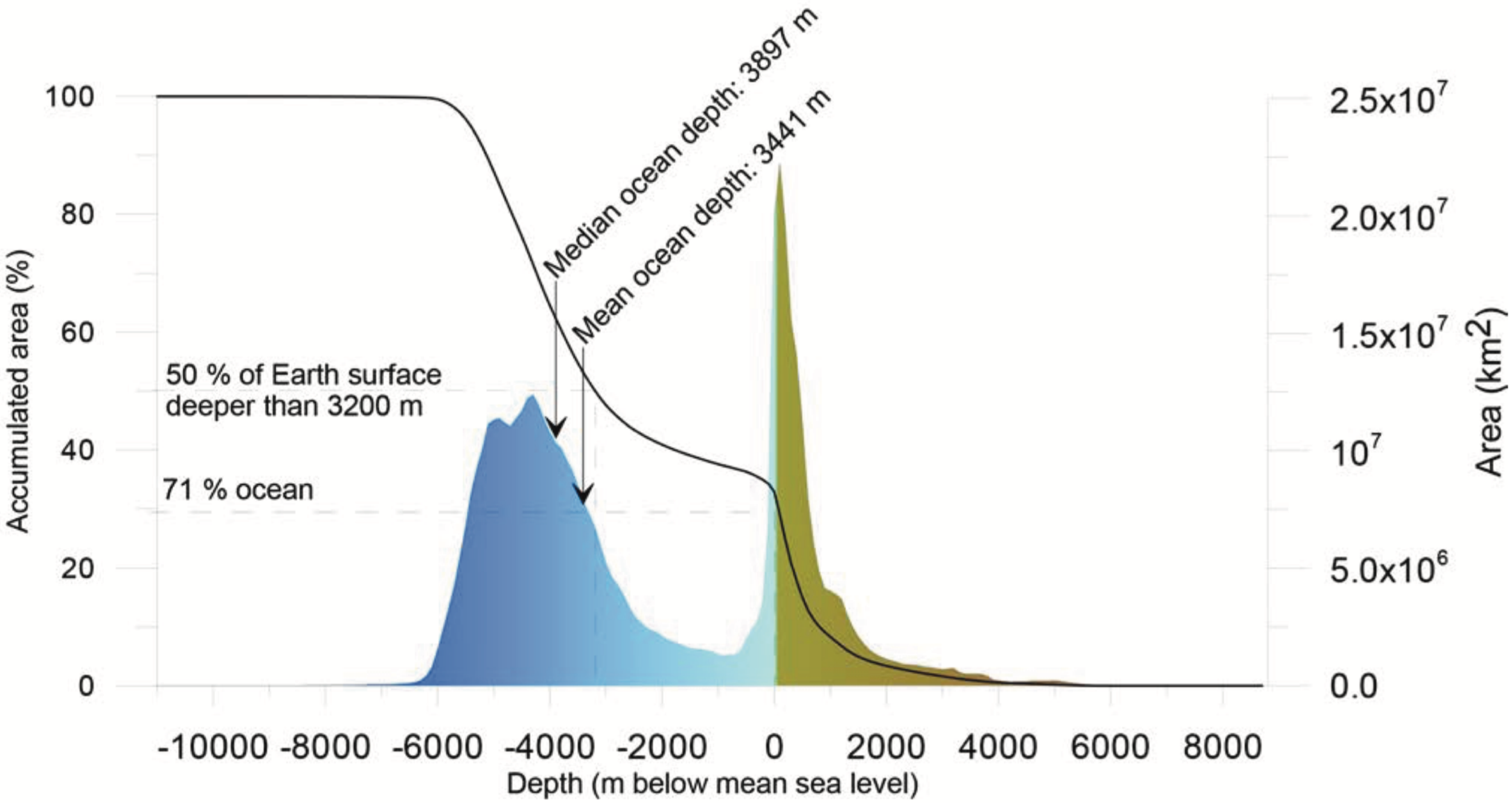


What about optical data? coverage? resolution? How much have we 'seen' of the seafloor?

- *Important to characterize the surface (ecosystems, infrastructure, geology, etc.)*
- *Temporal studies*
  - *Geology: earthquakes, landslides, glaciers, inondations, etc.*
  - *Biology: ecosystems variability (seasonal, long-term), characterization, evolution*
  - *Impact assessment: natural and anthropic hazards*

What have we 'seen' of the bottom of the ocean?

Challenges of deep-sea imaging



Earth's hypsographic curve - Oceans vs. continents

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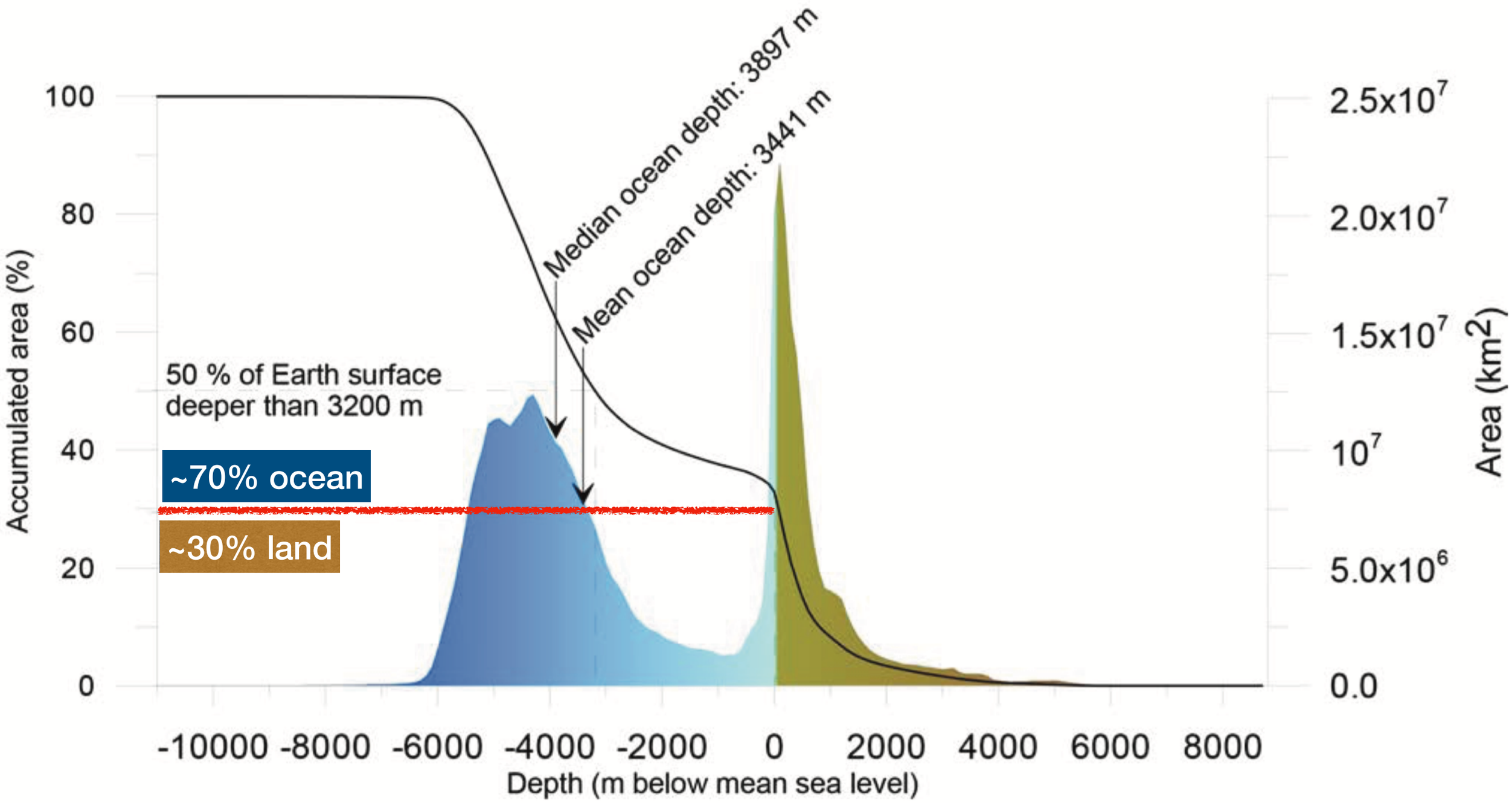

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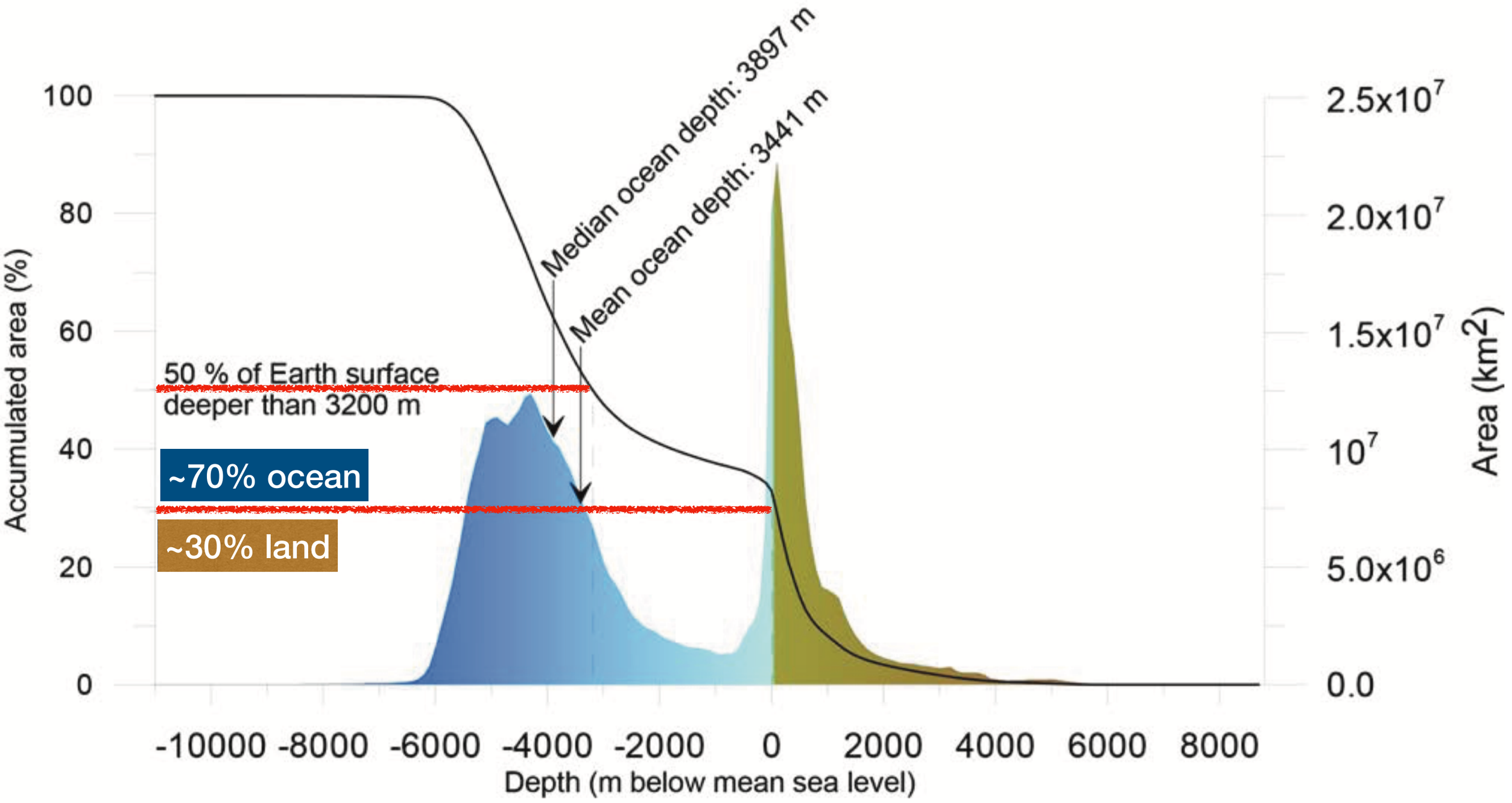

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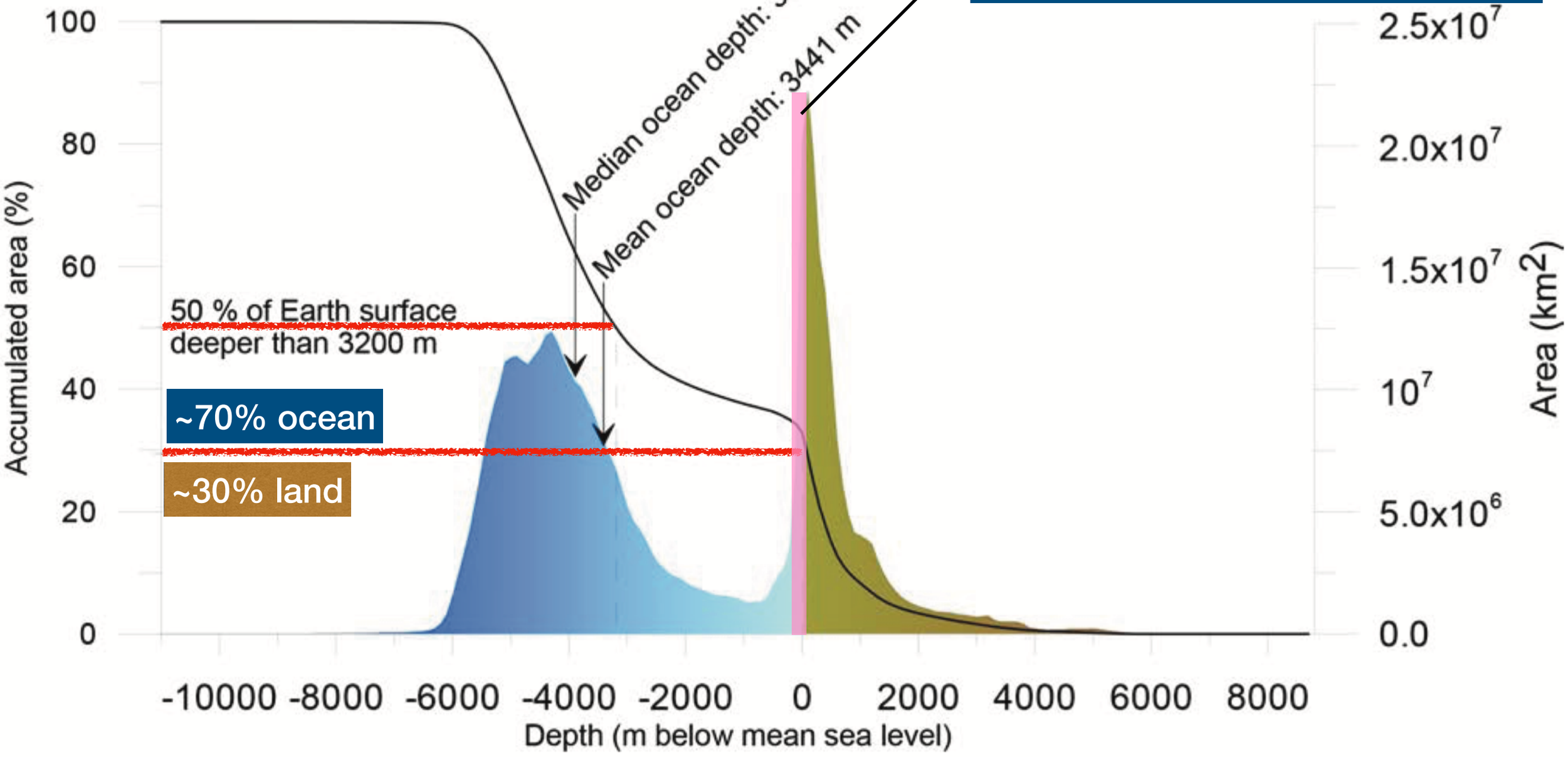
Challenges of deep-sea imaging

Photic zone -> ~200m
Seafloor visible from satellite to ~20 m in ideal visibility conditions



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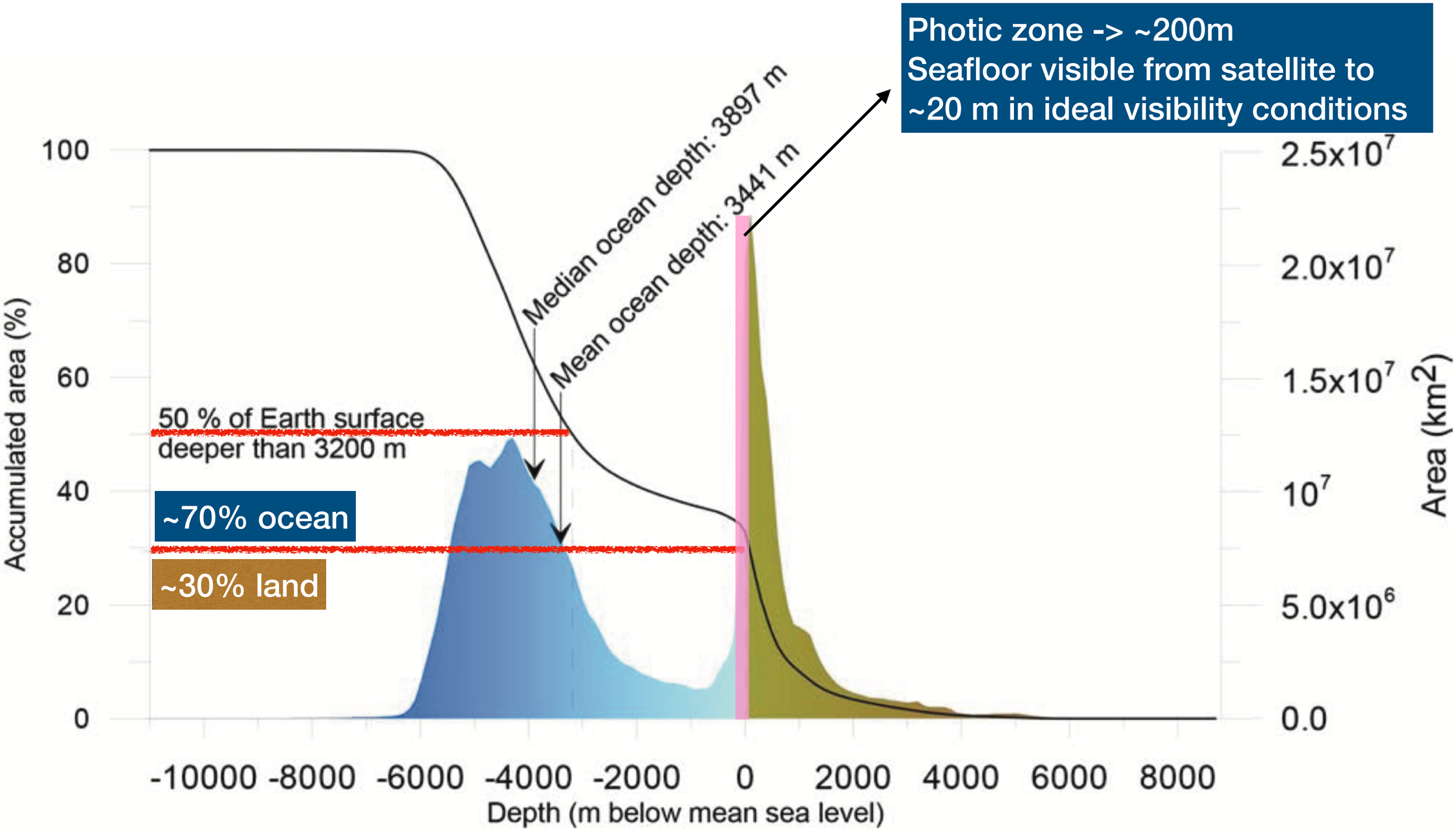
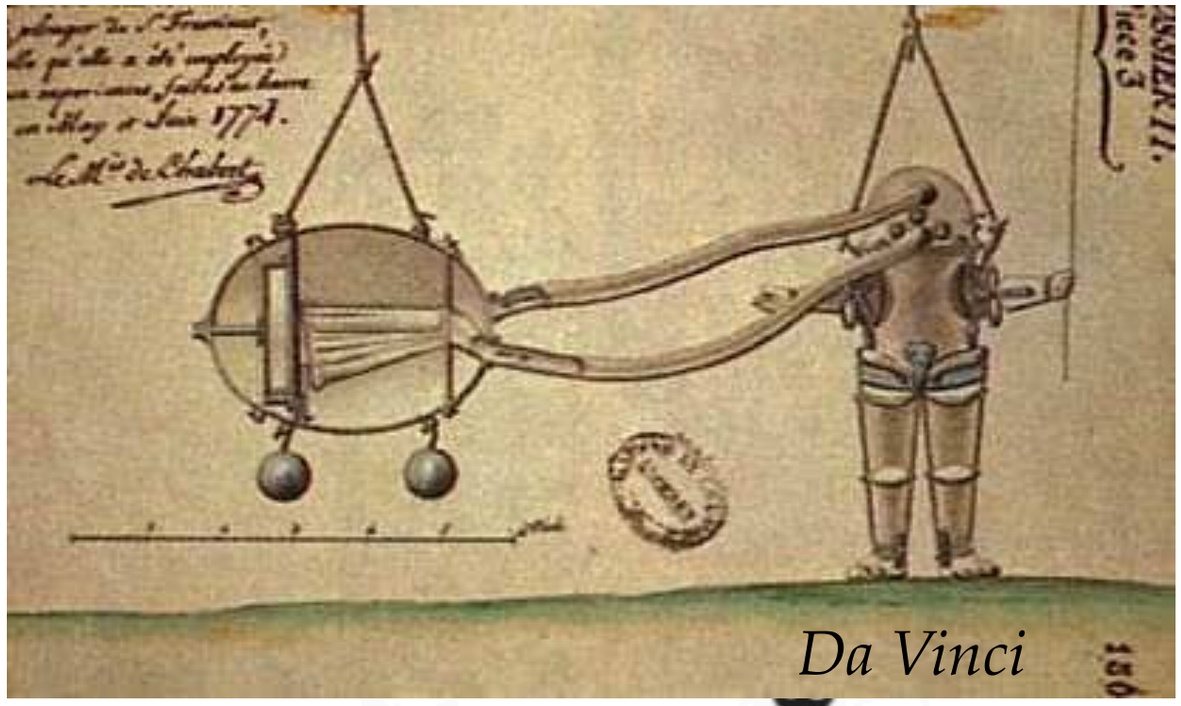


Limitations:

Need of illumination -> close range imaging (a few m)
Depth-pressure -> technological constraints
Water -> constrains on navigation (no electromagnetic waves, navigation)

What have we 'seen' of the bottom of the ocean?

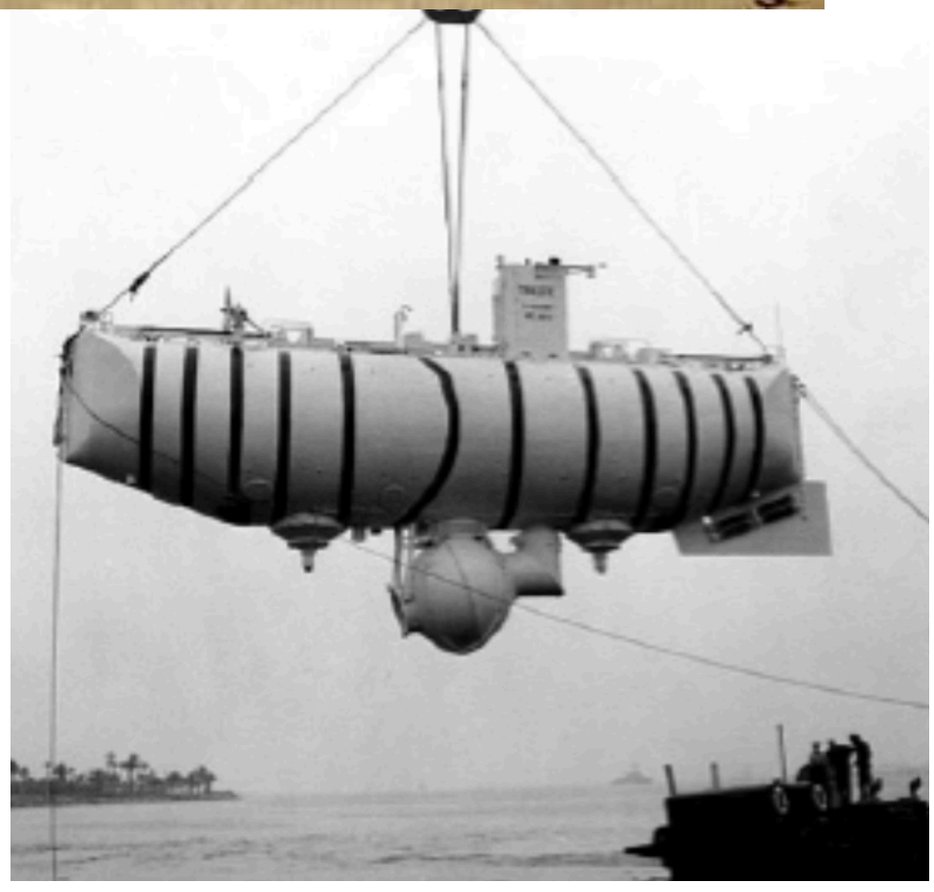
Charlemagne



Da Vinci

End 1700-1800

Beebe & Barton
1930 - 900m

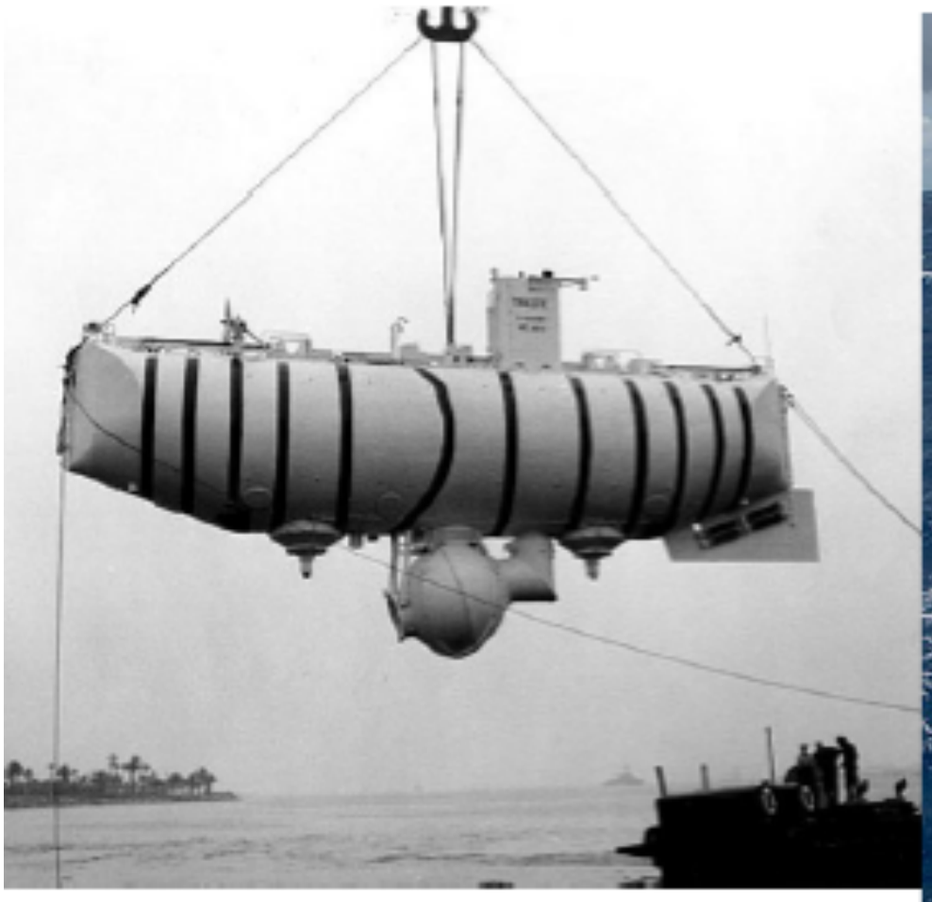


Trieste - 1960 - 11000m
Challenger Deep, Marianas

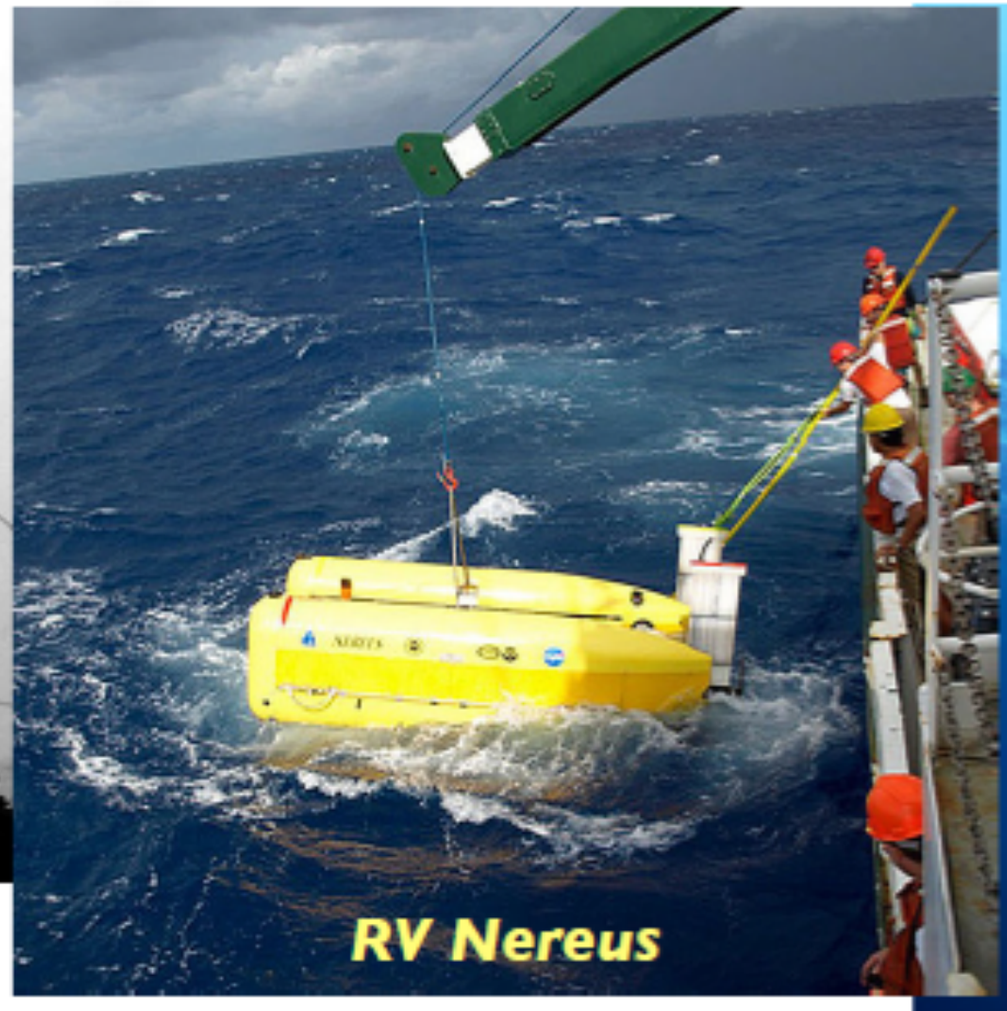
What have we 'seen' of the bottom of the ocean?

23/1/1960 - Trieste, *J. Picard & D. Walsh* - ~10916 m
3/1995 RV Kaiko - ~10911 m
31/5/2009 - RV Nereus - 10902 m
18/2/2012 - Deepsea Challenger - J. Cameron - 10898 m
4/2019 - DSV Limiting Factor - V. Vescovo - 10927 m

P=10 Tn/cm2



DSV Trieste

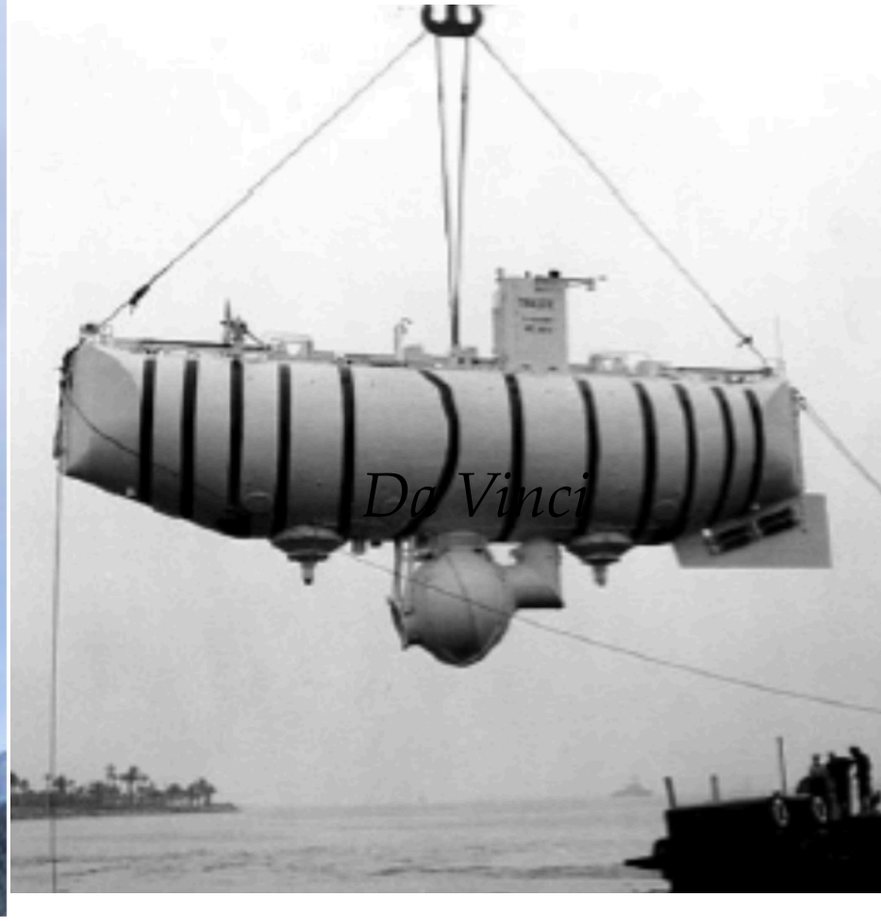


RV Nereus

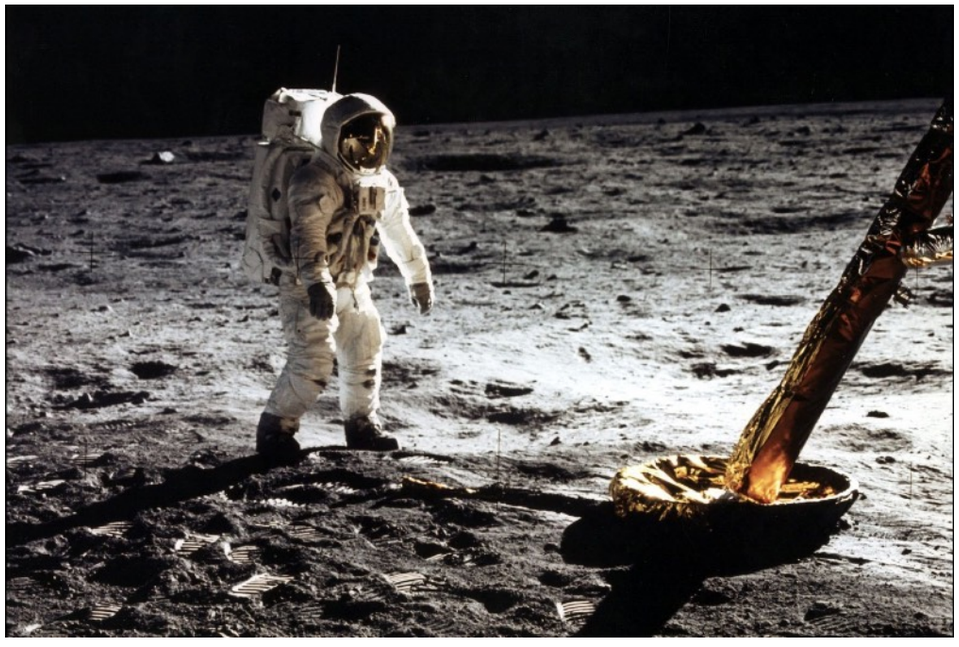
DSV Deepsea Challenger

Deepest point of the Oceans (Challenger Deep, Marianas): 5 visits in 60 years (<10 people)

What have we 'seen' of the bottom of the ocean?

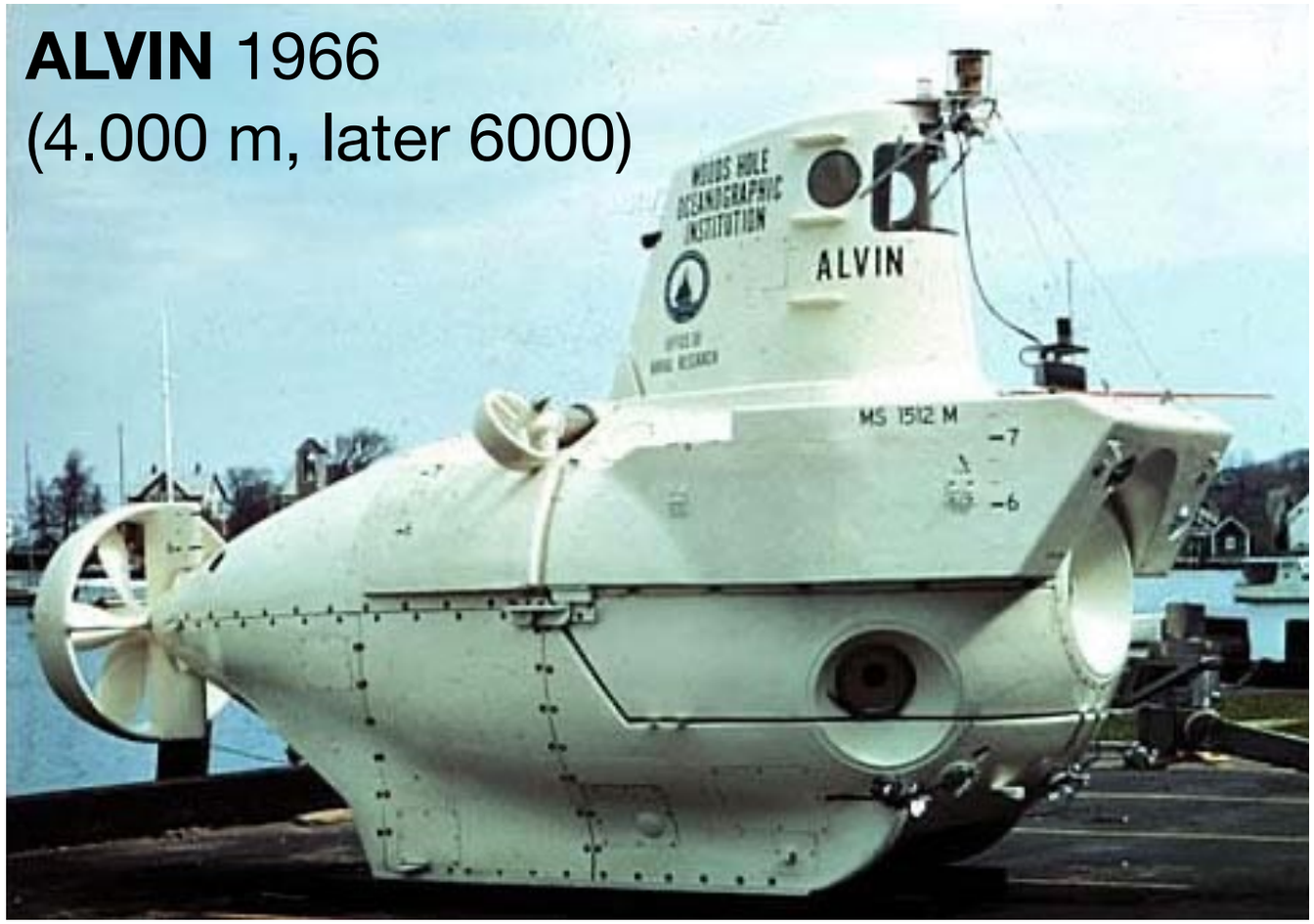


… vs. the highest point on Earth at 8848 m since 1953…



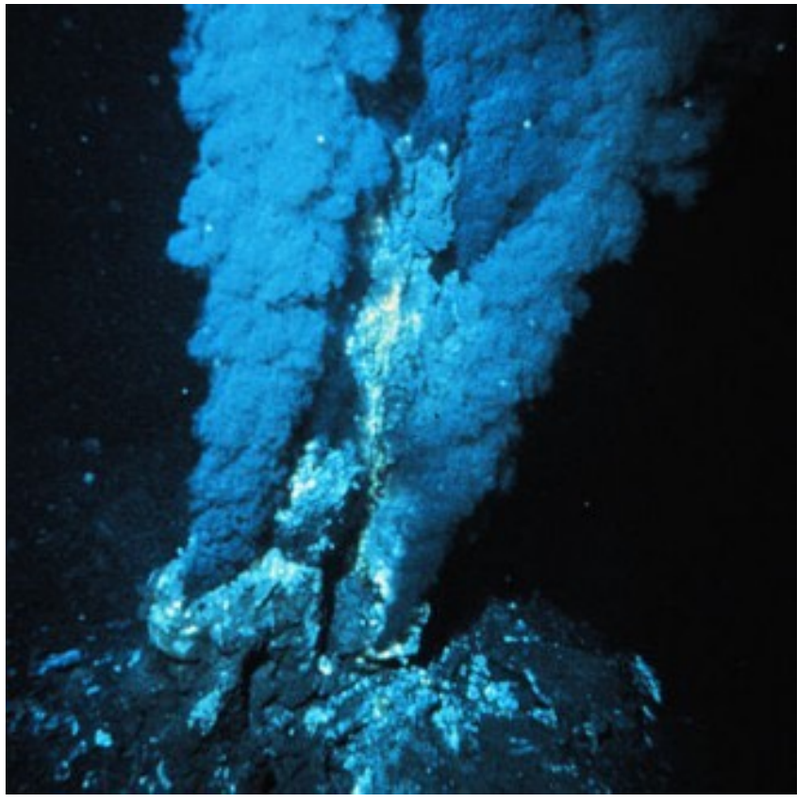
~ 12 personnes sur la Lune since Apollo XI in 1969

The start of a revolution - from submarines to robots

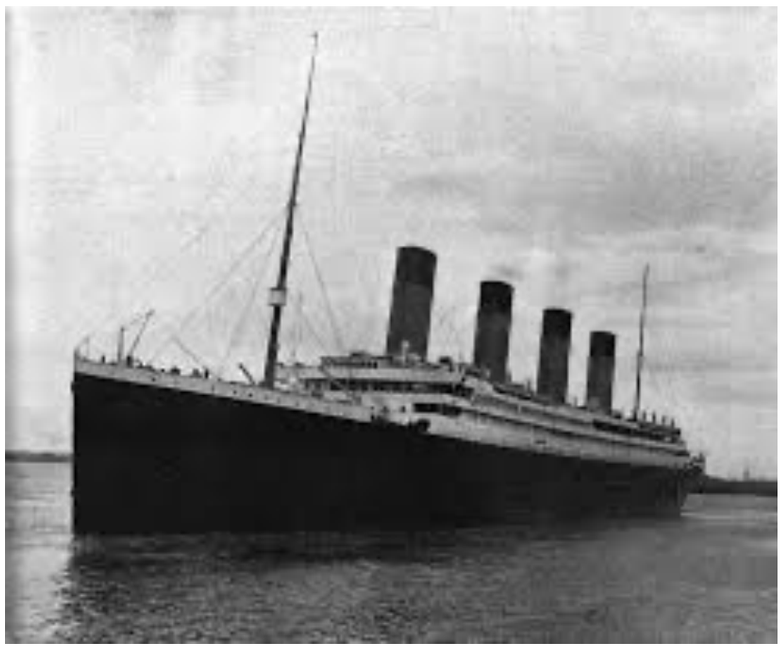


ALVIN 1966
(4.000 m, later 6000)

ALVIN 2020



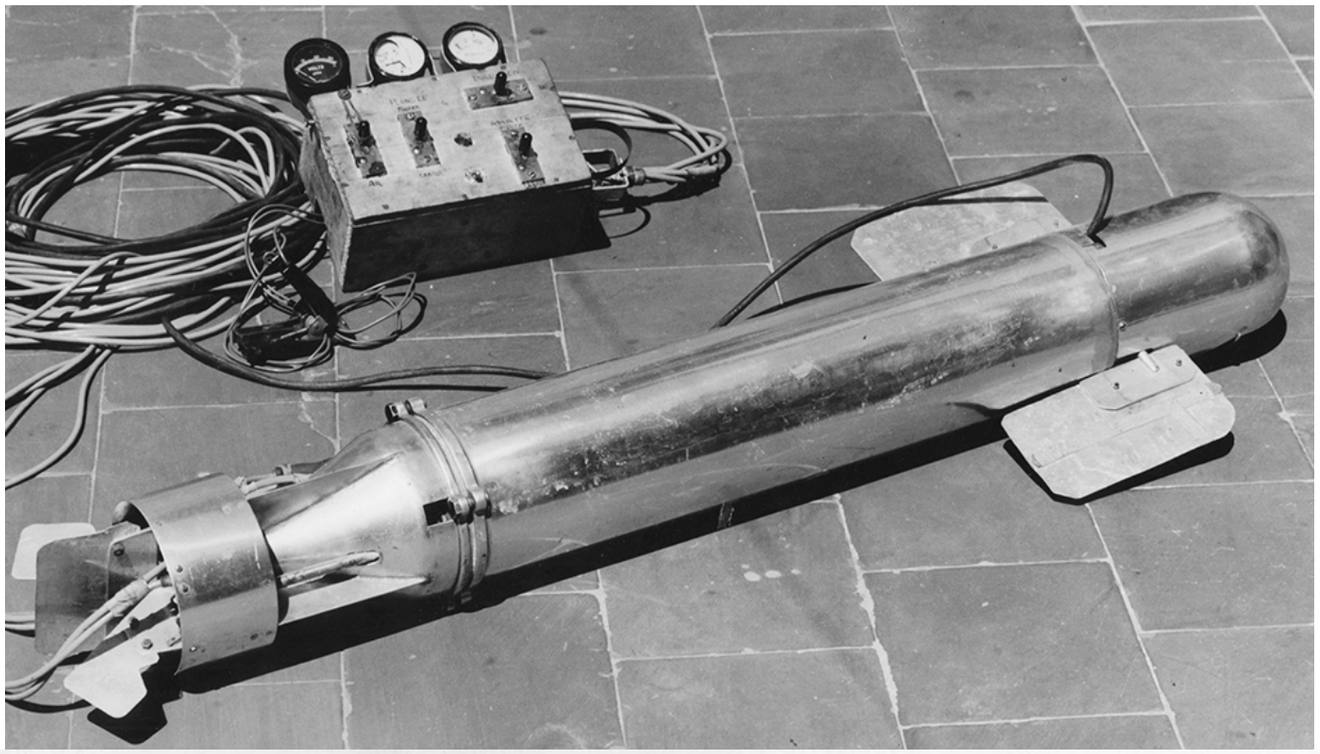
Discovery of hydrothermal vents
Galapagos Spreading Center- 1977



Discovery of TITANIC
North Atlantic - 1985

The start of a revolution - from submarines to robots

1st remotely operated vehicle
ROV POODLE (1953)



French adaptation of scuba scooter for imaging

Operated through cables

1st autonomous underwater vehicle
AUV SPURV (1957)

US Navy, oceanography
(temperature currents)

The start of a revolution - from submarines to robots

AUVs: More specialised and less democratized than ROVs - Survey and characterization of ocean seafllor and the water mass above

The start of a revolution - from submarines to robots

Acoustic surveys (bathymetry, sonar) & optical (camera, video, laser)

Physicochemical sensors (T, pH, turbidity, O2, chlorophyle, currentmeters…)

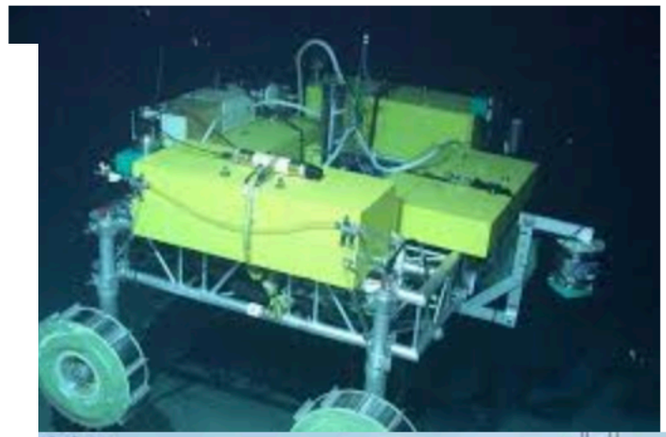
Expert sensors (e.g., plankton samplers, eDNA…)

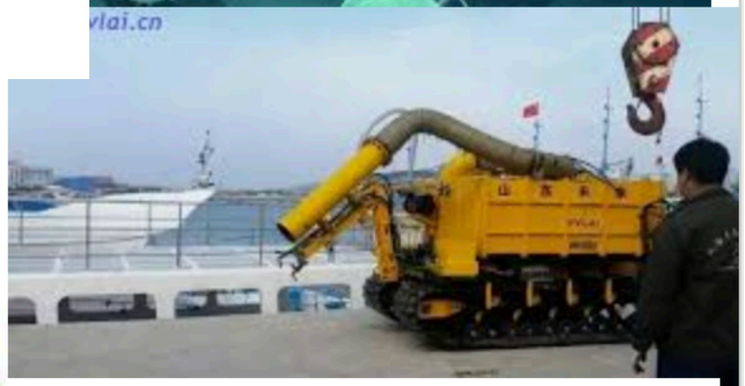
Navigation ~3-5 knots

AUVs: More specialised and less democratized than ROVs - Survey and characterization of ocean seafllor and the water mass above

The start of a revolution - from submarines to robots

Tethered: Limits speed to ~2 knots max - but access to data onboard
Unlimited power supply
Acoustic surveys (bathymetry, sonar) -> inefficient
Imaging -> Photomosaic and 3D reconstructions (camera, video)
Manipulators -> sampling, installation/recovery of instrumentation
All kinds of sensors & equipment (physical, chemical, samplers…) ->

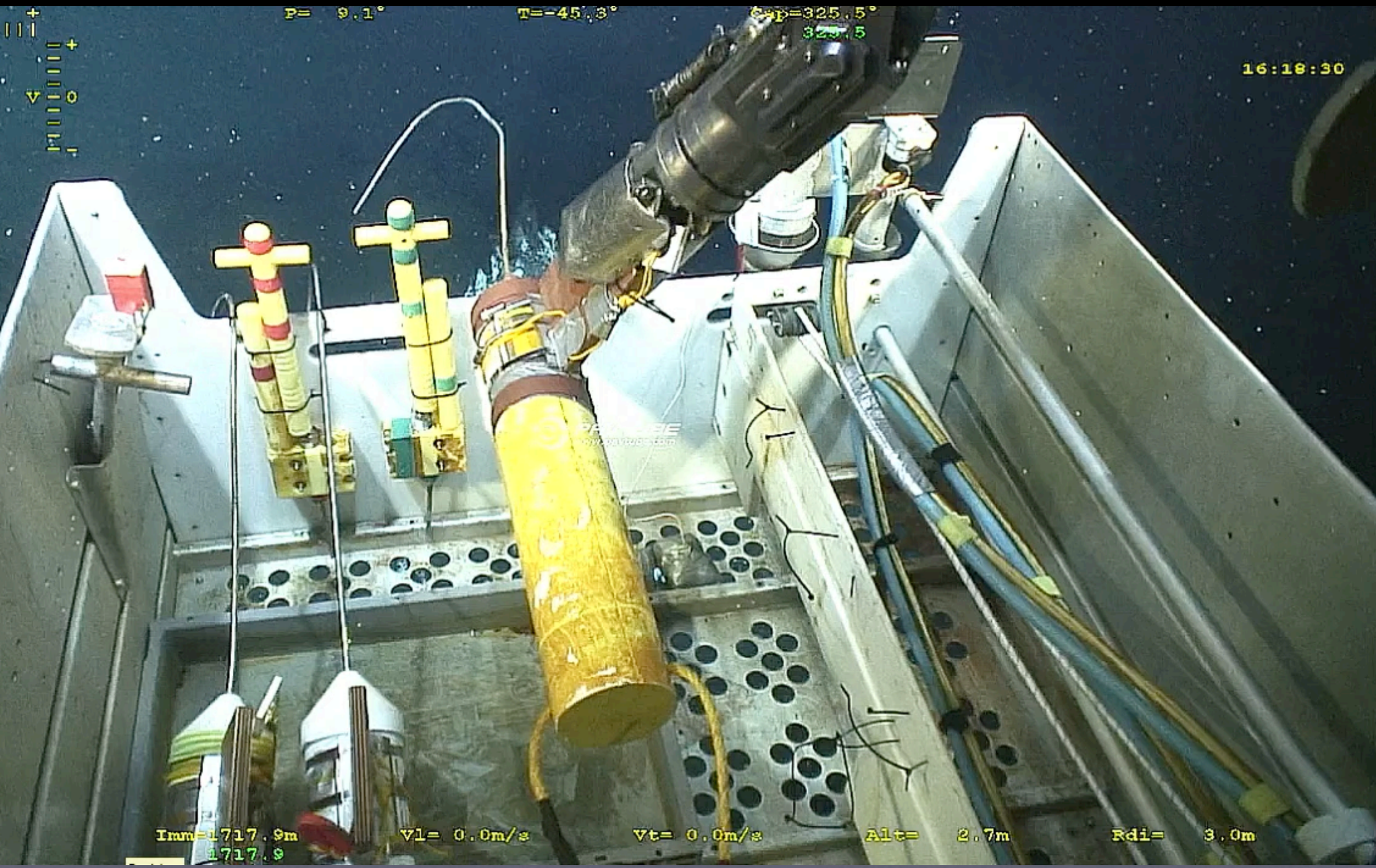




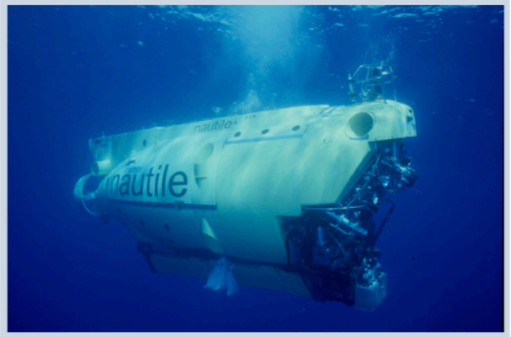
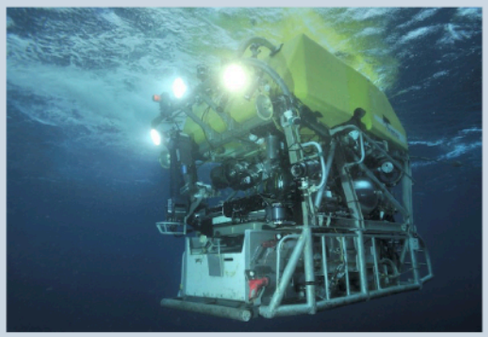
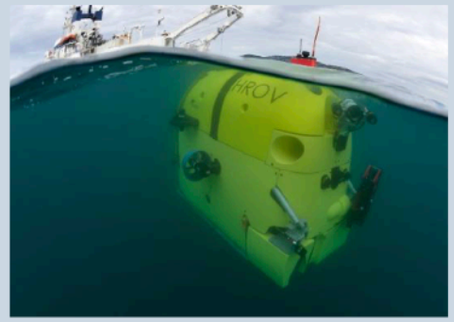
ROVs: Industrial revolution

Lucky Strike hydrothermal field (1700 m)

ROV VICTOR 6000



French Oceanographic Fleet (FOF) capacities for deep sea exploration

Nautile	Victor6000	UlyX	Ariane	Aster^{X} & Idef^{X}
				
				
Sous-marin habité	ROV	AUV	Hybrid ROV	AUV
6000m	**6000m**	**6000m**	2500m	3000m
depuis 1984	depuis 1997	Entrée en flotte prévue 2024	depuis 2017	depuis 2005
Exploration Intervention	Exploration Intervention Cartographie	Survey longue distance, inspection près du fond	Exploration Intervention Cartographie	Survey cartographique

What do we know about the ocean seafloor?

Mapped ~25% of the seafloor….

… but what have we seen of the seafloor?

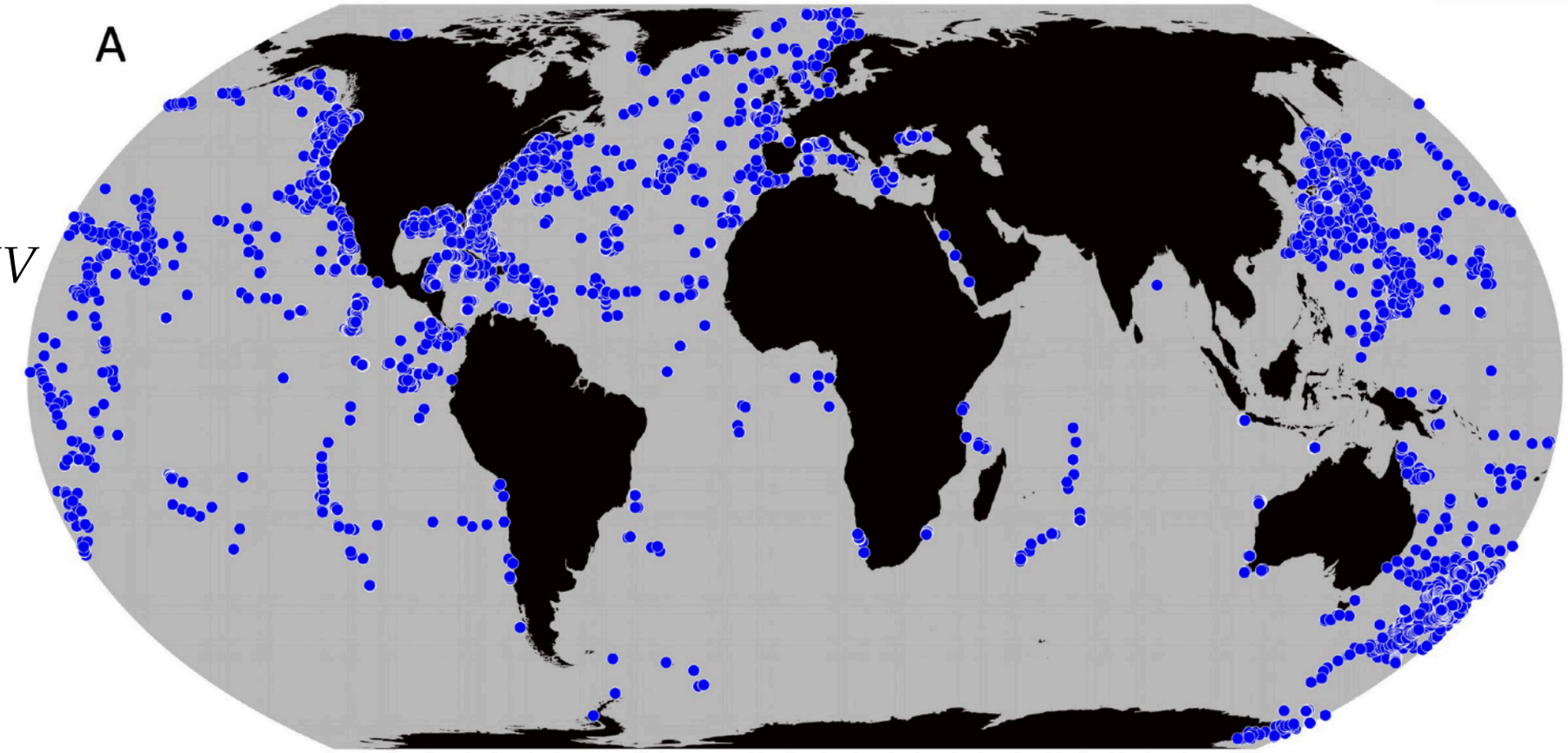
Satellites - up to 20 m waterdepth - limited resolution

Human diving -> limited in depth - few tens of m

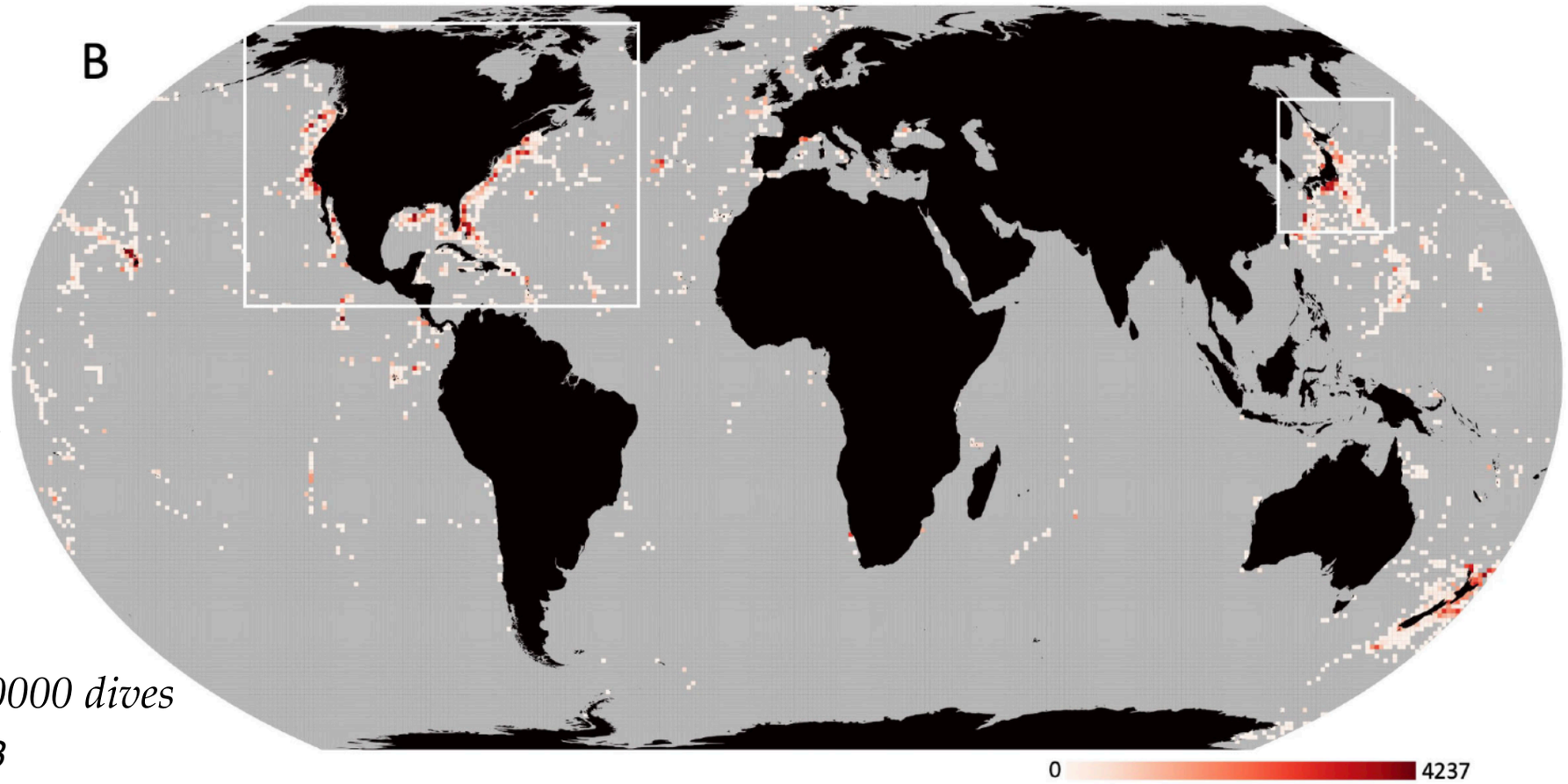
ROVs & AUVs?

What do we know about the ocean seafloor?

ROV+AUV dive sites



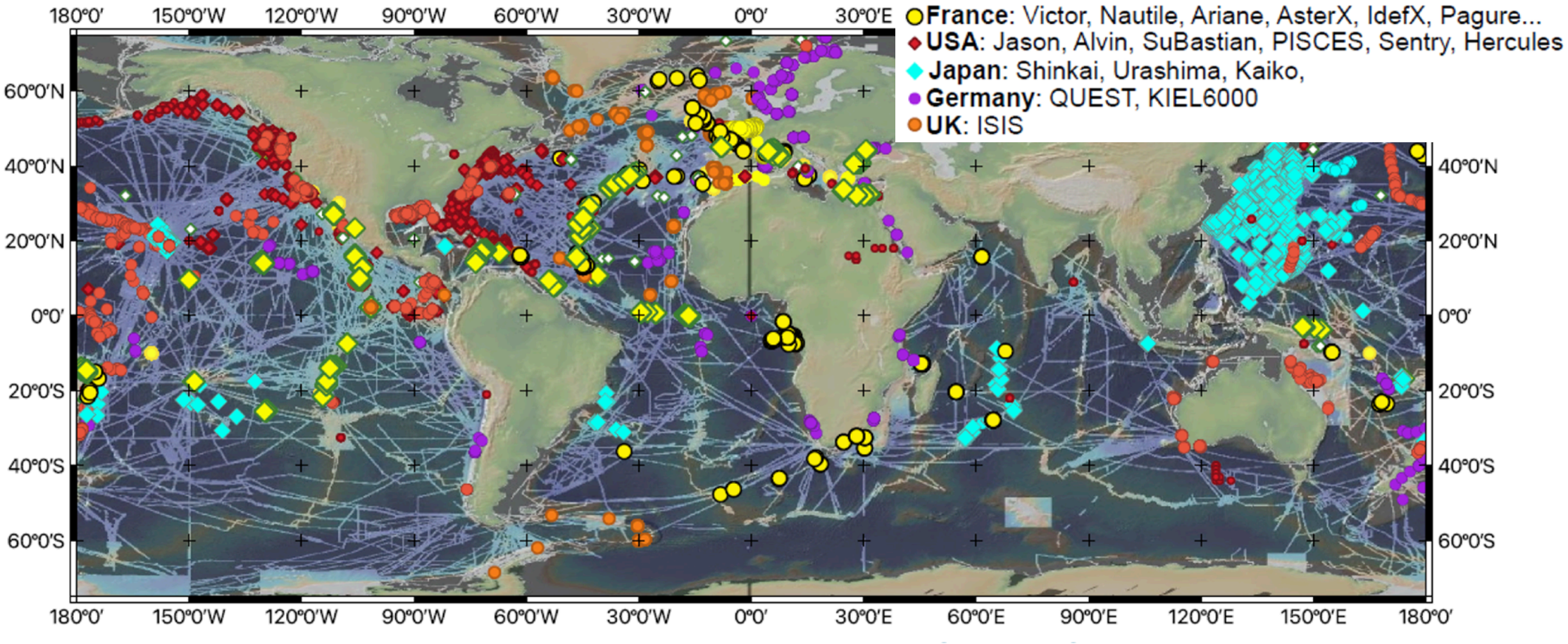
ROV+AUV number of dives per 100x100 km



Compilation of ~40000 dives

Kennedy et al., 2023

What do we know about the ocean seafloor?



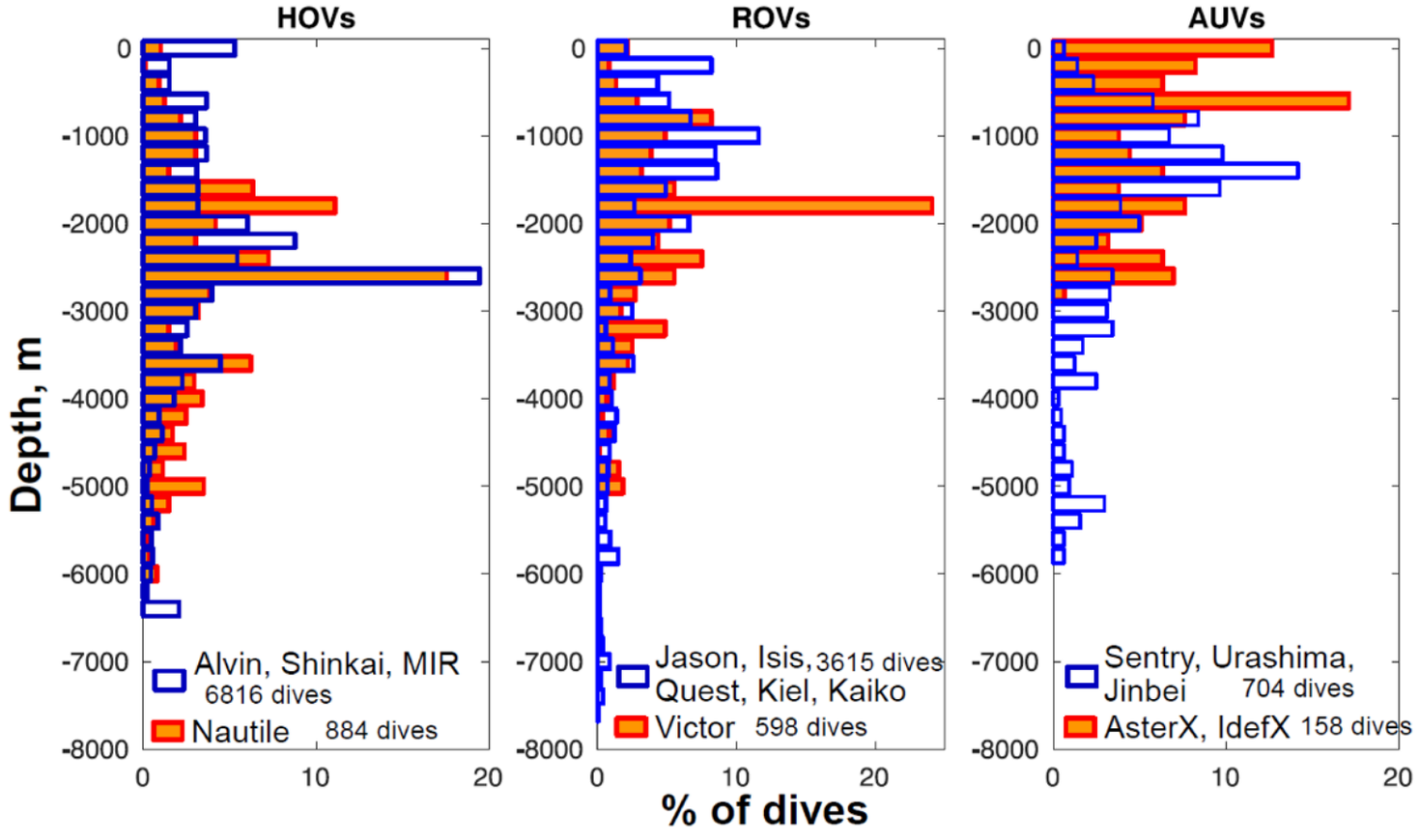
Even with modern technology, deep sea access a and studies is limited

Best-case scenario: ~50000 dives
~0.5 km2 viewed per dive
-> 25000 km2 'seen' vs 680 Mkm2

<0.01% (probably <0.001%) of seafloor images/viewed

>70% of dives at <3000 m

French access to all ocean and depths



The right time

1946: Start of dumping at sea (USA, Pacific)

1957: IAEA -> Advisory group on Ocean Radioactive Waste Disposal

1958: UNCLOS I Conference

1972: London Convention to prevent marine polution by dumping wastes adopted

1975: London Convention impemented, prohibition of high level waste dump

1983: Moratorium on low level waste dumping

1988: Impact assessment - CRESP Program

1993: Russia discloses high level nuclear waste dump (including fuel)

1994: Total prohibition of radioactive waste dump

1995: CRESP Assessment program

1996: London Protocole signed -> all ocean dumping forbidden (with exception)

2019: Mandated assessment (London Convention) - not realized

Preconized: follow up of the dump areas for environmental monitoring/assessment

Containment in barrels designed for ~25 years (plus resistance to impact)

What is the legacy of 40-80 years of waste dumping?

The right time

Preconized: follow up of the dump areas for environmental monitoring/assessment

Containment in barrels designed for ~25 years (plus resistance to impact)

What is the legacy of 40-80 years of waste dumping?

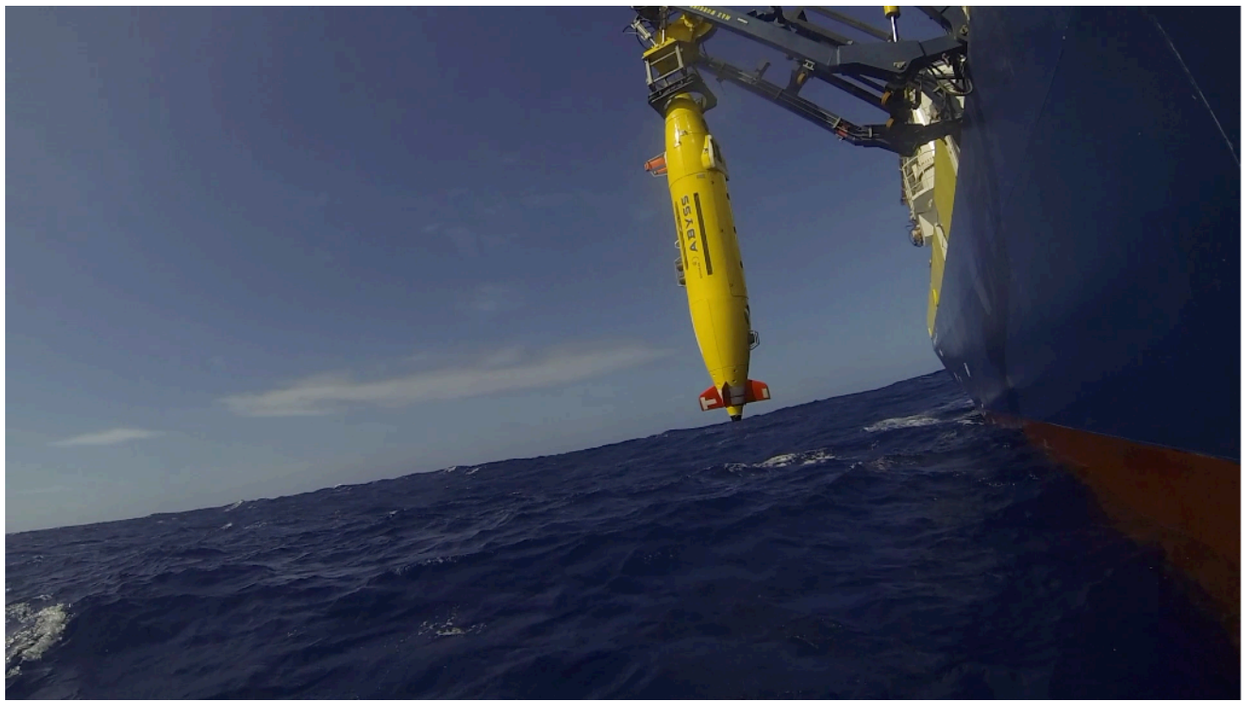
Better understanding of the ocean system at all levels (geology, biology, oceanography…)

We have tools and technology -> ROV, submersibles and AUVs from the FOF

Experience: 20 years of studies at mid-ocean ridges and other geological targets

Studies of environmental impact in ocean floor developping over last decade

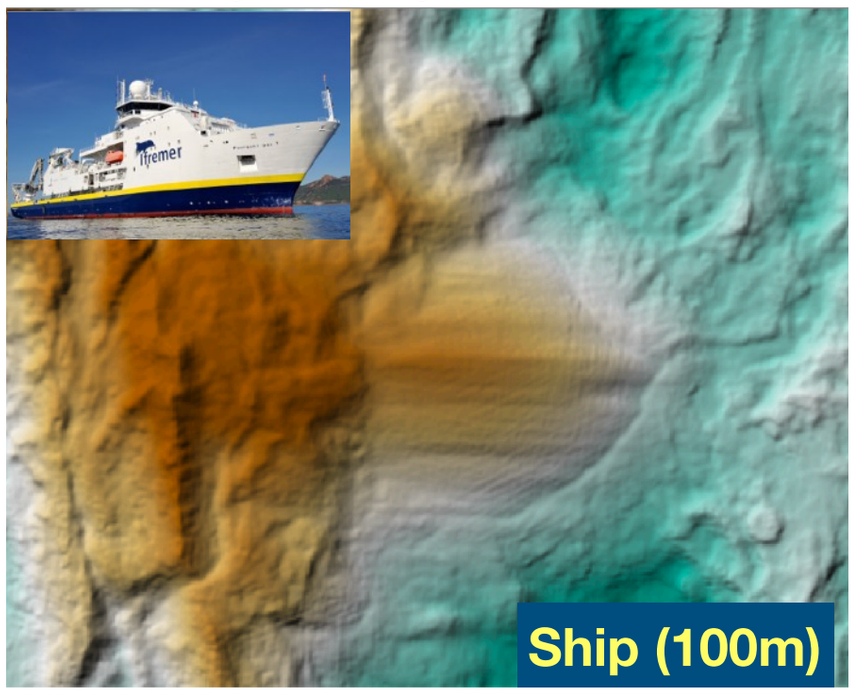
Coupling AUVs with ROVs: target identification & site studies

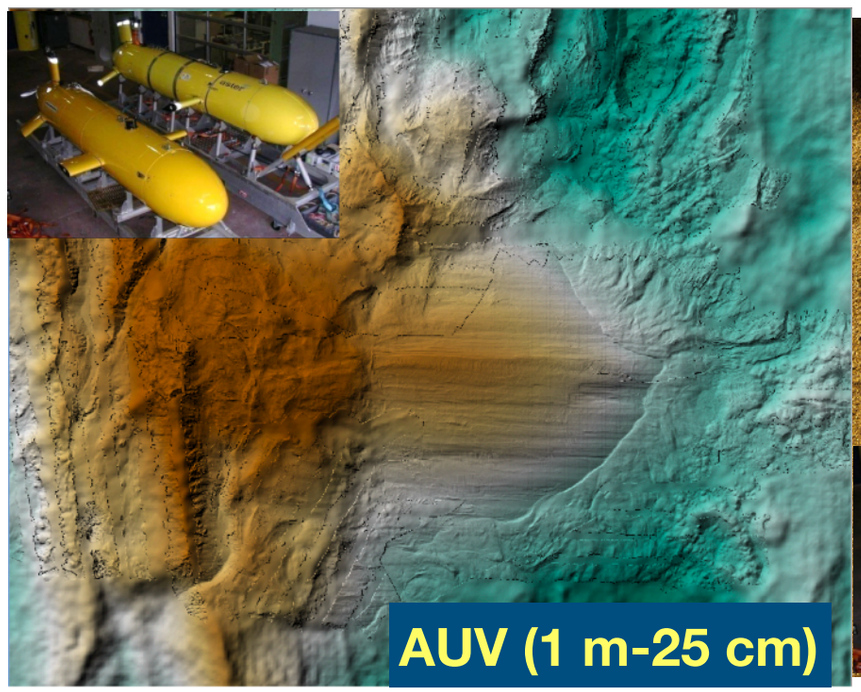


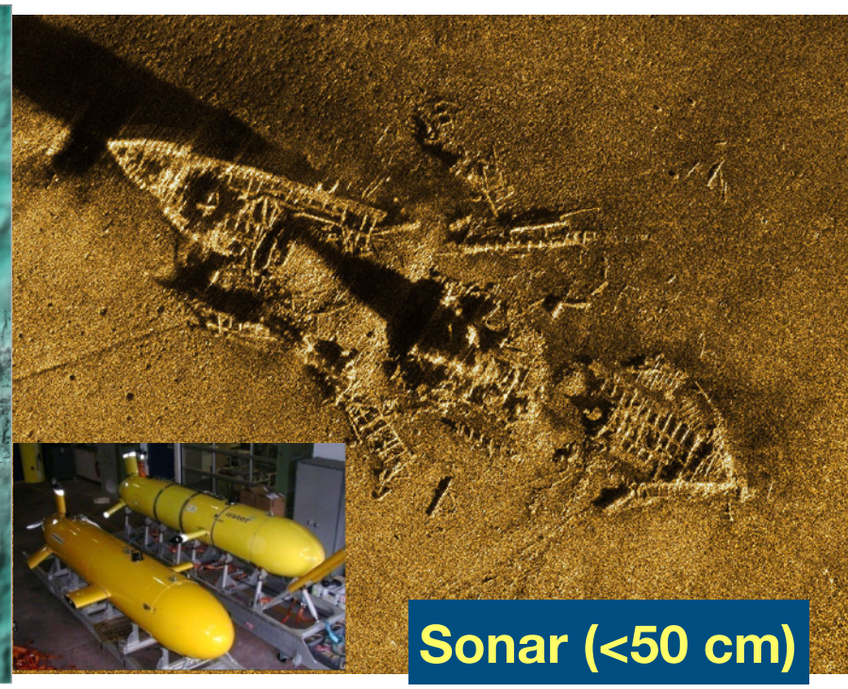
Coupling AUV mapping and ROV observations

Bathymetry: 10's km, 1m resolution

Sonar: 100's m, 0.1m resolution





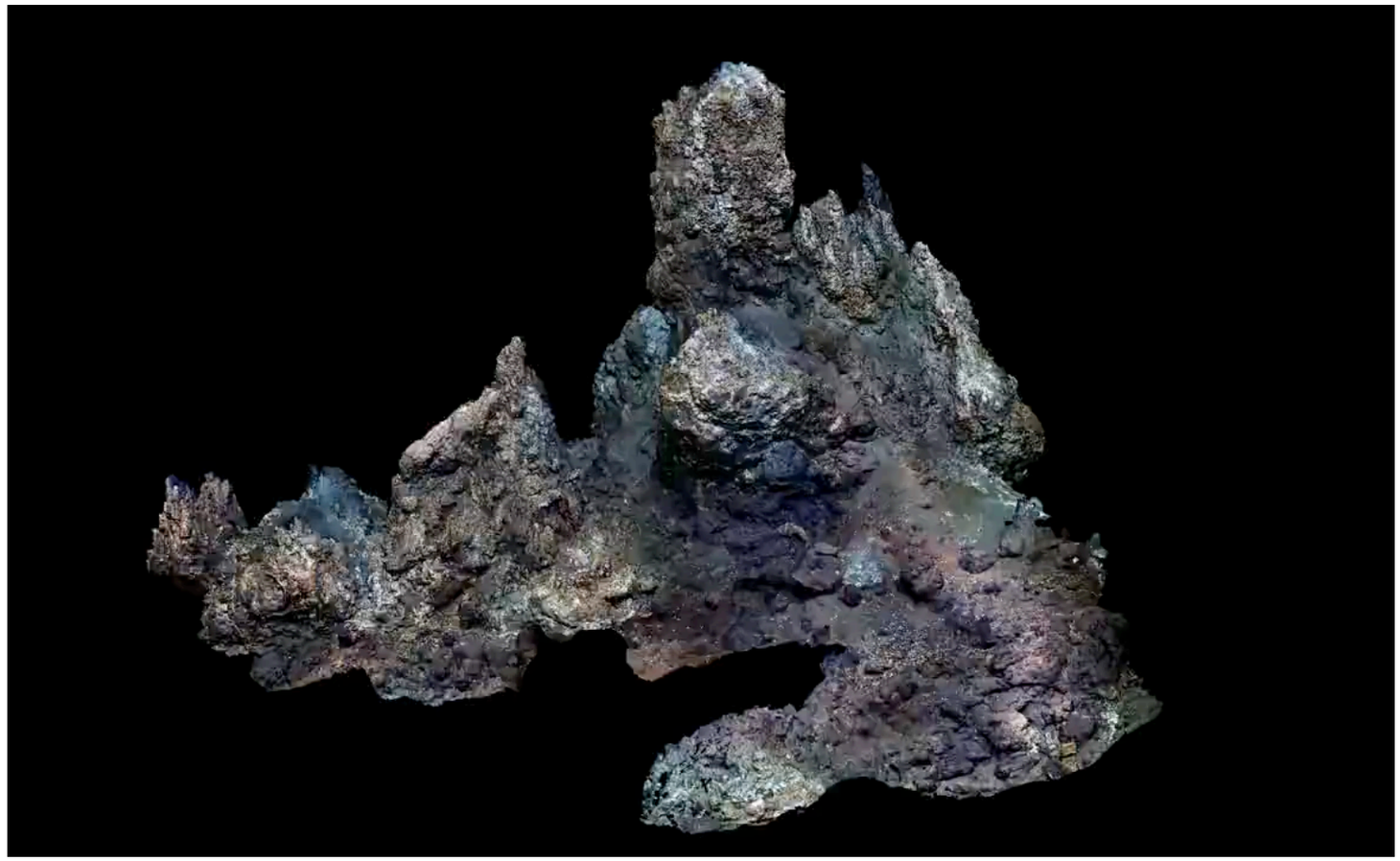


2.5 km

AUV/ROV coupling:
Span all spatial scales for work at seafloor

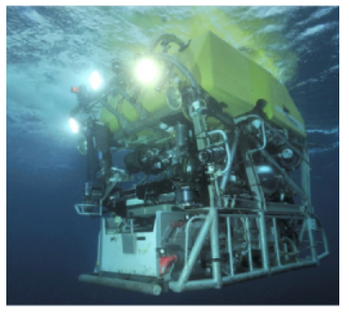
Needed to target sites of interest

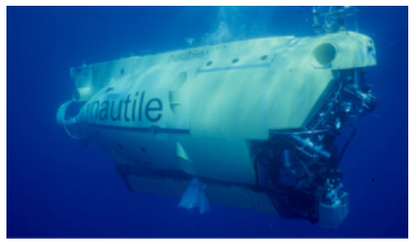
Systematic & comprehensive seafloor mapping impossible



Tour Eilffel Hydrothermal vent, Mid-Atlantic Ridge - ~20 m high

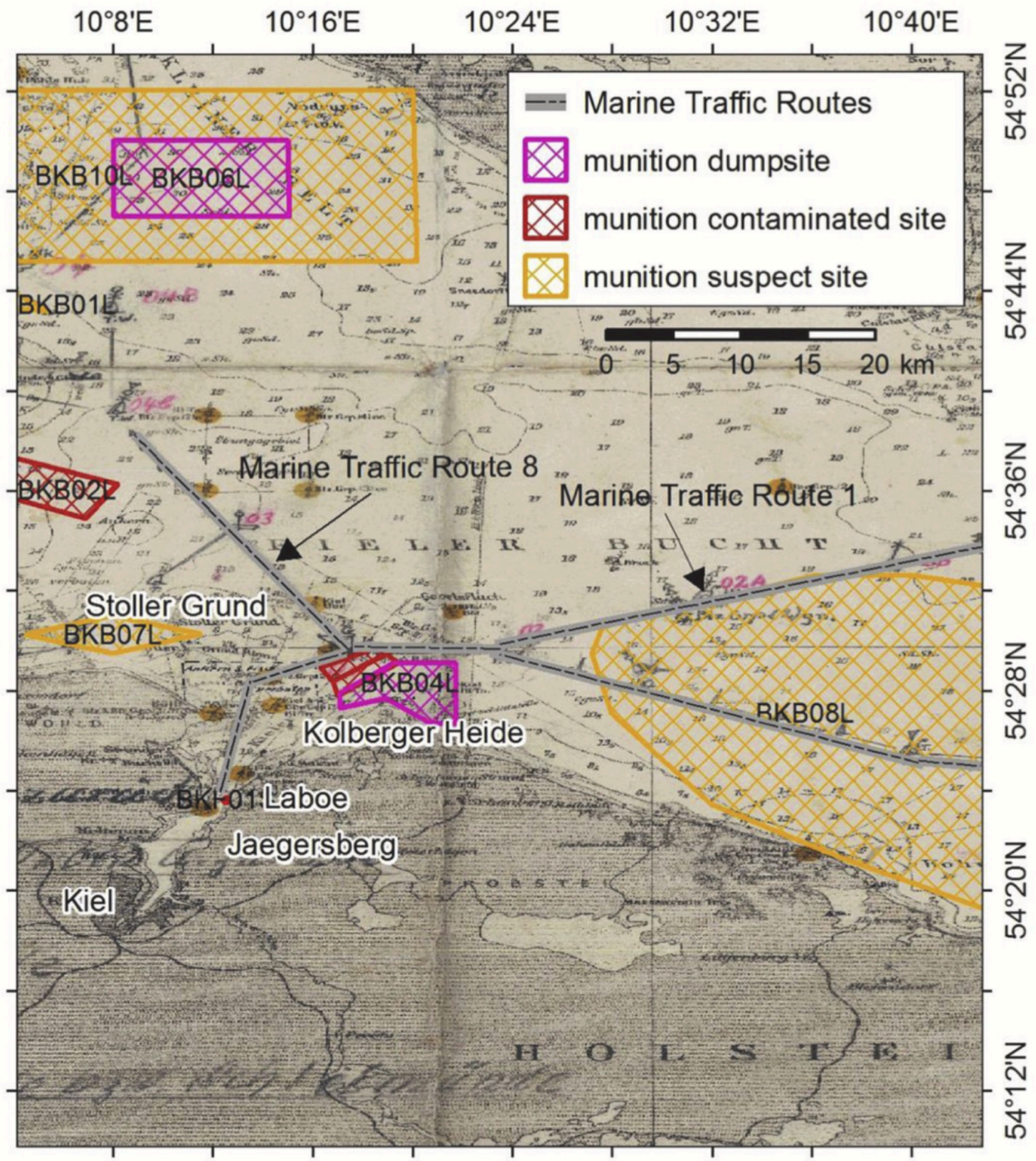
Optical:
10's of m
~1 mm resolution

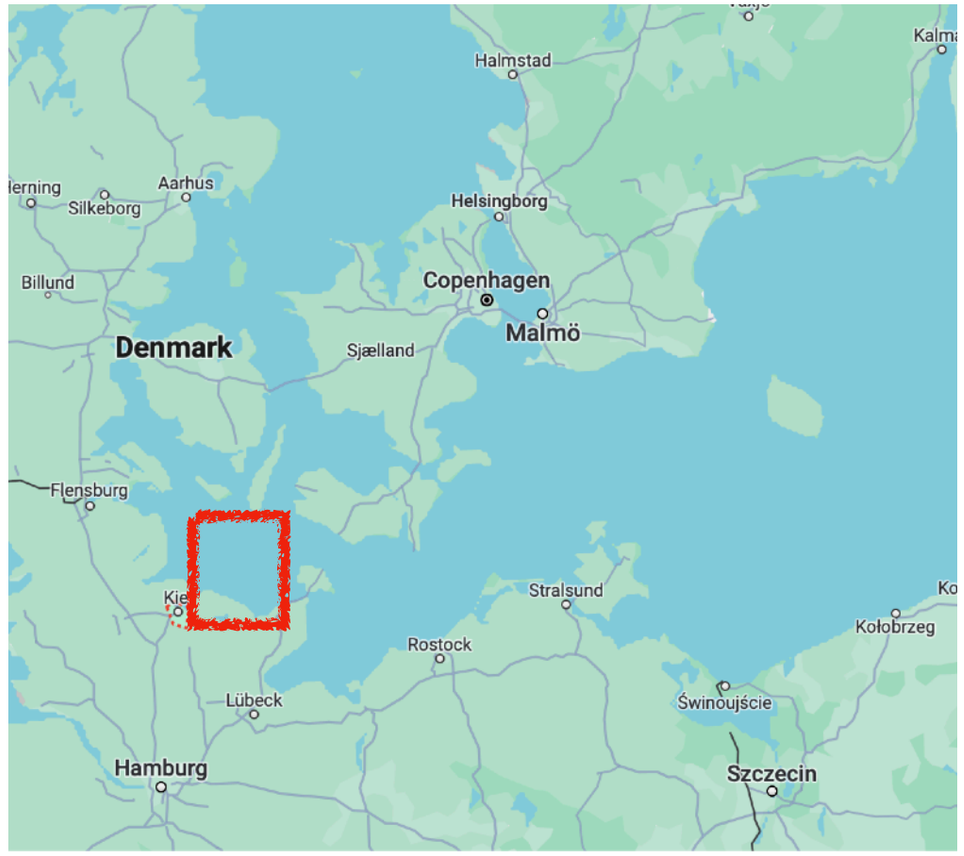




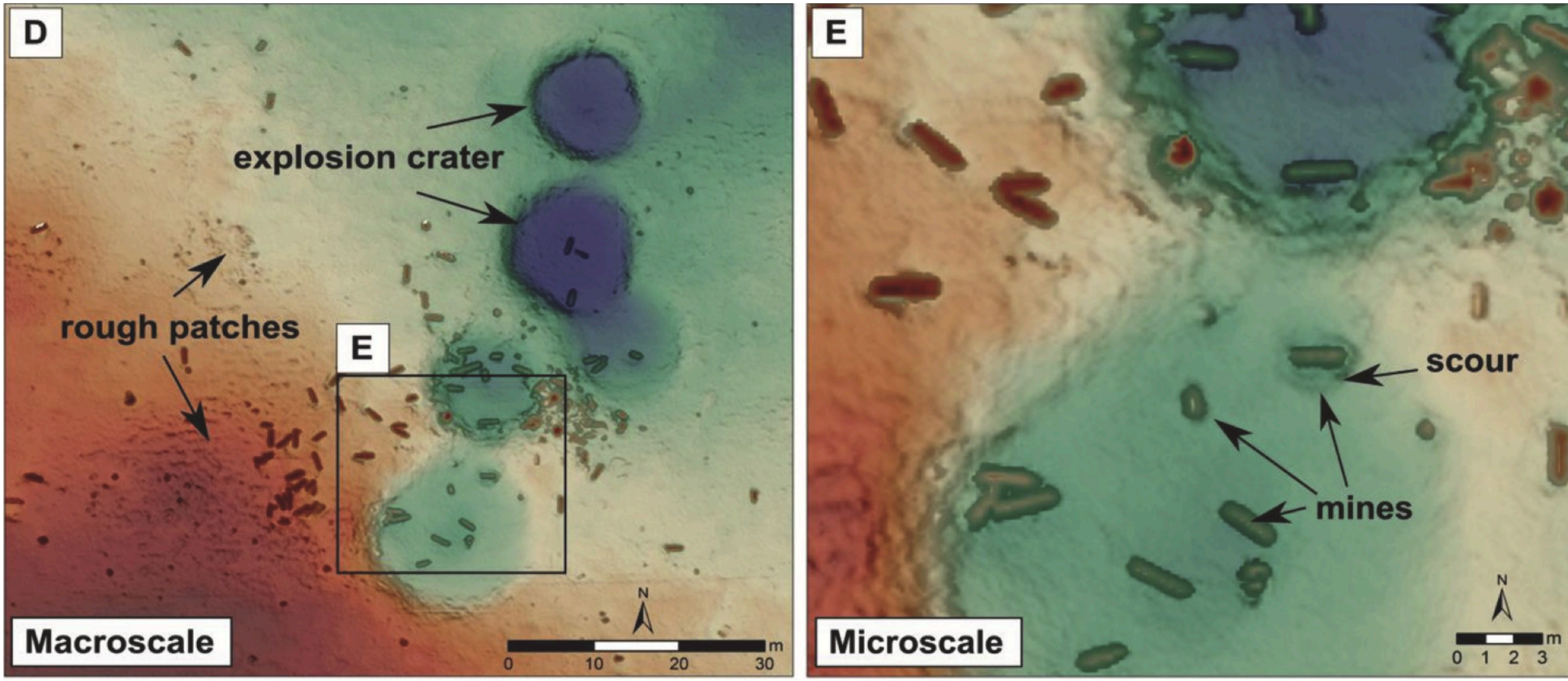
Coupling AUV mapping and ROV observations

Baltic Sea: Munitions at the seafloor



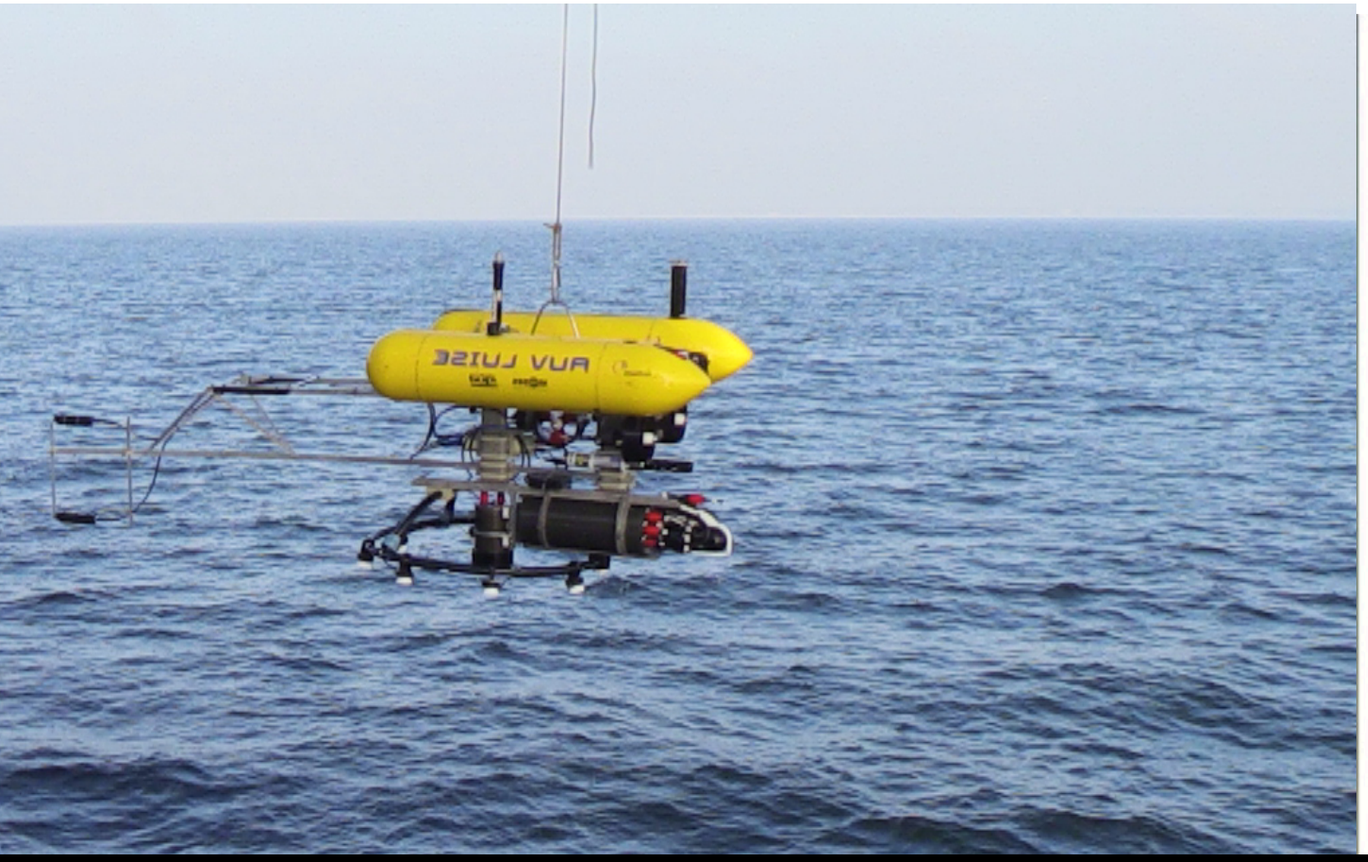


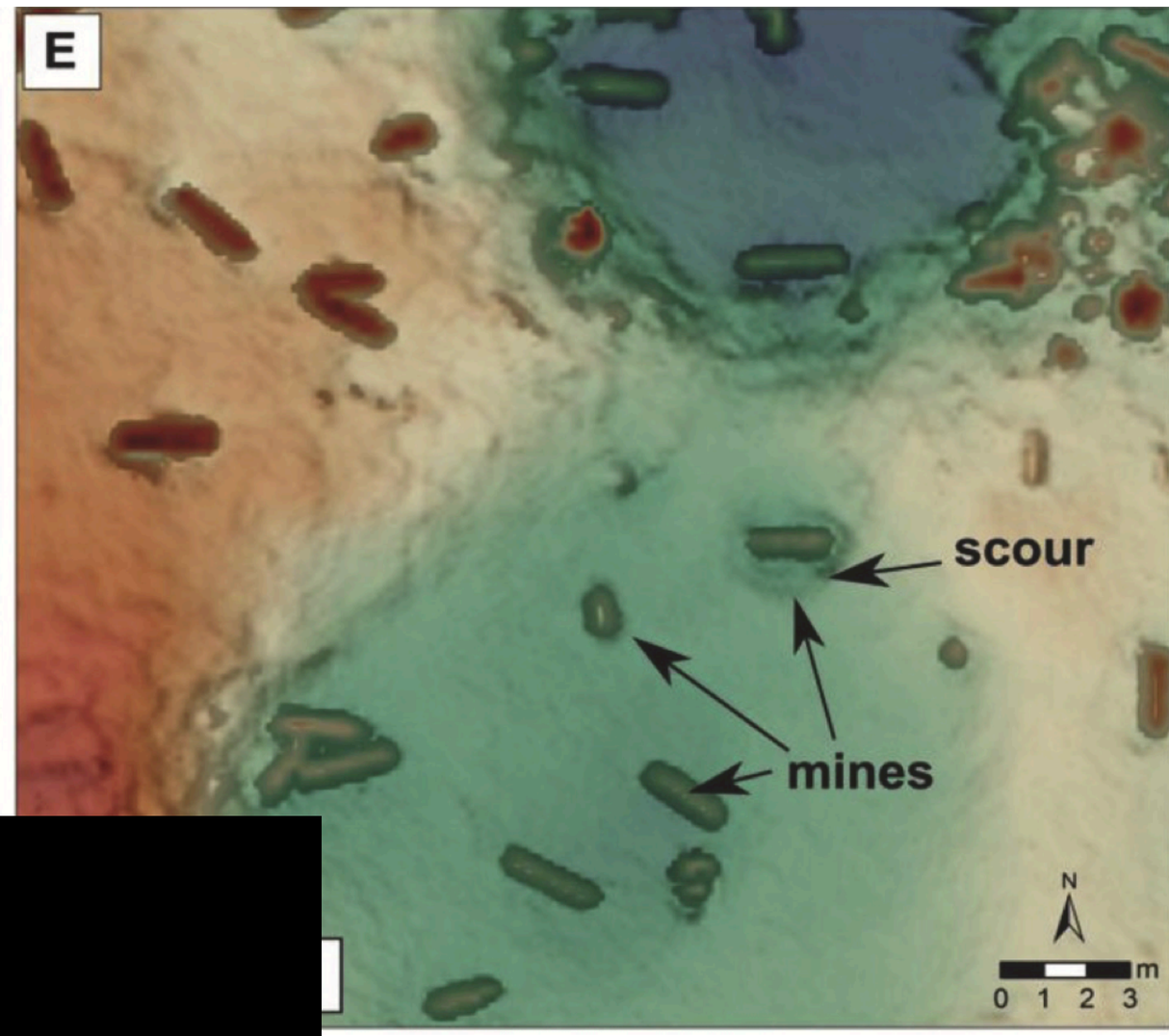
Coupling AUV mapping and ROV observations



High-resolution bathymetry -> explosion craters and munitions

Coupling AUV mapping and ROV observations





Optical mapping: photomosaics and 3D reconstruction

Planning for ordinance removal

The NODSSUM Project

Dumping in all oceans but concentrated in Atlantic and Arctic

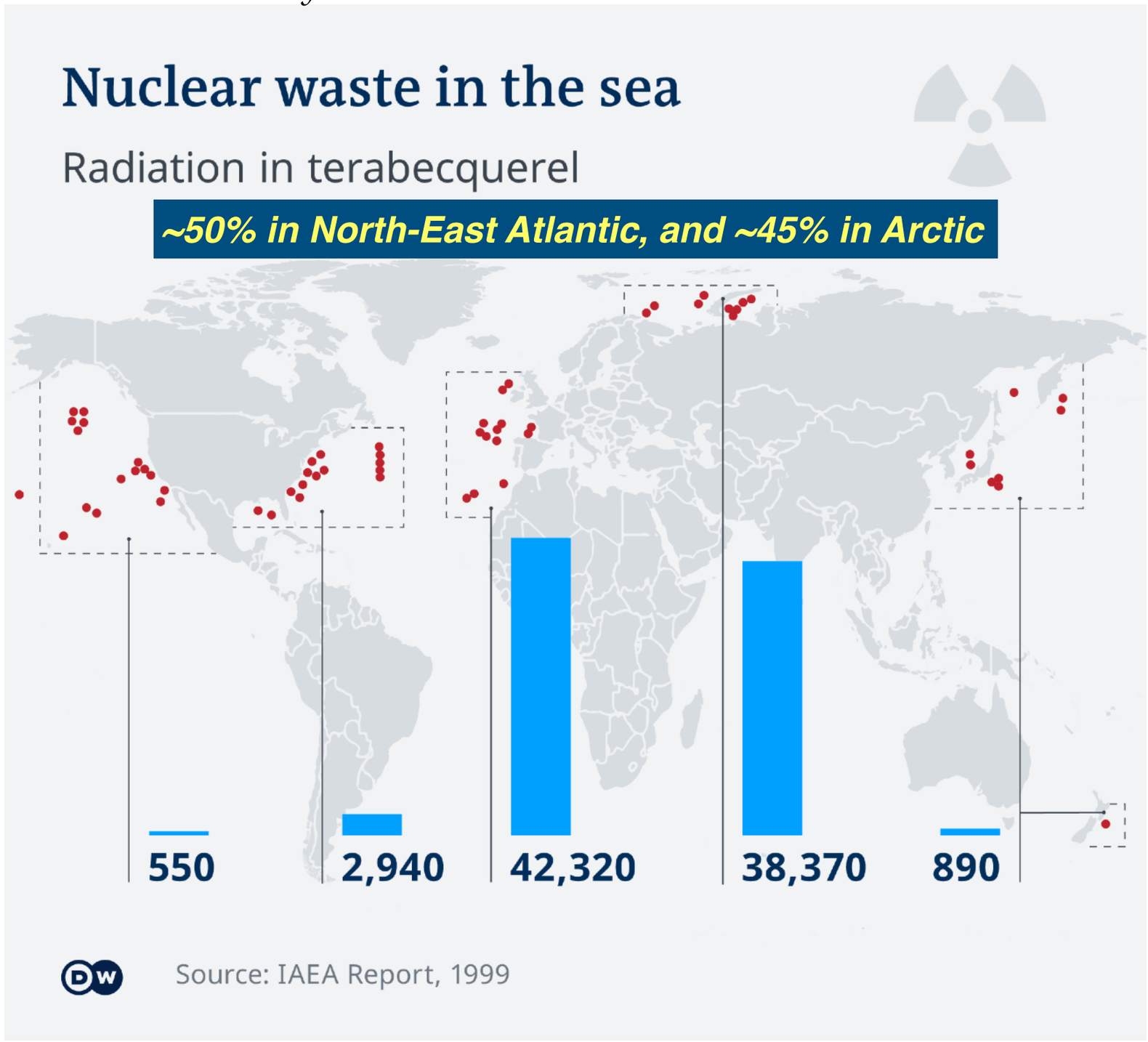
Nuclear waste:

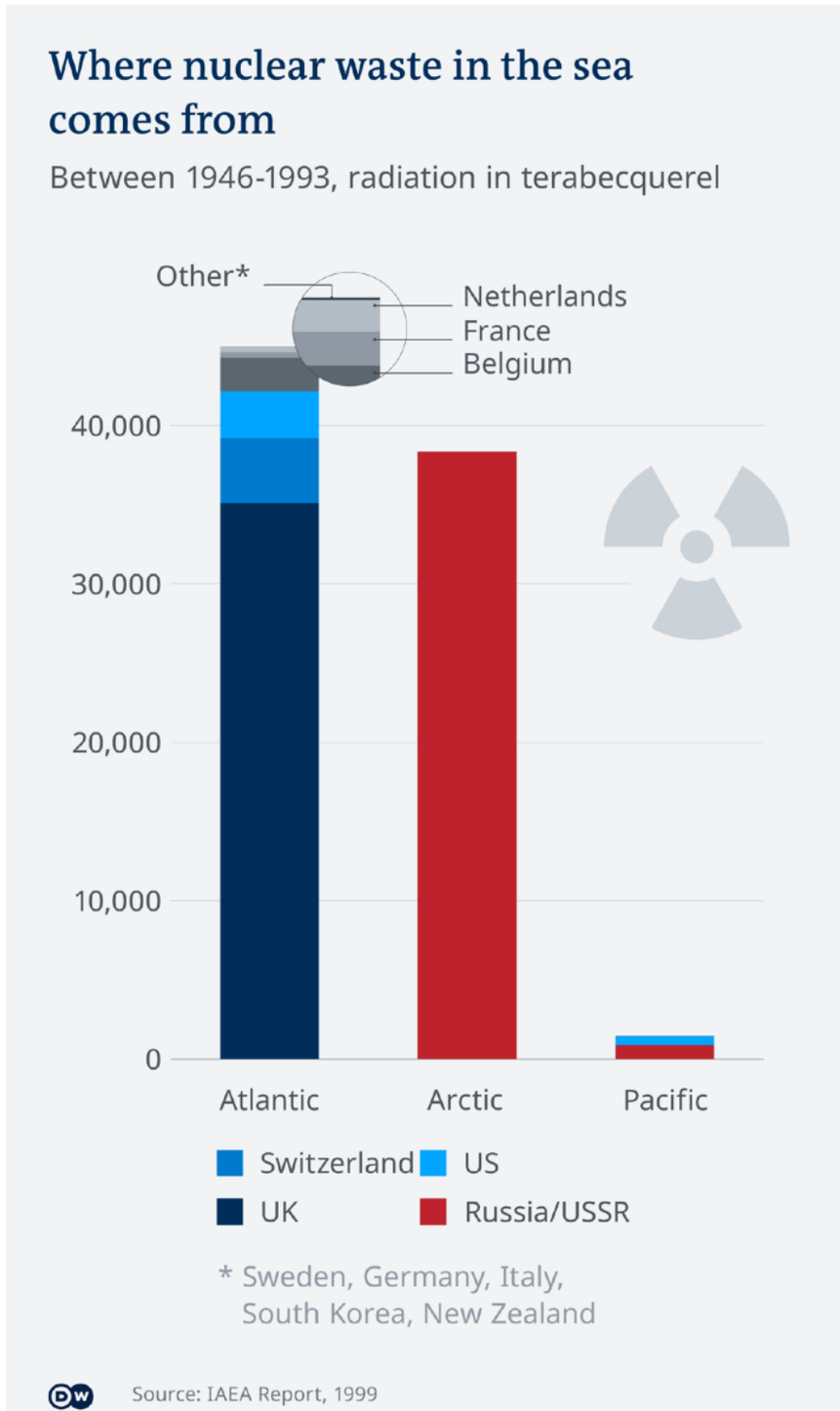
Reported to and coordinated by the International Atomic Energy Agency (IAEA.org)

… except USSR/Russia (late declaration of dumped materials)

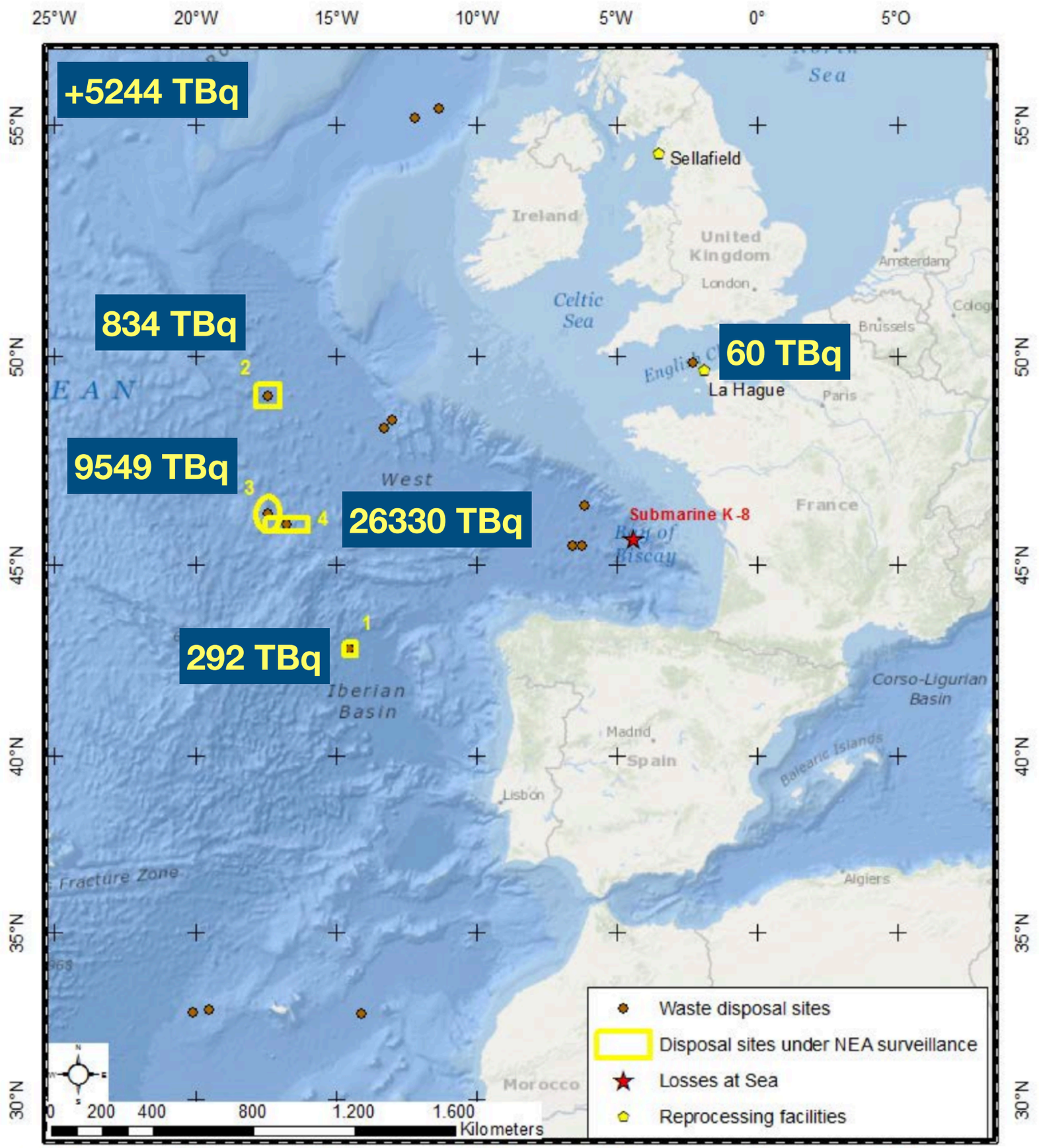
Main sources: UK, USSR (nuclear energy)

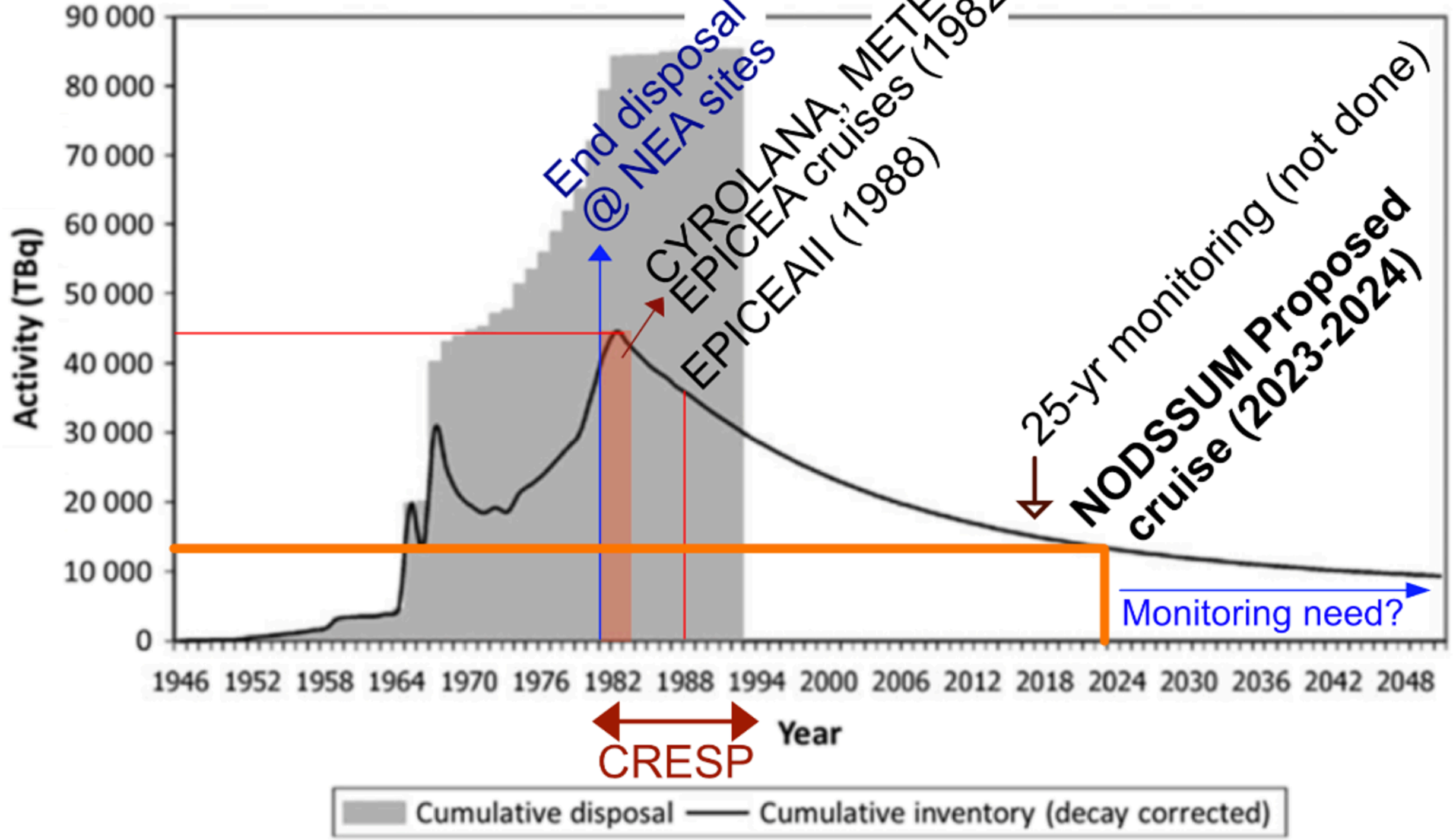
Military nuclear waste: 6 nuclear submarines + atomic warheads (3 USSR, 3 USA)





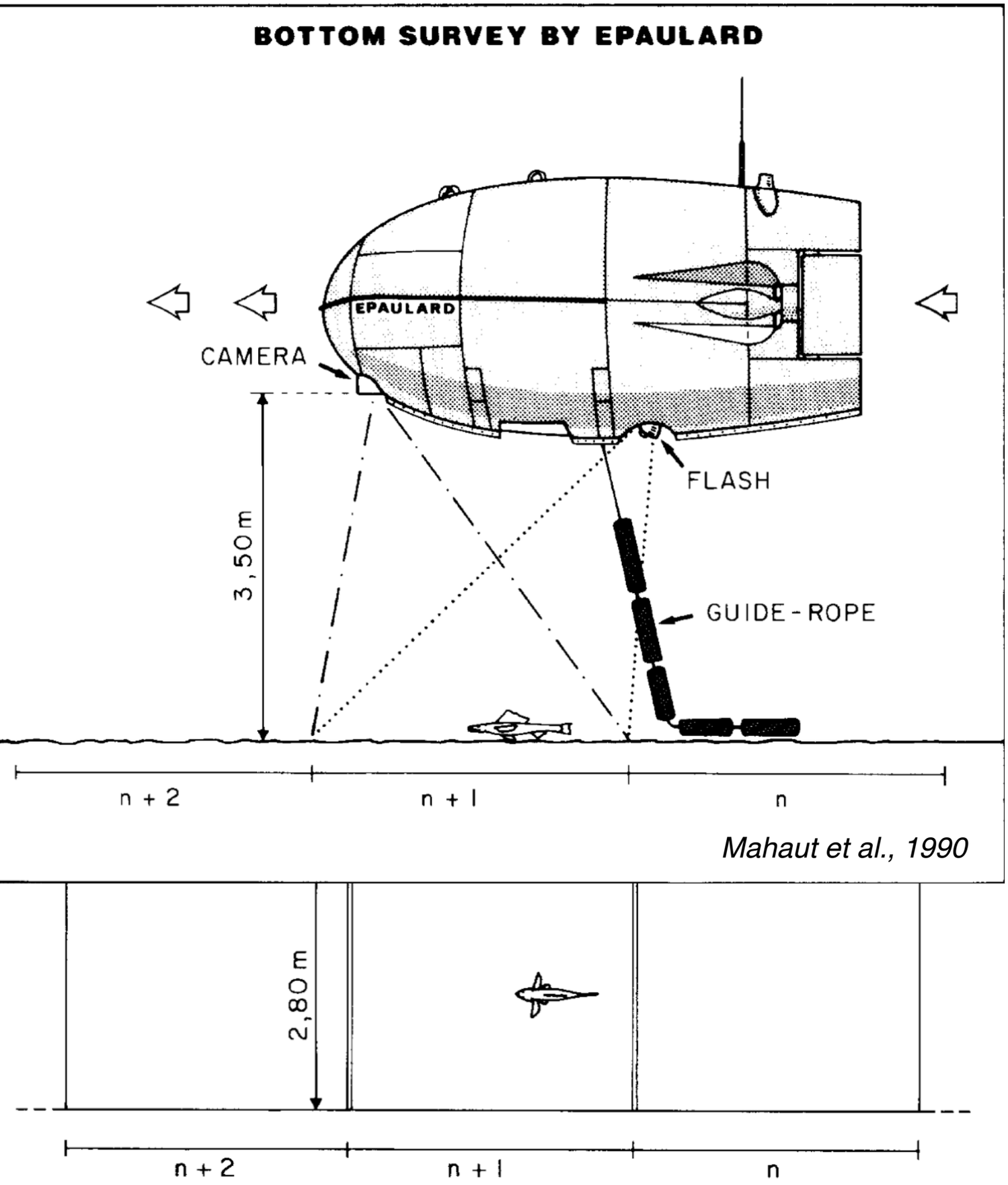
The NODSSUM Project - The North East Atlantic sites




Activity (TBq)
90 000
80 000
70 000
60 000
50 000
40 000
30 000
20 000
10 000
0
1946 1952 1958 1964 1970 1976 1982 1988 1994 2000 2006 2012 2018 2024 2030 2036 2042 2048
Year
End disposal @ NEA sites
CYROLANA, METEOR
EPICEA cruises (1982-84)
EPICEAII (1988)
25-yr monitoring (not done)
NODSSUM Proposed cruise (2023-2024)
Monitoring need?
CRESP
Cumulative disposal
Cumulative inventory (decay corrected)

EPAULAR (IFREMER, 1980) - 1st 6000 m

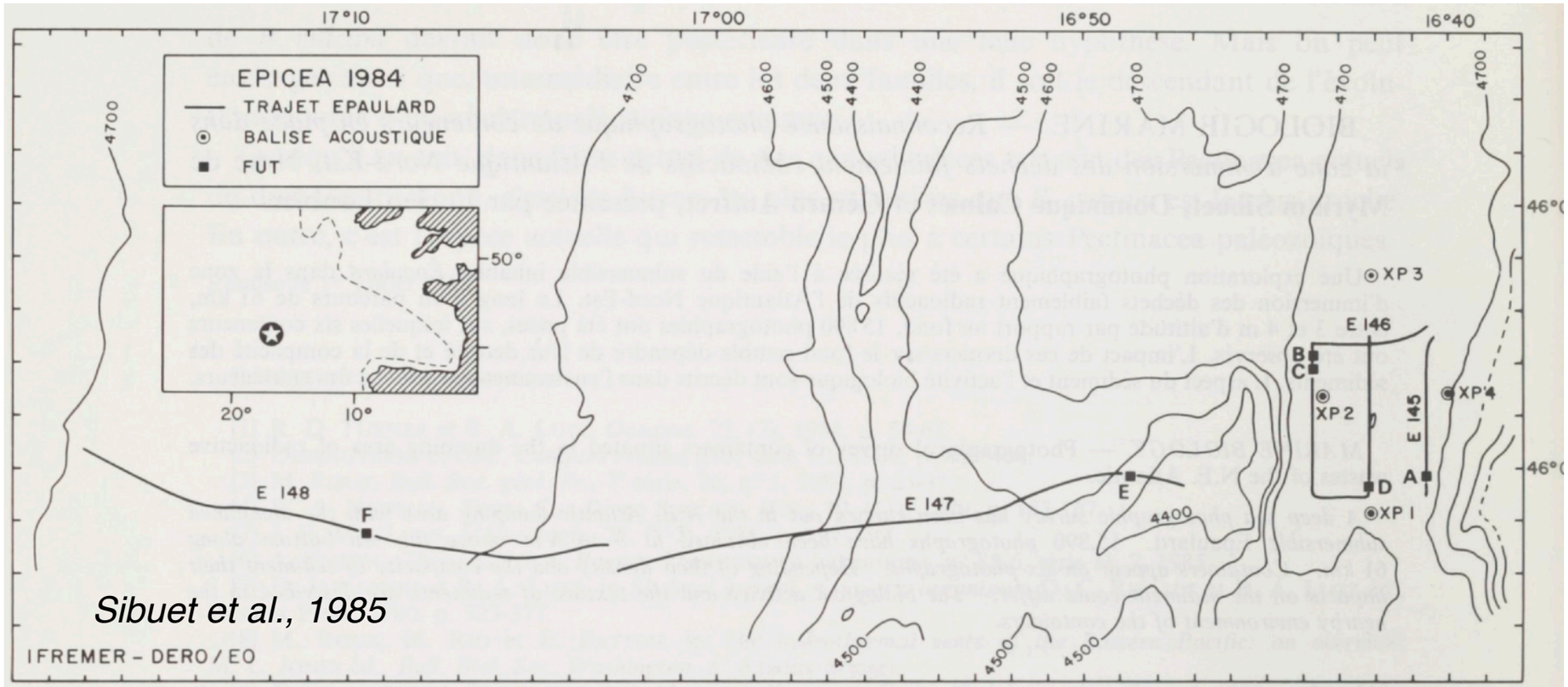
EPAULARD (IFREMER, 1980) - 1st 6000 m



Mahaut et al., 1990

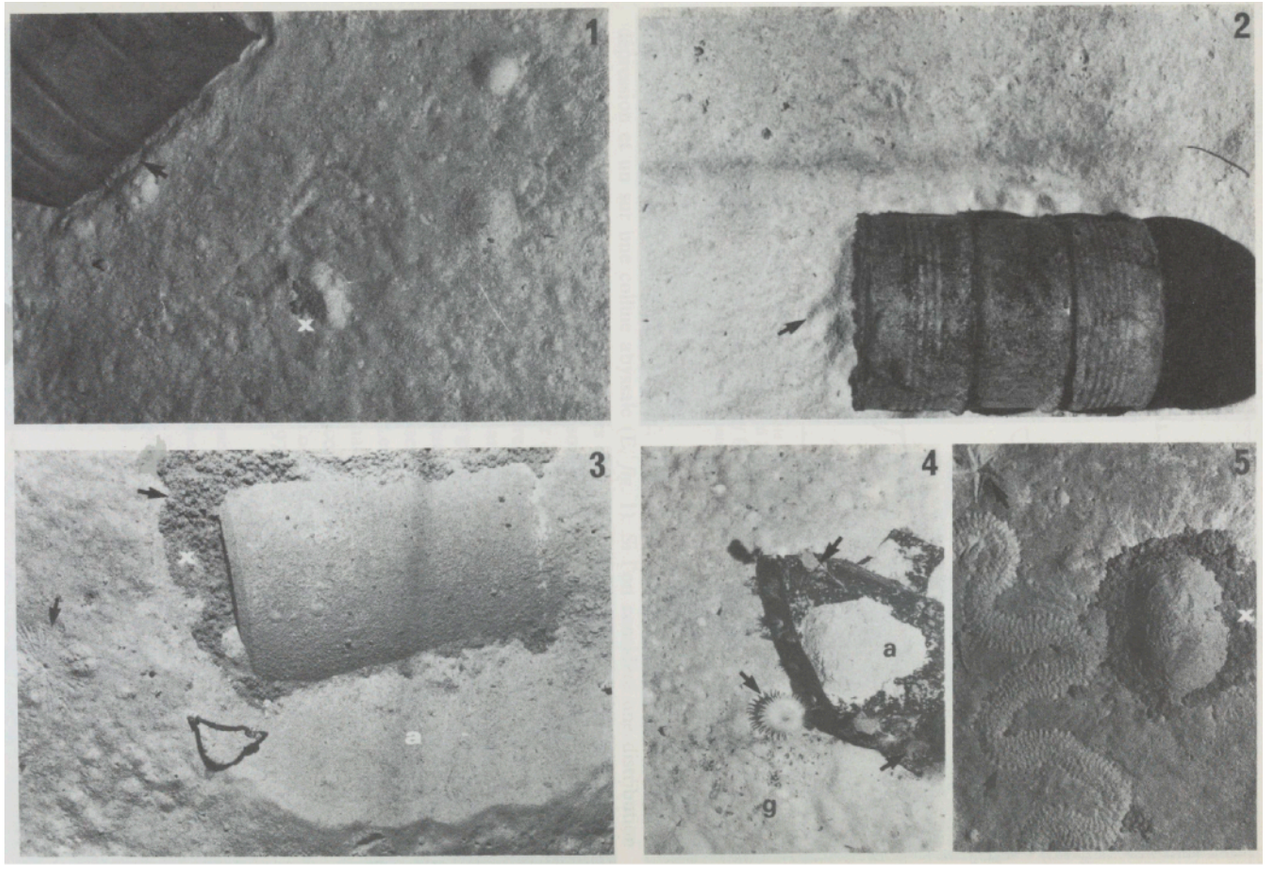
- 6000 m capability -> 1st
- Photography capability -> 1st
- ~35000 photos (film) + strobes
- Navigation ~3-4 m above seafloor -> ‘mechanical’ altimeter (guide rope, trigger of photos by loss of weight)
- Pre-programmed routes without communication to ship

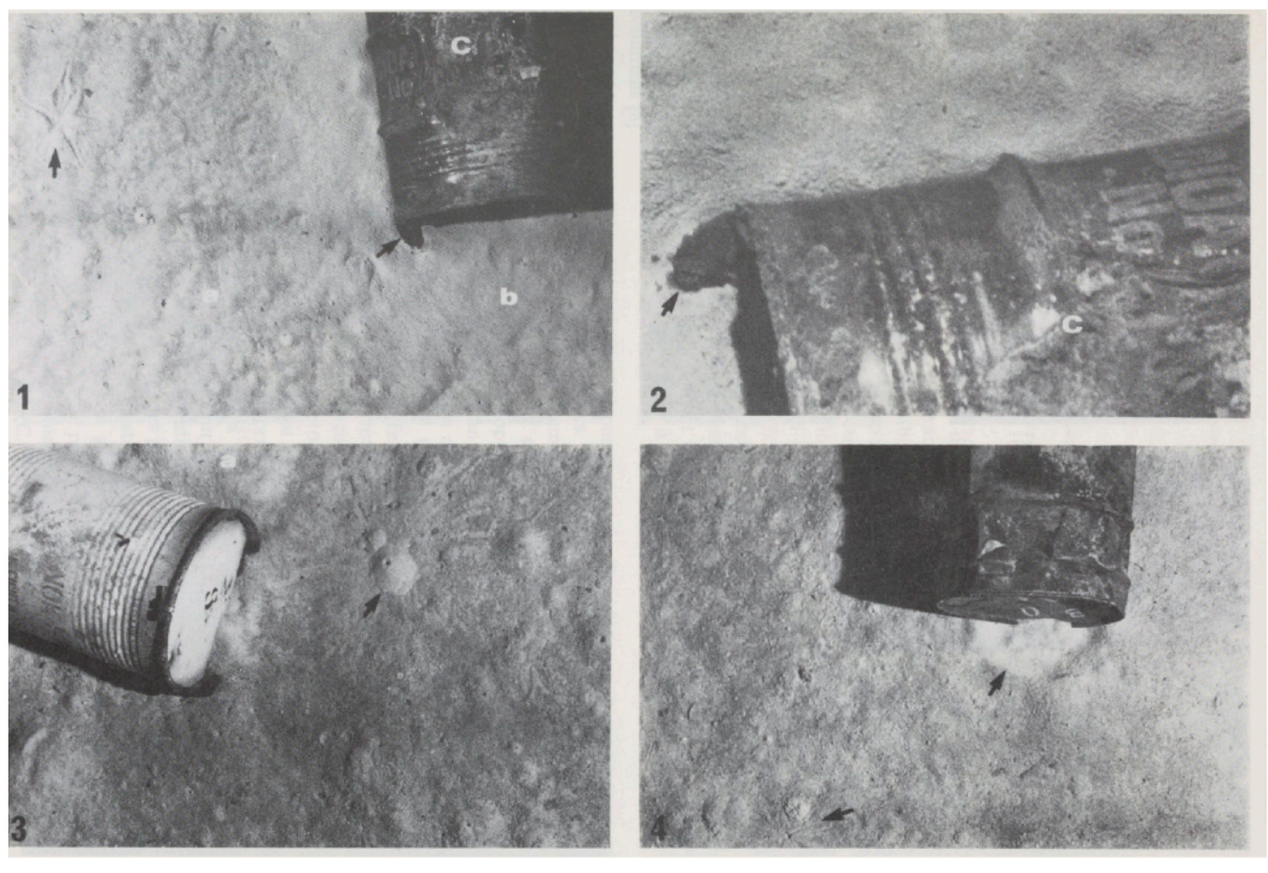
CRESP Monitoring program - EPICEA II Cruise (France)



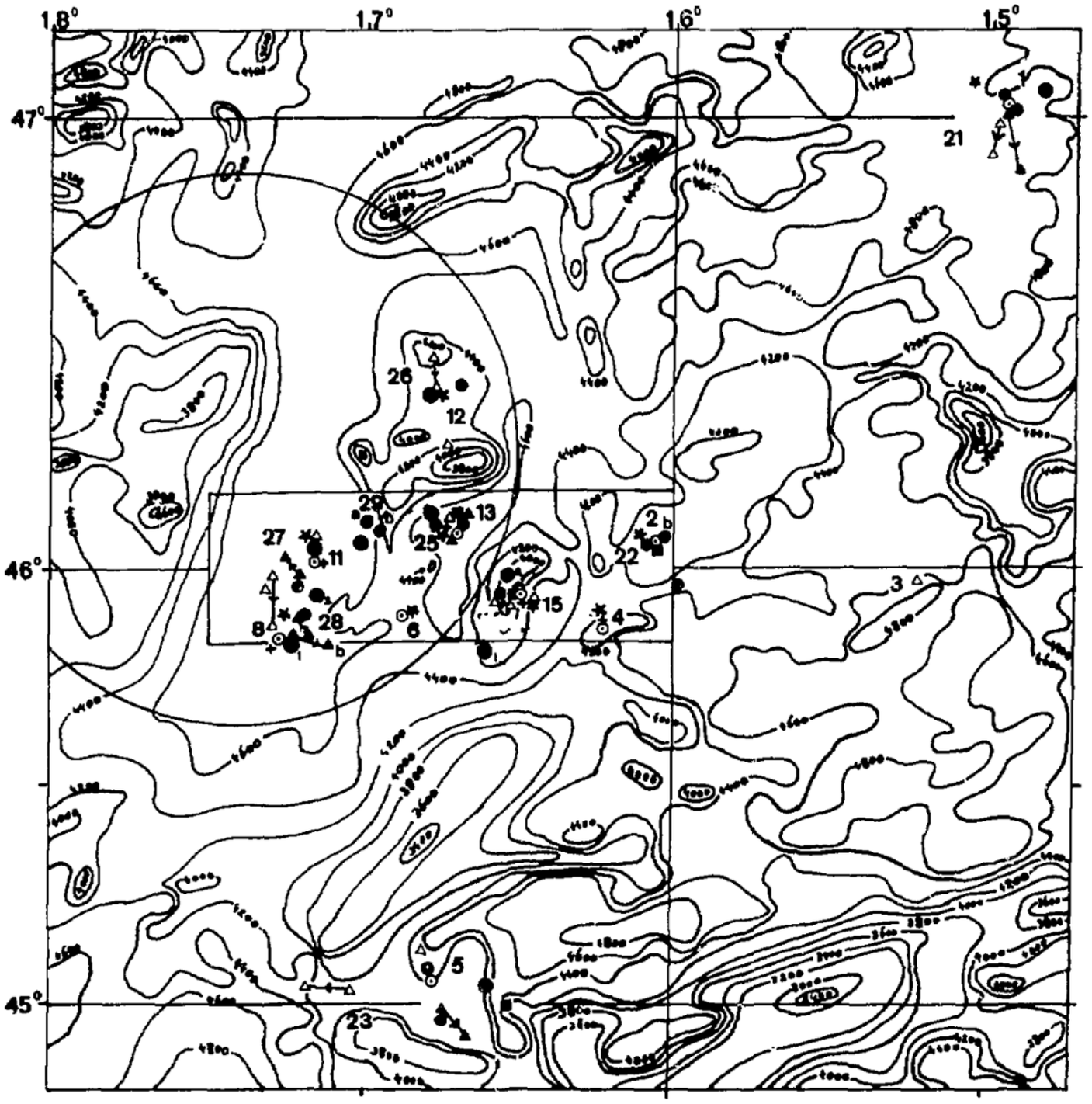
Sibuet et al., 1985

- 4 AUV dives
- 6 barrels photographed
- Evidence of radionucleid leak to environment





CRESP Monitoring program - DORA Program (Netherlands) + Germany



Monitoring pgm CRESP (81-95): Evidence of radionuclide transfer to the environment

Minimal environmental impact

No long term significant impact expected on humans

Monitoring stopped in the 90s

However
Biology & ecosystems of abyssal plain largely unknown

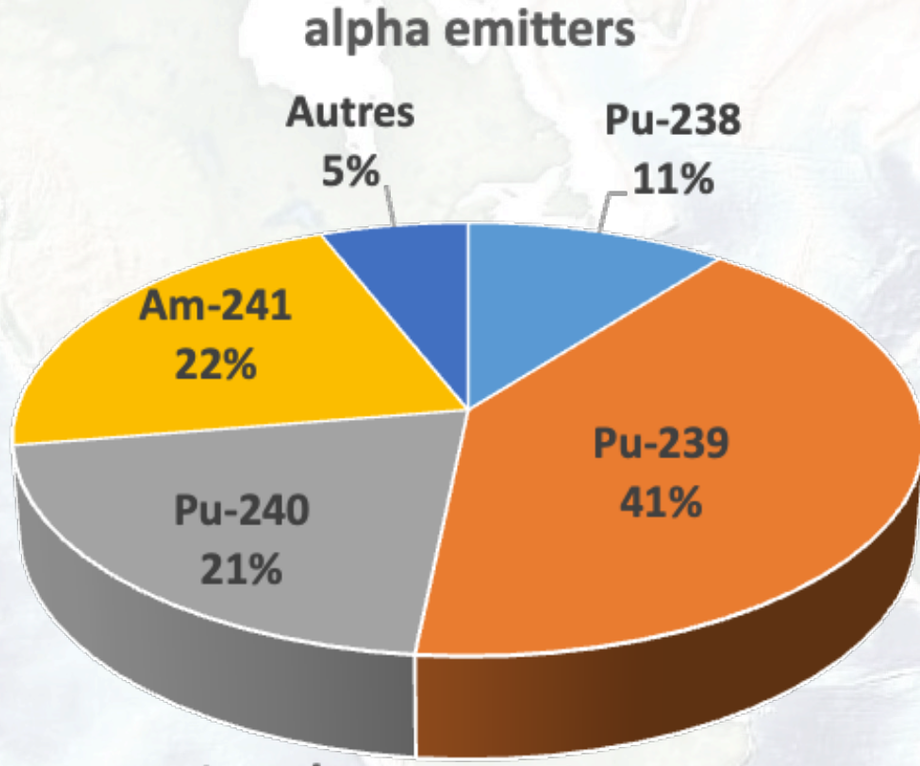
Data often partial and without detailed information (activity + uncertainties + location/density)

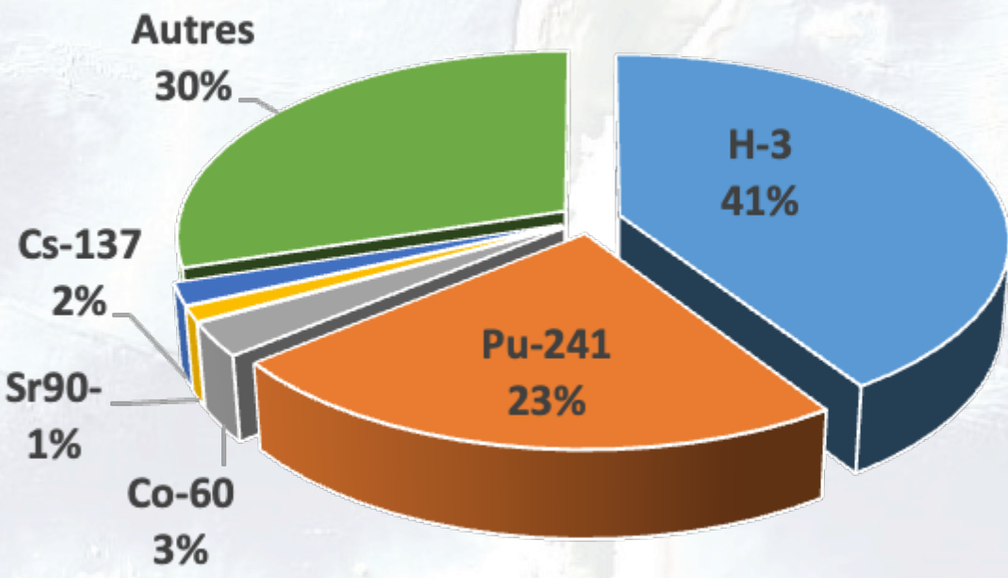
Sparse sampling (mostly water and sediment) but no context (position relative to barrels, unknown barrel status, distribution, and density)

Radionucleides in the NODSSUM study area

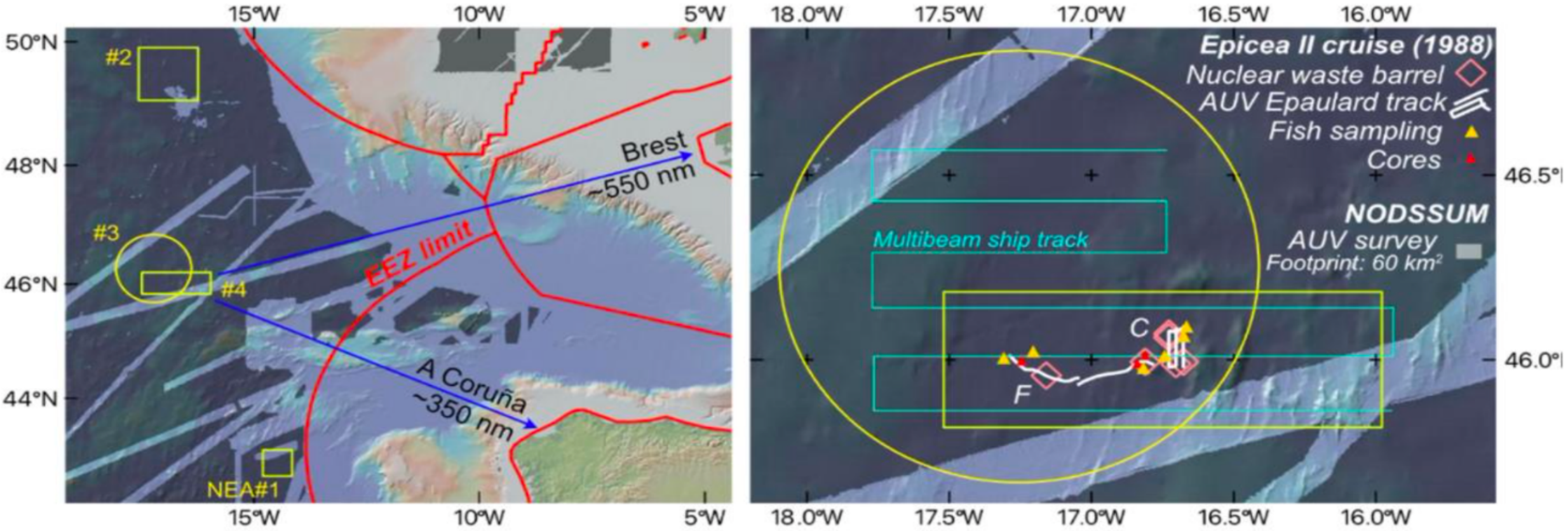
Alpha	Half-life	Range of annual beta/gamma composition %
^{210}Po	1,40E+02 d	0,4-1
^{226}Ra	1,60E+03 y	0,3-5
^{234}U	2,46E+05 y	0,01-0,2
^{235}U	7,04E+08 y	0,6-1,8
^{238}U	4,47E+09 y	0,01-0,2
^{237}Np	2,14E+06 y	0,00007-1,2
^{238}Pu	8,80E+01 y	6-12
^{239}Pu	2,41E+04 y	40-66
^{240}Pu	6,56E+03 y	12-23
^{242}Pu	3,73E+05 y	0,3-0,6
^{241}Am	4,33E+02 y	13-24
^{244}Cm	1,81E+01 y	0,1-0,2

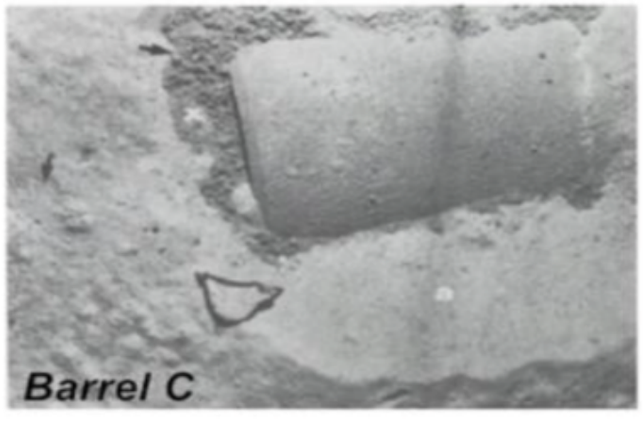
Bêta / gamma	Half-life	Range of annual beta/gamma composition %
^{3}H	1,23E+01 y	39-82
^{14}C	5,70E+03 y	0,21,5
^{35}S	9,20E+01 d	0,051,1
^{54}Mn	3,12E+02 d	0,0001-0,3
^{55}Fe	2,75E+00 y	0,0001-1
^{58}Co	7,09E+01 d	0,001-1,5
^{60}Co	5,27E+00 y	1,3-8,7
^{90}Sr	2,88E+01 y	1,2-2,6
^{125}I	5,90E+01 d	0,09-1,2
^{134}Cs	2,06E+00 y	0,1-1,3
^{137}Cs	3,01E+01 y	1,5-3,7
^{241}Pu	1,44E+01 y	12-47





NODSSUM study area: the NEA#3 &4 sites





Focus on area with most barrels (NEA#3&4) -> >250000 barrels in 100x50 km, up to 4500, + reference zone (for comparison)

Gaps:

- *No constrain on the distribution of barrels (radioactive source)*
- *Lack of context for samples and measurements relative to potential pollution sources*
- *Unknown status of barrels*
- *No knowledge of the ecosystems*
- *And lack of bathymetry!*

Deep sea studies: NODSSUM cruise strategy

2-cruise approach - ~60 days of total shiptime approved - to be scheduled

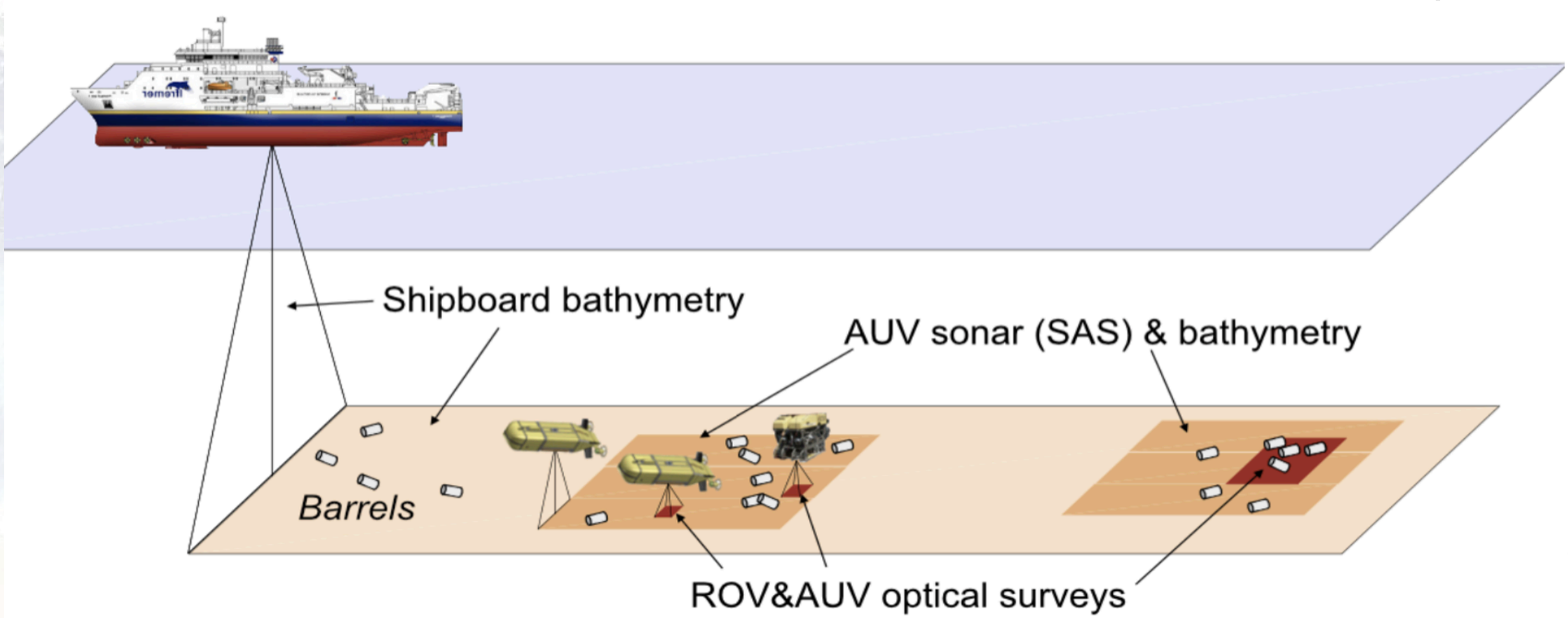
- Mapping to identify targets and obtain background radioactivity results (planning, security)
- Planning of sampling based on results from cruise #1 (optimization)

Cruise 1

#1 Mapping and identification of barrels - Bathymetry + AUV Sonar + AUV photo

Cruise 1&2

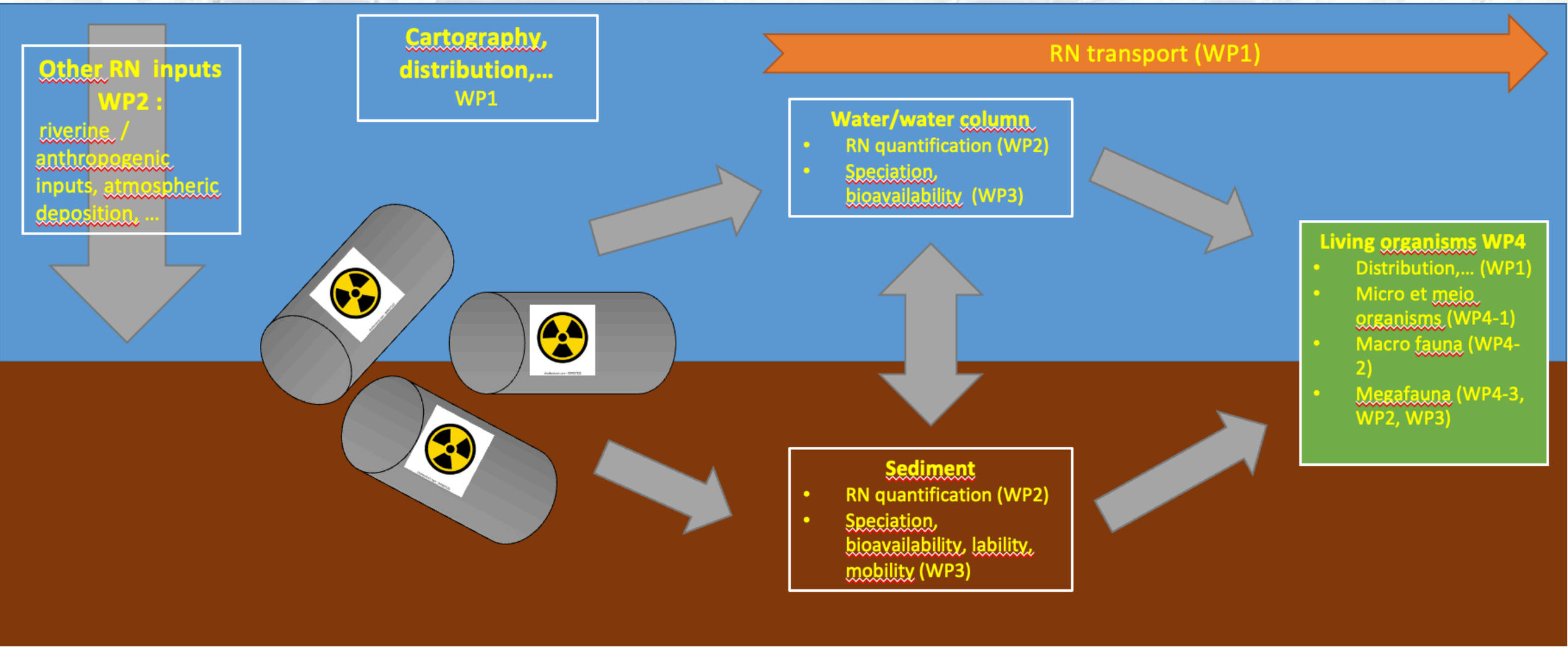
Sampling of sediment, biota, water column, relative to barrels (sources of RNs)
Evaluation of status and distribution of barrels -> inform for follow-up studies



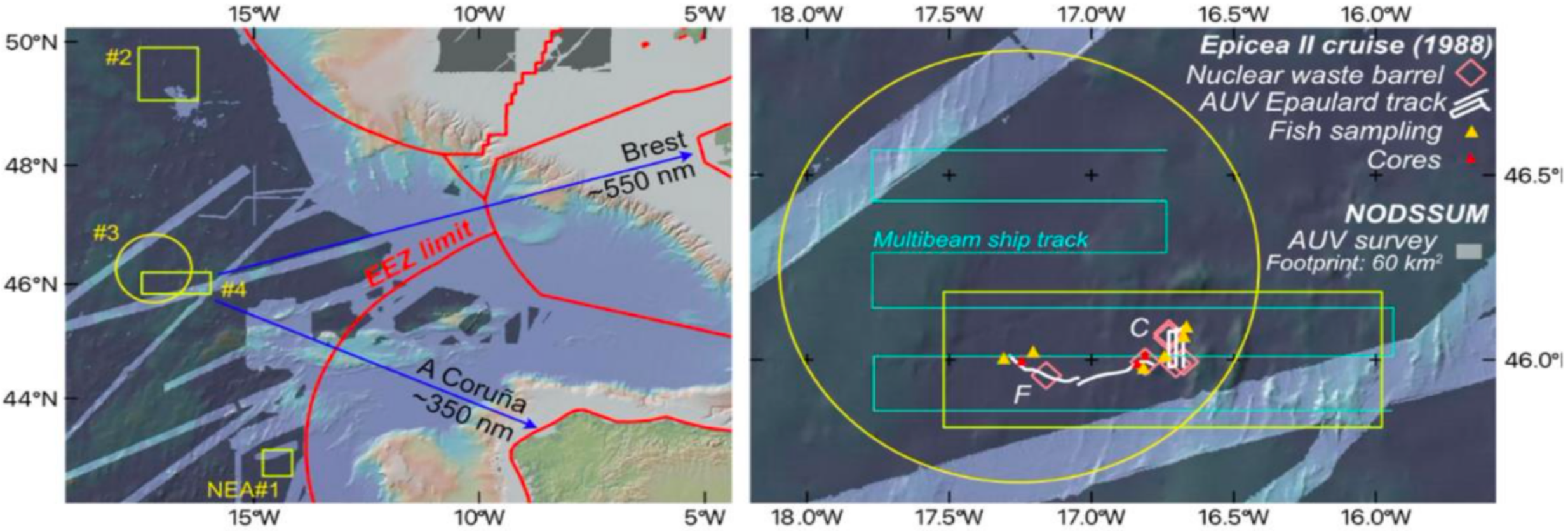
Deep sea studies: NODSSUM cruise strategy

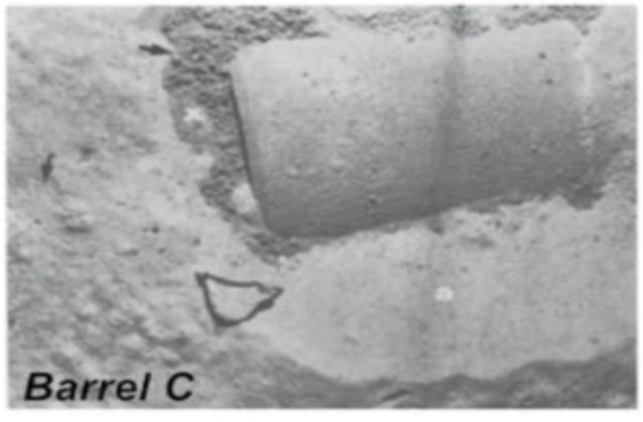
Field work strategy: - Couple AUV, ROV, and sampling devices
- Sedimentology, biology, oceanography, radionucleide studies

Goal: Status & assessment of the area - Transfert among compartments - strategy development



North East Atlantic dump sites





Focus on area with most barrels (NEA#4) -> ~200000 barrels in 100x50 km

Goals:

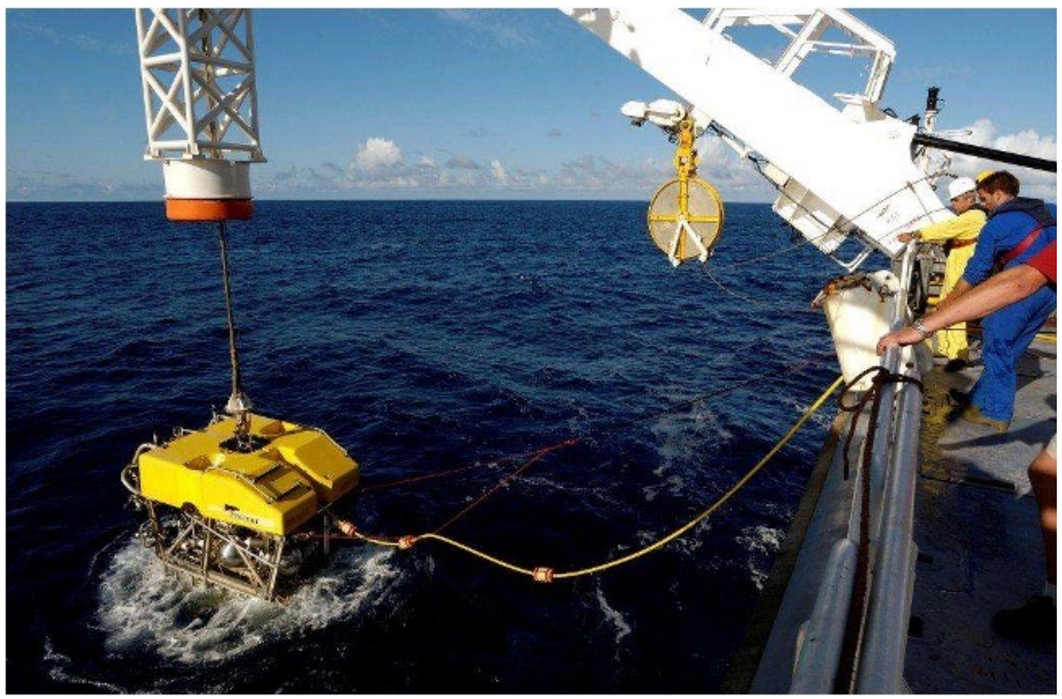
- Obtain information on distribution of barrels (sources)
- Evaluate physical status of barrels and impact on surrounding seafloor
- Characterize ecosystems
- Establish transferts of radionucleides in the deep ocean (barrel/sediment/water/biota)

NODSSUM project: Goals

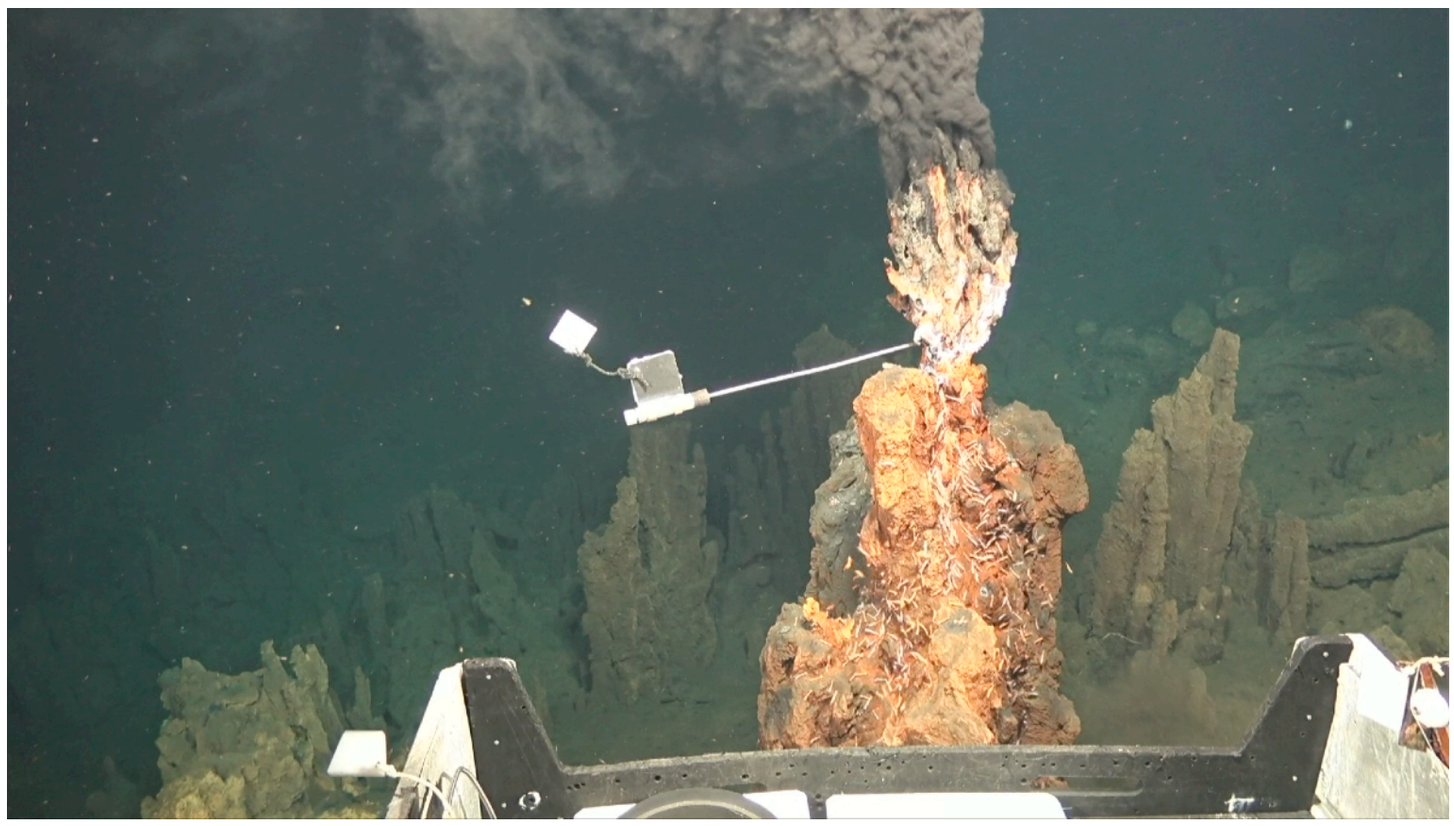
a) Identify and map barrels with AUV surveys (bathymetry, sonar) + imaging (photomosaics)
b) Evaluate the status of barrels
c) Sample sediments, water and biota in well-constrained context (relative to barrels locally and regionally as potential sources) to evaluate concentrations of radionucleids
d) etablish physicochemical environment (currents, O2, pH, Eh, etc of seawater)
e) Evaluate the impact of the barrels on the seafloor and ecosystems
f) Study the behavior and transfert of radionucleids in the deep ocean -> information on the dynamics of ecosystems

Anciliary studies:

Ecosystems (abyssal plains are largely unknown)
Sedimentology (vector of transpor of material and radionucleids)
Microplastics and other antrhopic impacts (litter)



NODSSUM project: deep sea vehicles



NODSSUM project: Field program & cruise strategy

2-cruise approach - ~60 days of total shiptime approved - to be scheduled

- Mapping to identify targets and obtain background radioactivity results (planning, security)
- Planning of sampling based on results from cruise #1 (optimization)

Cruise 1

#1 Mapping and identification of barrels - Bathymetry + AUV Sonar + AUV photo

Cruise 1&2

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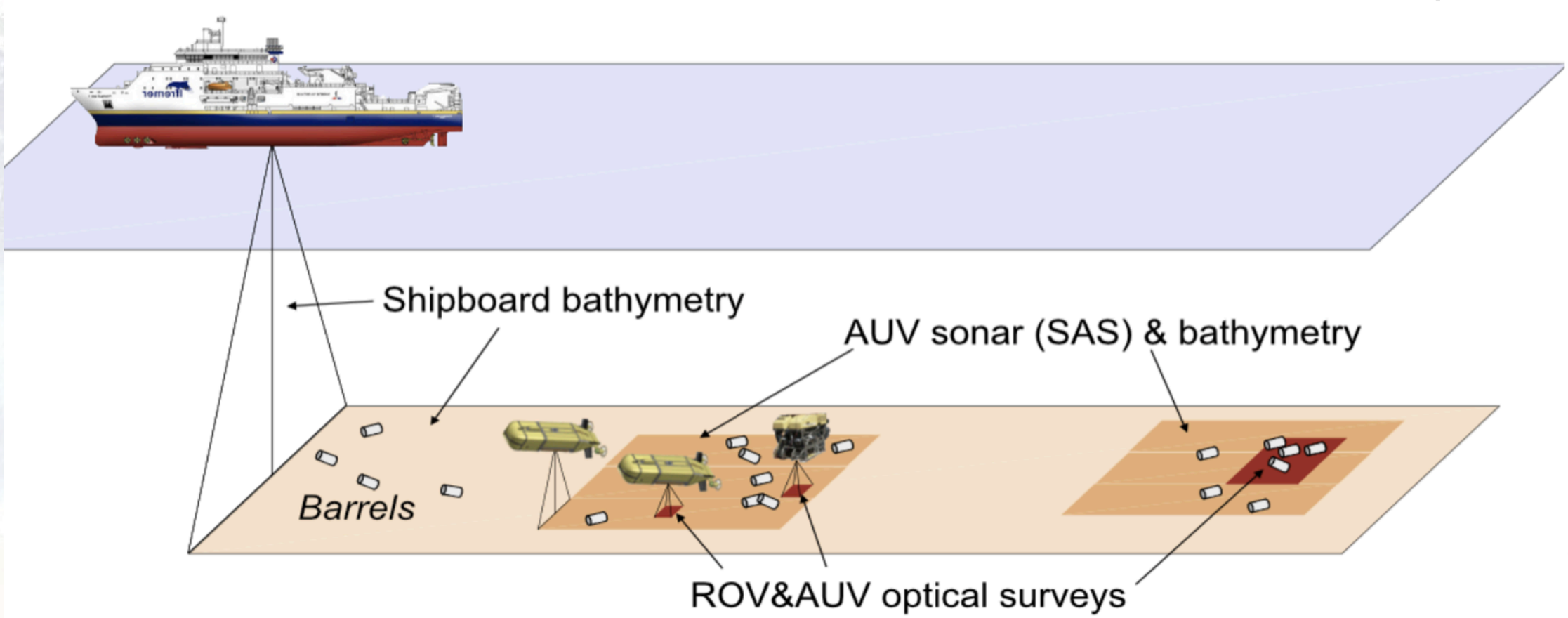
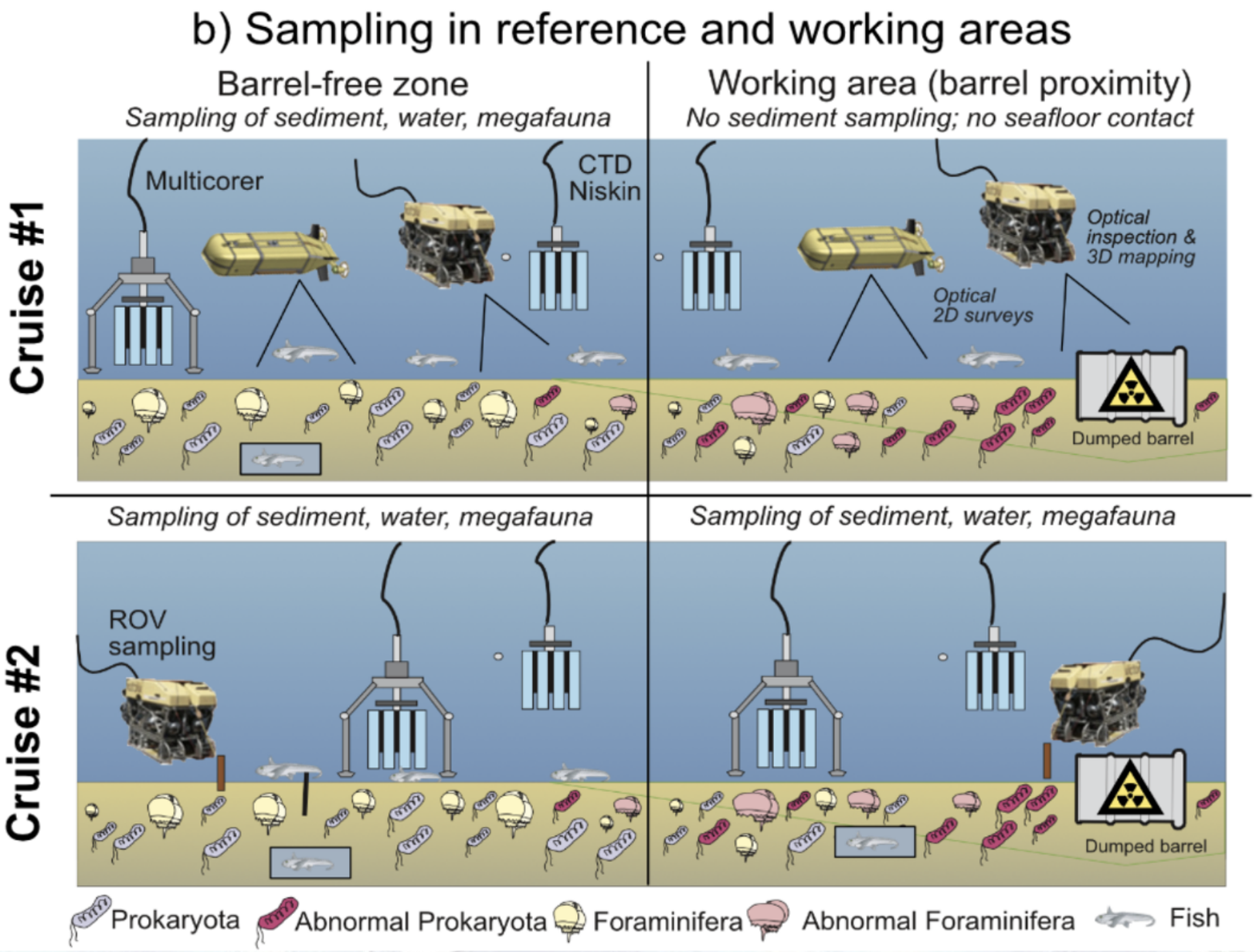


NODSSUM project: Field program & cruise strategy



Radionucleides in compartments

-CTD (water)/pumps

-Coring (sediment) -> ship + ROV

-Bio traps -> fish, nematodes, other

Environment & Technology

- Currents & pressure -> Mooring/seafloor (1-2 years)

-Novel instrumentation (RAMONES)

Development of resines

Potential ancillary studies

-Sedimentology and diffusion

-Microplastics

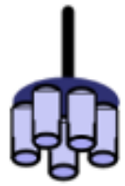
-Abyssal plain ecosystems

NODSSUM project: Field program & cruise strategy

NODSSUM I Cruise

SAS acoustic mapping
Optical surveys - 2D
Gamma ray detector

Optical inspection
3D optical surveys
Gamma ray detector

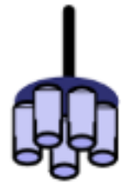


Multicorer
(Zone I)

Niskins
& CTD

NODSSUM II Cruise

Optical inspection
3D optical surveys
Sampling+coring
Gamma ray detector

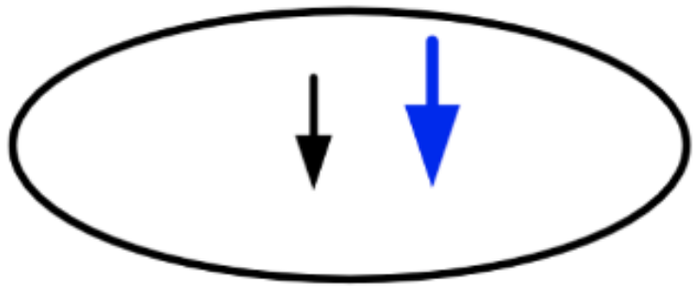


Multicorer
(Zone I)

Niskins
& CTD

Study site

Reference site



NODSSUM project: Field program & cruise strategy

Field work strategy: - Couple AUV, ROV, and sampling devices
- Sedimentology, biology, oceanography, radionucleide studies

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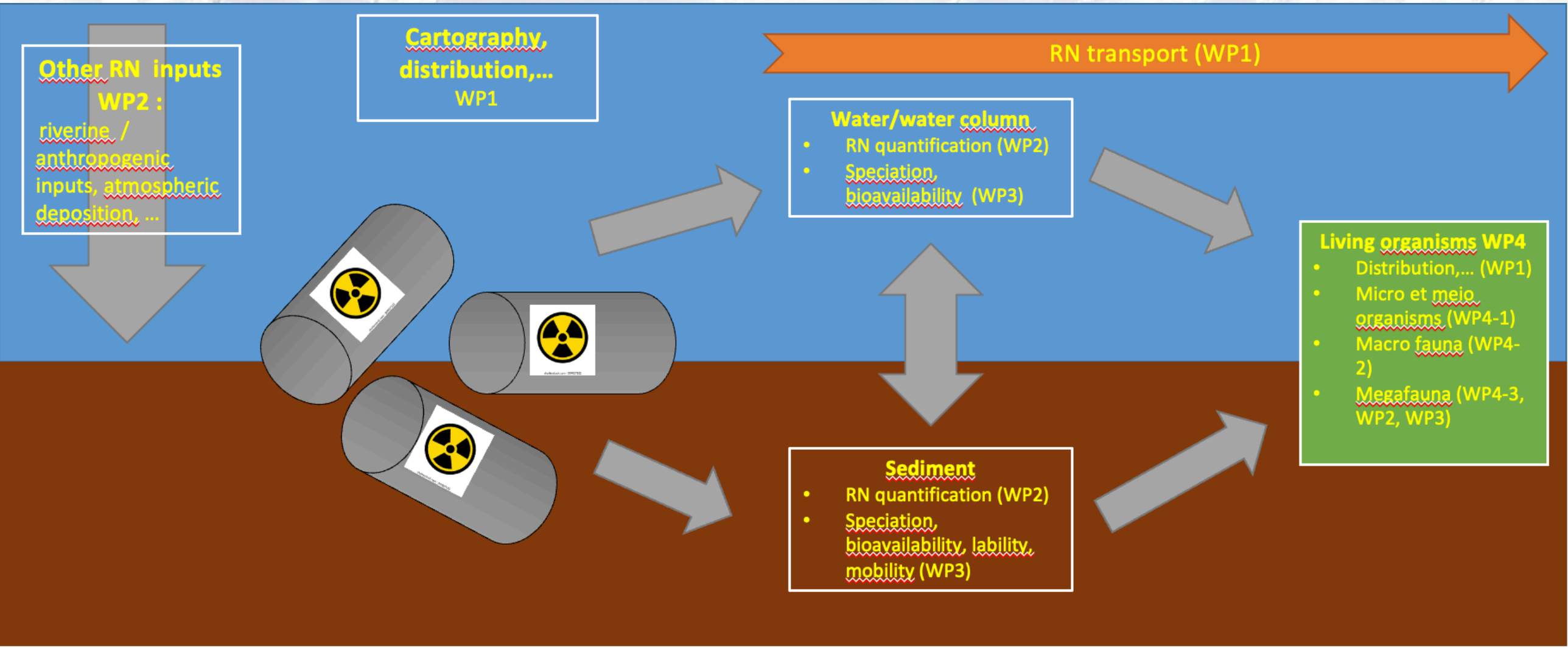


NODSSUM project: Timeline

Proposal submitted in 2021 -> Classed P1 (programmable between 2022 & 2025)

AUV Ulyx: delay in delivery to FOF -> Transfert and science cruise in June 2024 (Mediterranean)

NODSSUM#1 cruise in scenario for 2025 but:

- Mixed science/technical cruise to implement the sonar system
  -> risk of reduced surveyed area
- No ROV nor Nautile -> sampling only from ship in reference areas or away from barrels

Other constraints:

- ROV Victor is refurbished end 2025-April 2026
- Nautile is maintained (government decision against advise of scientists)
  -> requires refurbishing in 2026?
- Constraints on availability of technical team (VICTOR, Ulyx, Nautile)
- Problems with supplies
- Ship schedule: limited number of days + expected budget cuts

NODSSUM#2 Scenario 2026 seems compromised, 2027 more likely

Explore other possibilities (cooperations with other parties?) & eventual follow-up studies (cycle from proposal to cruise can go beyond 5 years)

NODSSUM Team

PIs: P. Chardon (Clermont Ferrand - IN2P3) & J. Escartin (ENS Paris - INSU)

Fontanier Christophe - U. Angers
Mertzimekis Theo - U. Athens
Olive Jean-Arthur - ENS Paris
Gracias Nuno - U. Girona
Sellam Addil - IPHC
Van Beek Pieter -Univ. Toulouse III LEGOS
Mallet Clarisse - U. Clermont Auvergne
Leclerc Frederique - Univ. Cote d'Azur
Duffa Celine - IRSN
Radakovitch Olivier- IRSN
Lacasce Joseph - U. Oslo
Gini Caroline -U. St Johns
Menot Lennaick - IFREMER
Fabri Marie-Claire - IFREMER
Arnaubec Aurelien - IFREMER
Chavagnac Valérie - CNRS/Univ. Toulouse III
Barreyre Thibaut - U. Bergen
Andreani Muriel - U. Lyon
Landesman Catherine - SUBATECH

Souhaut Marc - U. Toulouse III
Zambardi Thomas - U. Toulouse III
Escartin Javier - CNRS/ENS, Paris
Chardon Patrick - Lab. Physique Clermont (UMR6533)
Maigne Lydia - Lab. Physique Clermont (UMR6533)
Breton Vincent - Lab. Physique Clermont (UMR6533)
Busato Emmanuel - Lab. Physique Clermont (UMR6533)
Biron David - U. Clermont Auvergne
Del Nero Mirella - IPHC
Montavon Gilles - SUBATECH
Peron Olivier - SUBATECH
Charmasson Sabine - IRSN

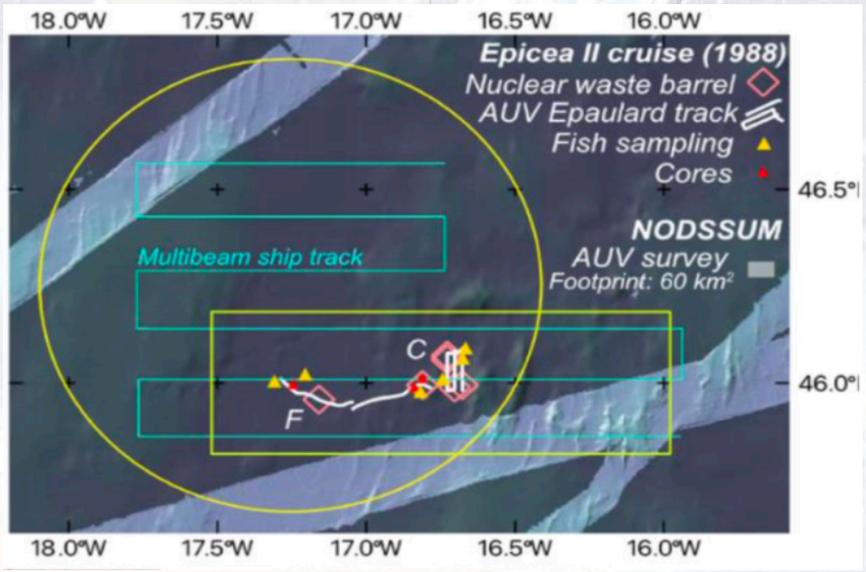
Context & Perspectives

- Casquests/Hurd deep cruise (FR) - just finished
  - Water column, sediments (outside dump area)
  - Tests of preconcentration media

- RADIOCEAN (IN2P3/INSU) 2021-24
  - Database (available knowledge)
  - Development RN preconcentration media (Cs, Pu, Am)
  - Improvement analysis protocoles

- RAMONES (EU) - PI: U. Athens
  - New detectors -> adapt deep-sea studies

- PEPR Océan profond
  - 2024 onwards, funding for science (not cruises)
  - Support NODSSUM science



Anticipate follow up even before NODSSUM Cruises -> lag proposal/cruise
Concept of follow-up or monitoring

Other areas/topics of interest:

Casquest/Hurd deep -> mapping + sampling
Munitions + radioactive waste
-> coastal vessels and light AUVs/ROVs

Characterization & monitoring of Pacific Atolls
-> CEA monitoring & deep-sea environment not covered

Role of microplastics vs. radionucleides -> inert or active?) -> sampling, fluxes, distribution

PEPR Océan Profond

Project for RN behavior & fluxes in ocean
Natural + artificial
Couple with broader anthropic impact studies

What do we know about the ocean seafloor?

multibeam bathymetry only available for ~25% of the seafloor

Resolution ~100 m per pixel

www.gmrt.org

Context & Perspective

NODSSUM will benefit from the developments & research projects:

- RADIOCEAN (IN2P3/INSU) 2021-2024
- RAMONES (EU)
- Casquests/Hurd deep cruise (FR)
- PEPR Océan profond

Perspectives

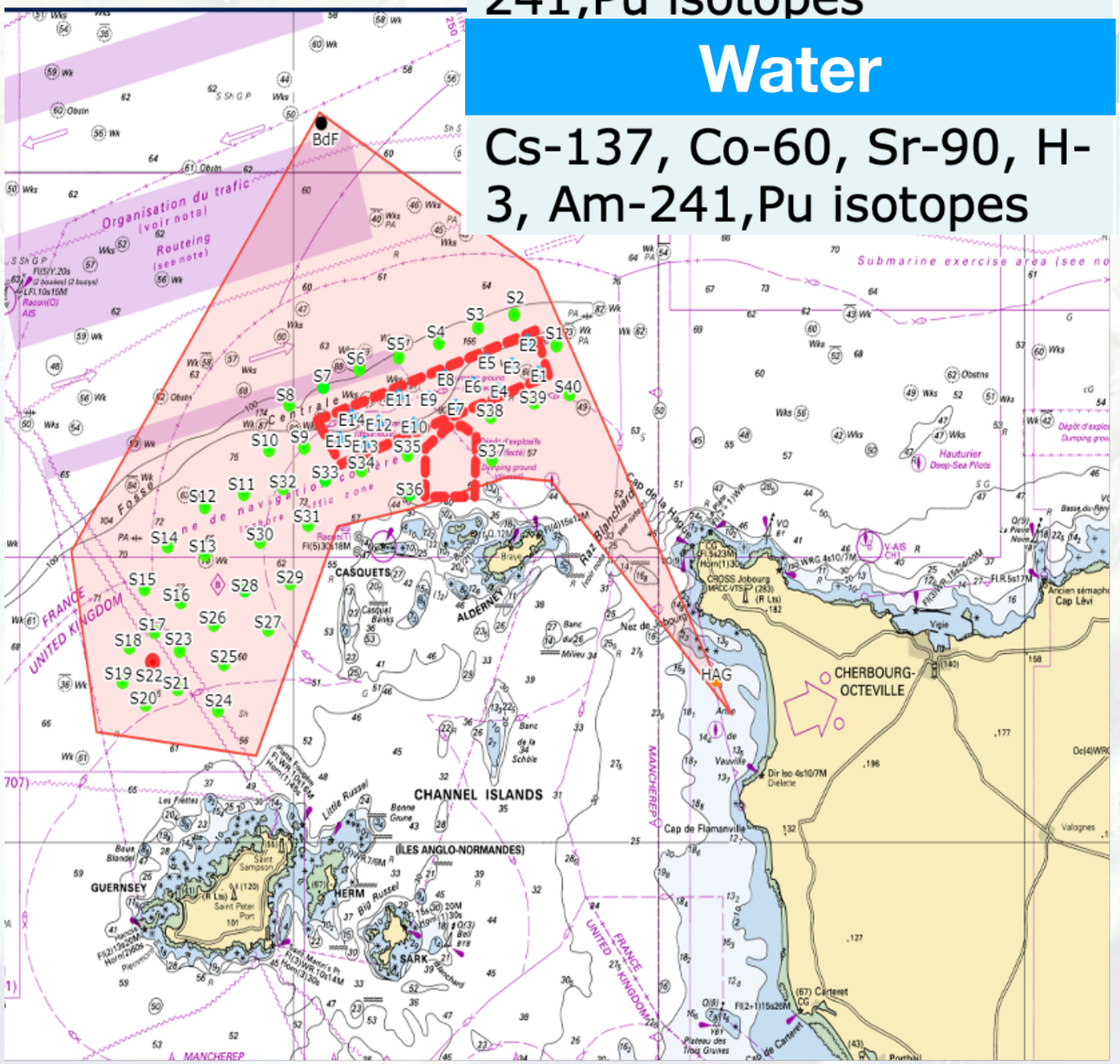
- Monitoring & assesment strategies & techniques, full ocean depth
- Transport & mobility of RNs
- Environmental assesment

Sediments

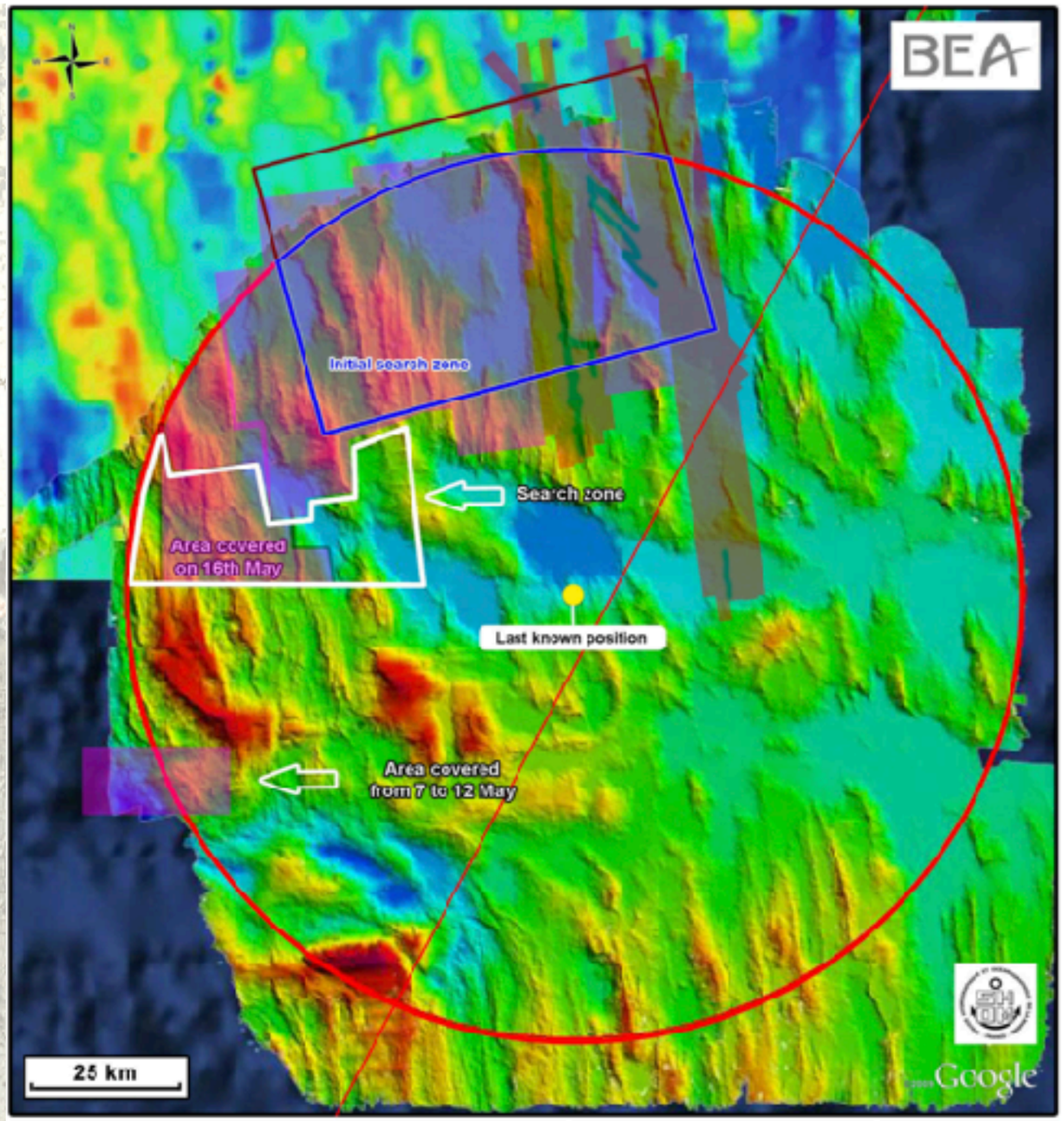
Cs-137, Co-60, Am-241,Pu isotopes

Water

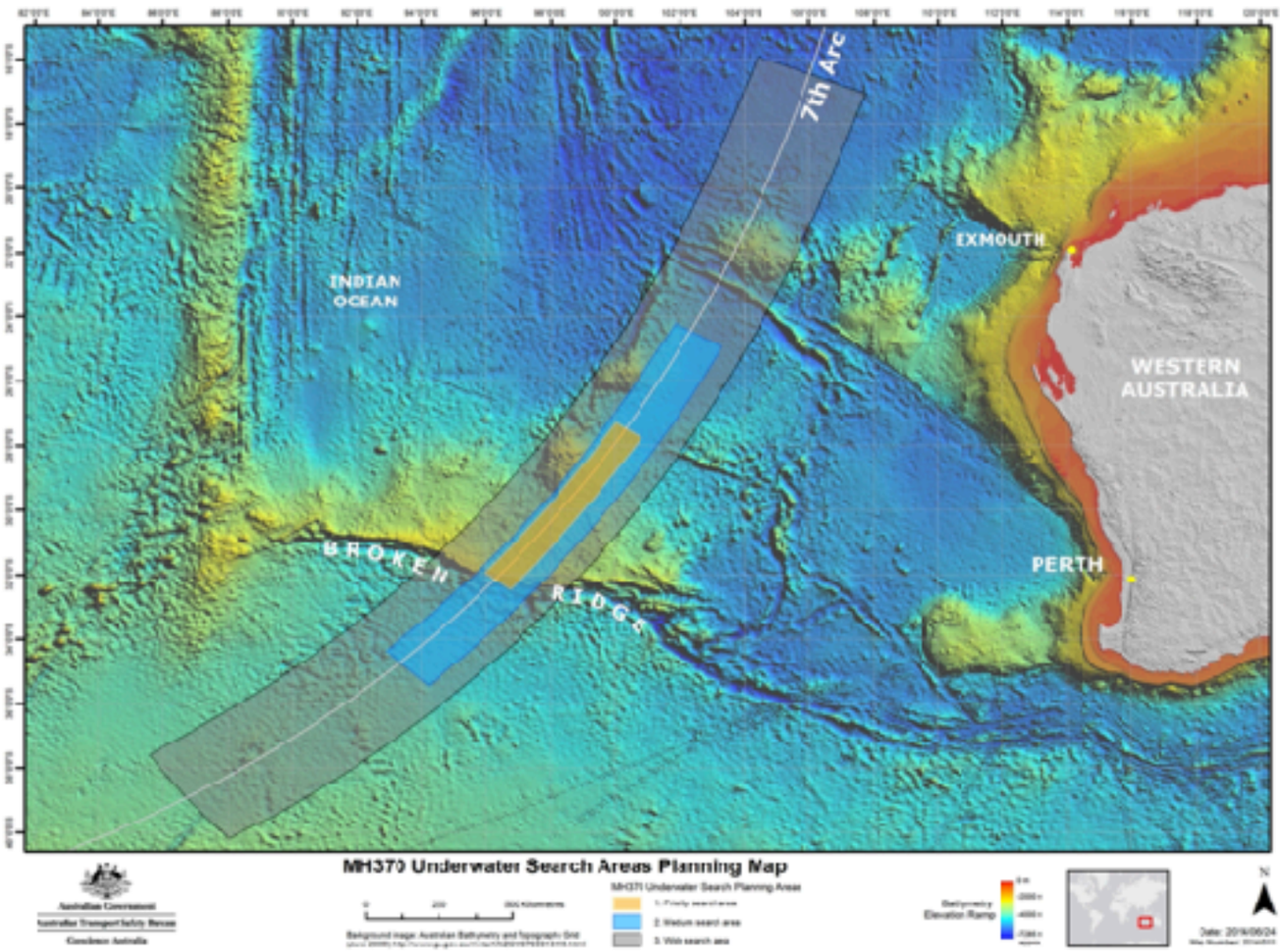
Cs-137, Co-60, Sr-90, H-3, Am-241,Pu isotopes



Coupling AUV mapping and ROV observations

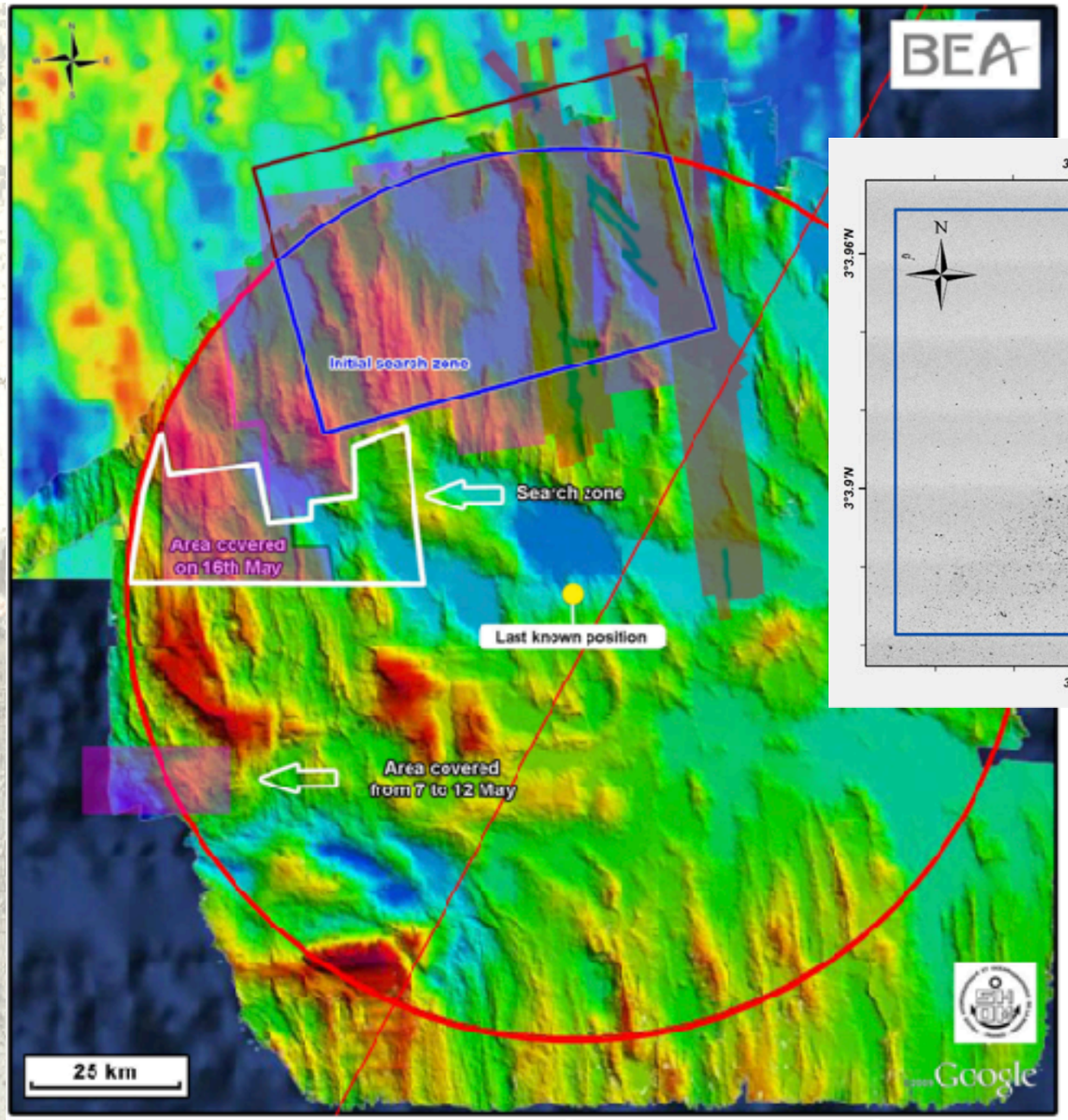


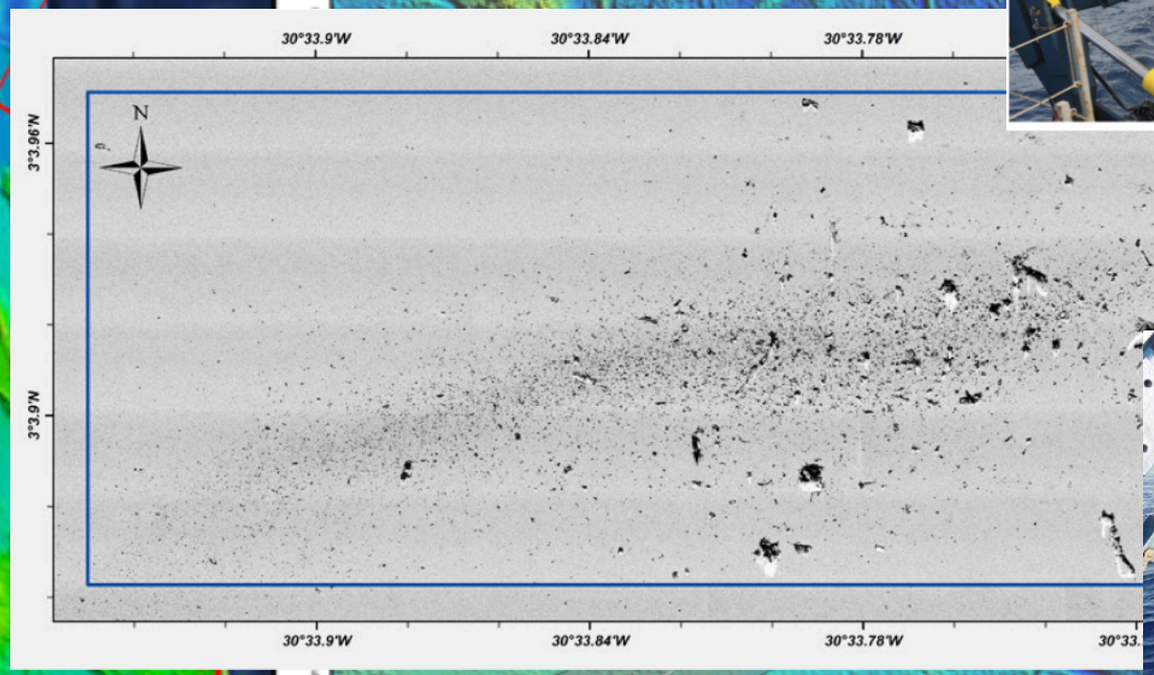
Paris-Rio AF 447 Airbus search
1/2009 Crash
Recovered 5/2011

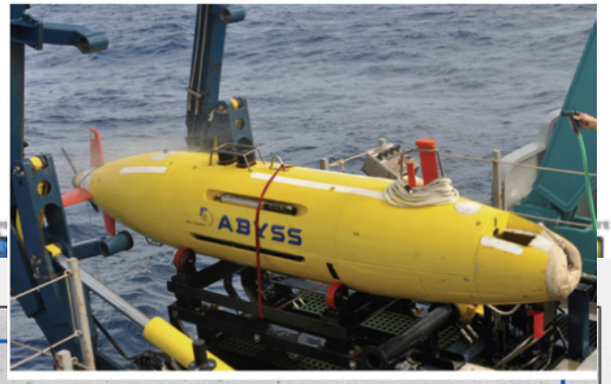


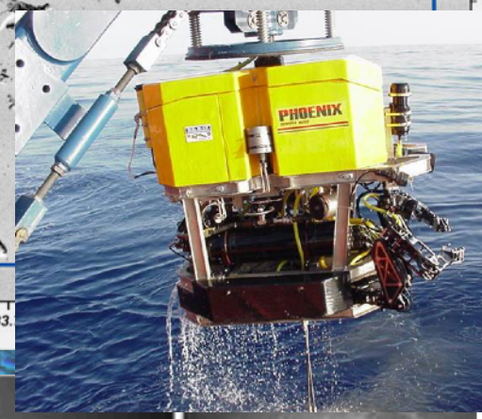
Malaysian Airlines MH370
3/2014 Crash
Not found after intensive searches

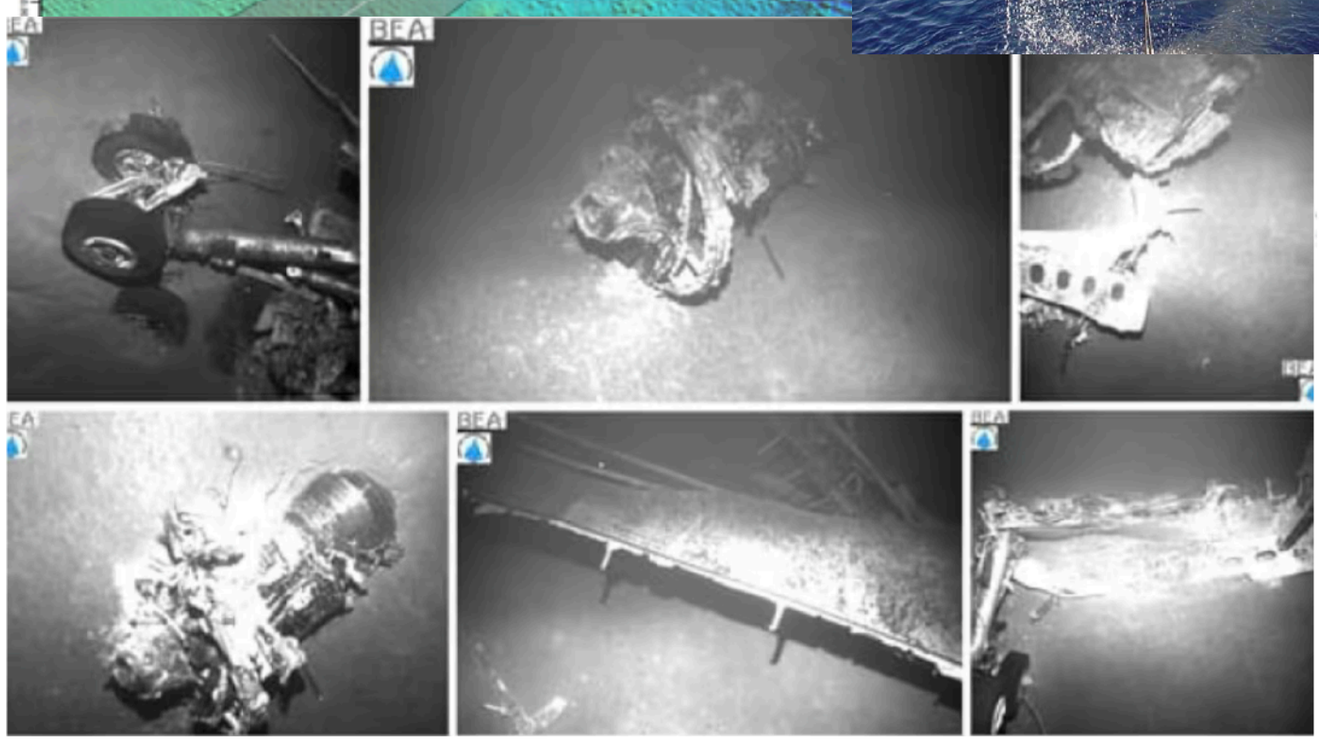
Coupling AUV mapping and ROV observations











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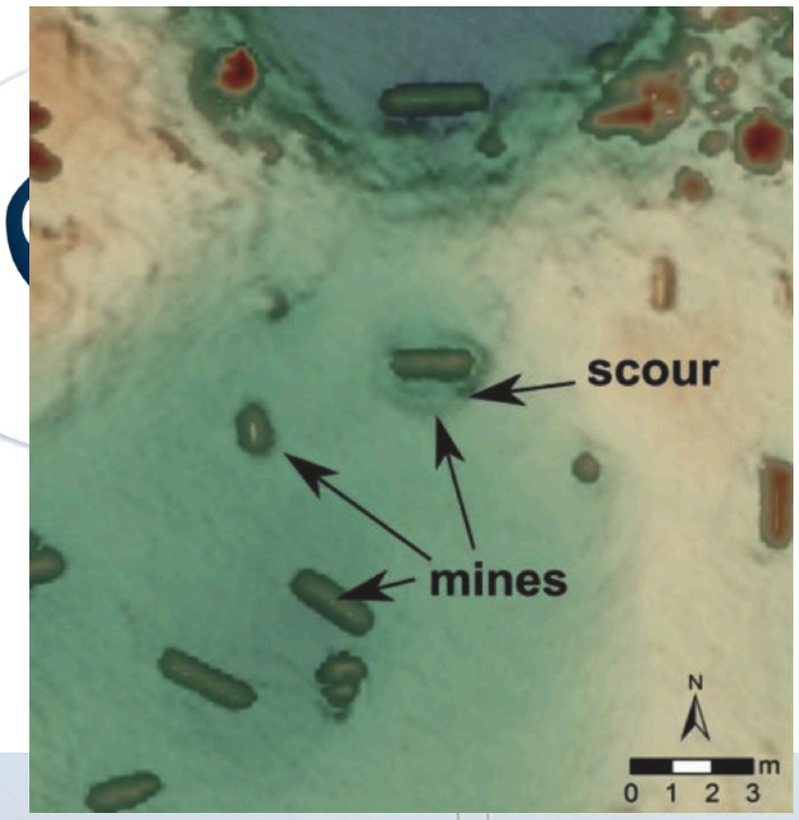
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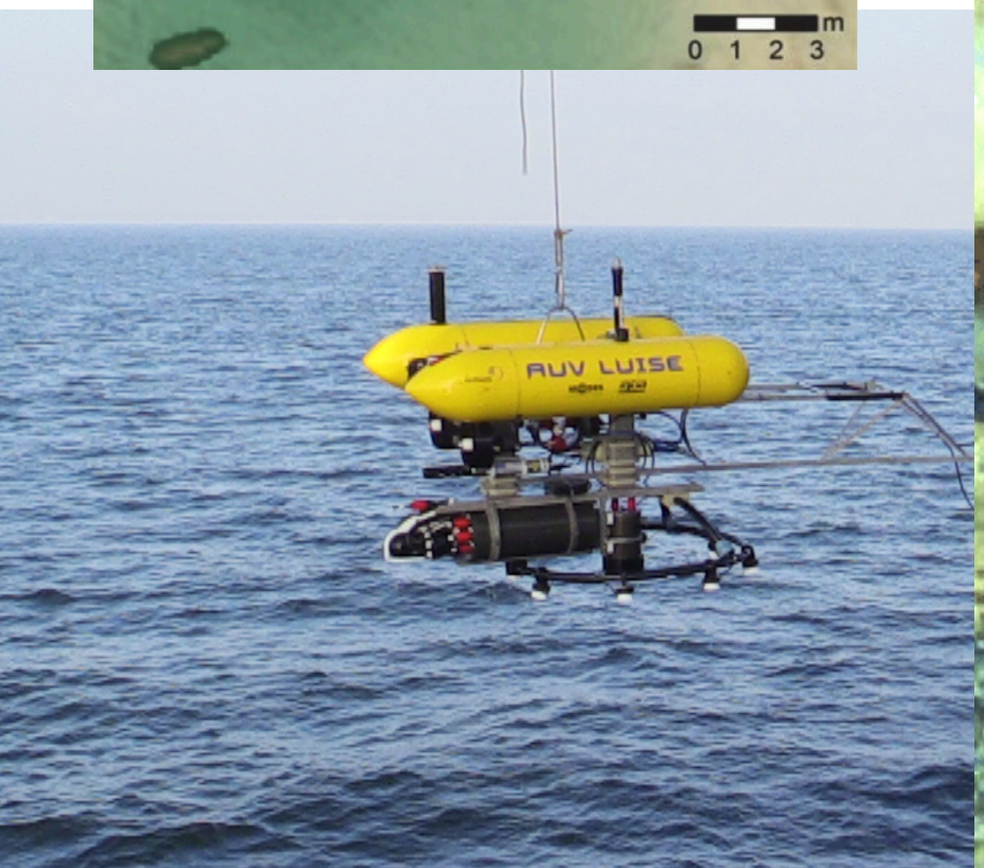
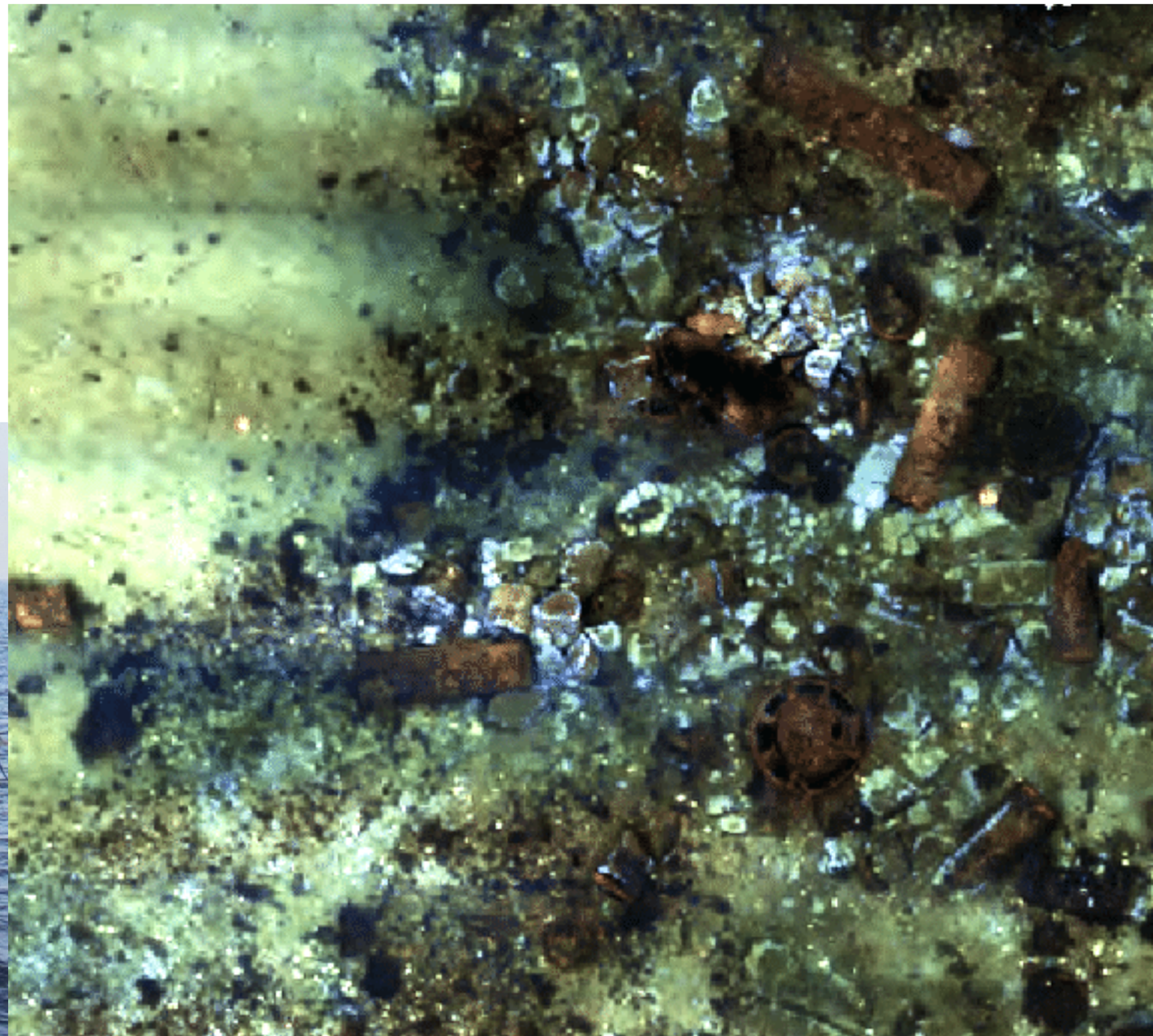
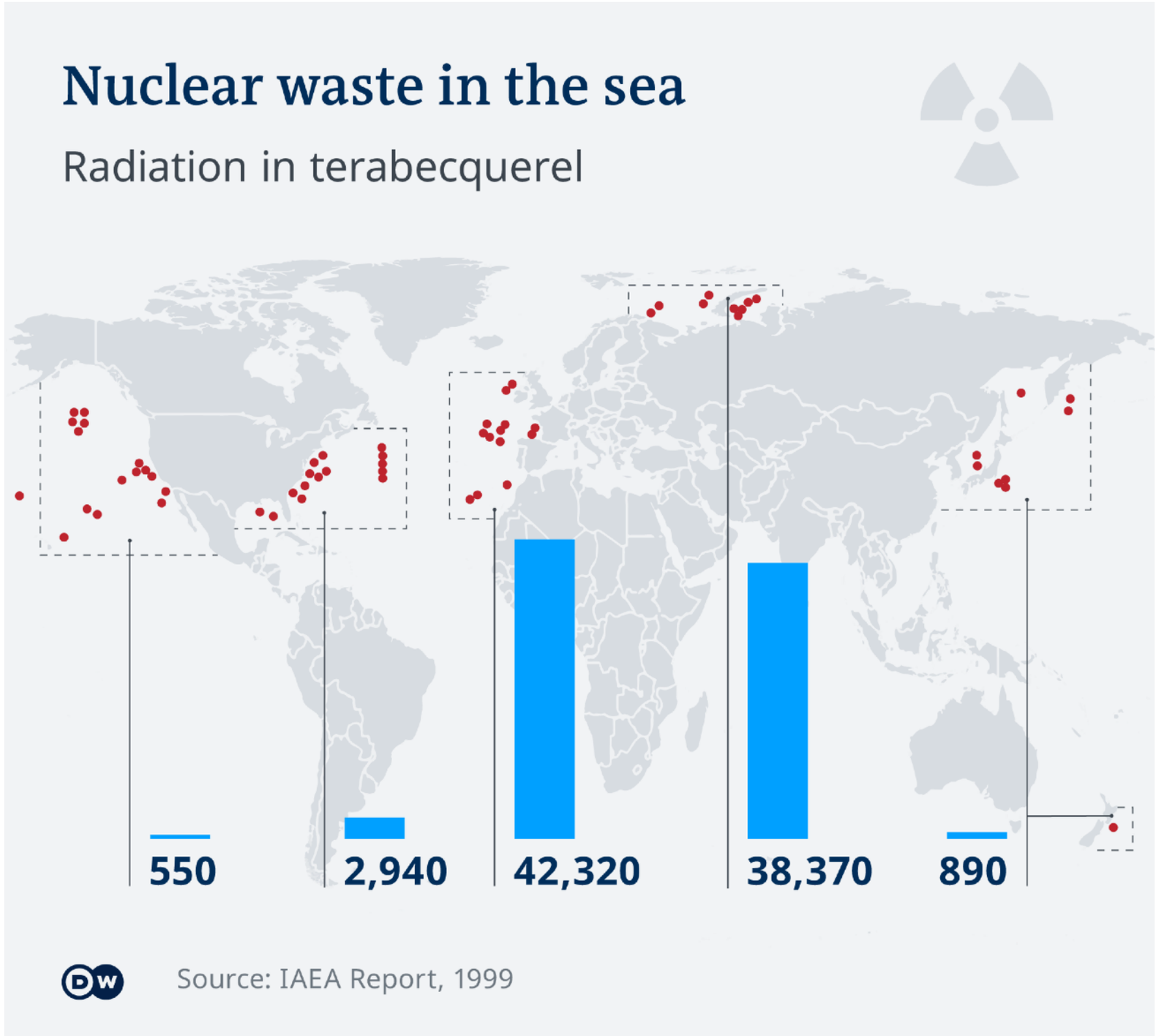
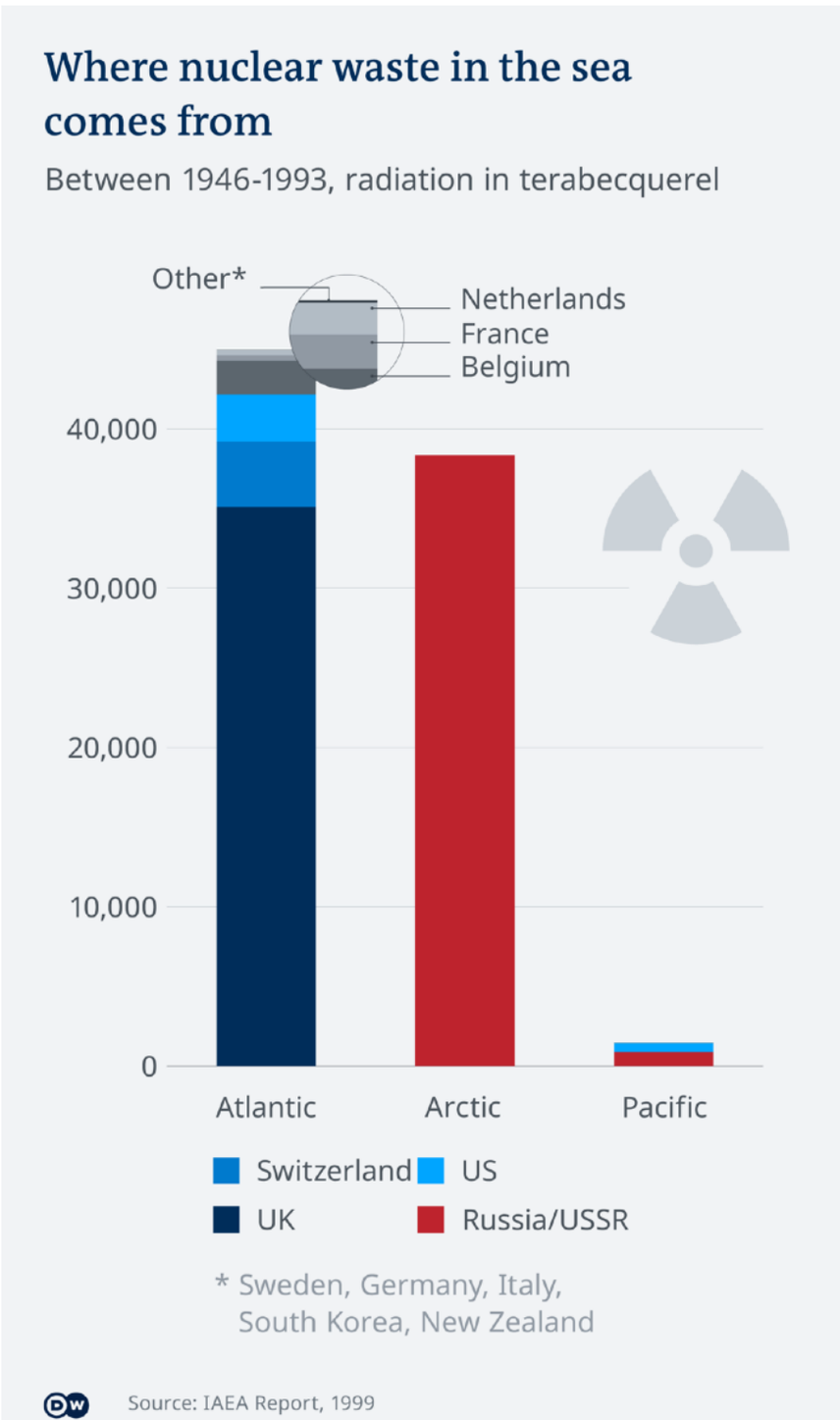

AUV LUISE



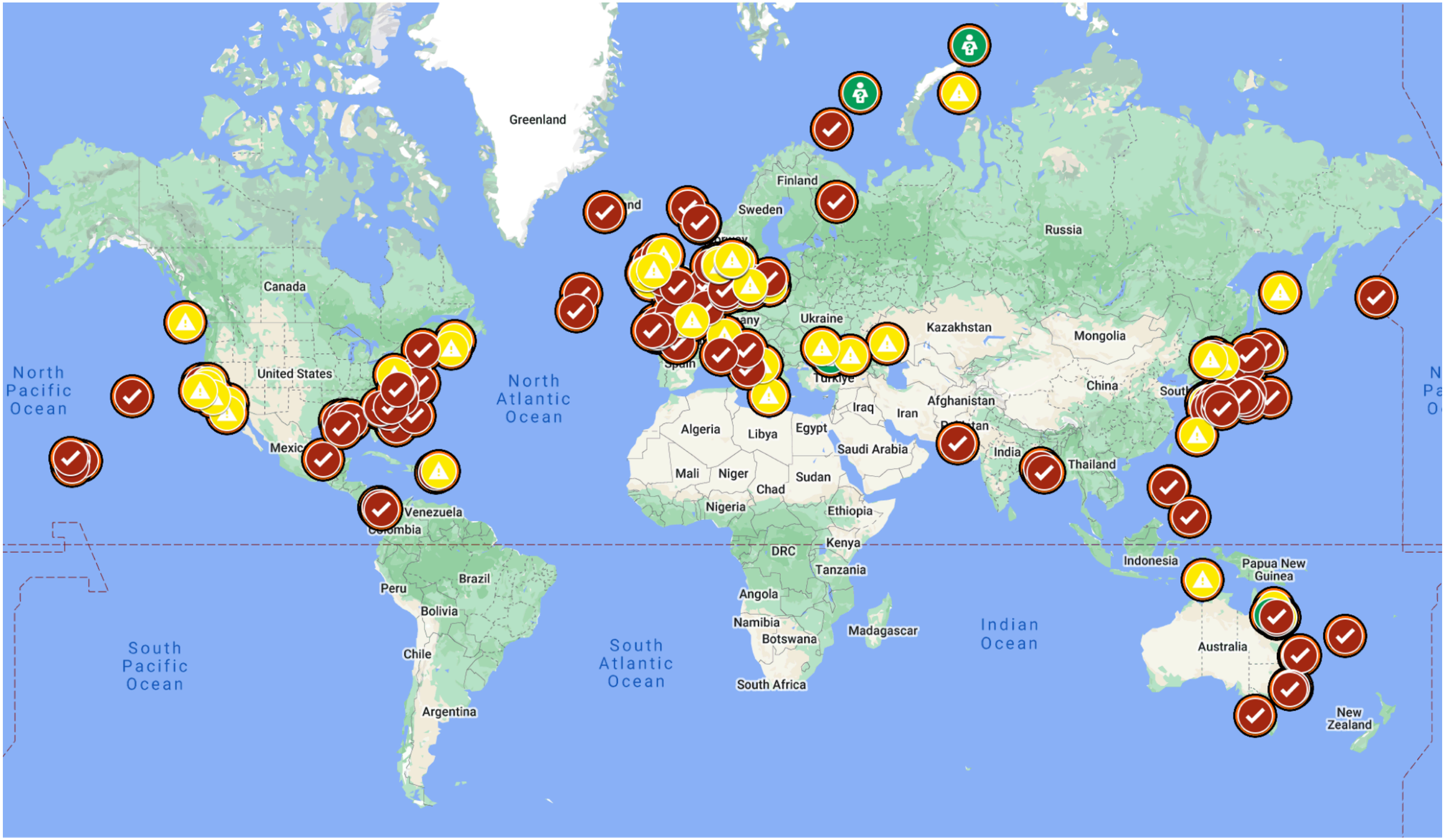
Ocean dumping of nuclear waste

Dumping in all oceans but concentrated in Atlantic and Arctic
Nuclear waste:
Reported to and coordinated by the International Atomic Energy Agency (IAEA.org)
… except USSR/Russia (late declaration of dumped materials)
Main sources: UK, USSR (nuclear energy)
Military nuclear waste: 6 nuclear submarines + atomic warheads (3 USSR, 3 USA)





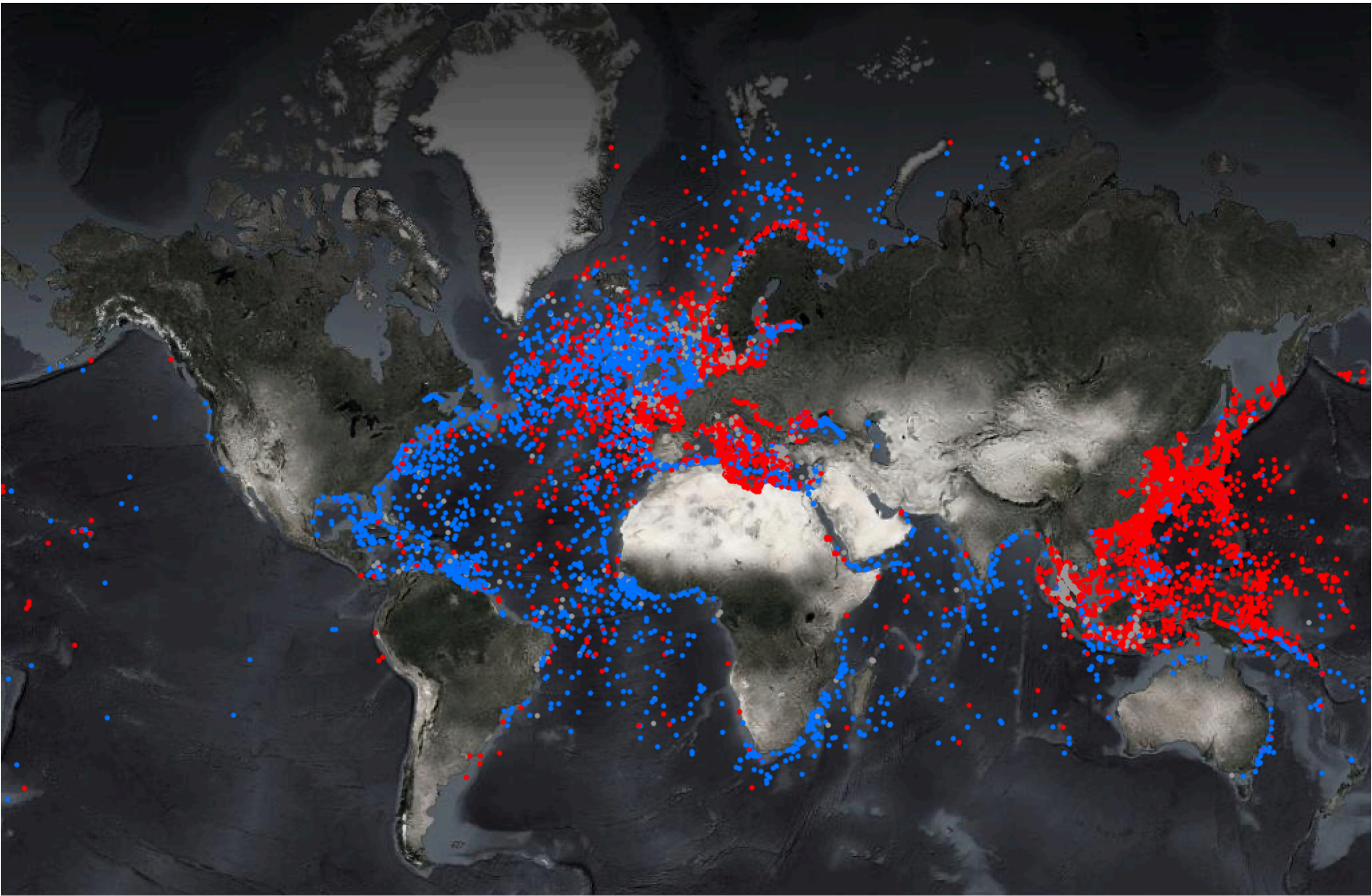
Munitions dumpsites



https://www.google.com/maps/d/u/0/viewer?mid=1ALnyOrN5JQ8H50znwJqI_Sj8IwE&ll=33.19079345338871,21.49138562440703&z=2

Sunken ships

WWII ships (>15000 - ww2sunkenships.ca) - total estimated to a few millions



Komsomolets

K278 submarine - USSR

Barents Sea (off Norway)

Sunk in 1989 with nuclear reactors
+ 2 nuclear warheads

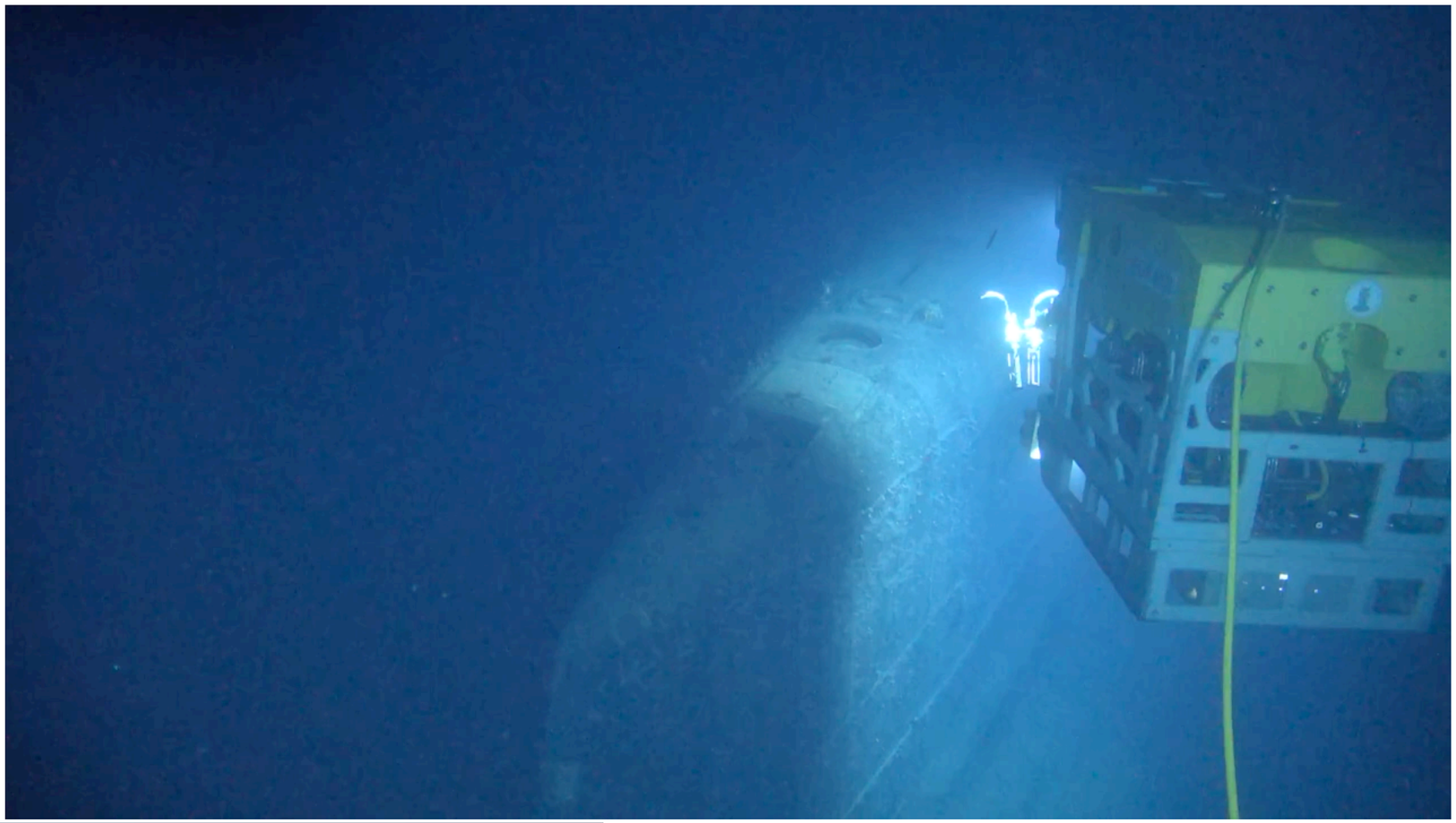
1994: Pu leaks from bombs

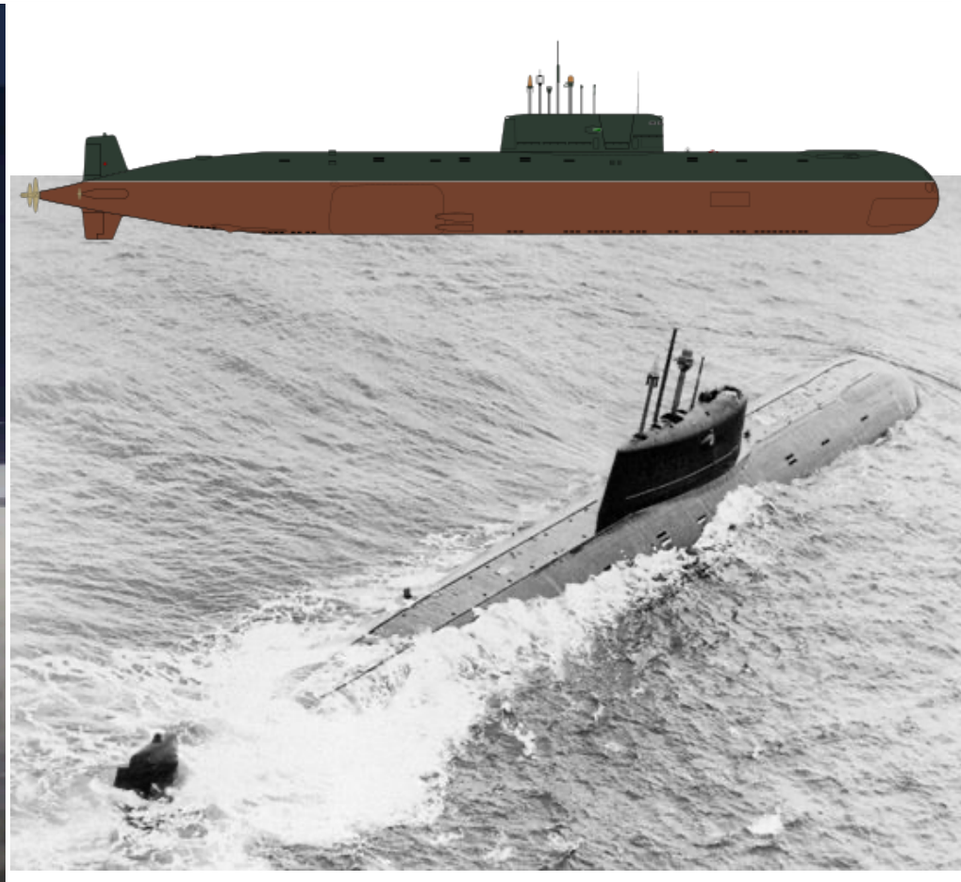
1995: sealing of cracks + cover of bombs

2019: Extreme dilution
-> no detectable impact in nearby waters due to dilution

https://www.youtube.com/watch?v=HWKAfqL-F2c

https://www.youtube.com/watch?v=y8luUCdflxs





Nuclear waste in the abyssal Atlantic

Deep ocean robots to investigate anthropic impacts

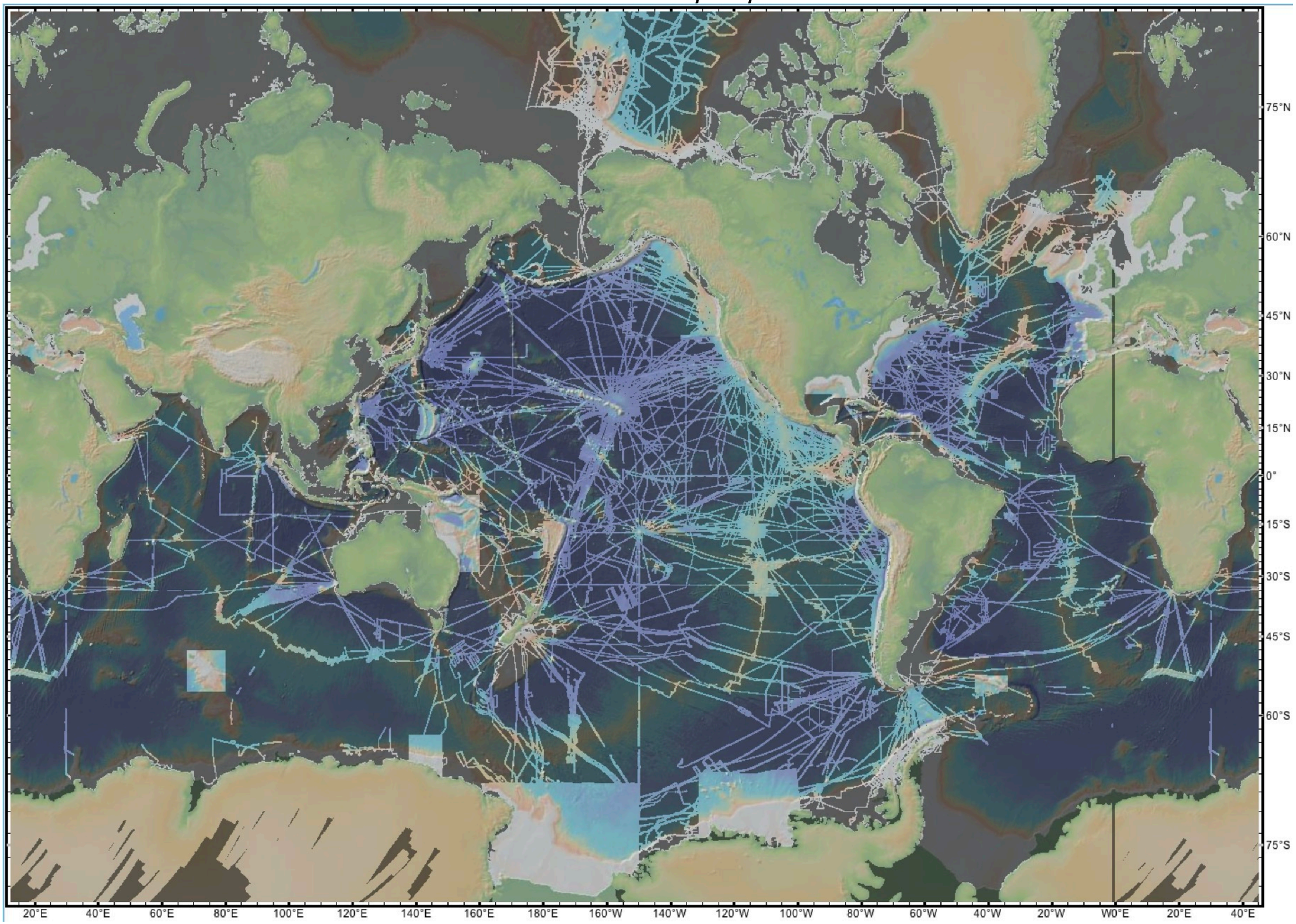
https://www.youtube.com/watch?v=2bd8cOlIXjo

aso

What do we know about the ocean seafloor?

multibeam bathymetry only available for ~25% of the seafloor

Resolution ~100 m per pixel



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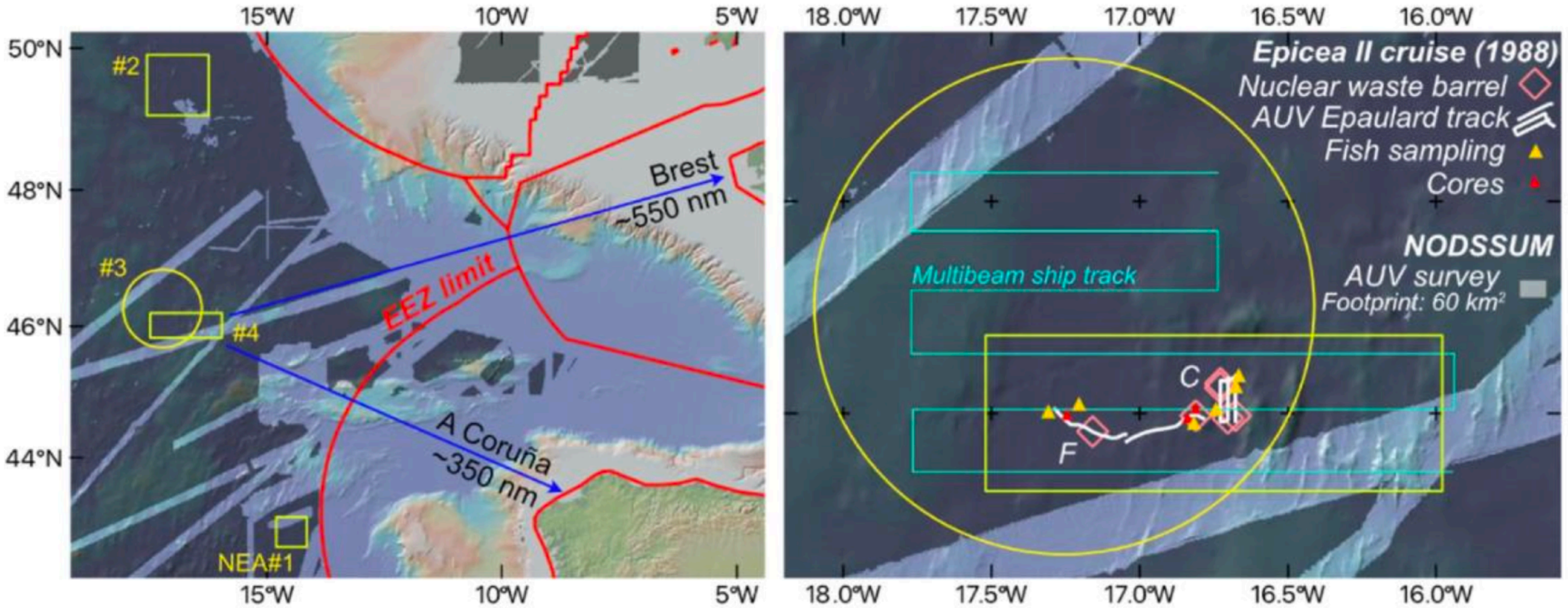
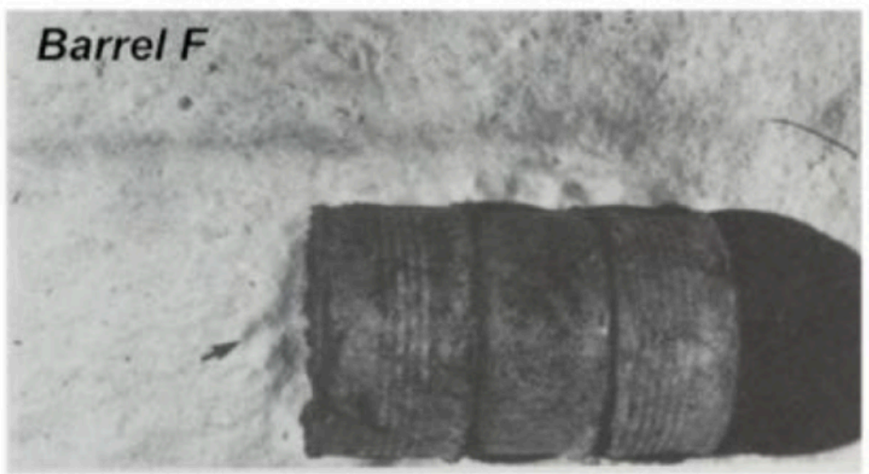
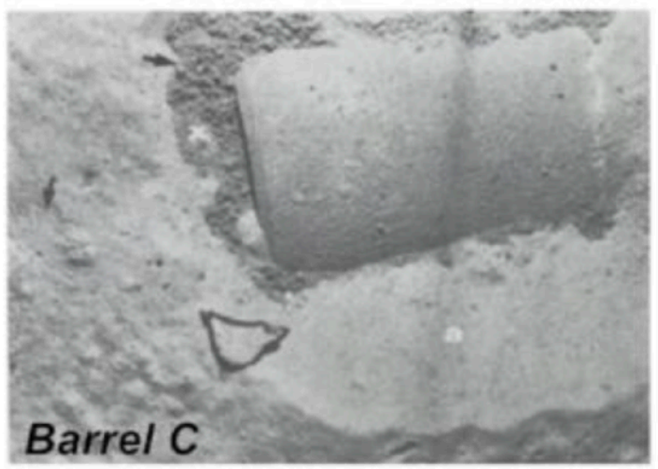
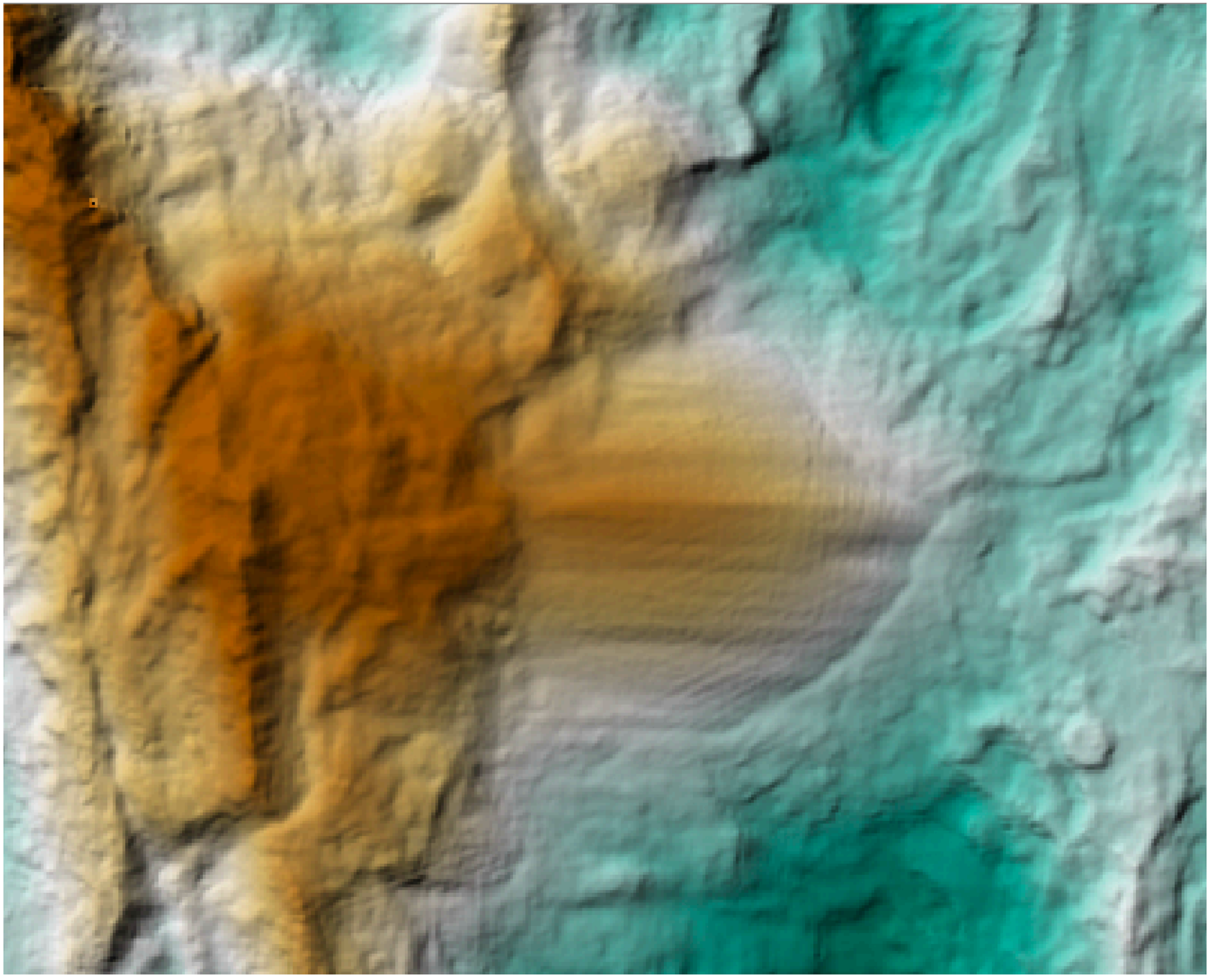

15°W
10°W
5°W
50°N
48°N
46°N
44°N
#2
#3
#4
NEA#1
Brest
~550 nm
EEZ limit
A Coruña
~350 nm
18.0°W
17.5°W
17.0°W
16.5°W
16.0°W
Epicea II cruise (1988)
Nuclear waste barrel
AUV Epaulard track
Fish sampling
Cores
NODSSUM
AUV survey
Footprint: 60 km²
Multibeam ship track
C
F

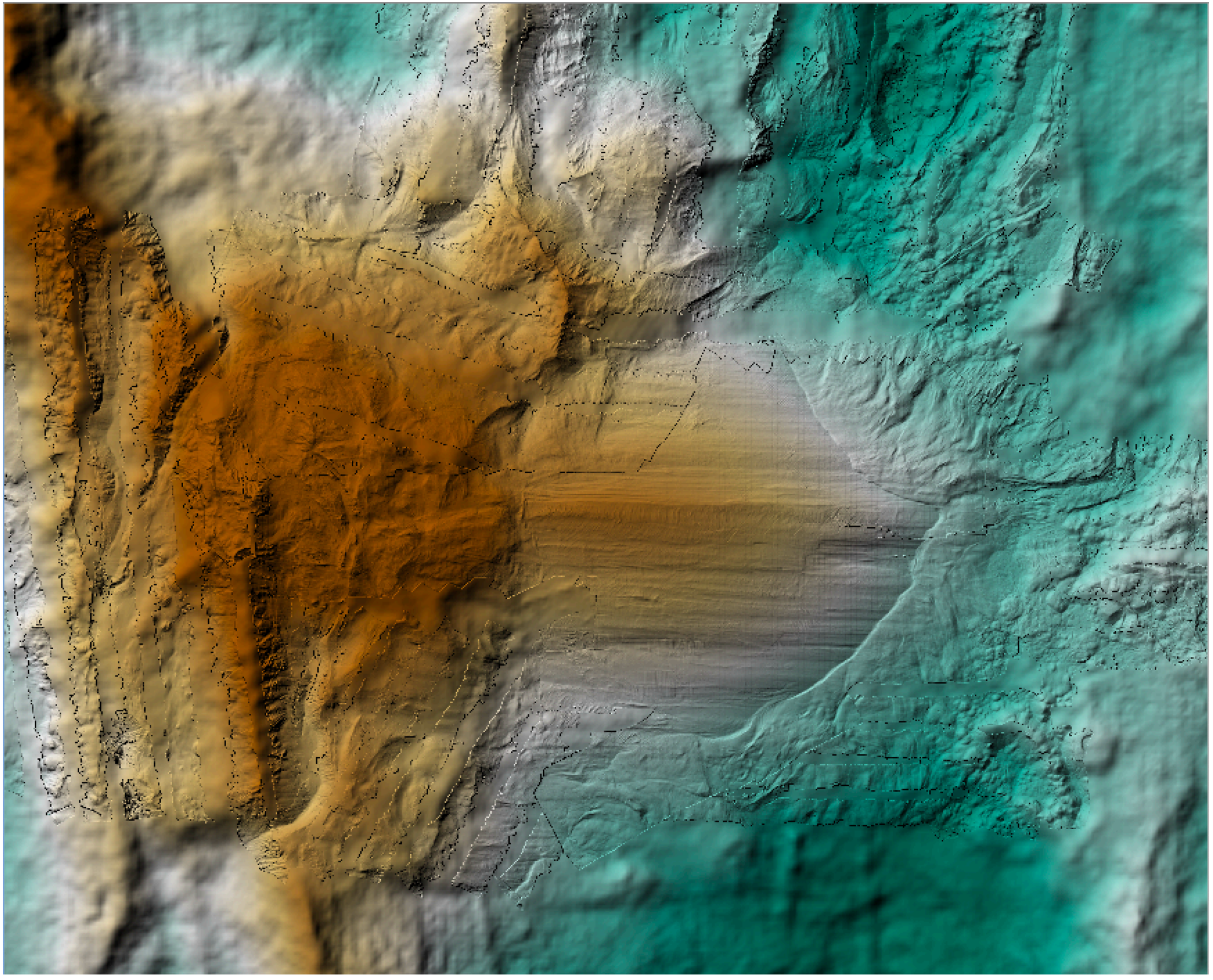

Barrel F


Barrel C

MAR 13°20'N detachment, shipboard bathymetry

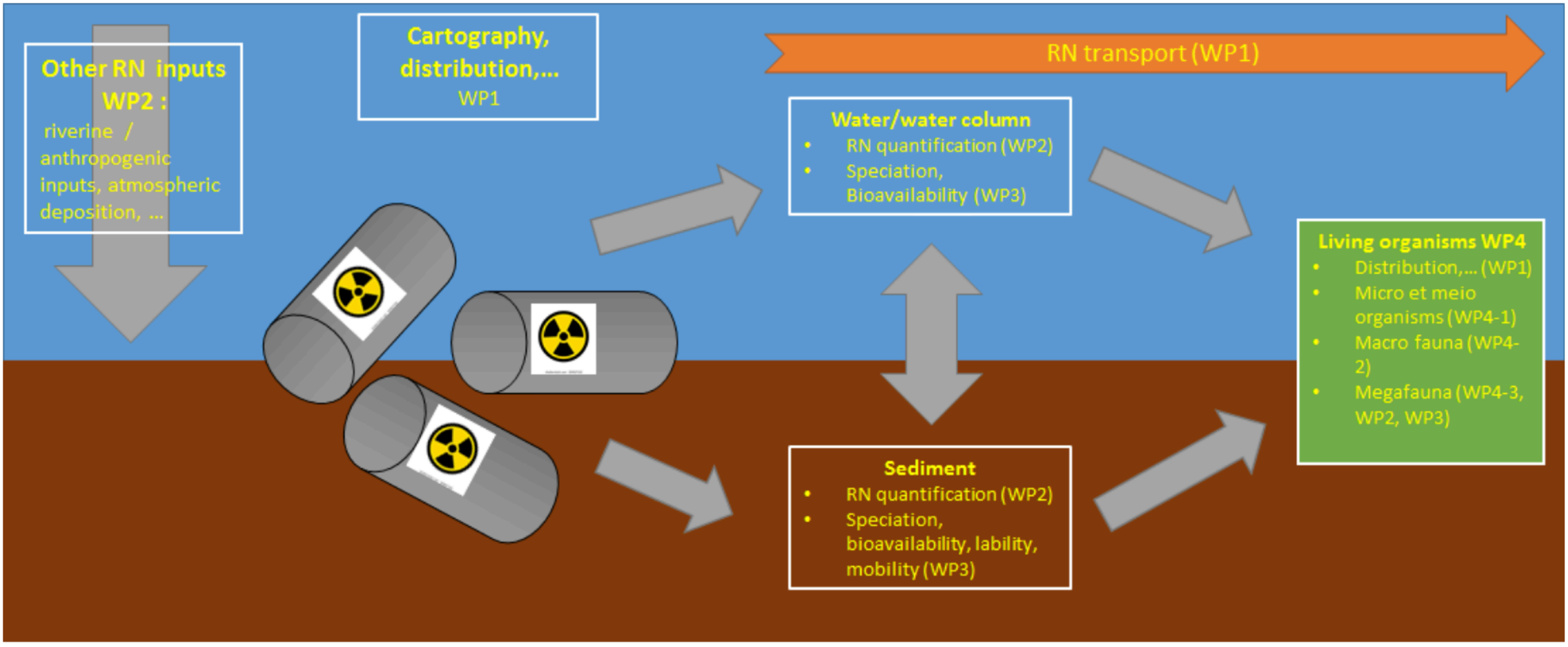


MAR 13°20'N detachment, AUV bathymetry



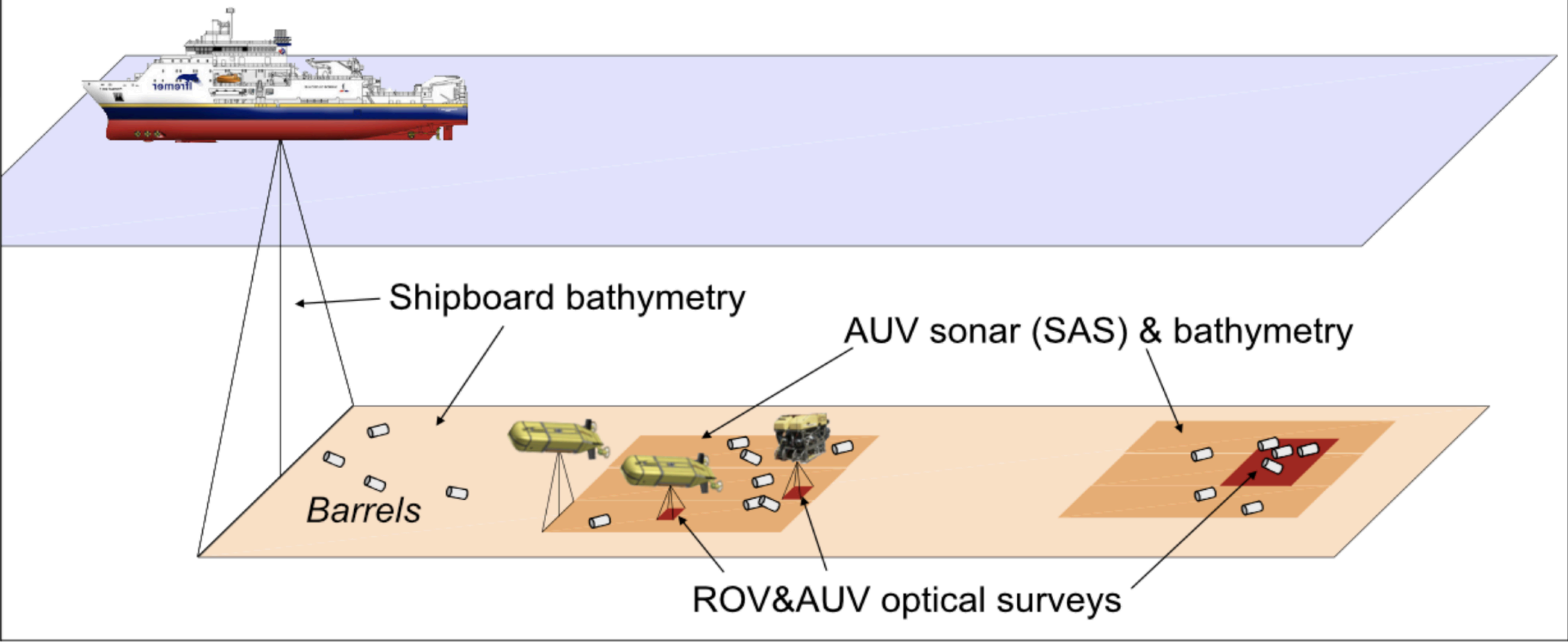
Alpha	Half-life		Range of annual beta/gamma composition %	
^{210}Po	1,40E+02	day	0,4	0,8
^{226}Ra	1,60E+03	year	0,3	5
^{234}U	2,46E+05	year	0,01	0,2
^{235}U	7,04E+08	year	0,6	1,8
^{238}U	4,47E+09	year	0,01	0,2
^{237}Np	2,14E+06	year	0,00007	1,2
^{238}Pu	8,80E+01	year	6	12
^{239}Pu	2,41E+04	year	40	66
^{240}Pu	6,56E+03	year	12	23
^{242}Pu	3,73E+05	year	0,3	0,6
^{241}Am	4,33E+02	year	13	24
^{244}Cm	1,81E+01	year	0,1	0,2

Bêta / gamma	Half-life		Range of annual beta/gamma composition %	
^{3}H	1,23E+01	year	39	82
^{14}C	5,70E+03	year	0,2	1,5
^{35}S	9,20E+01	day	0,05	1,1
^{54}Mn	3,12E+02	day	0,0001	0,3
^{55}Fe	2,75E+00	year	0,0001	1
^{58}Co	7,09E+01	day	0,001	1,5
^{60}Co	5,27E+00	year	1,3	8,7
^{90}Sr	2,88E+01	year	1,2	2,6
^{125}I	5,90E+01	day	0,09	1,2
^{134}Cs	2,06E+00	year	0,1	1,3
^{137}Cs	3,01E+01	year	1,5	3,7
^{241}Pu	1,44E+01	year	12	47


Other RN inputs WP2 :
riverine / anthropogenic inputs, atmospheric deposition, …
Cartography, distribution,…
WP1
RN transport (WP1)
Water/water column
RN quantification (WP2)
Speciation, Bioavailability (WP3)
Living organisms WP4
Distribution,… (WP1)
Micro et meio organisms (WP4-1)
Macro fauna (WP4-2)
Megafauna (WP4-3, WP2, WP3)
Sediment
RN quantification (WP2)
Speciation, bioavailability, lability, mobility (WP3)

Survey strategy

a) Identification, mapping, and inspection of dumped radioactive waste



b) Sampling in reference and working areas

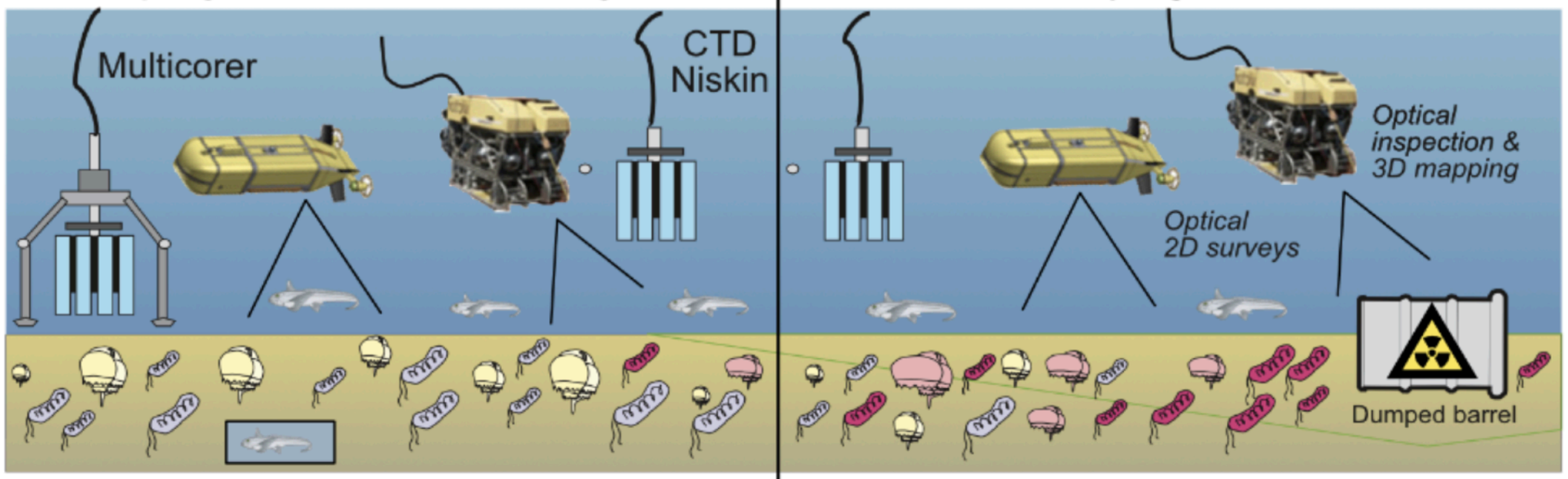
Barrel-free zone

Sampling of sediment, water, megafauna

Working area (barrel proximity)

No sediment sampling; no seafloor contact

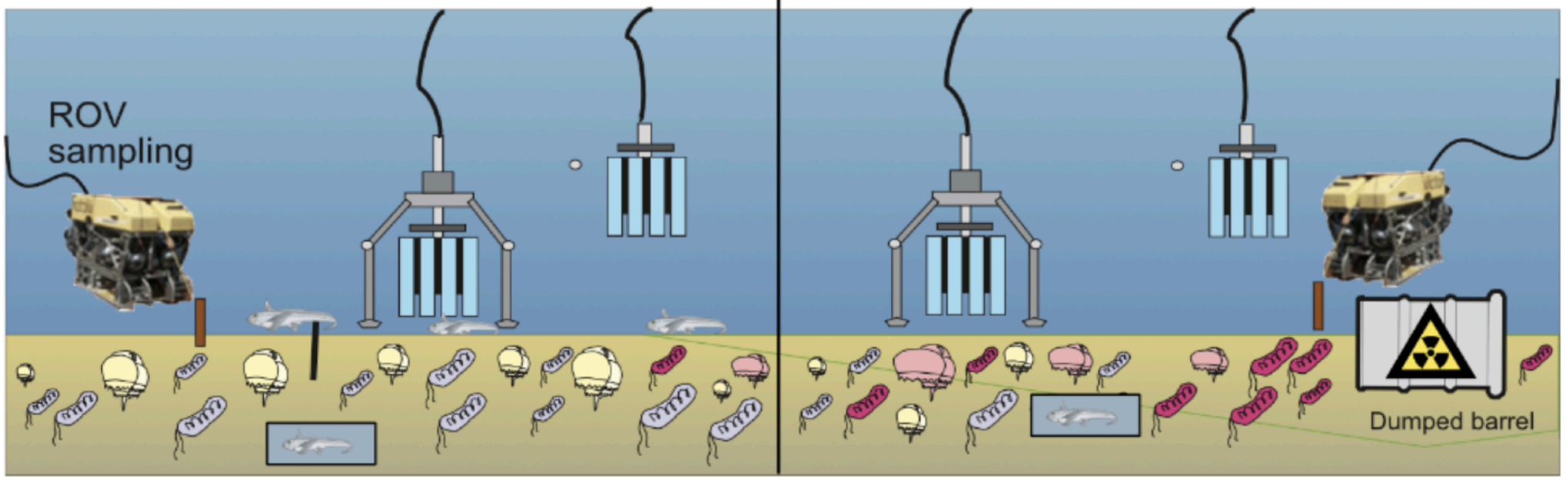
Cruise #1



Sampling of sediment, water, megafauna

Sampling of sediment, water, megafauna

Cruise #2

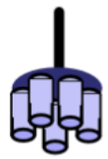


Prokaryota · Abnormal Prokaryota · Foraminifera · Abnormal Foraminifera · Fish

NODSSUM I Cruise

SAS acoustic mapping
Optical surveys - 2D
Gamma ray detector

Optical inspection
3D optical surveys
Gamma ray detector

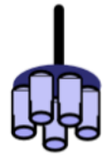


Multicorer
(Zone I)

Niskins
& CTD

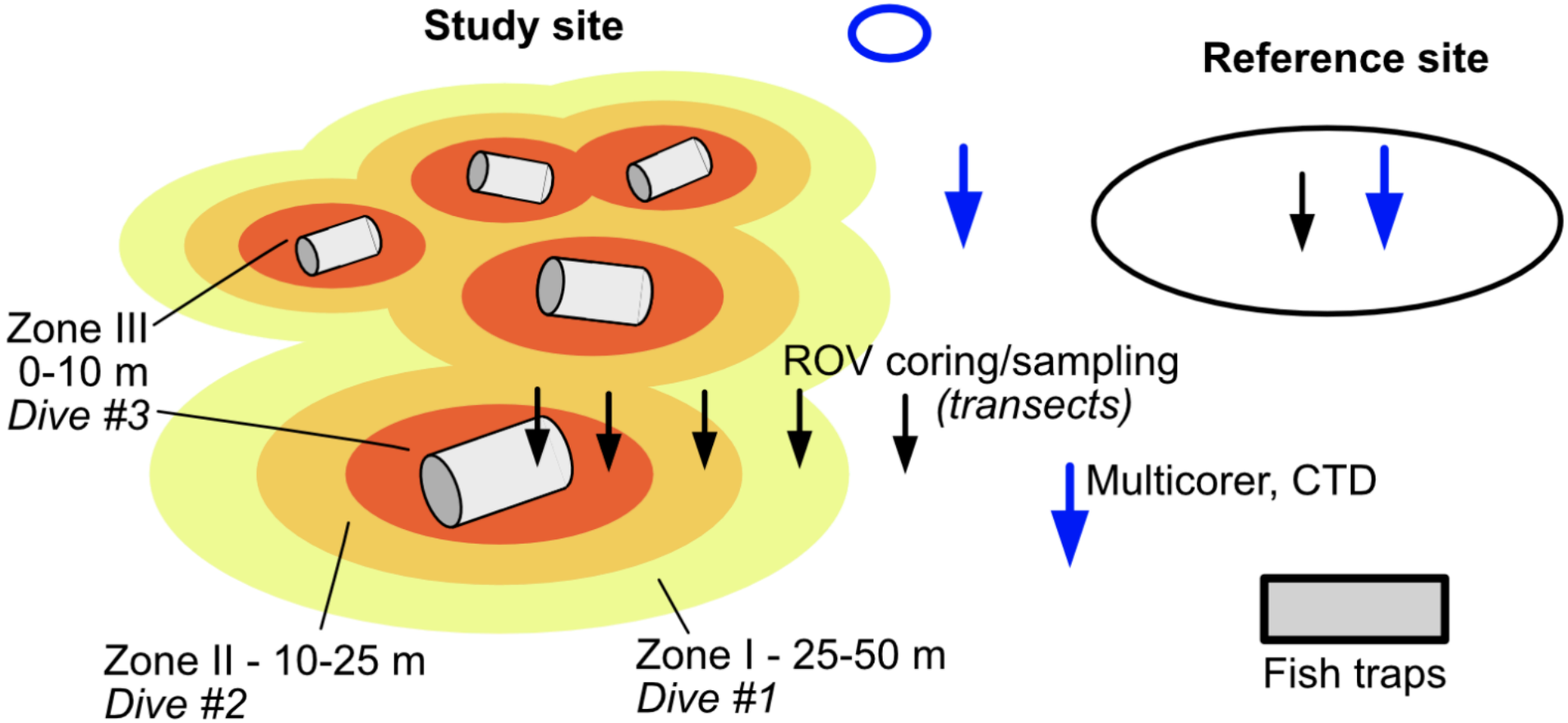
NODSSUM II Cruise

Optical inspection
3D optical surveys
Sampling+coring
Gamma ray detector

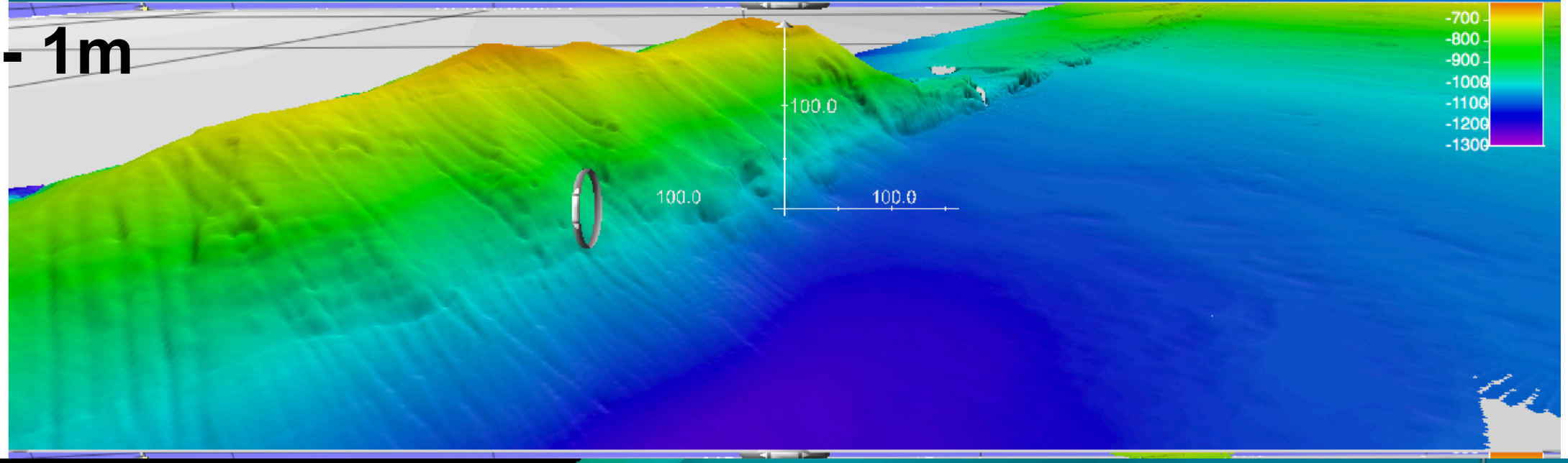


Multicorer
(Zone I)

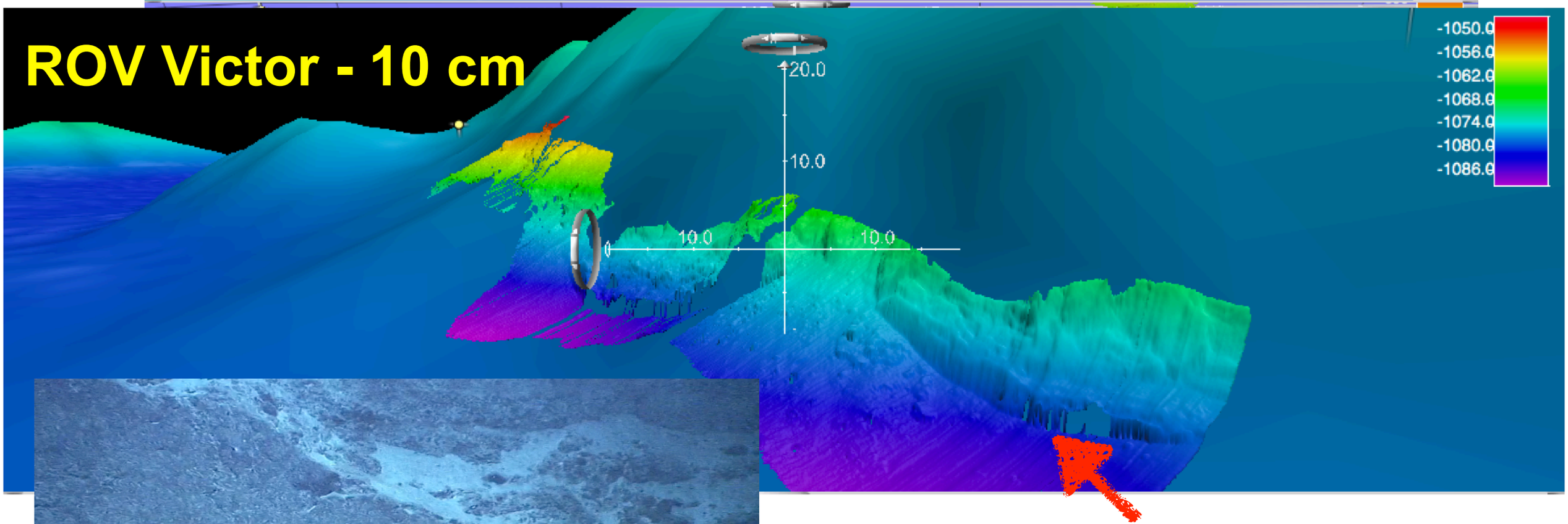
Niskins
& CTD



AUV - 1m

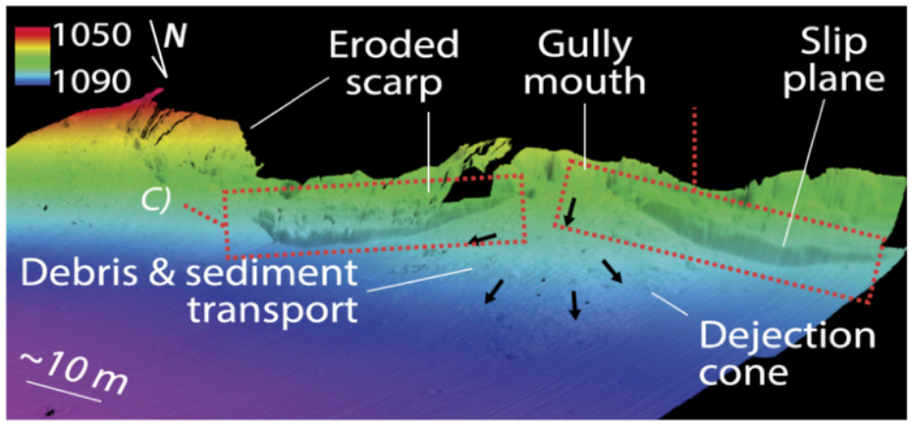


ROV Victor - 10 cm



3D mapping and earthquake geology

Risk and hazard assessment
(earthquake cycle, tsunami sources)

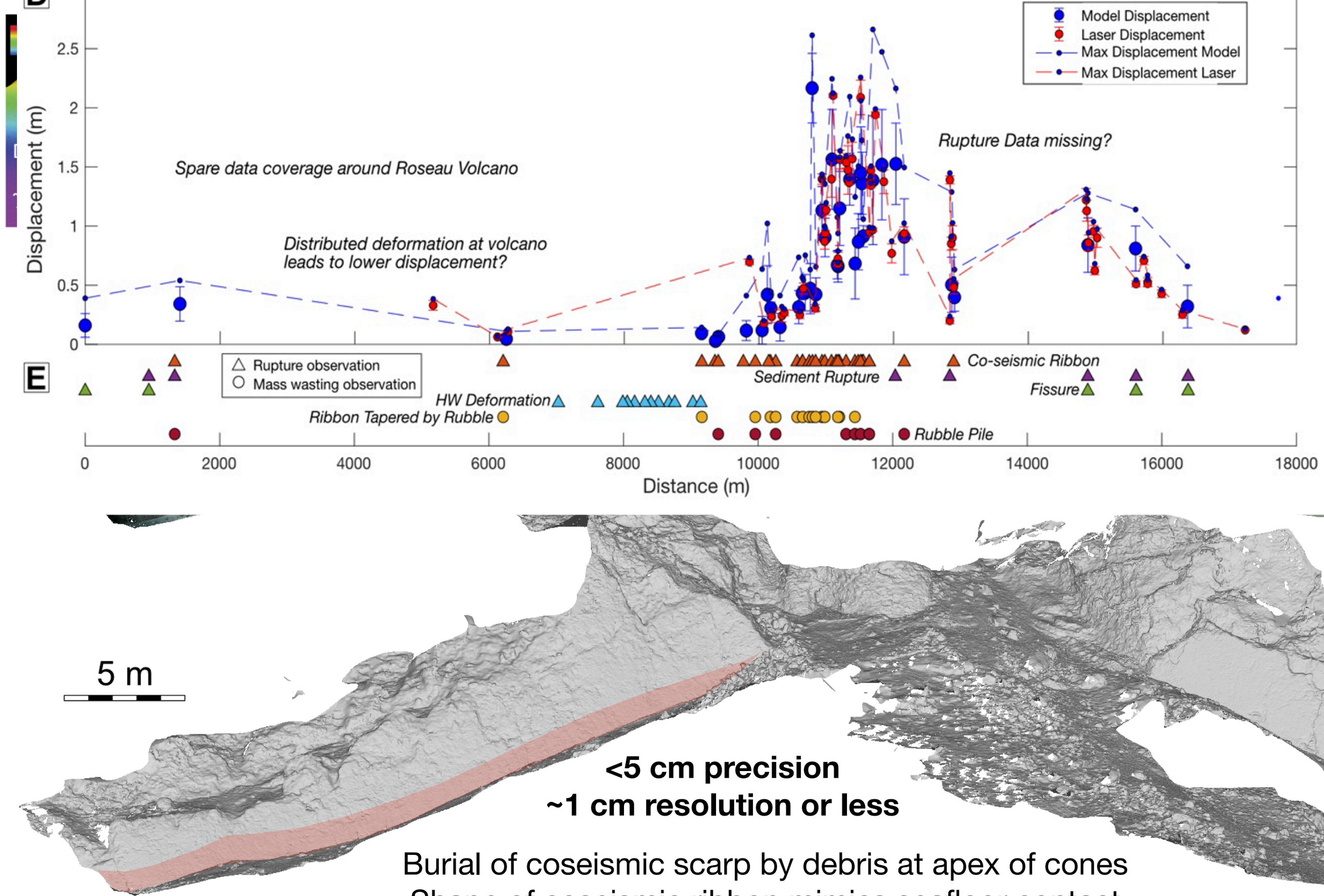


Escartín et al. [2016]

5 m

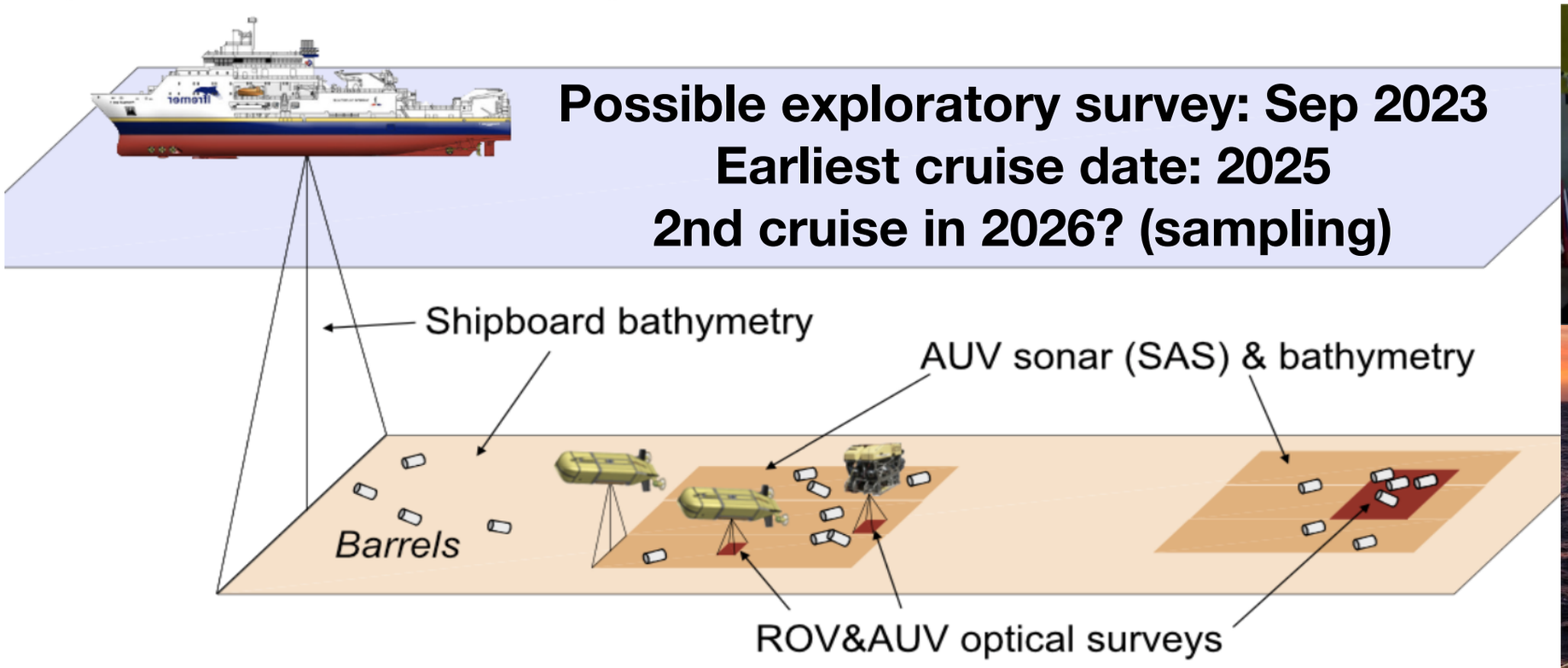
Burial of coseismic scarp by debris at apex of cones
Shape of coseismic ribbon mimics seafloor contact

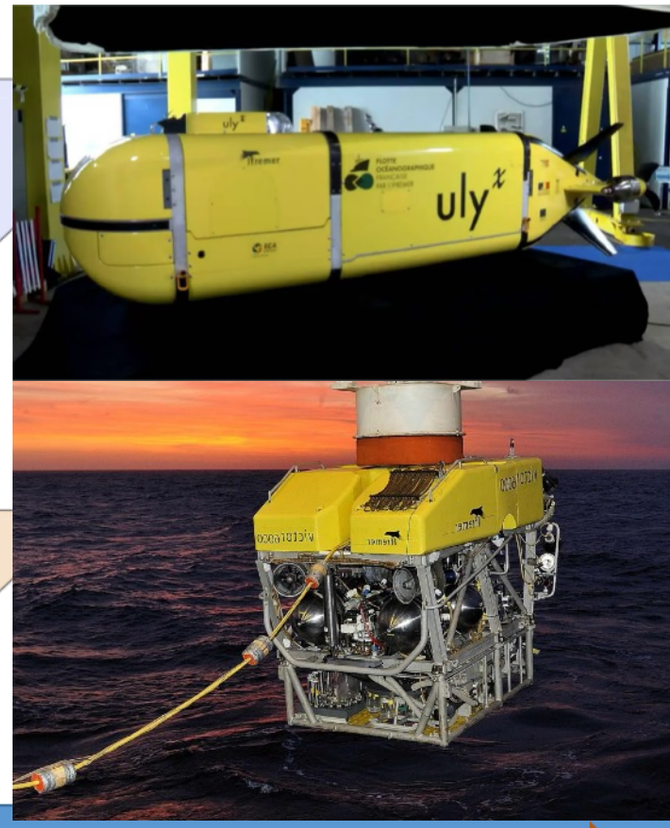
3Dmodels: Quantitative geology + context (samples, observations) + communication



3Dmodels: Quantitative geology + context (samples, observations) + communication

a) Identification, mapping, and inspection of dumped radioactive waste





Other RN inputs WP2 :
riverine / anthropogenic inputs, atmospheric deposition, …

Cartography, distribution,…
WP1

RN transport (WP1)

Water/water column
- RN quantification (WP2)
- Speciation, bioavailability (WP3)

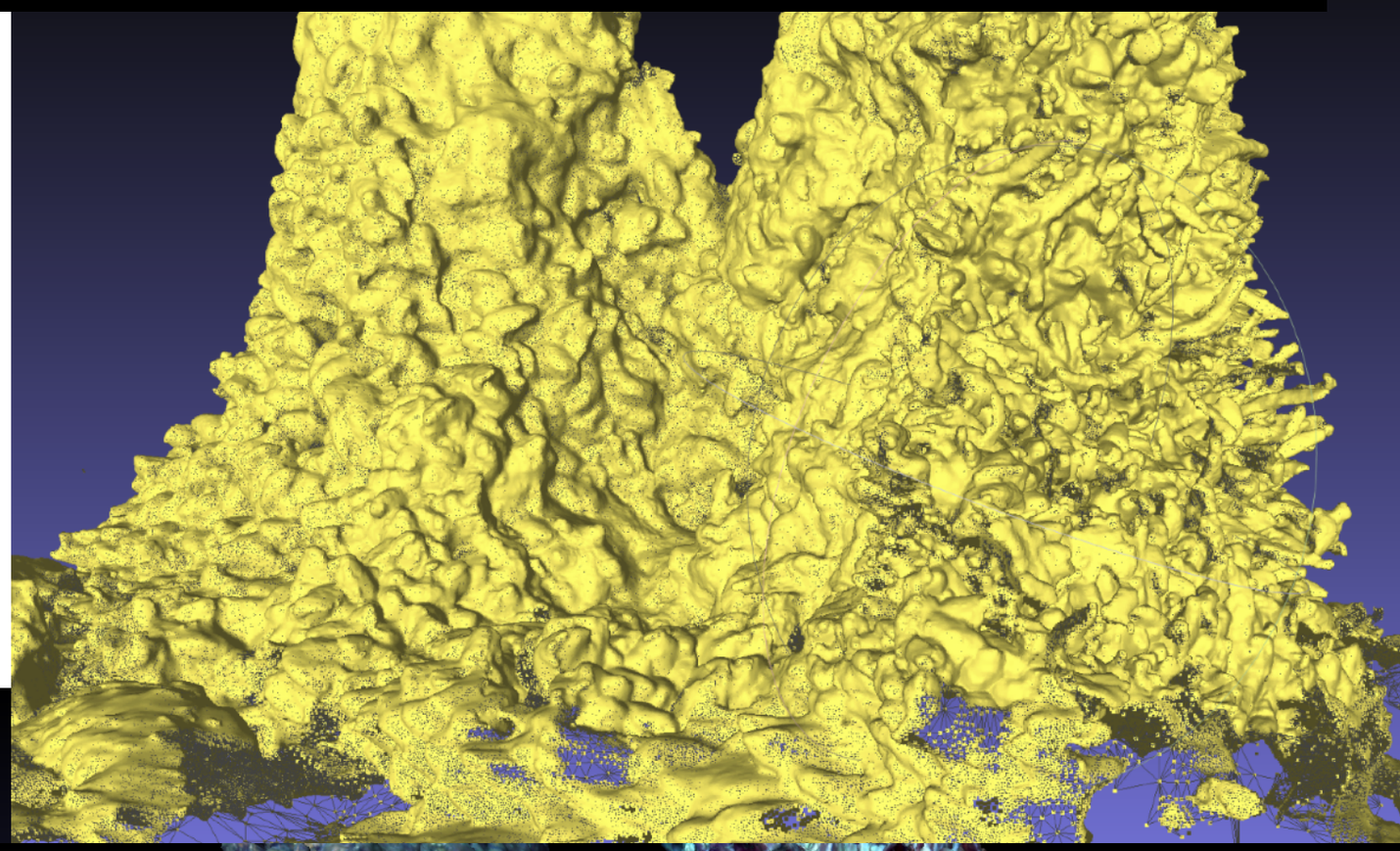
Sediment
- RN quantification (WP2)
- Speciation, bioavailability, lability, mobility (WP3)

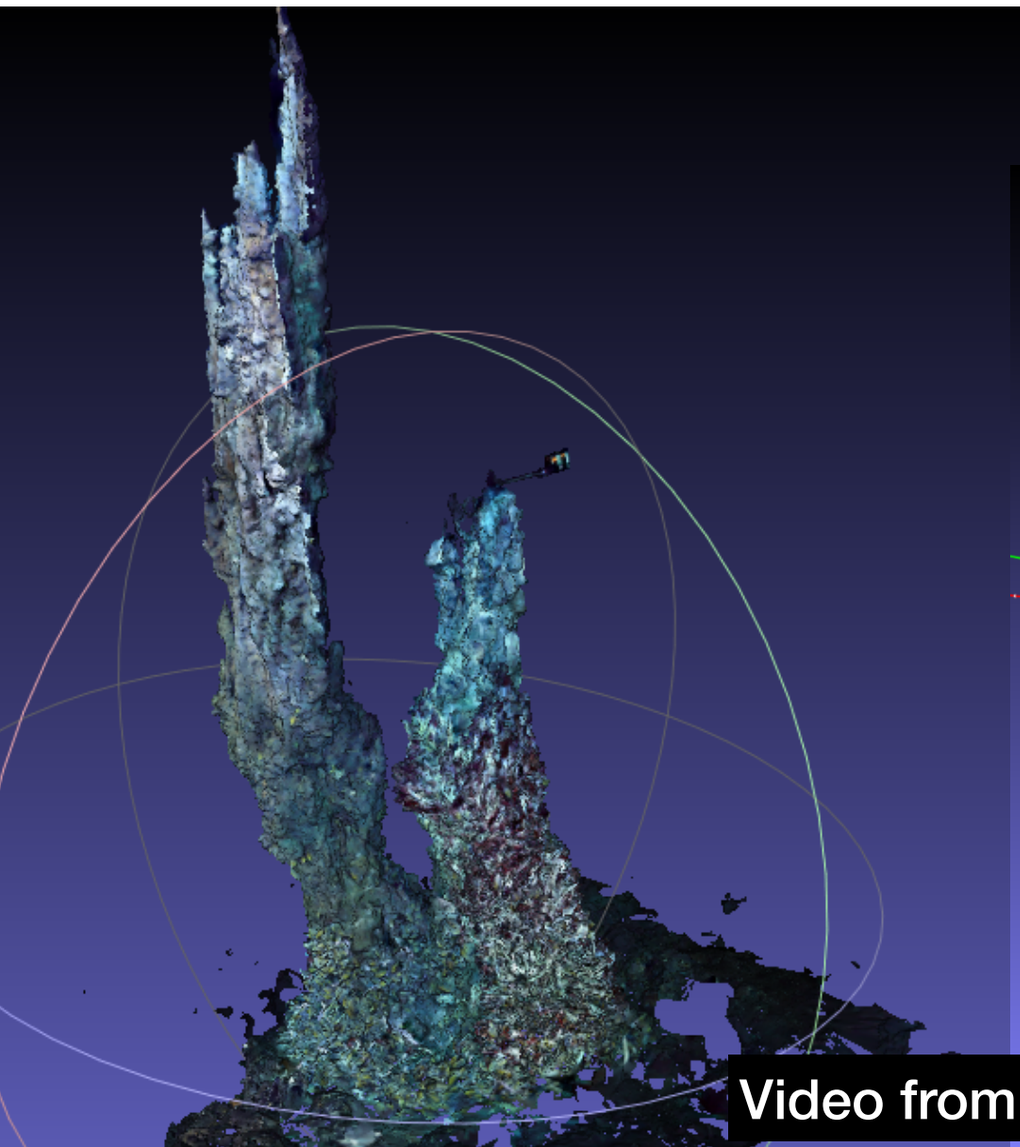
Living organisms WP4
- Distribution,… (WP1)
- Micro et meio organisms (WP4-1)
- Macro fauna (WP4-2)
- Megafauna (WP4-3, WP2, WP3)

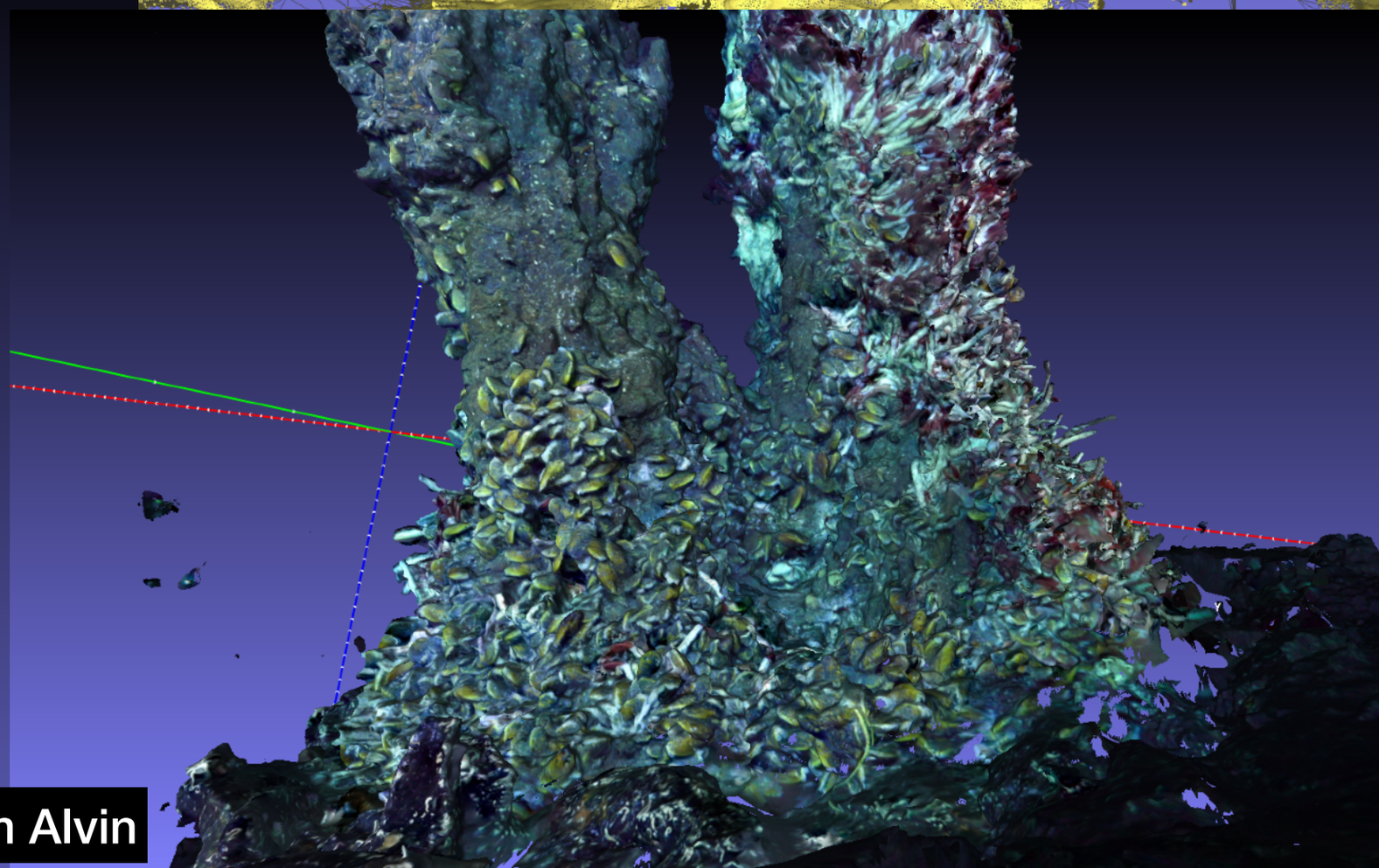
Resource imaging 2D/3D: U. of Girona, Computer Vision and Robotics Group

Research: Computer vision robotics

Services: CORONIS
IQUA robotics
(Asparus and Girona robots)







Video from Alvin

Anthropic impact - radiactive waste in the deep ocean
NODSSUM Cruise project

NODSSUM will benefit from the developments of 2 research projects:

- RADIOCEAN (IN2P3/INSU)
  - Database (available knowledge)
  - Development of RN preconcentration media (Cs, Pu, Am)
  - Improvement of the analysis protocol
- RAMONES (Europe)
  - New generation of detectors coupled with robotics and intelligent information systems for long-term monitoring of radioactivity (natural or artificial) in underwater environment (eg gamma sniffer,…)

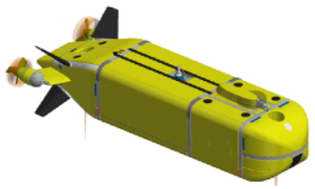
And a scientific context of deep sea research:

PEPR Research program on ‘Deep Ocean’ (France)

Arrival of new AUV 6000 Ulyx

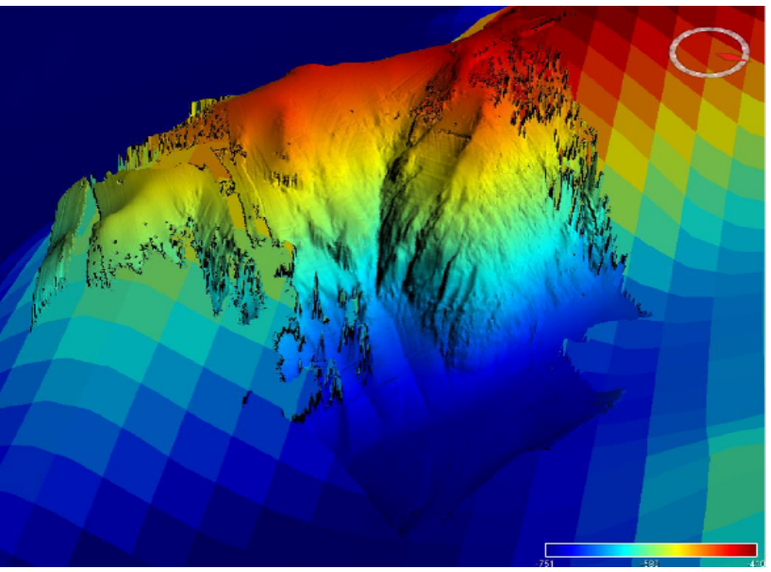
New technology developments: underwater LIDAR

New systems for French navy in cooperation with CNRS (6000m AUV+ROV) -> geostrategy

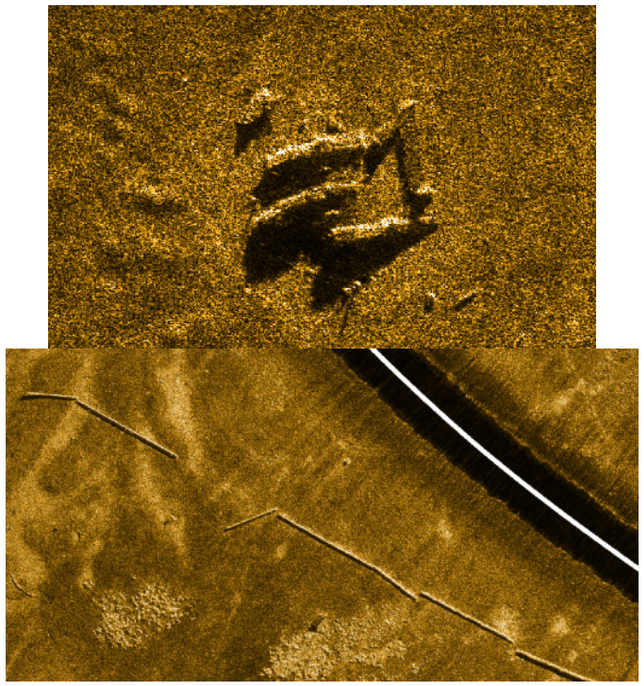


Outils déployés

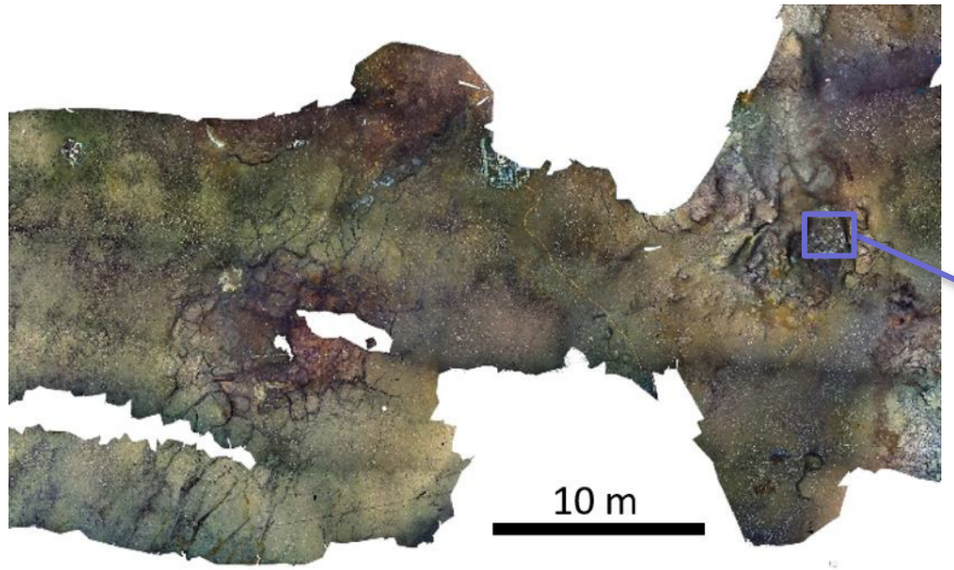
- Ulyx (6000 m): cartho acoustique (sonar et bathy) et optique (imagerie verticale)



Bathymétrie (~20-50 cm)

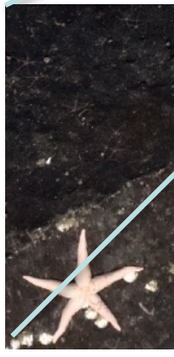


Sonar (~10-20 cm)



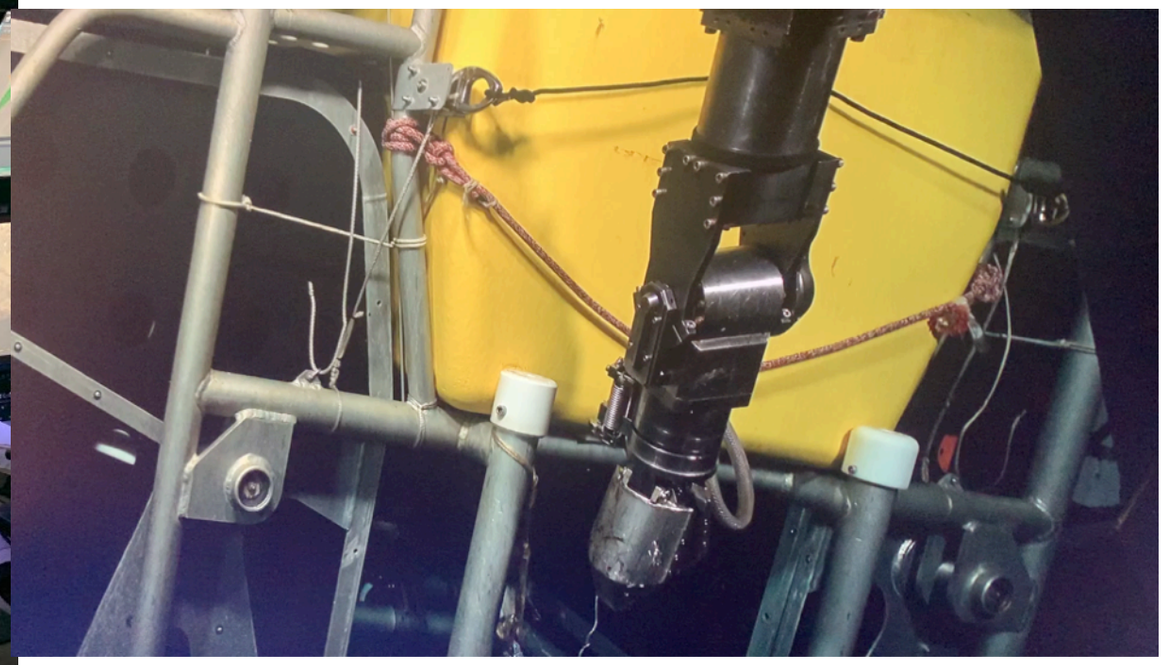
Images (<1 cm)

1. Detection de futs (bathy, sonar)
2. inspection optique



Outils déployés

- ROV - VICTOR (6000m)



Projet Arc-en-sub

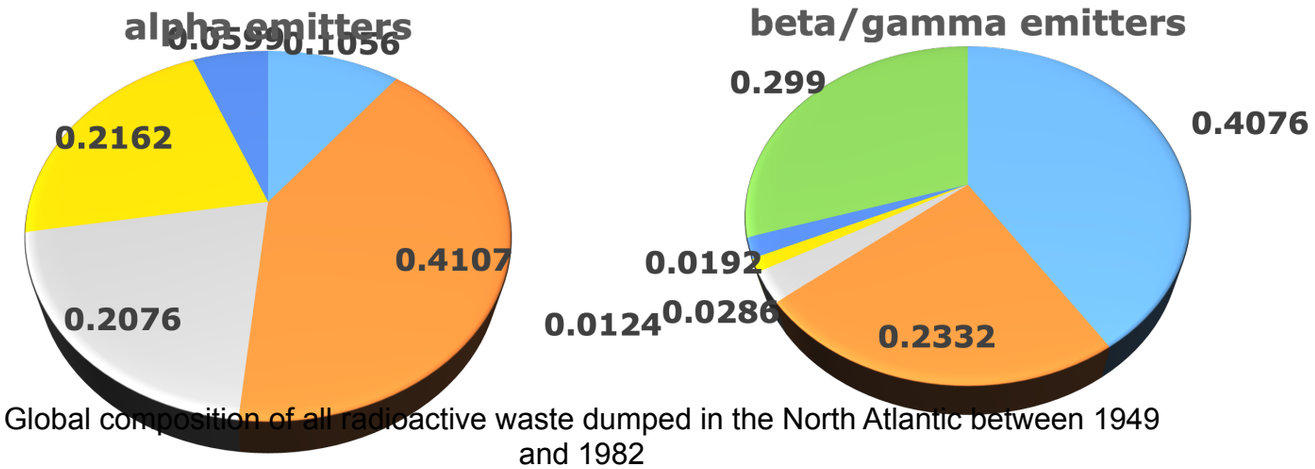
Contexte

Emetteurs alpha : 2% Emetteurs bêta gamma : 98%

Alpha	Half-life	Range of annual beta/gamma composition %	Bêta / gamma	Half-life	Range of annual beta/gamma composition %
^{210}Po	1,40E+02 d	0,4-1	**^{3}H**	1,23E+01 y	39-82
^{226}Ra	1,60E+03 y	0,3-5	**^{14}C**	5,70E+03 y	0,21,5
^{234}U	2,46E+05 y	0,01-0,2	^{35}S	9,20E+01 d	0,051,1
^{235}U	7,04E+08 y	0,6-1,8	^{54}Mn	3,12E+02 d	0,0001-0,3
^{238}U	4,47E+09 y	0,01-0,2	^{55}Fe	2,75E+00 y	0,0001-1
^{237}Np	2,14E+06 y	0,00007-1,2	^{58}Co	7,09E+01 d	0,001-1,5
^{238}Pu	8,80E+01 y	6-12	^{60}Co	5,27E+00 y	1,3-8,7
^{239}Pu	2,41E+04 y	40-66	**^{90}Sr**	2,88E+01 y	1,2-2,6
^{240}Pu	6,56E+03 y	12-23	^{125}I	5,90E+01 d	0,09-1,2
^{242}Pu	3,73E+05 y	0,3-0,6	^{134}Cs	2,06E+00 y	0,1-1,3
^{241}Am	4,33E+02 y	13-24	**^{137}Cs**	3,01E+01 y	1,5-3,7
^{244}Cm	1,81E+01 y	0,1-0,2	**^{241}Pu**	1,44E+01 y	12-47

- ≈300 000 fûts (métal/béton)
- ≈42PBq (98% β/γ, 2% α)
- Matrice de confinement : bitumineuse ou cimentaire
- Conçu pour résister à l'immersion et l'impact sur le plancher océanique

  => confinement induit estimé à 15/25 ans



Global composition of all radioactive waste dumped in the North Atlantic between 1949 and 1982

Contexte

L’immersion comme solution de gestion des déchets TFA/FA de la fin WW2 à la fin des années 80

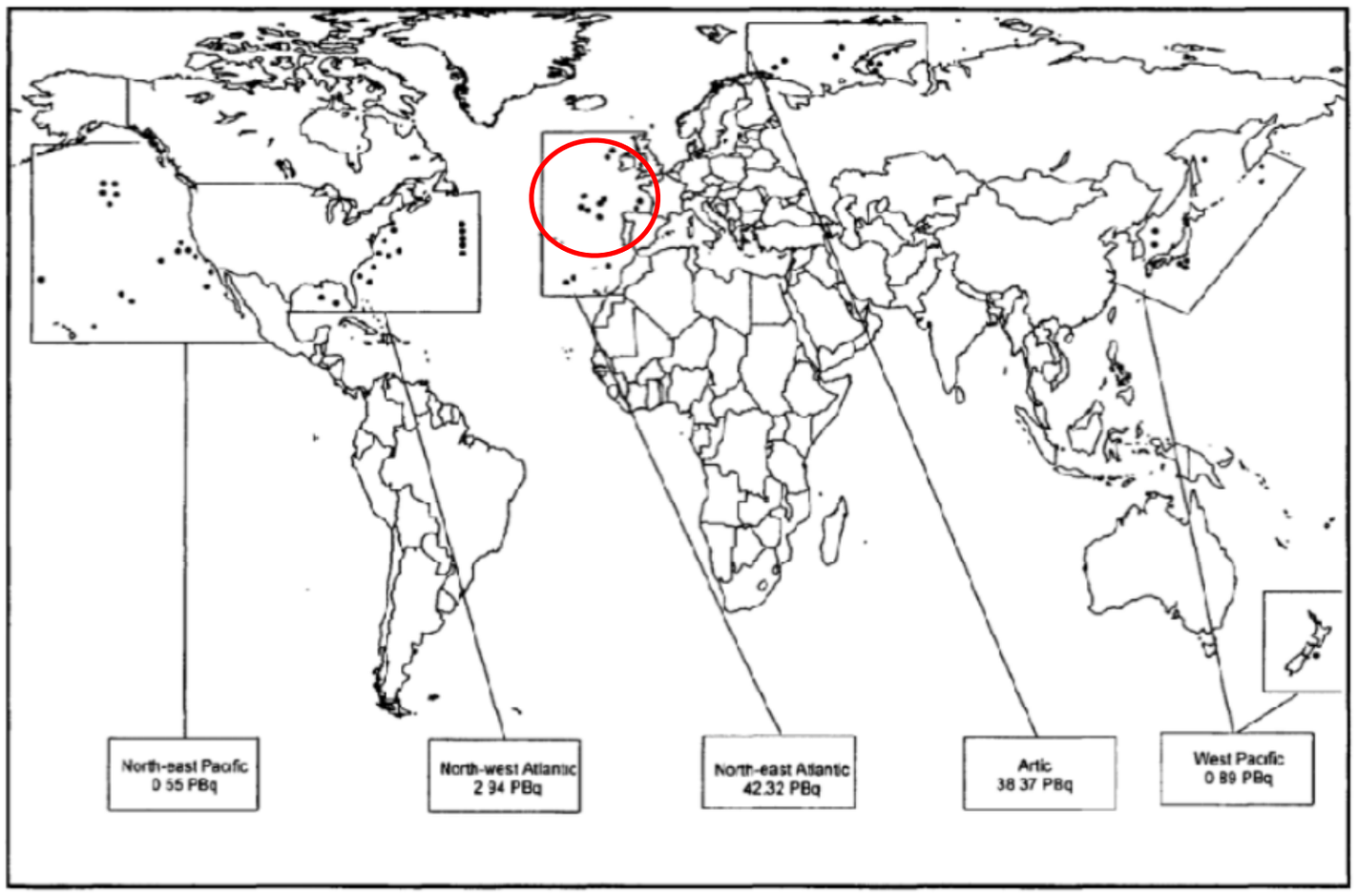
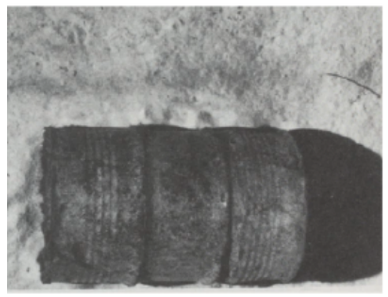
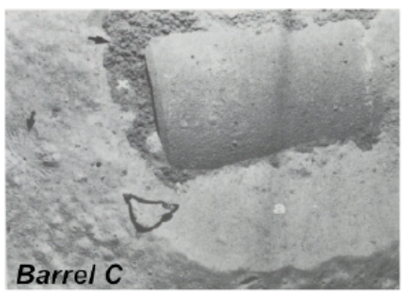


FIG. 1. Disposal at sea of radioactive waste – worldwide





A priori, les déchets relèvent des catégories TFA/FA (déchets de laboratoire, de recherche et mise au point…)

Les objectifs du projet

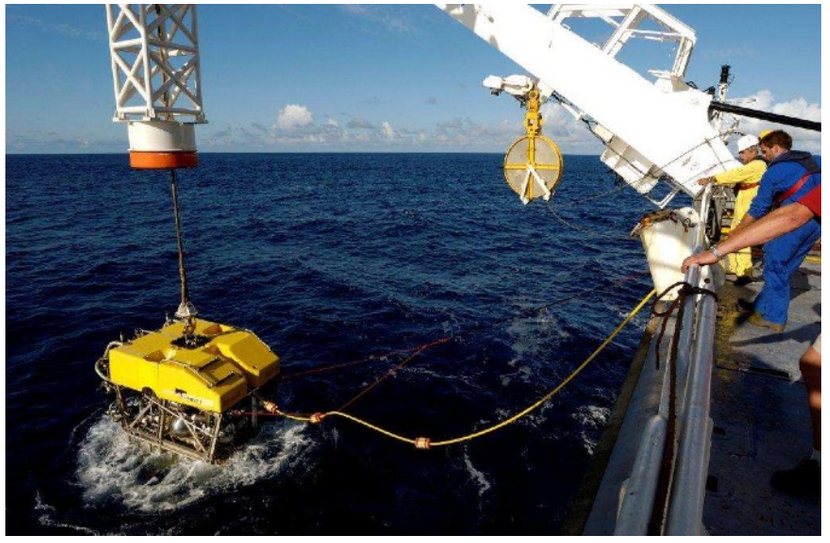
Stratégie de prélèvement

a) **Identifier et cartographier** la distribution des fûts à l'aide de l'AUV Ulyx (IFREMER) équipé d'un système de sonar et cameras optiques à très haute résolution

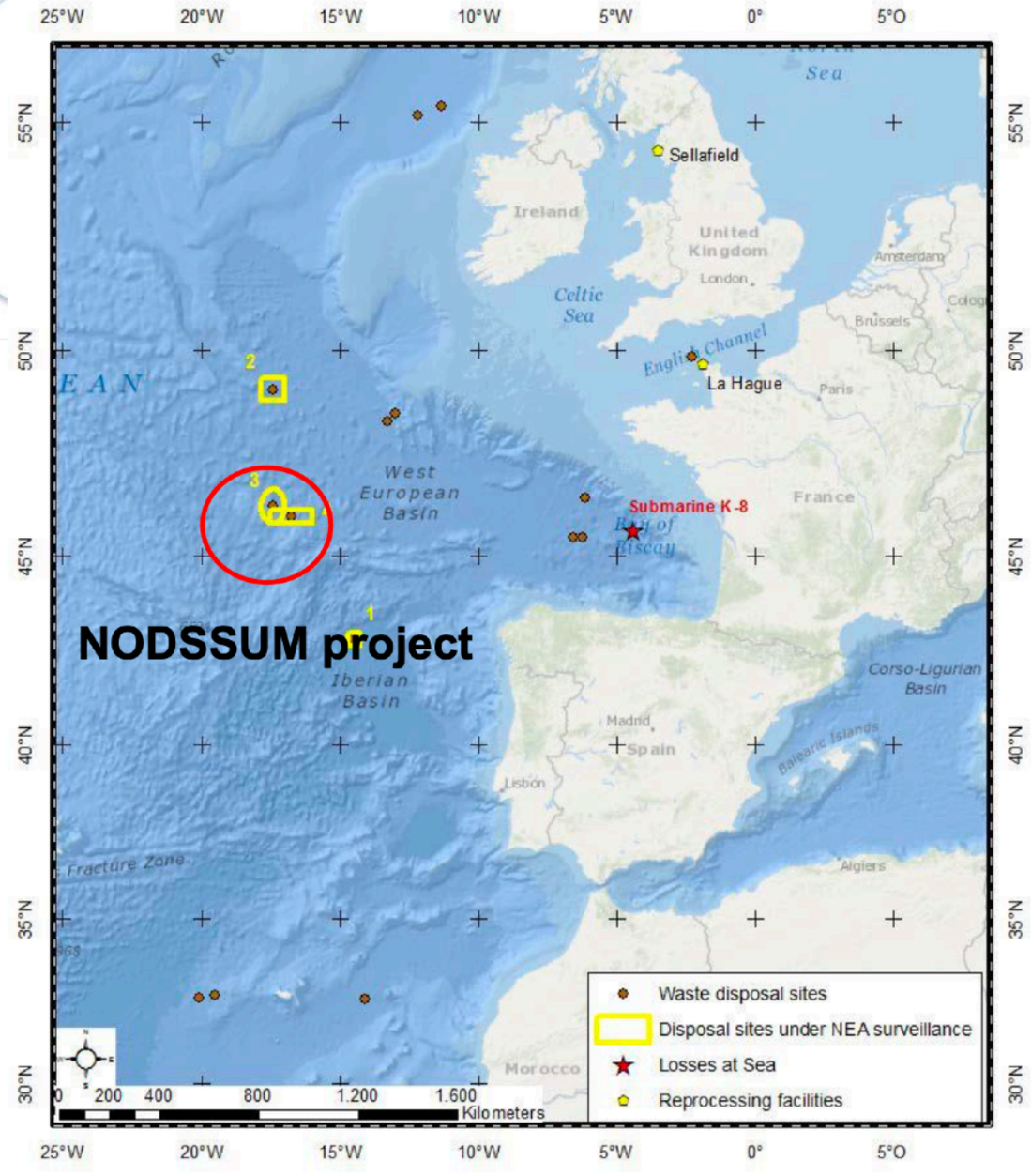
b) Evaluer **l'état des fûts** dans les zones sélectionnées par l'AUV en utilisant le ROV Victor (IFREMER)

c) Réaliser des **prélèvements** d'eau, sédiments et matrices biologiques dans les zones sélectionnées pour évaluer les variations spatiales et à différentes échelles (de la dizaine de km à la proximité immédiate des fûts).

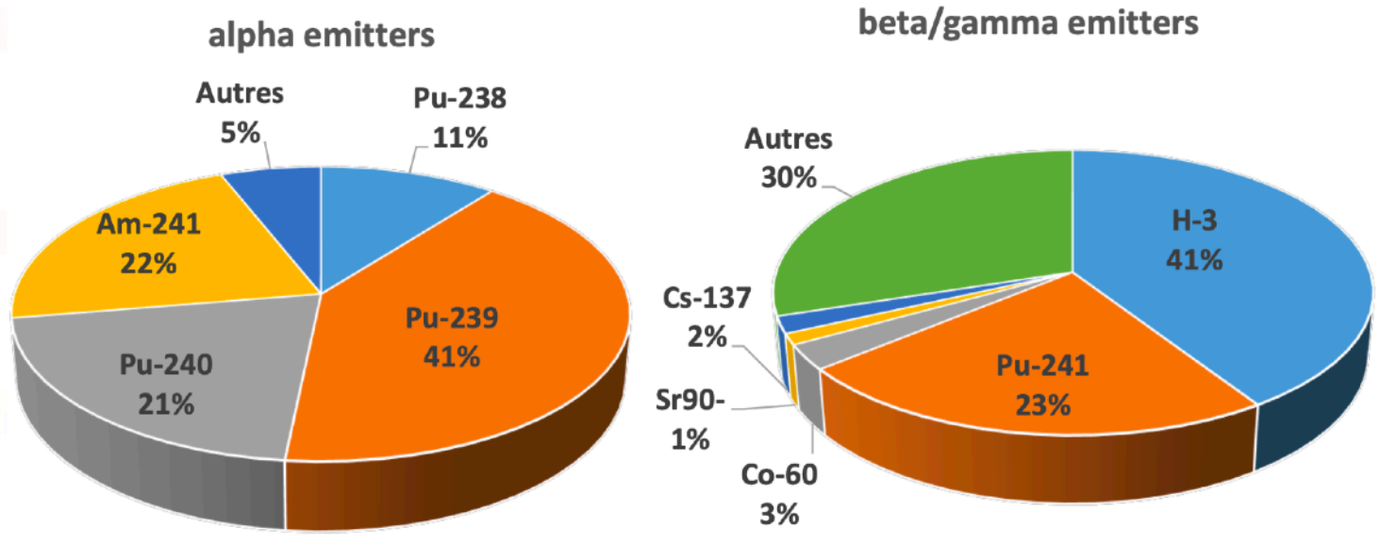
d) Evaluer les **impacts :** perturbation physique du fond marin et effets sur les écosystèmes (macro et micro)



Contexte : N-E Atlantic dump site (49-82)

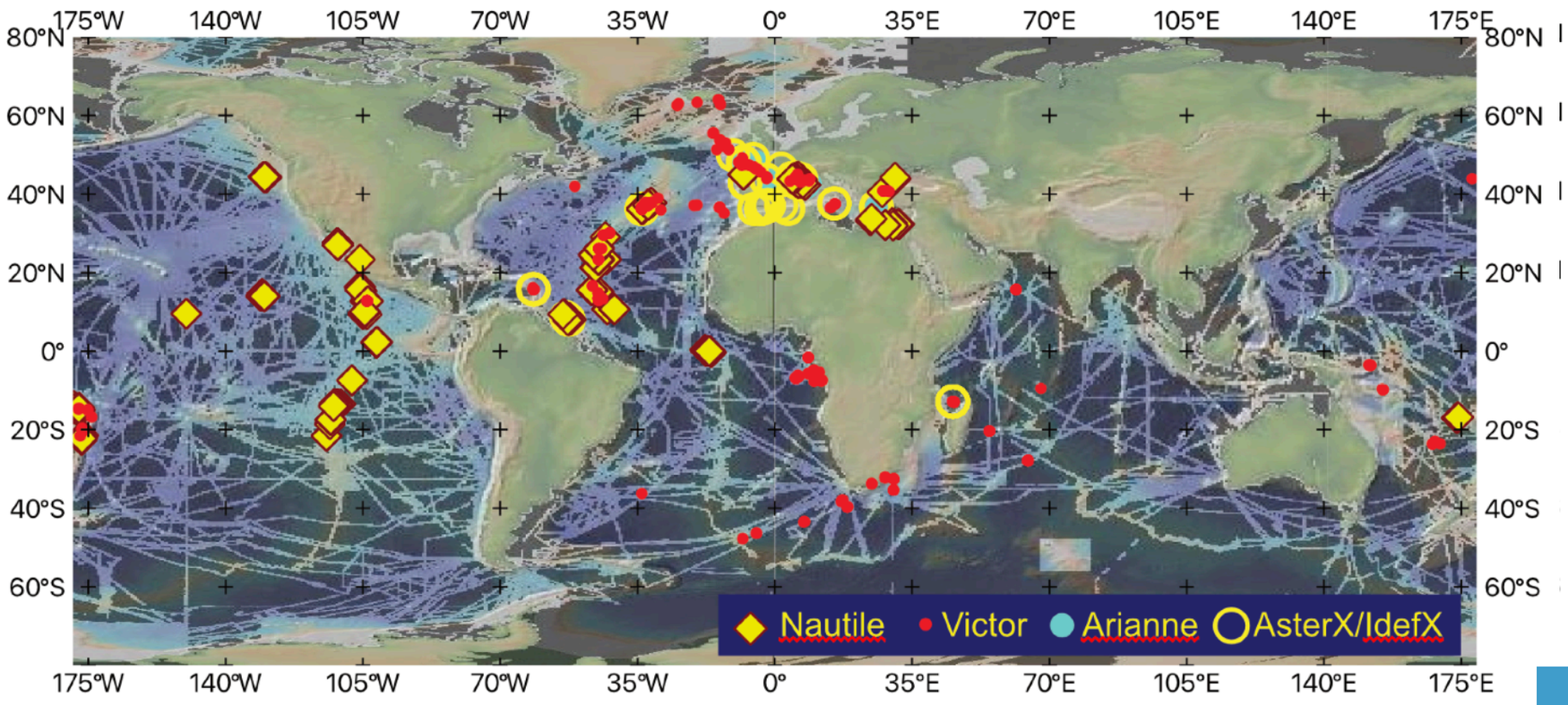


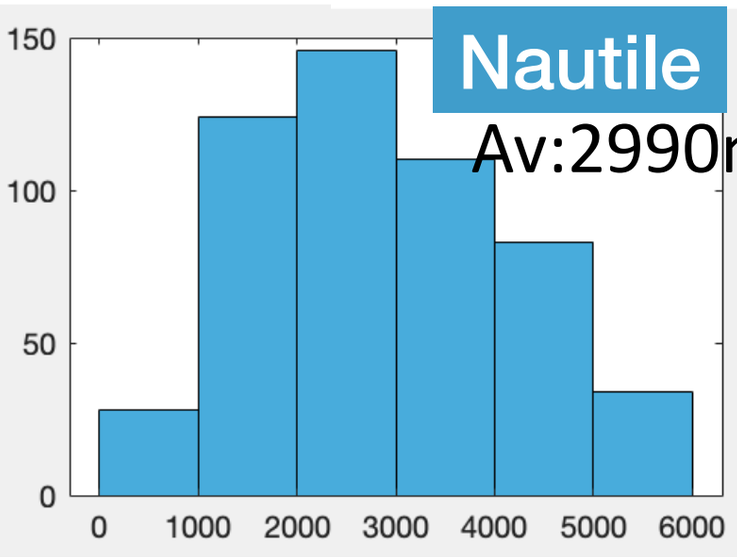
- ≈300 000 metal/concrete containers designed to ensure waste containment during descent and impact at sea floor => containment barrier for 15-20 years
- **<u>Concrete/bitumen matrix</u>**
- ≈42PBq (98% β/γ, 2% α) ***Chernobyl: 2000 PBq***

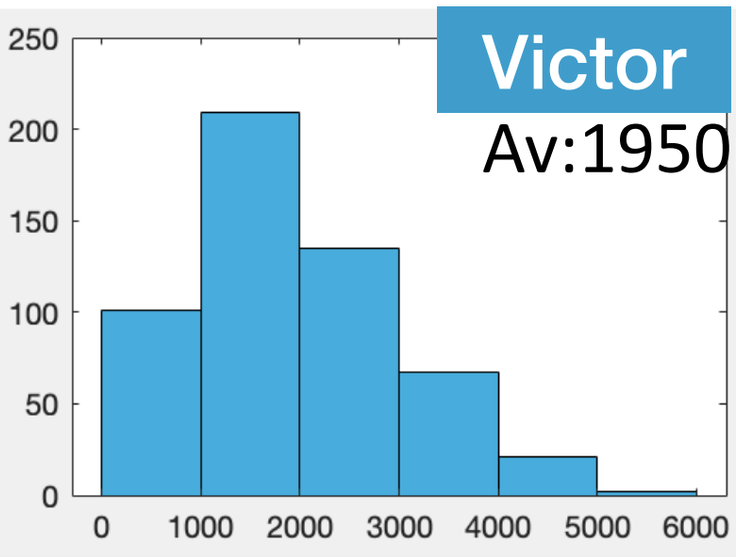


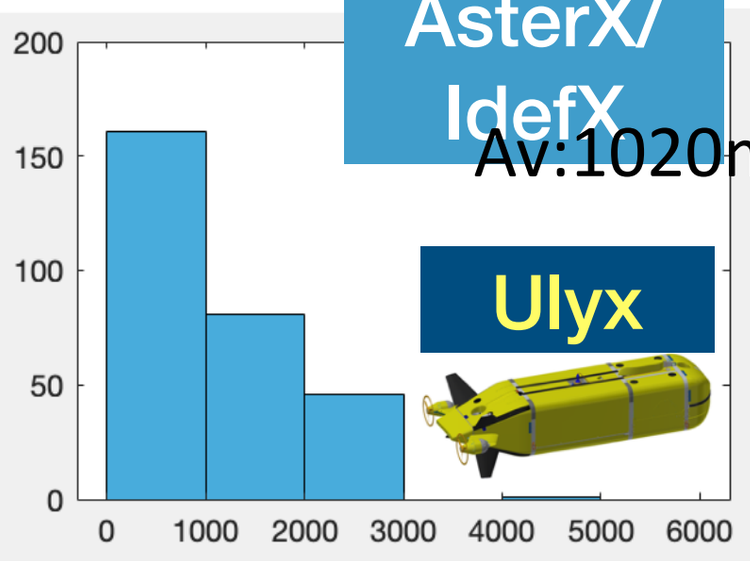
Global composition of all radioactive waste dumped in the North Atlantic between 1949 and 1982

Data Courtesy of SISMER - to be completed/validated









ulvx – AUV 6000

Mechanical characteristics:

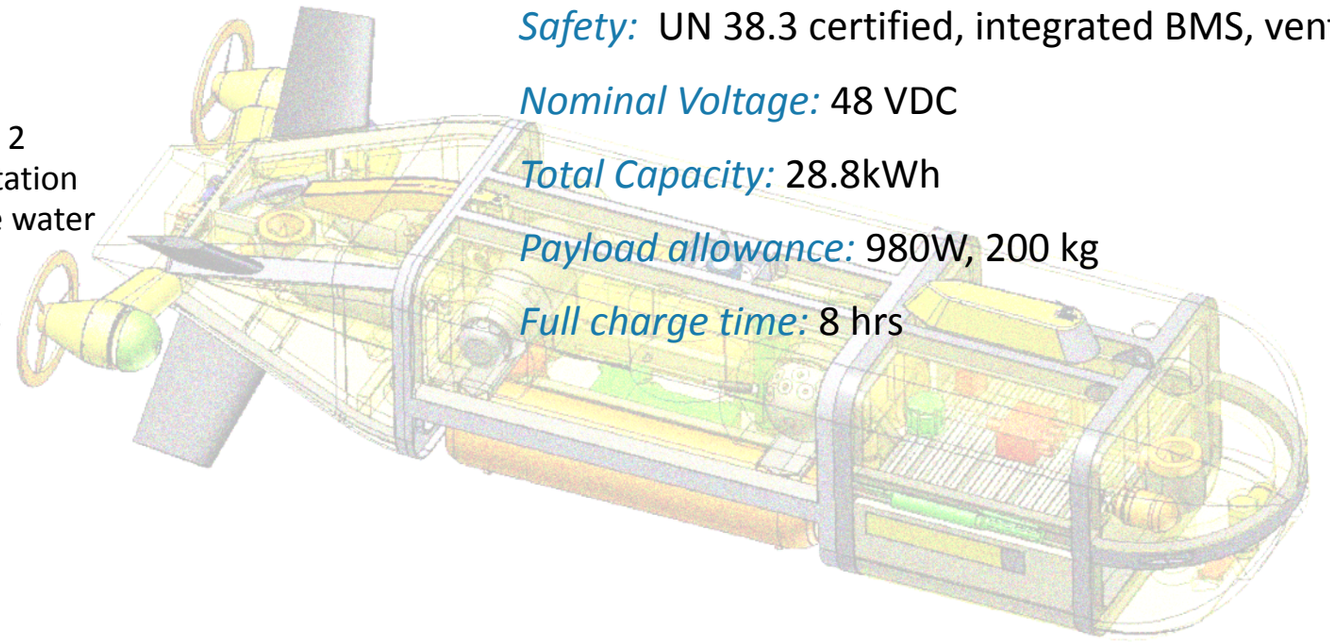
Mass: 2750 kg

Depth rating: 6000m

Size: (lwh) 4.5*0.8*1.2m

Actuators: 2 longitudinal thrusters, 2 vertical thrusters, one thrust orientation unit, 4 actuated rudders, reversible water ballast

Transportability: 2x 20ft containers



Electrical characteristics :

Battery type: LiIon battery in 1 atm pressure housings

Safety: UN 38.3 certified, integrated BMS, vent

Nominal Voltage: 48 VDC

Total Capacity: 28.8kWh

Payload allowance: 980W, 200 kg

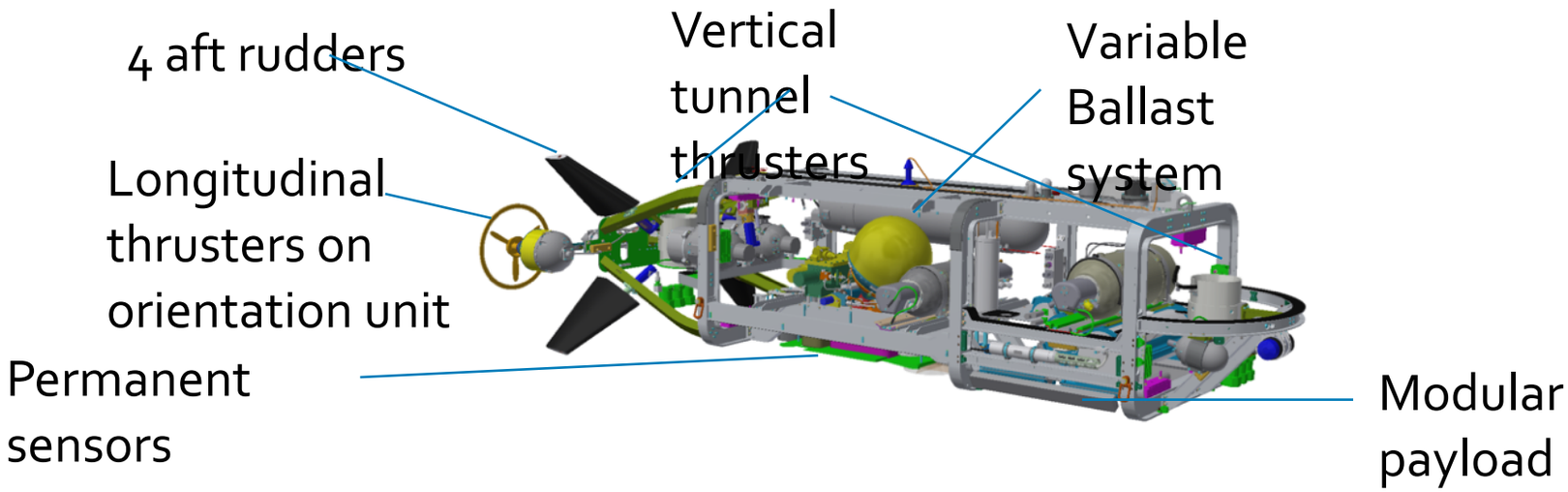
Full charge time: 8 hrs

Operational capabilities:

Dive duration: 24 to 44 hours depending on payload

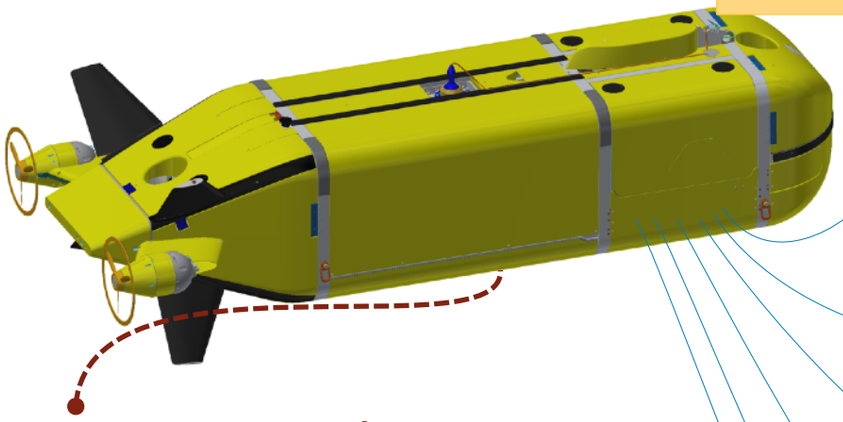
Survey task: 30m to 100m altitude, speed up to 2.5 m/s

Local inspection task: 2m to 10m altitude , speed 0 m/s (**hover**) to 1m/s terrain following



FLOTTE OCÉANOGRAPHIQUE FRANÇAISE PAR L'IFREMER

Payloads



Charge utile modulaire (reconfigurable)

Low frequency sub-bottom profiler
Model: IxBlue Echoes 5000
Frequency : 2-6 kHz
Resolution : 15 cm
Data: 24 bit raw data / segy 32 bits

Synthetic Aperture Sonar
Model: IxBlue SAMS 150
Frequency: 150 kHz
Resolution: 7cm , 250m swath

300 kHz ADCP: Teledyne RDI Pioneer

High accuracy positioning Beacon and ranging device
Additional positioning beacon combining range measurement to aid and improve inertial navigation performance
Model: IxBlue RAMSES

RAMAN spectrometer (perspective future)
Detection, identification and in situ analysis of minerals or gas hydrates

Sampling (perspective future)
in situ water sampling with separated circuits, 30 samples

Equipements à poste

Image acquisition payload:
16M pixel high quality image sensor for 2D optical mapping, 3D reconstruction

Multi Beam Echosounder
Acoustic bathymetry and water column reflectometry
Model: Kongsberg Maritime EM2040
Frequency: 200 kHz to 400 kHz
Beams: 400

CTD:
Model: Seabird SBE 49
temperature, conductivity, pressure;
sampling: 16Hz

Multi-parameter sensor suite:
Up to 6 small scale sensors including:
3x Magnetometer(s), Nephelometer, Eh, pH, O2, Redox

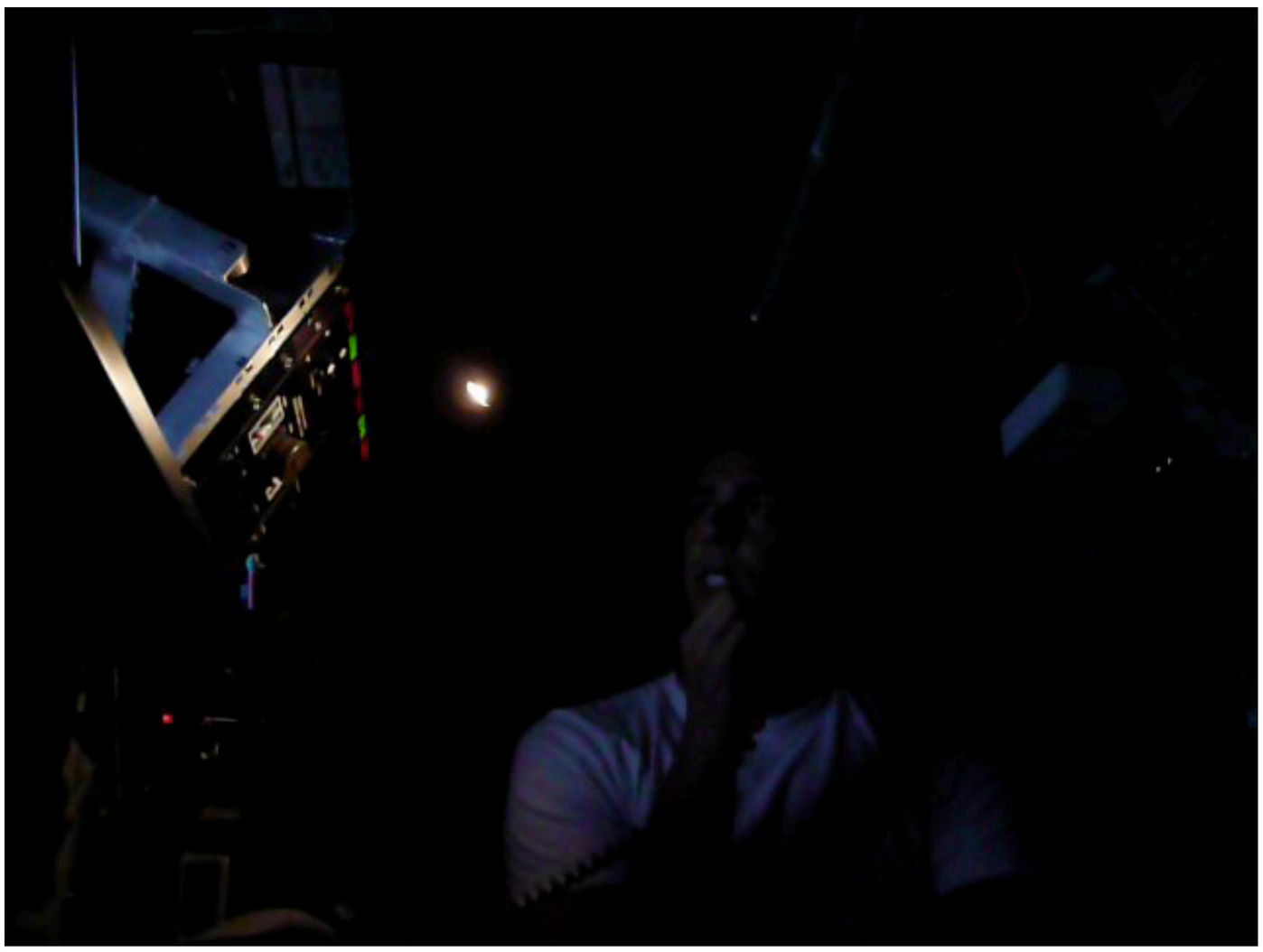
FLOTTE OCÉANOGRAPHIQUE FRANÇAISE PAR L'IFREMER

Tools

Submersibles

MG&G M1/M2
Fall 2023-2024
J. Escartín

ENS DÉPARTEMENT DE GÉOSCIENCES



Benefits:

- Vision

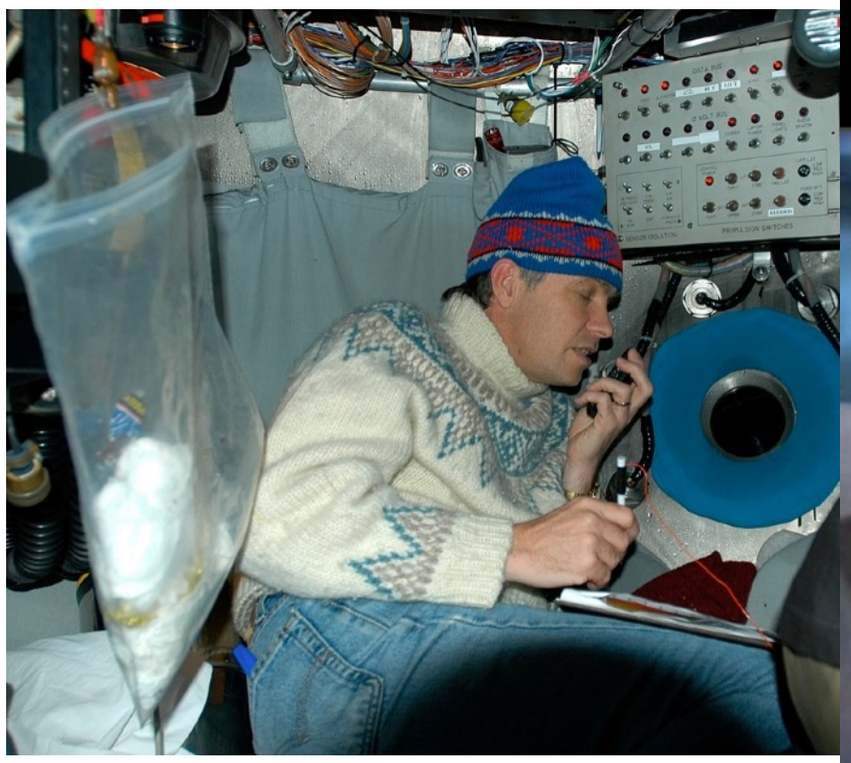
Drawbacks:

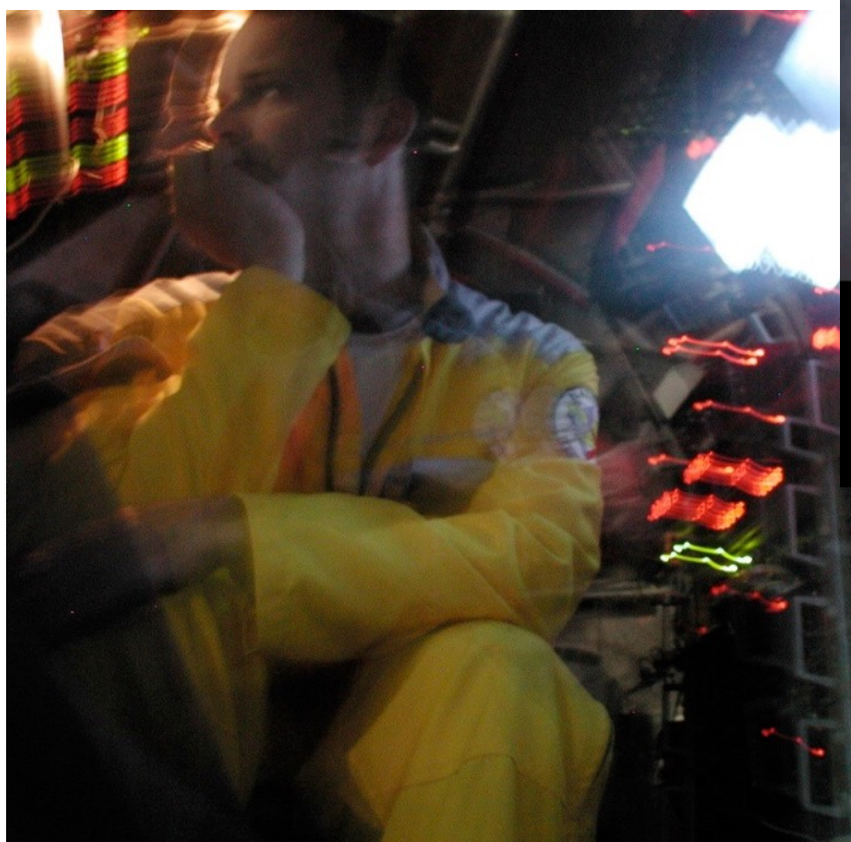
- Security
- Operations & maintenance
- No surface link -> isolated and limited personnel

Tools

Submersibles

ENS DÉPARTEMENT DE GÉOSCIENCES





Drawbacks:

- Security
- Operations & maintenance
- No surface link -> isolated and limited personnel

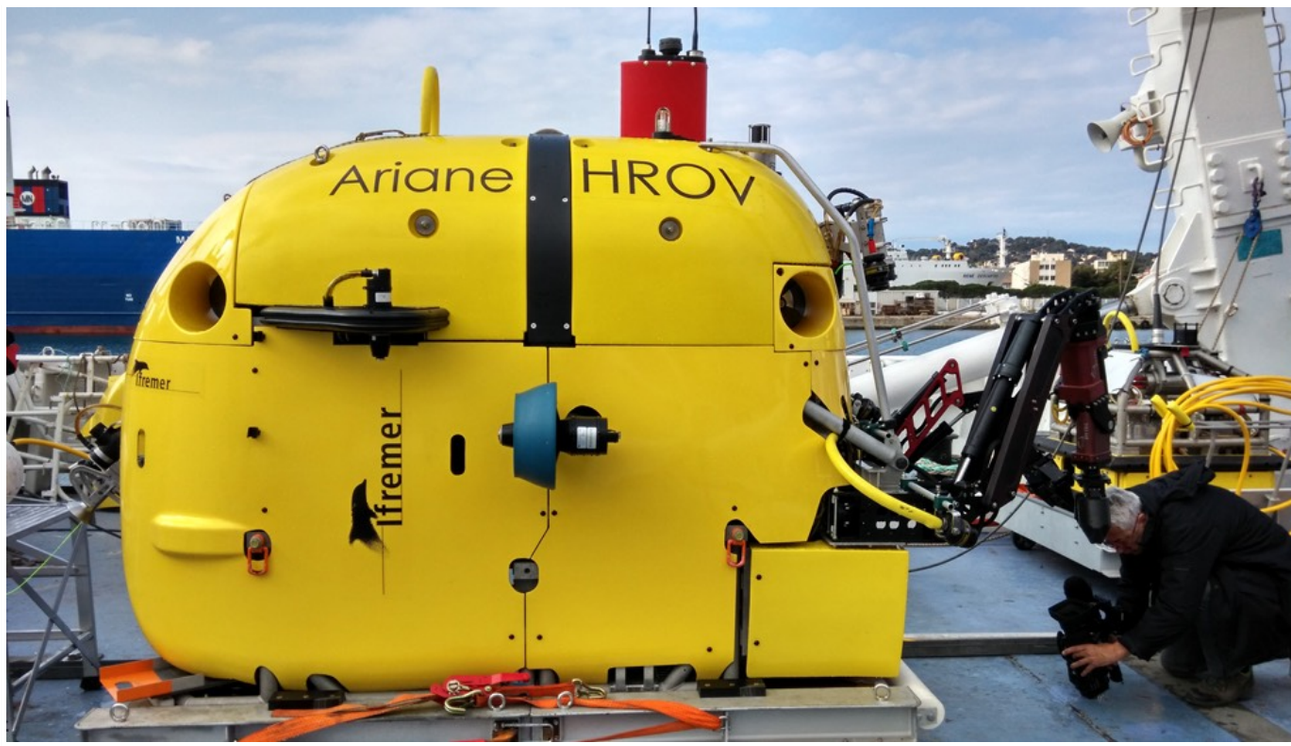
Tools

MG&G M1/M2
Fall 2023-2024
J. Escartín

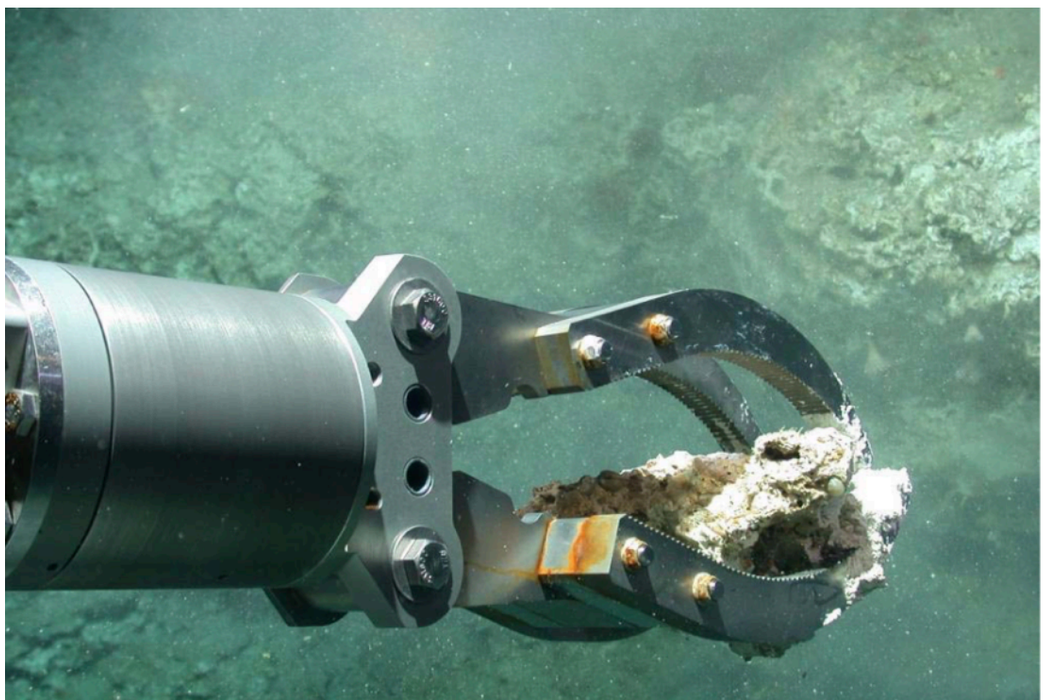
ENS DÉPARTEMENT DE GÉOSCIENCES

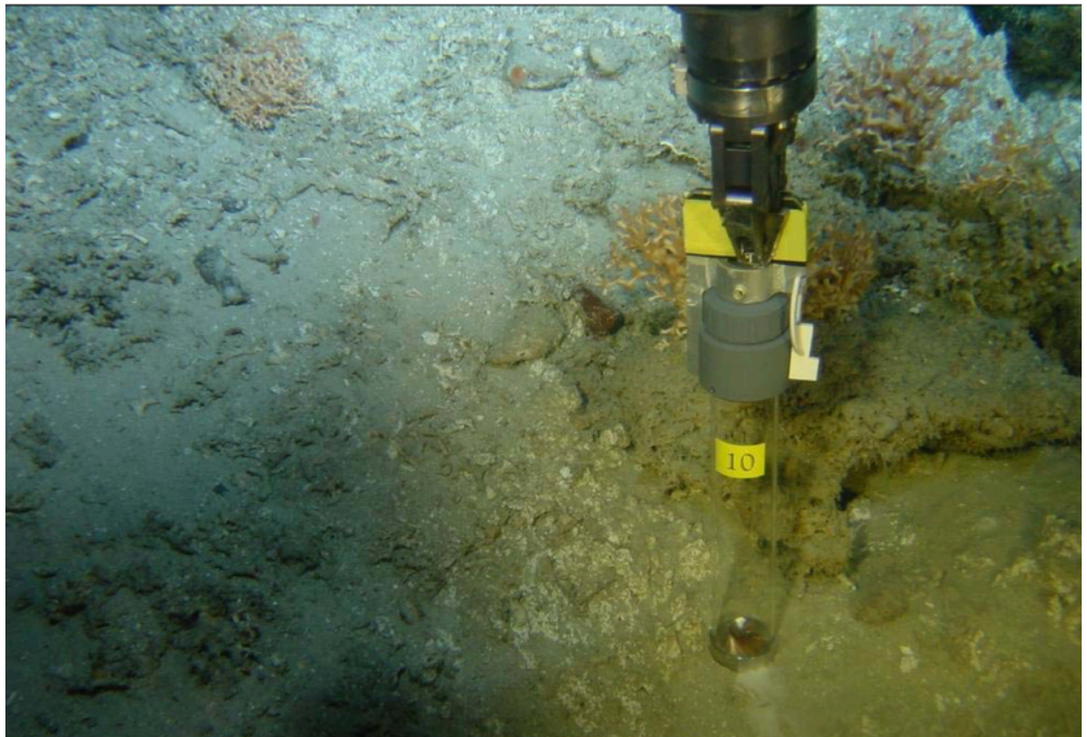
Remotely operated vehicles

VICTOR6000



Arianne





Tools

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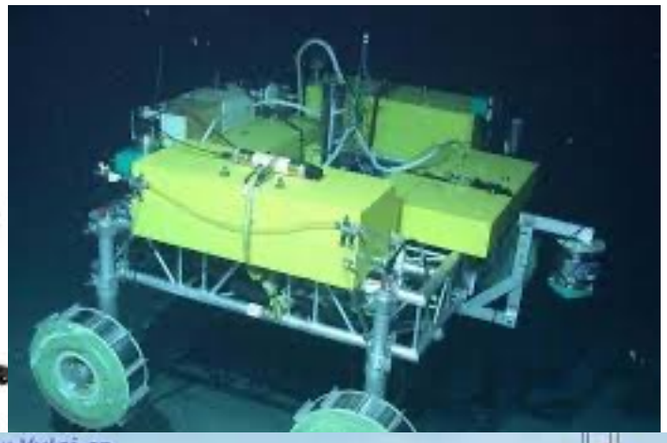
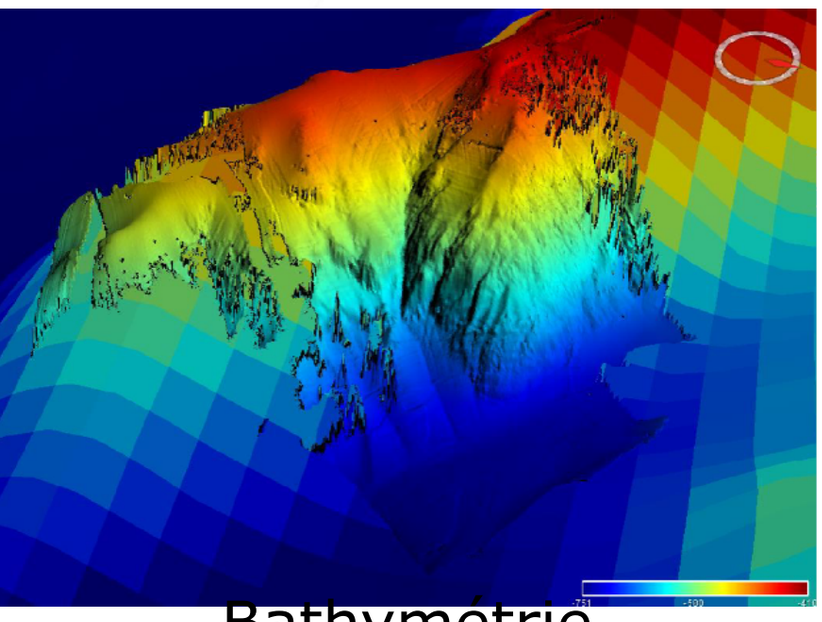
Remotely operated vehicles -> the industrial revolution

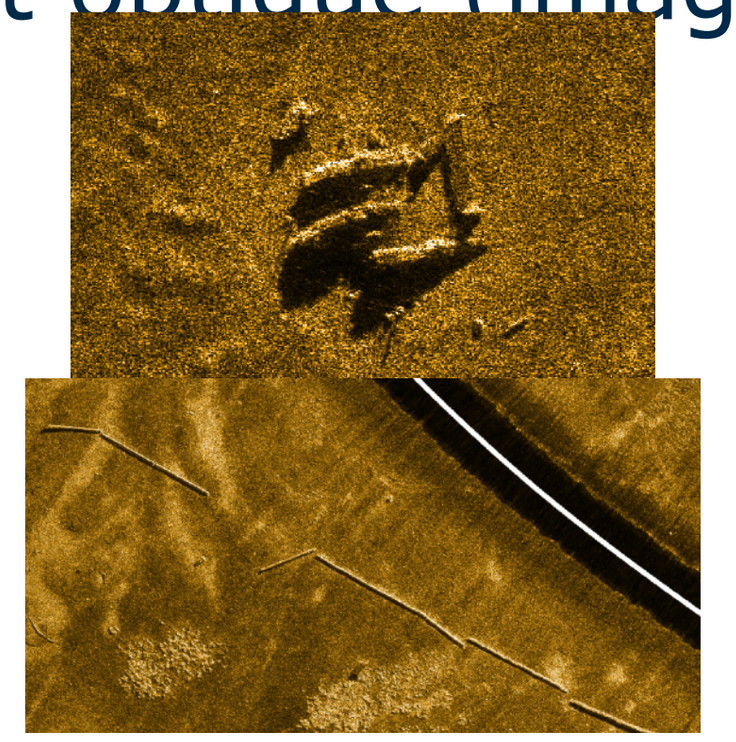


Outils déployés

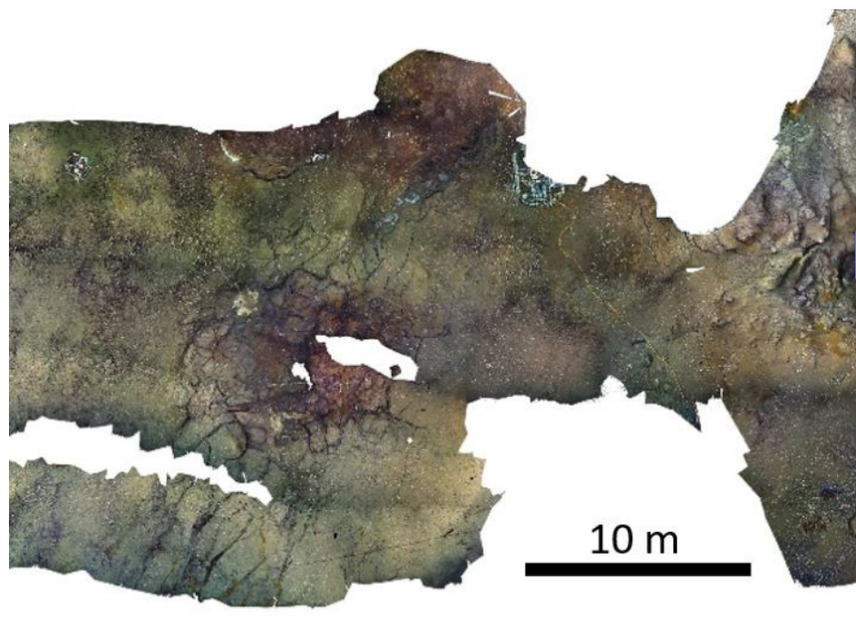
- Ulyx (6000 m): cartho acoustique (sonar et bathy) et optique (imagerie verticale)



Bathymétrie (~20-50 cm)



Sonar (~10-20 cm)



Images (<1 cm)

1. Detection de futs (bathy, sonar)
2. inspection optique