A Concept for Seabed Rare Earth Mining in the Eastern South Pacific

Lloyd's Register Educational Trust

Group A

6th September 2012

University of Southampton

Musa Bashir | Sung-Hee Kim | Evangelia (Lila) Kiosidou | Hugh Wolgamot | Wei Zhang

Introduction

Rare Earth Elements

REE Resources

Environment & Politics

Exploration

New Concept

Finance & Risk

Conclusions & Recommendations

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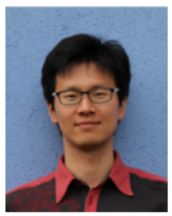

Sung-Hee Kim

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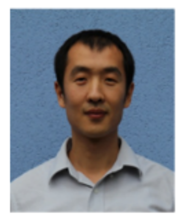

Wei Zhang

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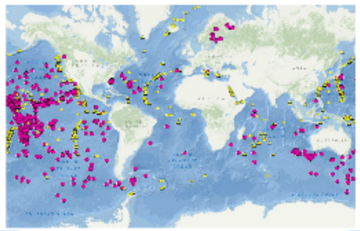
Prezi

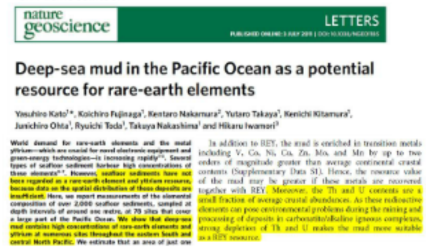
Seabed Resources

- Manganese nodules (1970s, 1980s, renewed interest)
- Seafloor massive sulfides (Nautilus minerals, Papua New Guinea)

http://www.isa.org.jm/



- Kato (2011): considerable concentration of rare earth elements on Pacific seafloor.


nature geoscience LETTERS

Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements

Yasuhiro Kato[1*], Koichiro Fujinaga[1], Kentaro Nakamura[2], Yutaro Takaya[1], Kenichi Kitamura[1], Junichiro Ohta[1], Ryuichi Toda[1], Takuya Nakashima[1] and Hikaru Iwamori[3]

- No mining of this resource yet - day after tomorrow!

Introduction

Seabed legal regime

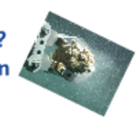
- Nations control Exclusive Economic Zones (EEZ) – 200 nautical miles from coastline
- International Seabed Authority (ISA) controls the remainder "the Area"

EEZ: Brown
the Area: Blue

http://www.seaaroundus.org/eez/

Introduction

Why seabed exploitation?
- land mineral depletion
- population growth



Aim: New concept "day after tomorrow"

Thank you:
- LRET

Prezi

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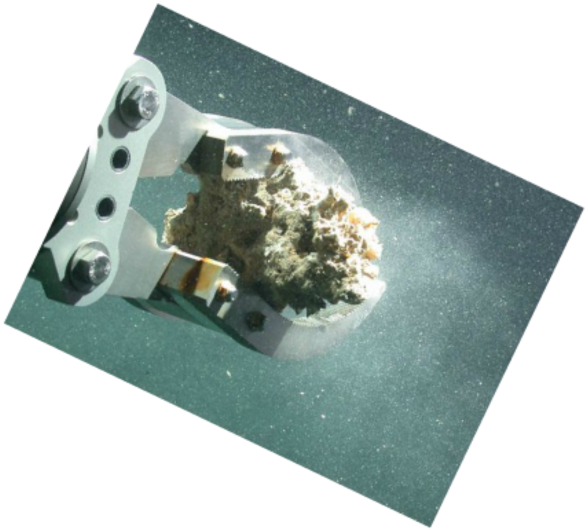

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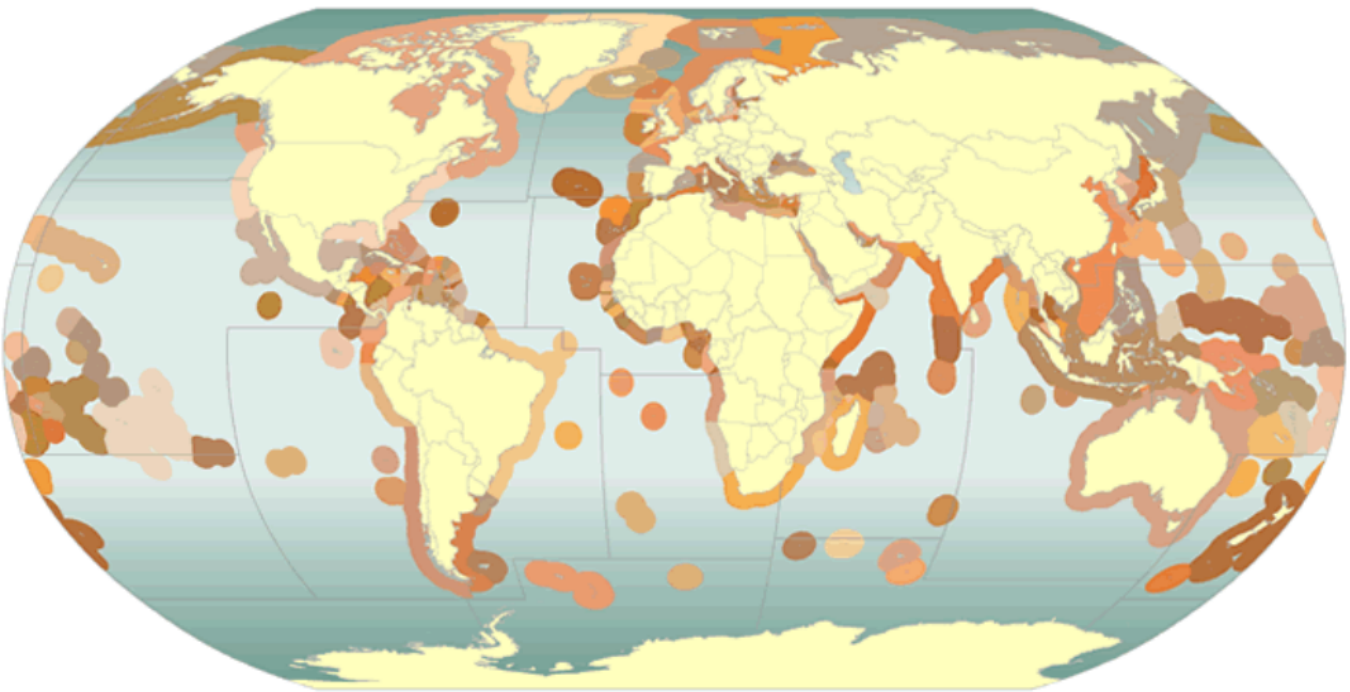

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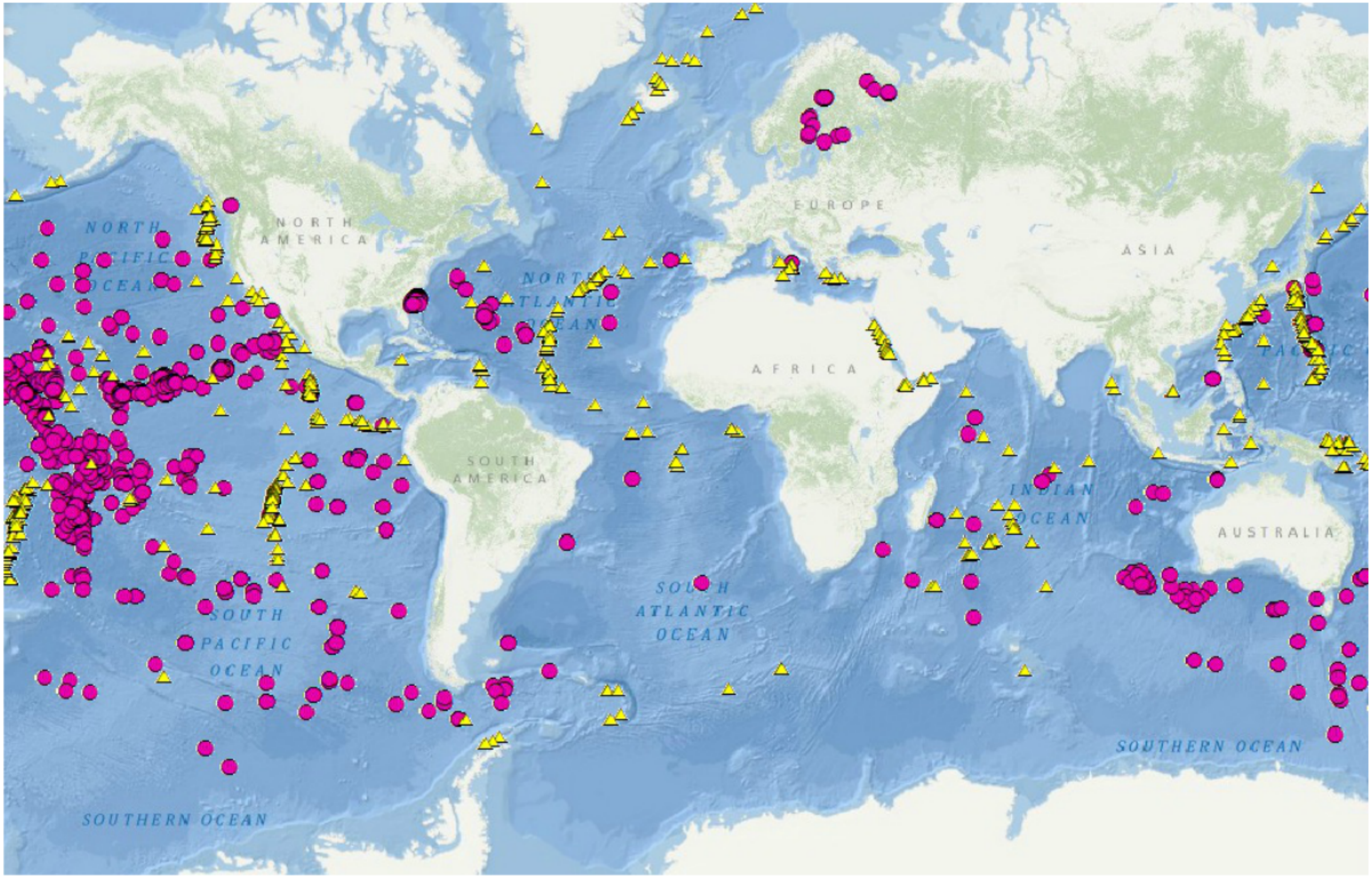

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nature geoscience

LETTERS

PUBLISHED ONLINE: 3 JULY 2011 | DOI: 10.1038/NGEO1185

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World demand for rare-earth elements and the metal yttrium—which are crucial for novel electronic equipment and green-energy technologies—is increasing rapidly[1-3]. Several types of seafloor sediment harbour high concentrations of these elements[4-7]. However, seafloor sediments have not been regarded as a rare-earth element and yttrium resource, because data on the spatial distribution of these deposits are insufficient. Here, we report measurements of the elemental composition of over 2,000 seafloor sediments, sampled at depth intervals of around one metre, at 78 sites that cover a large part of the Pacific Ocean. We show that deep-sea mud contains high concentrations of rare-earth elements and yttrium at numerous sites throughout the eastern South and central North Pacific. We estimate that an area of just one

In addition to REY, the mud is enriched in transition metals including V, Co, Ni, Cu, Zn, Mo, and Mn by up to two orders of magnitude greater than average continental crustal contents (Supplementary Data S1). Hence, the resource value of the mud may be greater if these metals are recovered together with REY. Moreover, the Th and U contents are a small fraction of average crustal abundances. As these radioactive elements can pose environmental problems during the mining and processing of deposits in carbonatite/alkaline igneous complexes, strong depletion of Th and U makes the mud more suitable as a REY resource.

- **No mining of this resource yet - day after tomorrow!**

Rare Earth Elements

Uses of REE

- Glass and polishing
- Phosphors
- Catalysts
- Ceramics
- Magnets
- Metallurgy

Defence and renewable energy applications

Supply and demand

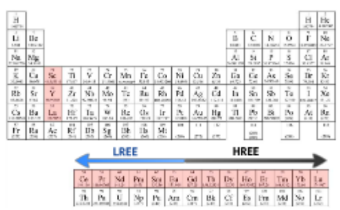
Supply: China (97% of world production in 2010 = 119 000 tonnes REO)

Demand:
1) Japan
2) USA
3) Germany
4) France

GROWING

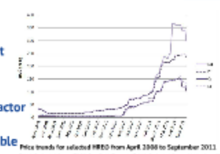
Chinese and world production of REO between 1992-2010

What are Rare Earth Elements? (REE)



Price

- Prices vary by element
- HREE more expensive than LREE
- Chinese policy a big factor (quota, etc)
- Large variations possible



Price trends for selected HREO from April 2008 to September 2011

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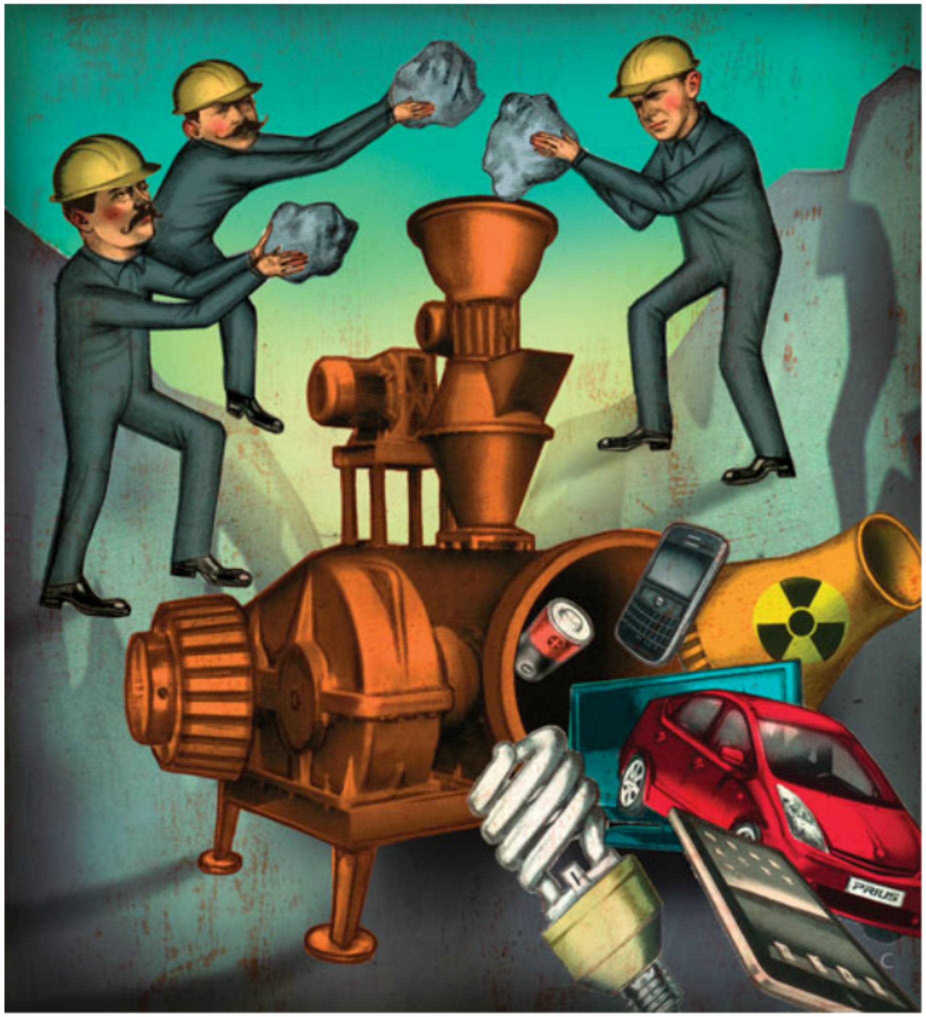
What are Rare Earth Elements? (REE)

1 H 1.00794																1 H 1.00794	2 He 4.002602
3 Li 6.941	4 Be 9.012182											5 B 10.811	6 C 12.0107	7 N 14.00674	8 O 15.9994	9 F 18.9984032	10 Ne 20.1797
11 Na 22.989770	12 Mg 24.3050											13 Al 26.981538	14 Si 28.0855	15 P 30.973761	16 S 32.066	17 Cl 35.4527	18 Ar 39.948
19 K 39.0983	20 Ca 40.078	21 Sc 44.955910	22 Ti 47.867	23 V 50.9415	24 Cr 51.9961	25 Mn 54.938049	26 Fe 55.845	27 Co 58.933200	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92160	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.818	50 Sn 118.710	51 Sb 121.760	52 Te 127.60	53 I 126.90447	54 Xe 131.29
55 Cs 132.90545	56 Ba 137.327	57 La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.078	79 Au 196.96655	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98038	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 (269)	111 (272)	112 (277)		114 (289) (287)		116 (289)		118 (293)

LREE ← → HREE

58 Ce 140.116	59 Pr 140.90765	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967
90 Th 232.0381	91 Pa 231.03588	92 U 238.0289	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Uses of REE



Larotonda, C.: http://www.bcbusinessonline.ca/energy-and-resources/hunt-bcs-rare-earth-metals

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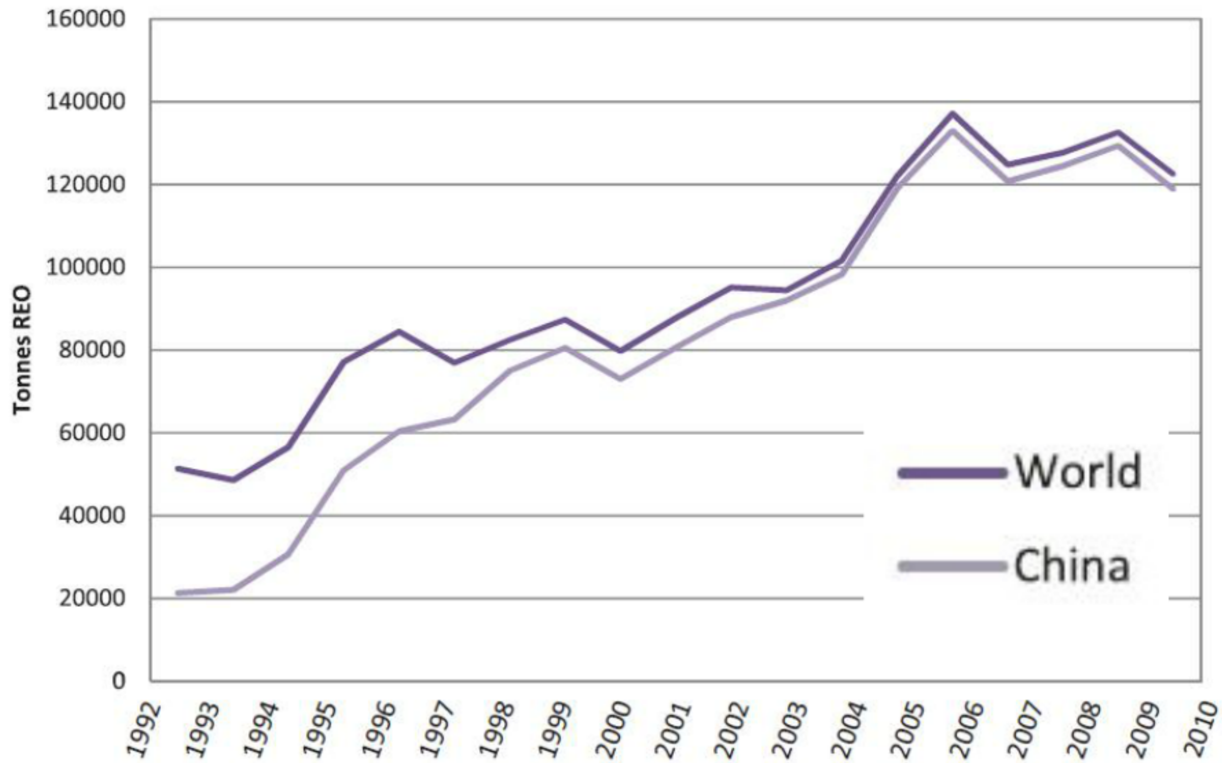

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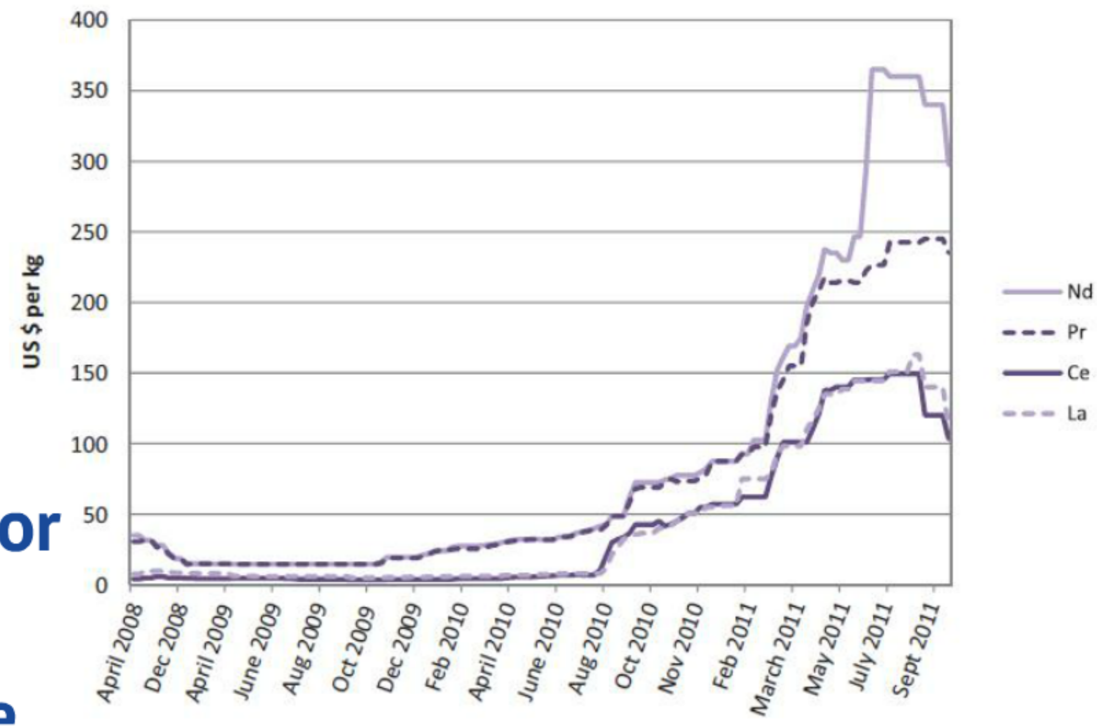

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http://trugroup.com/rare-earth-conference

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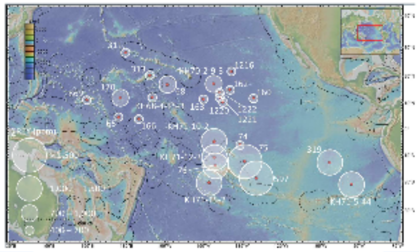
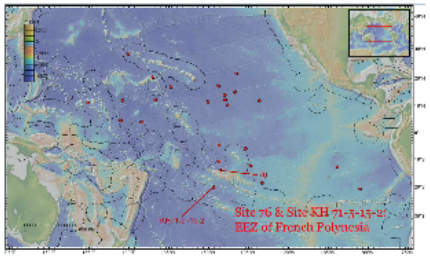
REE in Pacific Ocean- Study Sites



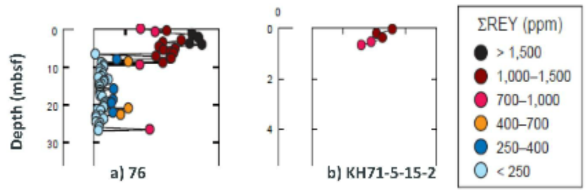
Selection of Sites



REE Resources

REE Locations: Core samples

- Water depth: ~4500m
- Site 76: 0-5 mbsf avg ≈1300ppm
- HREE ~200ppm (high)
- Site KH 71-5-15-2: 0-0.72 mbsf avg ≈1000ppm. More data required.



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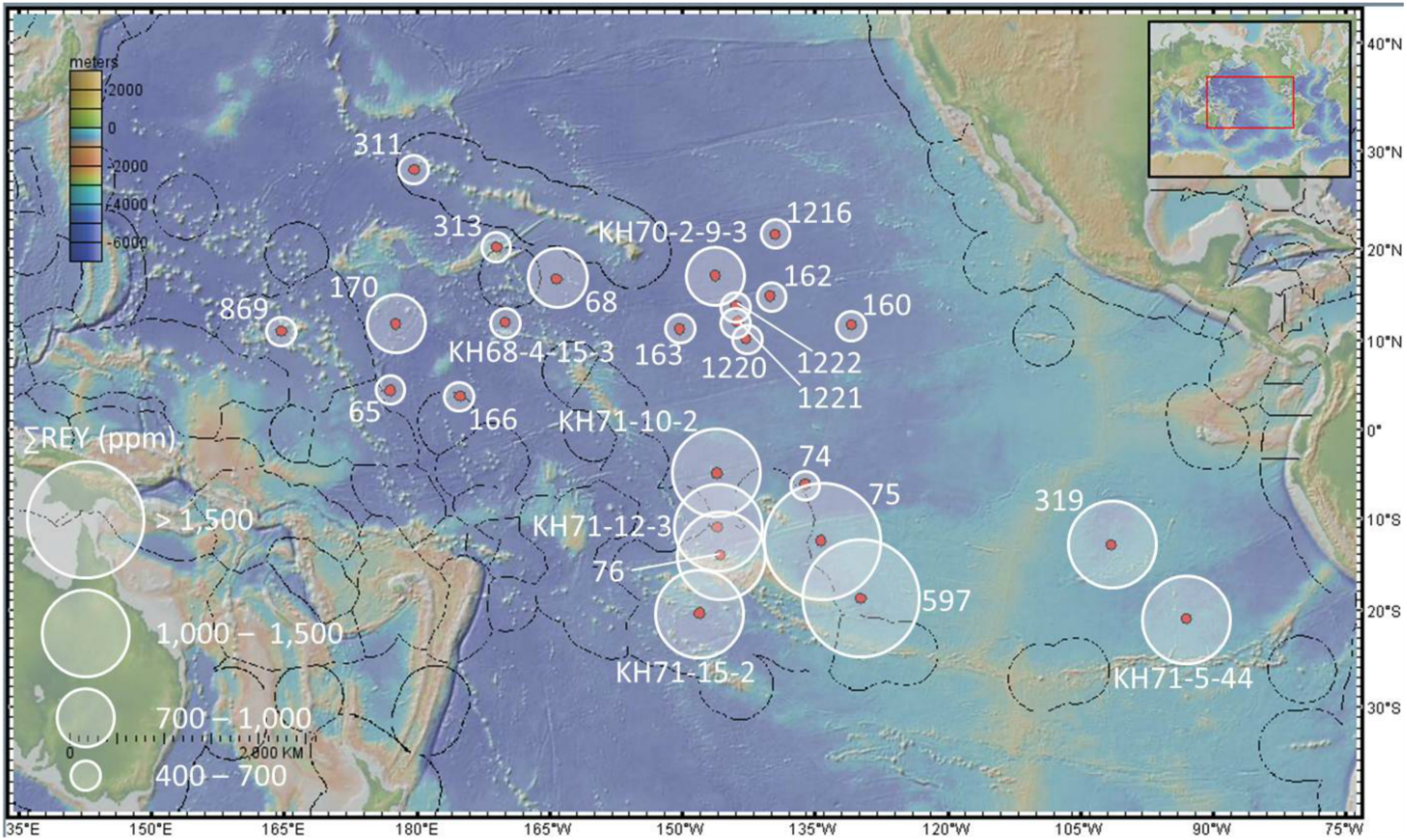

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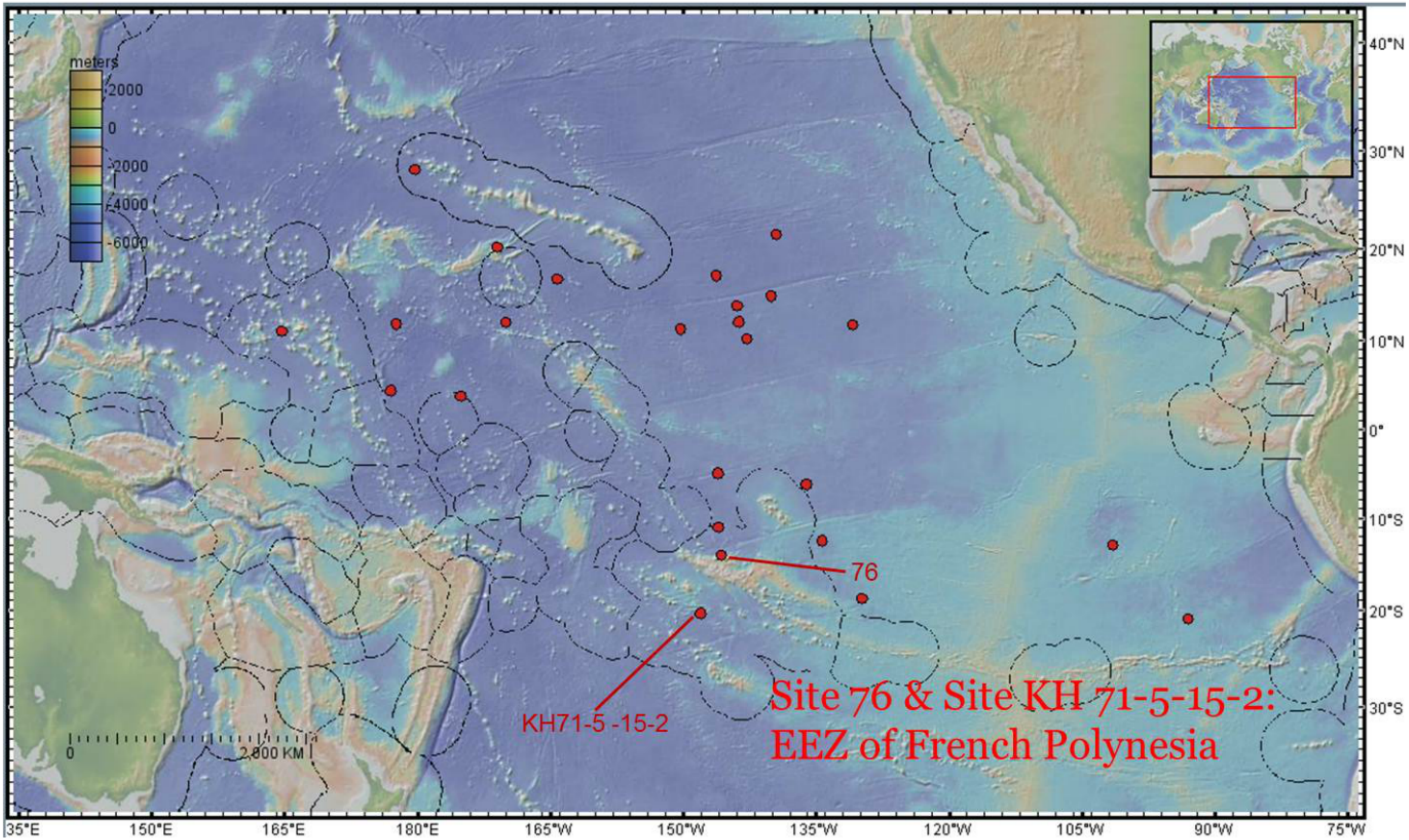

Prezi

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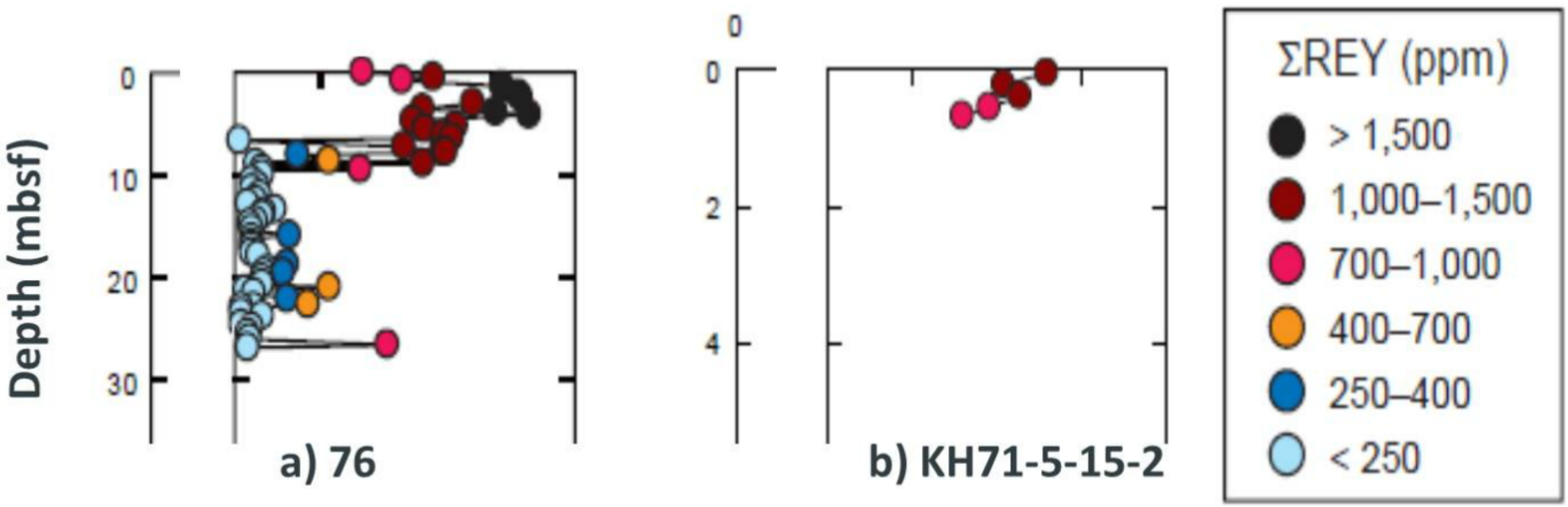
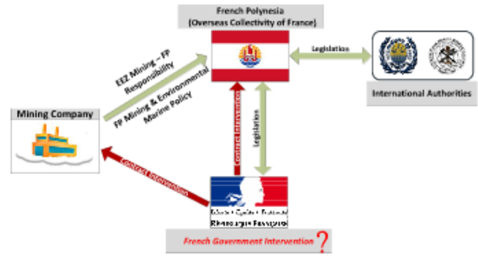
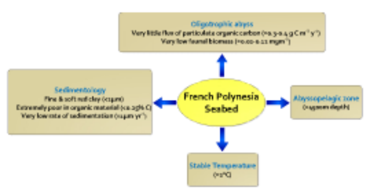


Environment & Politics

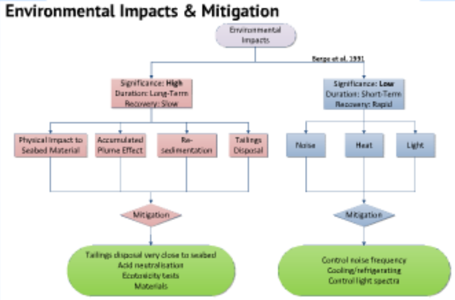
French Polynesia Politics



Existing Seabed Environment



Environmental Impacts & Mitigation



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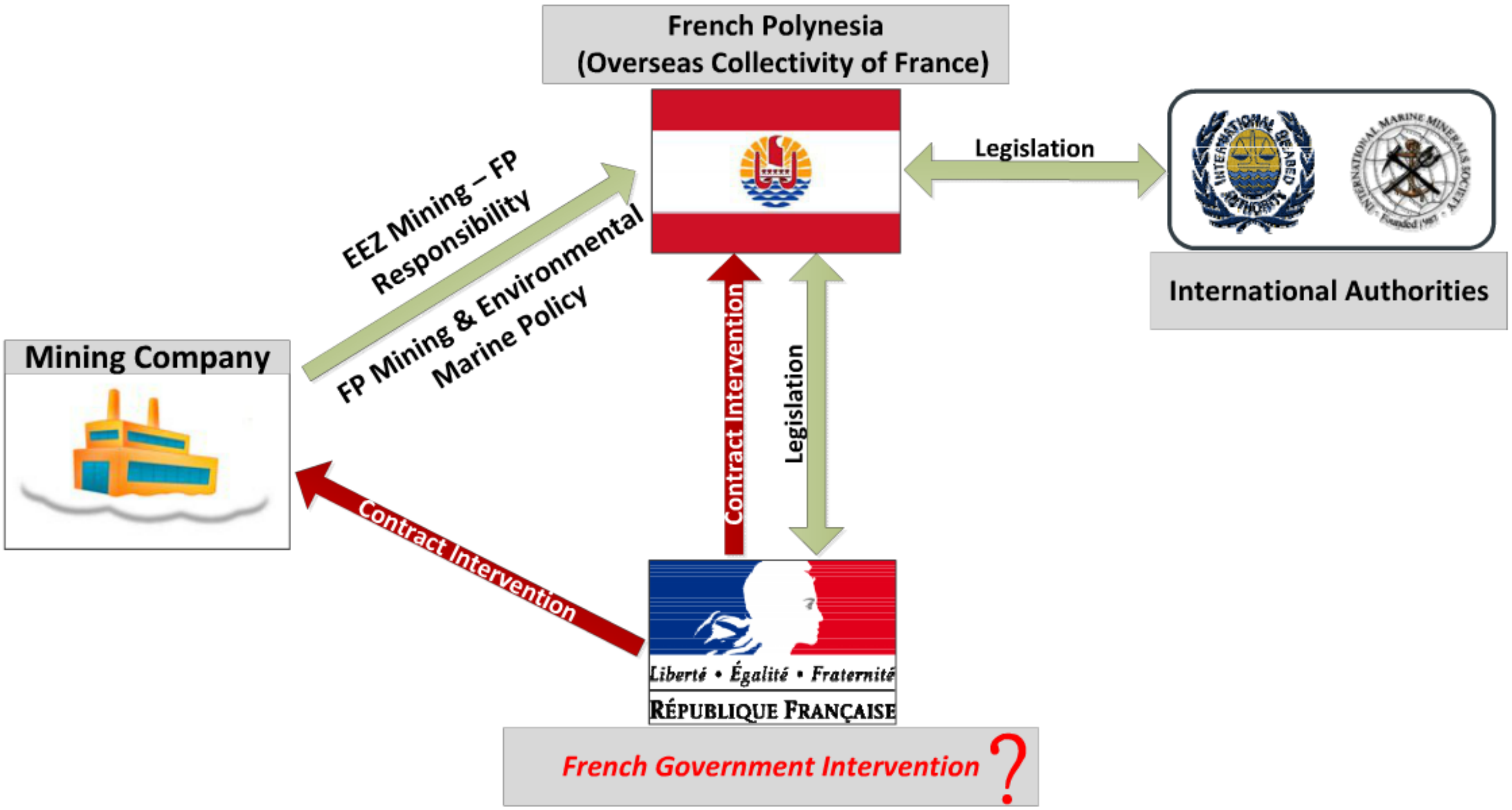

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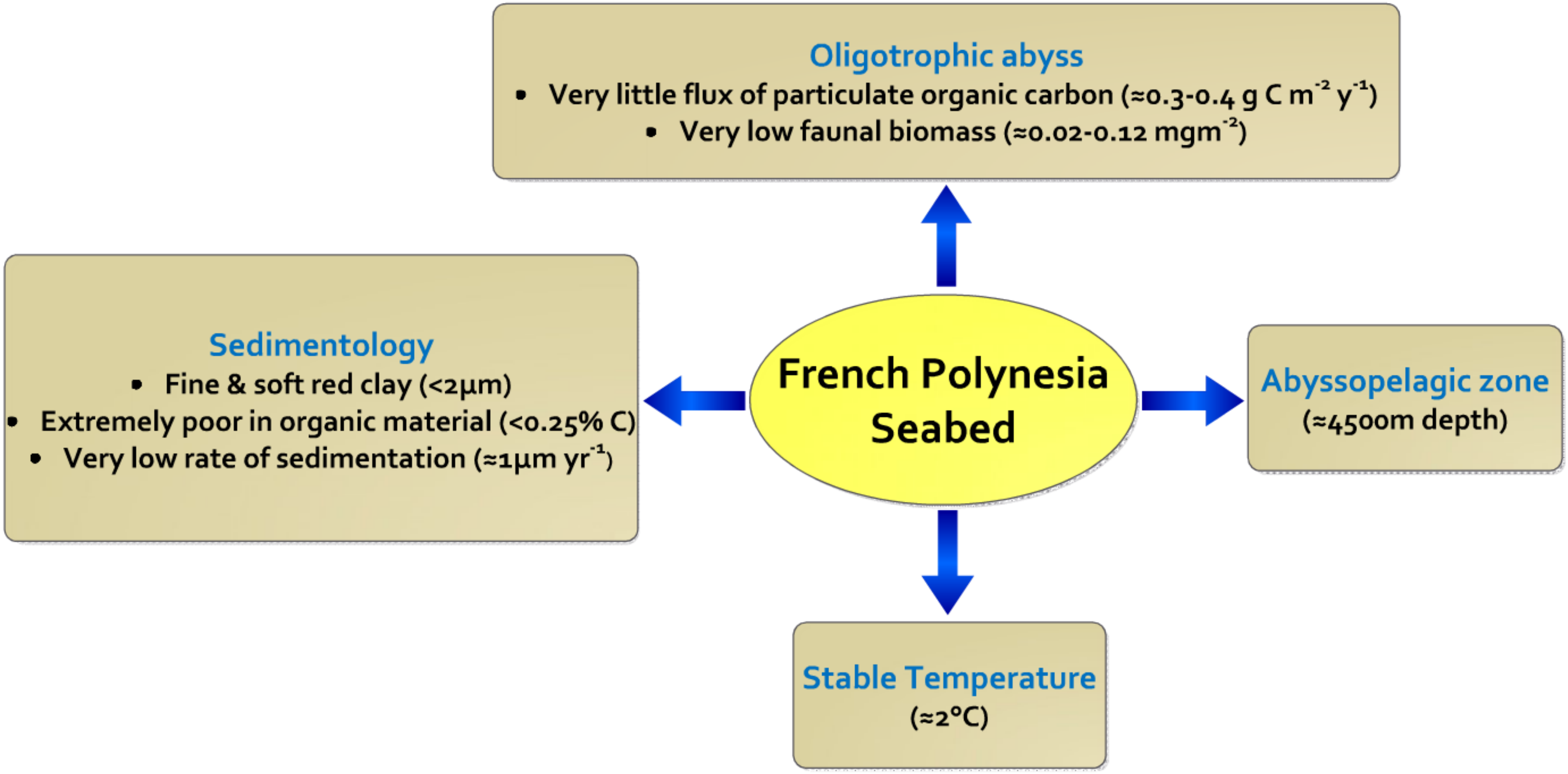

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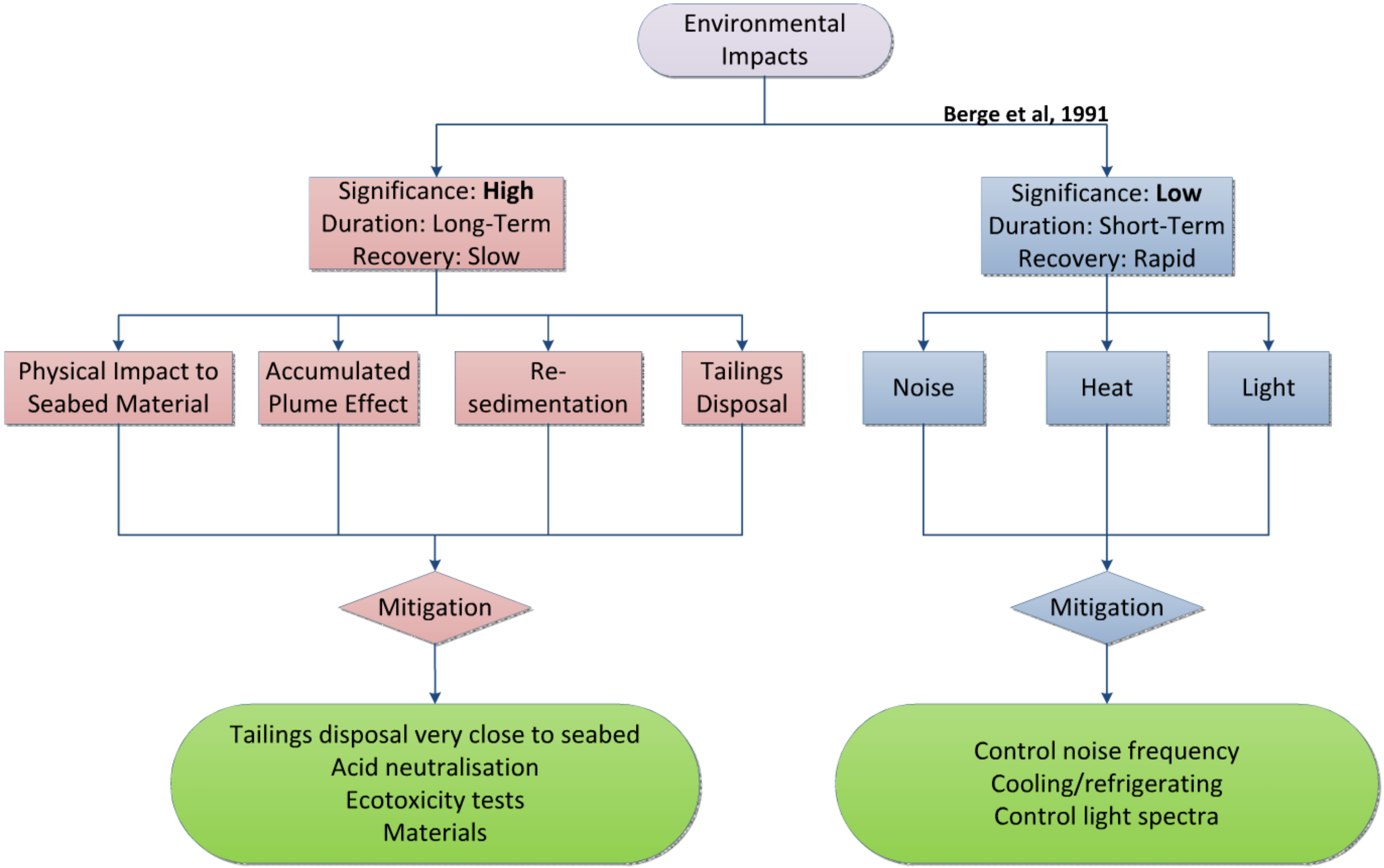

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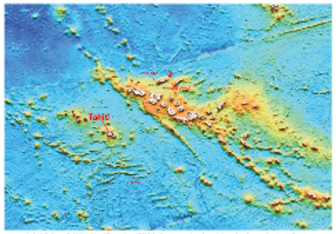
Bathymetry

Existing Bathymetry

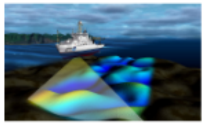
Jordahl et al, 2004 - 0.005 degree grid



Acquiring new bathymetry

Acoustic methods:

- Multibeam echo sounder
- Side-scan sonar



Exploration

REE resource exploration and quantification

- Area profile
- Depth profile
- Current information: sediment cores analysed with mass spectrometry in lab

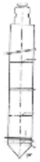
Test deployment method

CPT - Cone Penetrometer Test

- Usually used for soil strength investigations

ROV

- Remotely operated vehicle
- Commonly used subsea tool
- CPT for ROV deployment already exists

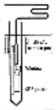


http://www.geomarine.co.uk/downloads/geoROV-Tech-Spec-Rev.7.pdf

Geophysical/Geochemical Testing

X-Ray Fluorescence Spectroscopy (XRF)

Used: land REE mines, underwater applications,
CPT deployment
Window in probe is delicate



Laser-Induced Breakdown Spectroscopy (LIBS)

Used: underwater applications,
CPT deployment
Much more rugged

General Considerations

Acid leach

- REE removed from mud into solution
- (>90% in 5hr 0.5mol/L HCl RTP - Kato et al, 2011)

Transport to surface

- Most seabed mining - hydraulic riser system

Bathymetry

Existing Bathymetry

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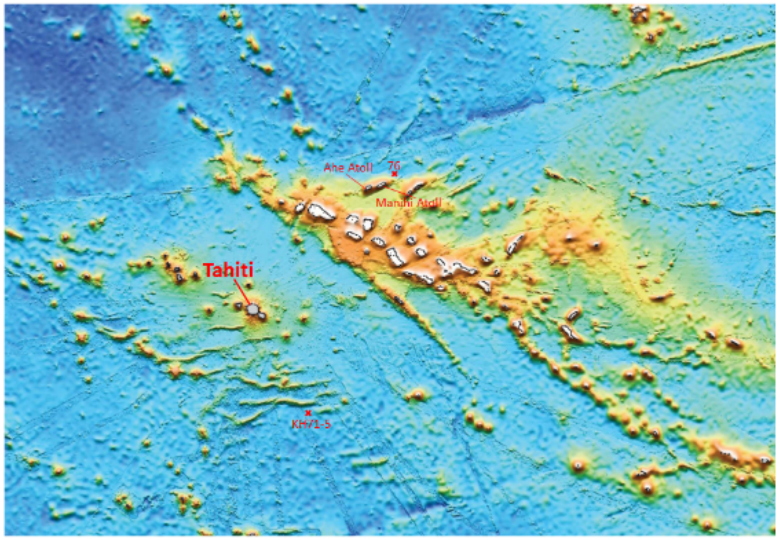

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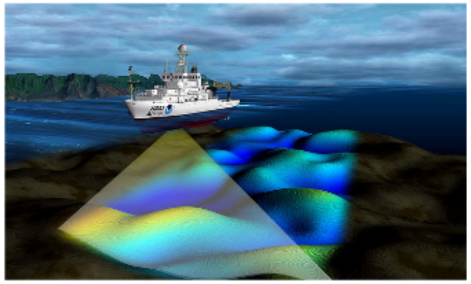

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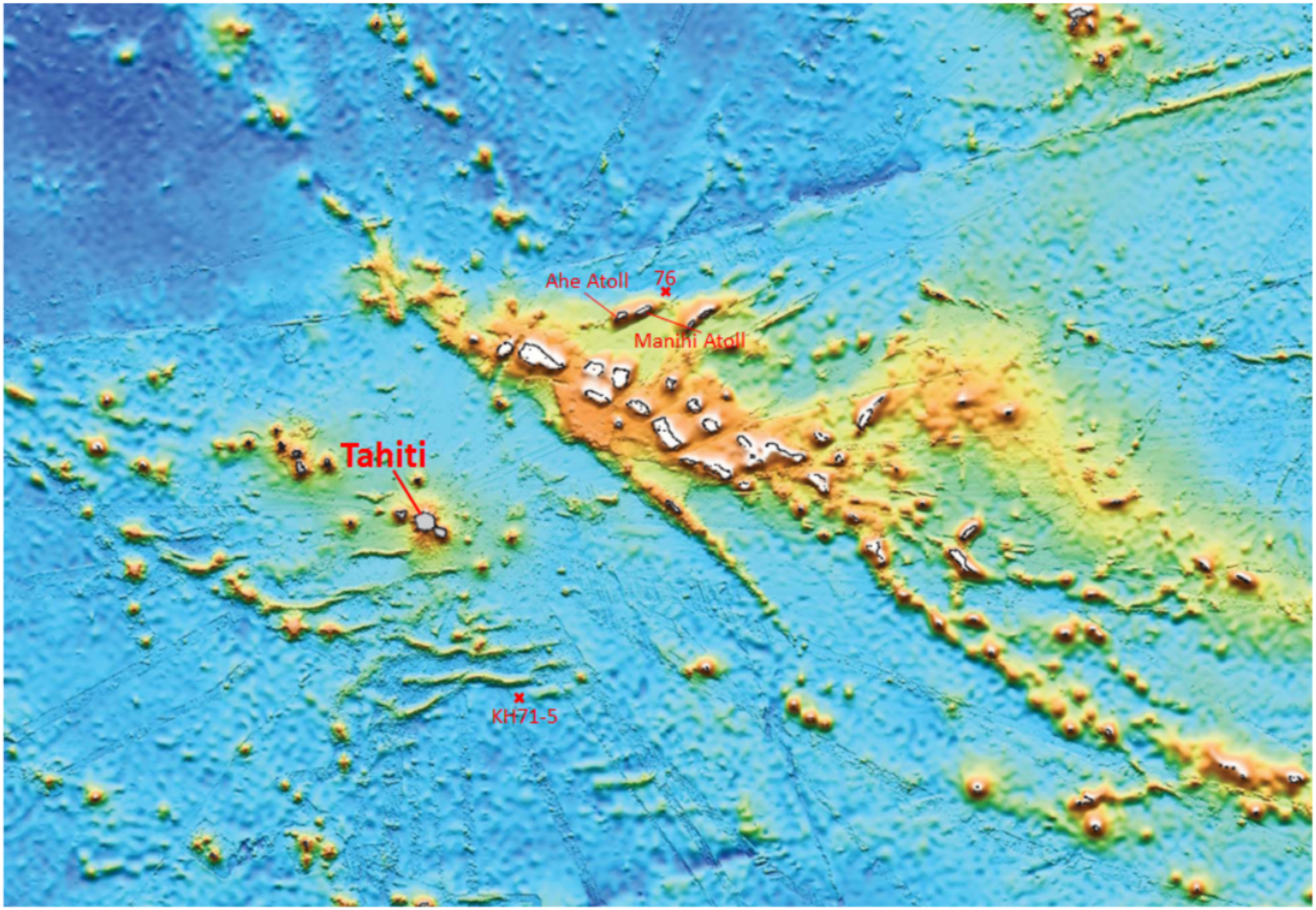

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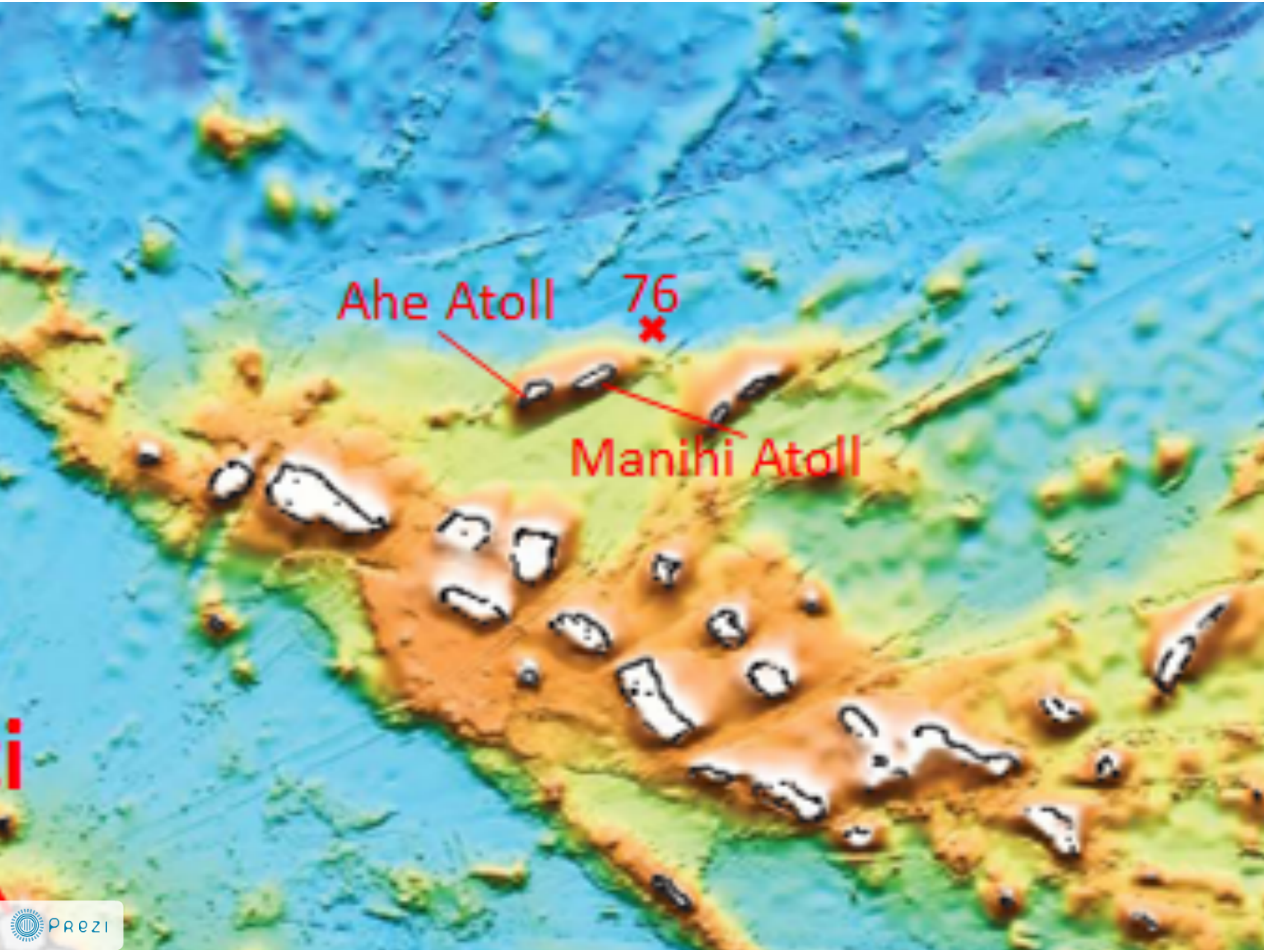
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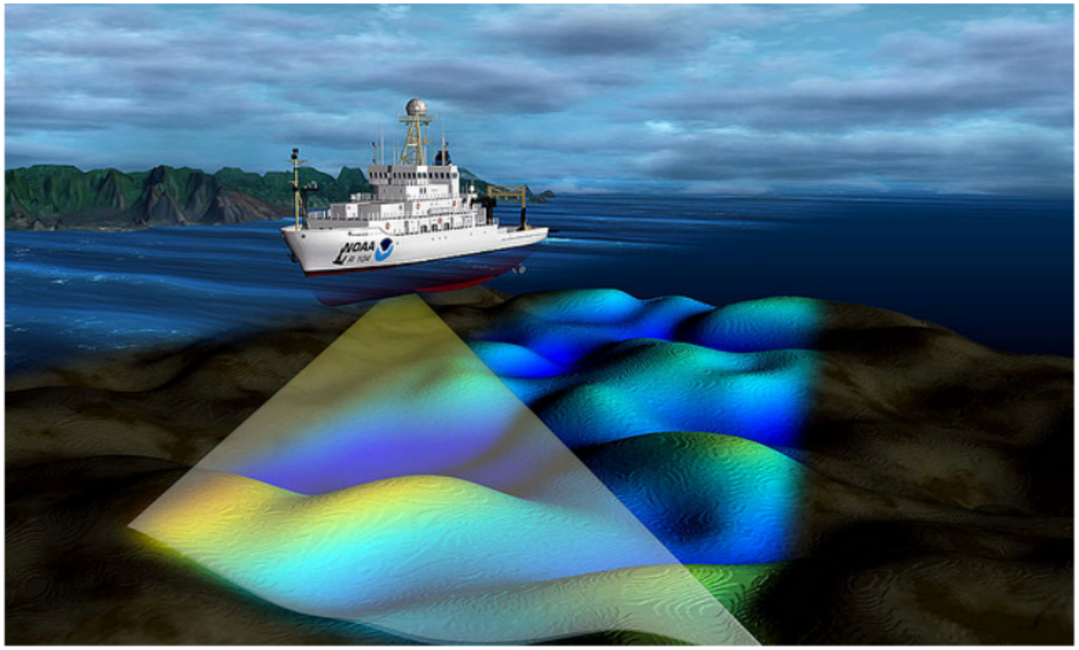

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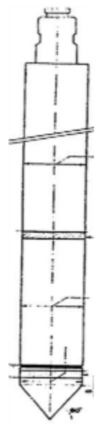

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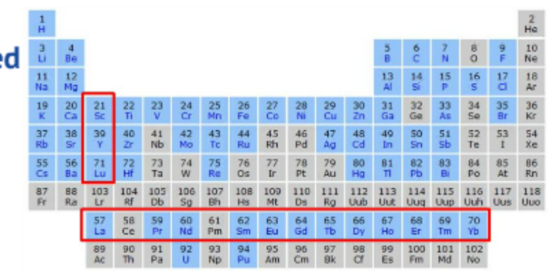

Applied photonics: http://www.appliedphotonics.co.uk/Libs/capabilities_libs.htm

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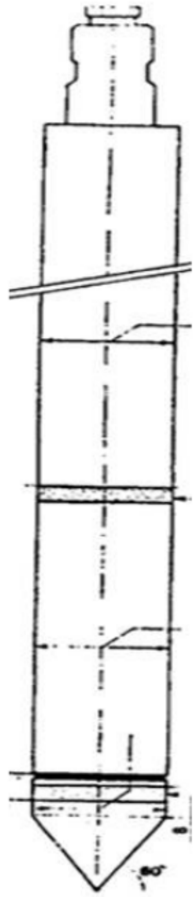

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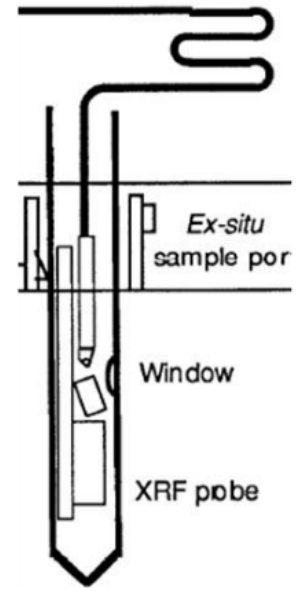

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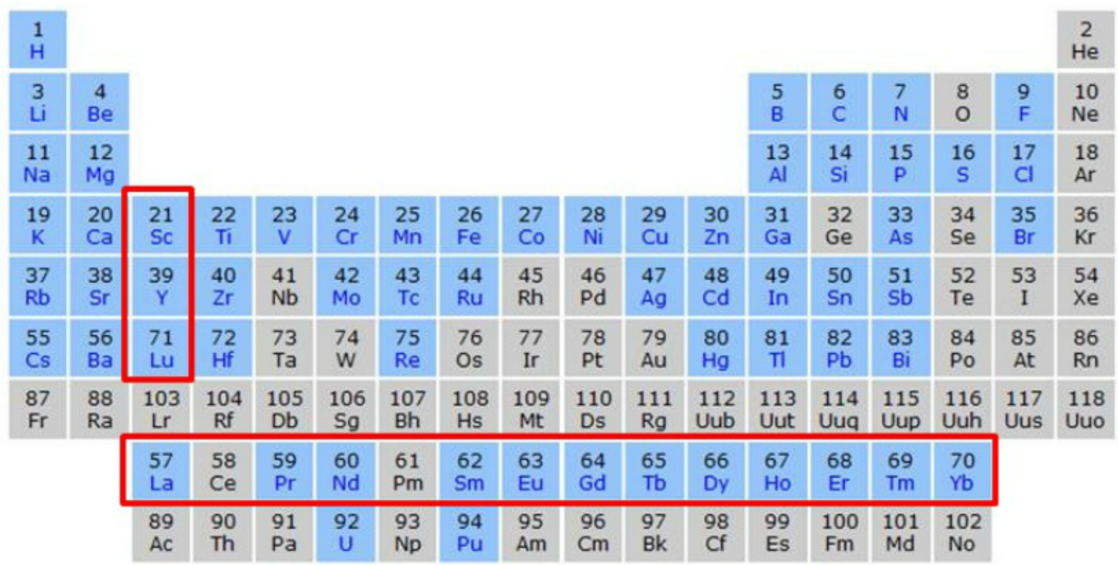

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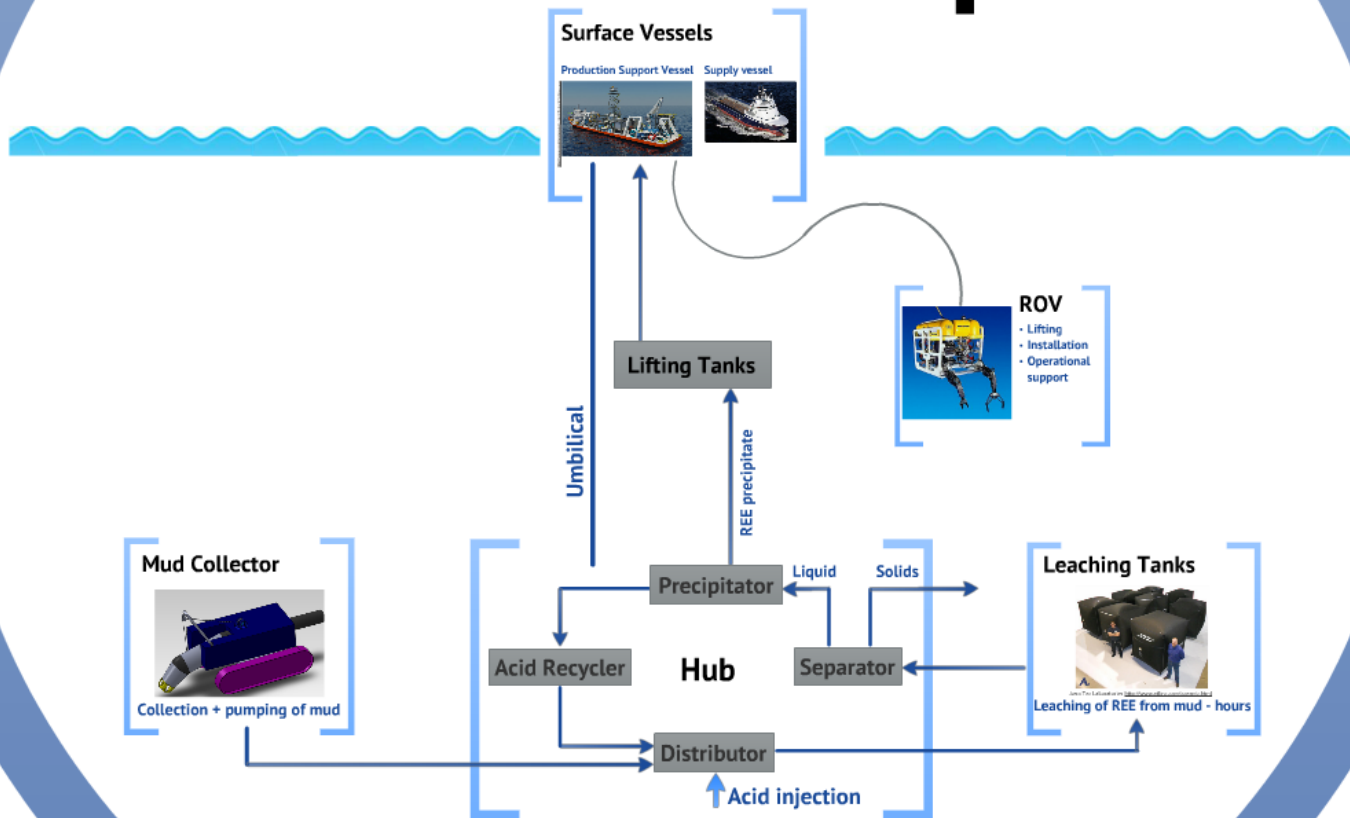
- REE removed from mud into solution (>90% in 3hr 0.5mol/L HCL RTP - Kato et al, 2011)

Transport to surface
- Most seabed mining - hydraulic riser system
- Nautilus riser system (1600m deep) = $101 million or 26% total CAPEX
- Our sites 4500m deep and 1000ppm.

Our concept - no riser! → seafloor processing

New Concept



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seafloor processing

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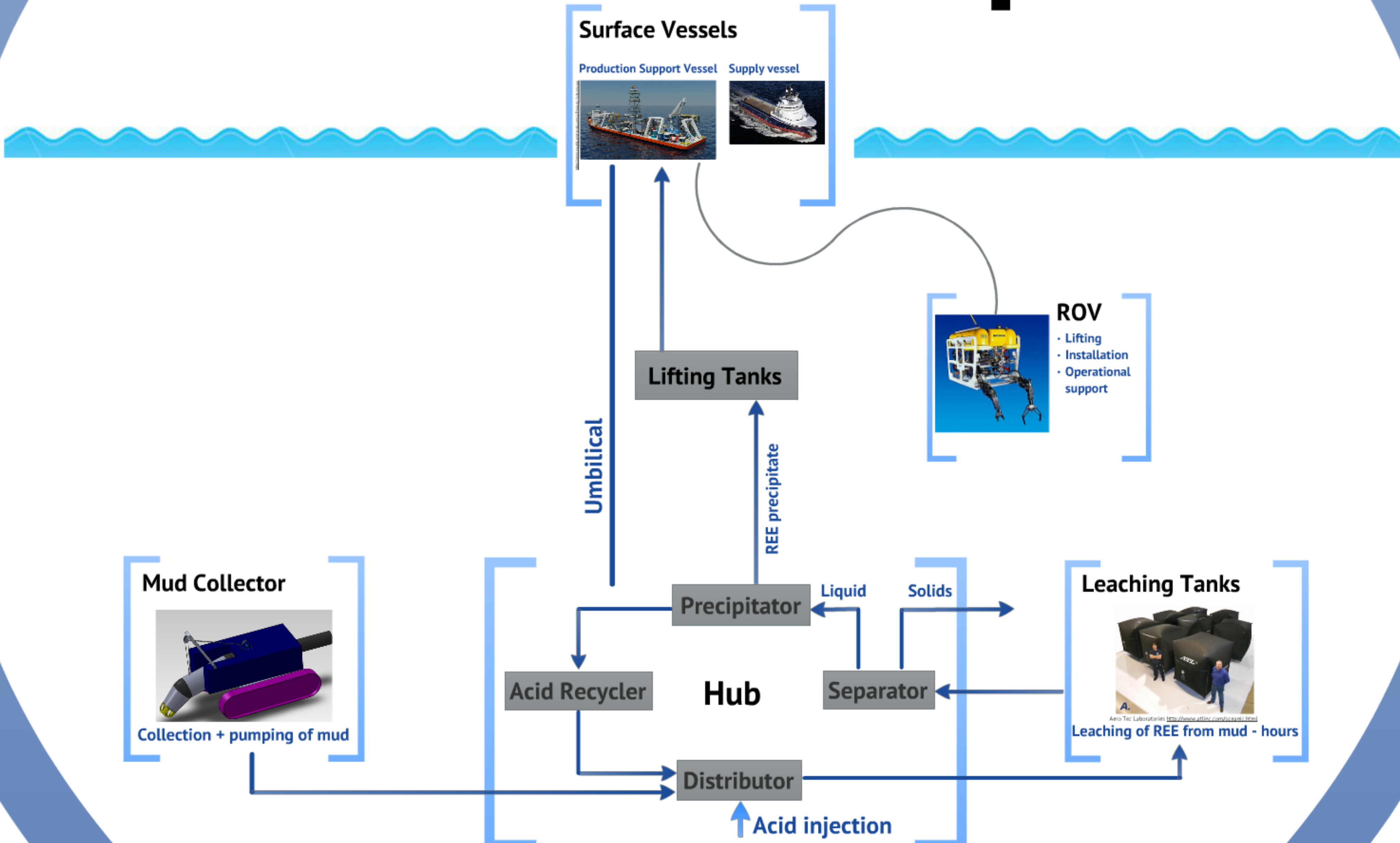
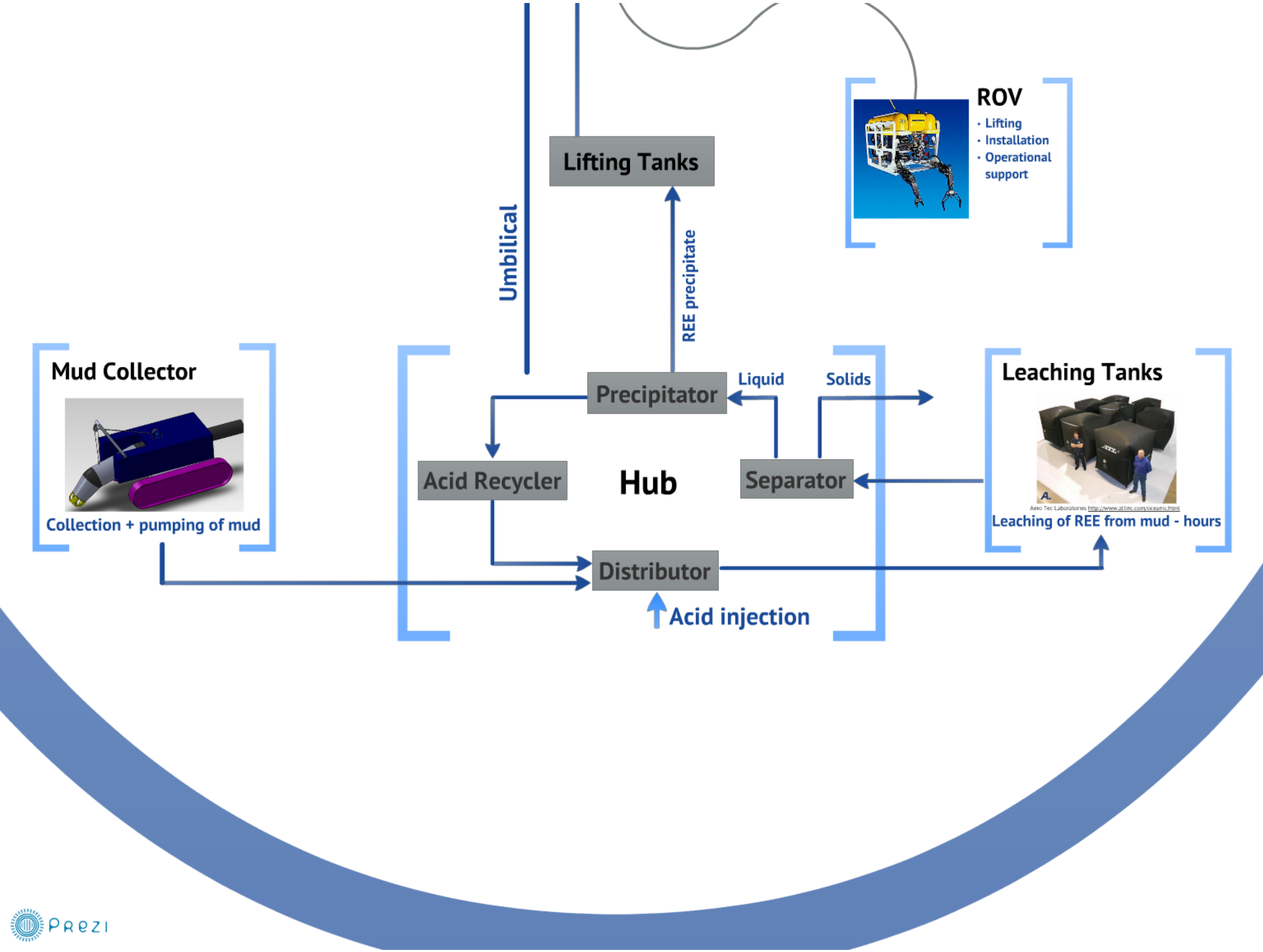


Surface Vessels

Production Support Vessel

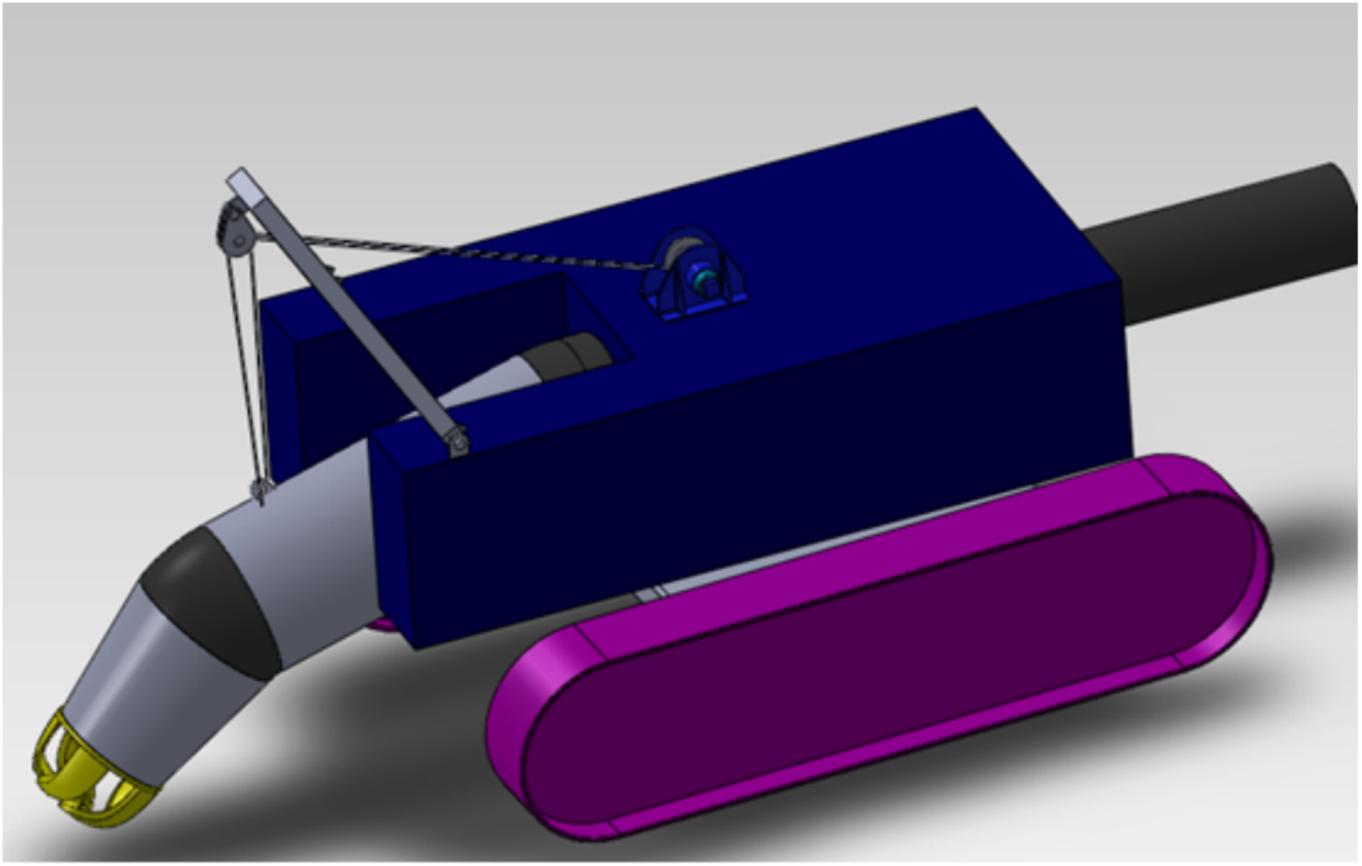
http://www.nautilusminerals.com/s/Projects-Solwara.asp

Supply vessel

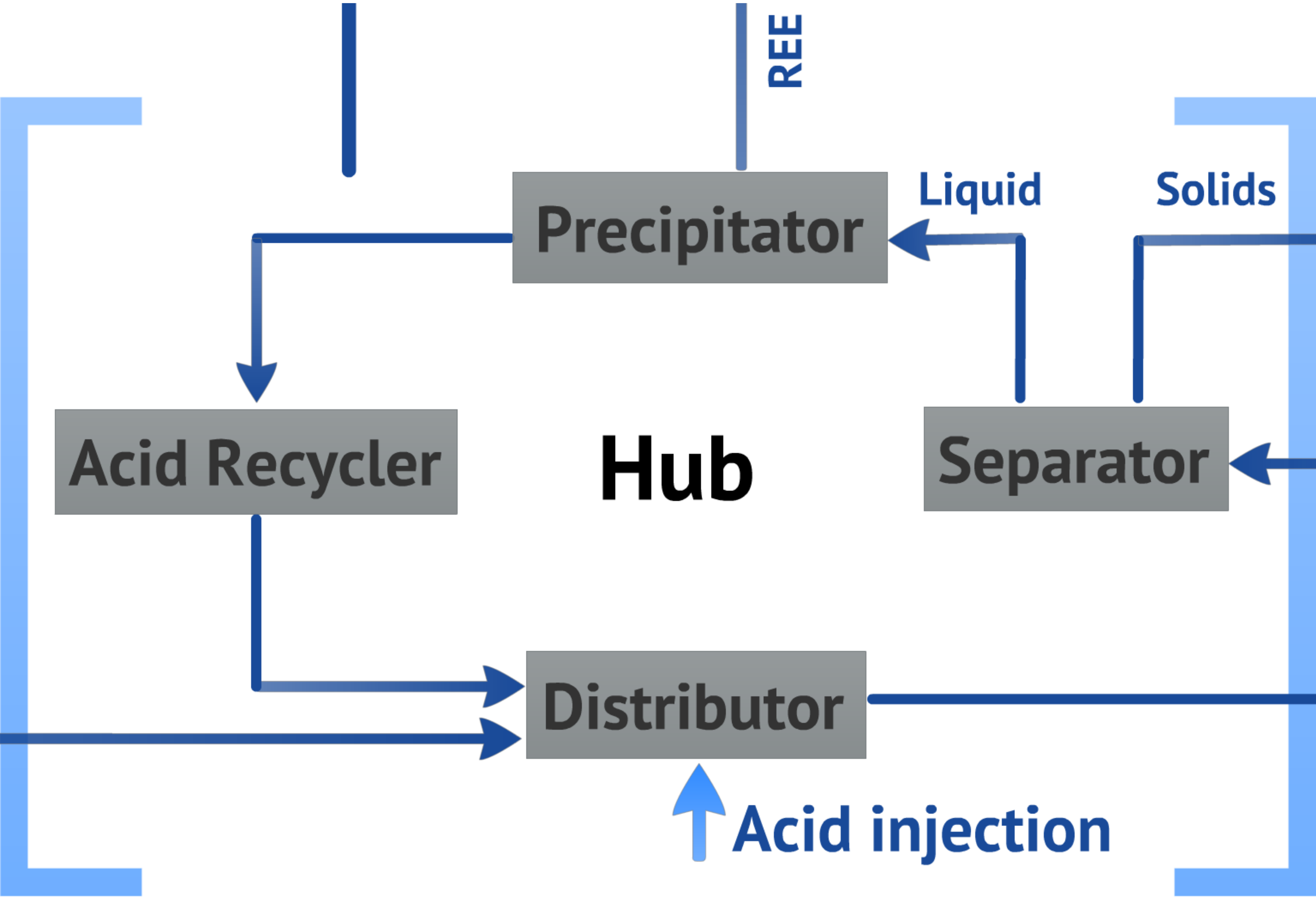


ROV
• Lifting
• Installation
• Operational support
Lifting Tanks
Umbilical
REE precipitate
Mud Collector
Collection + pumping of mud
Precipitator
Liquid
Solids
Leaching Tanks
Aero Tec Laboratories http://www.atlinc.com/oceanic.html
Leaching of REE from mud - hours
Acid Recycler
Hub
Separator
Distributor
Acid injection

Mud Collector



Collection + pumping of mud


REE
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Precipitator
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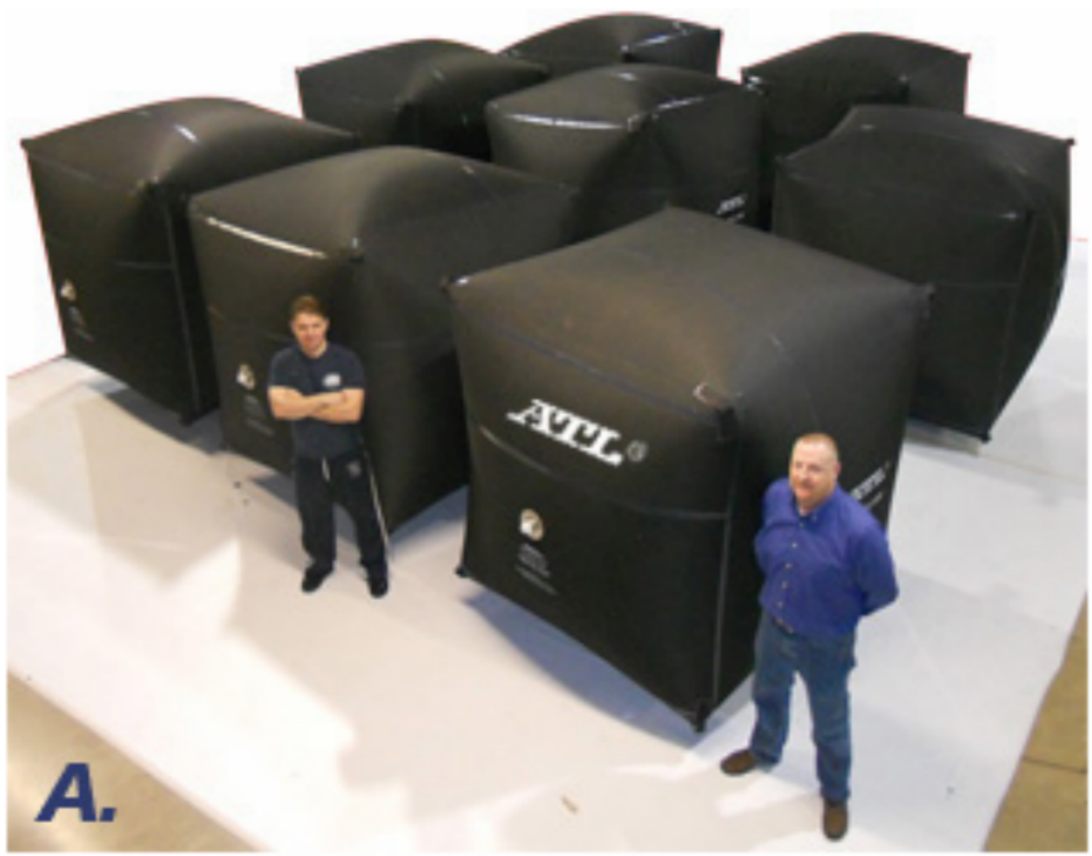
Acid injection

Leaching Tanks



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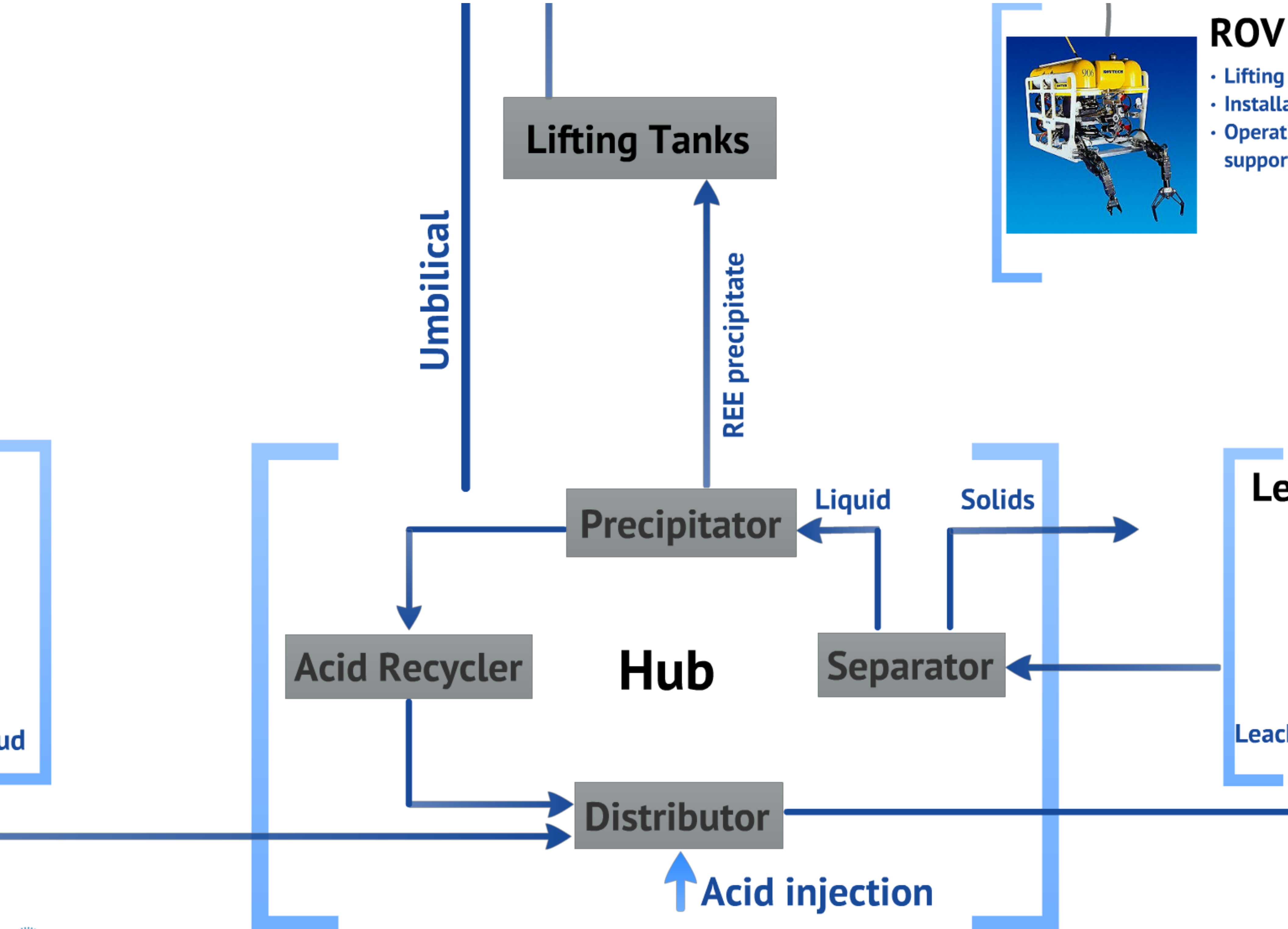
Leaching of REE from mud - hours



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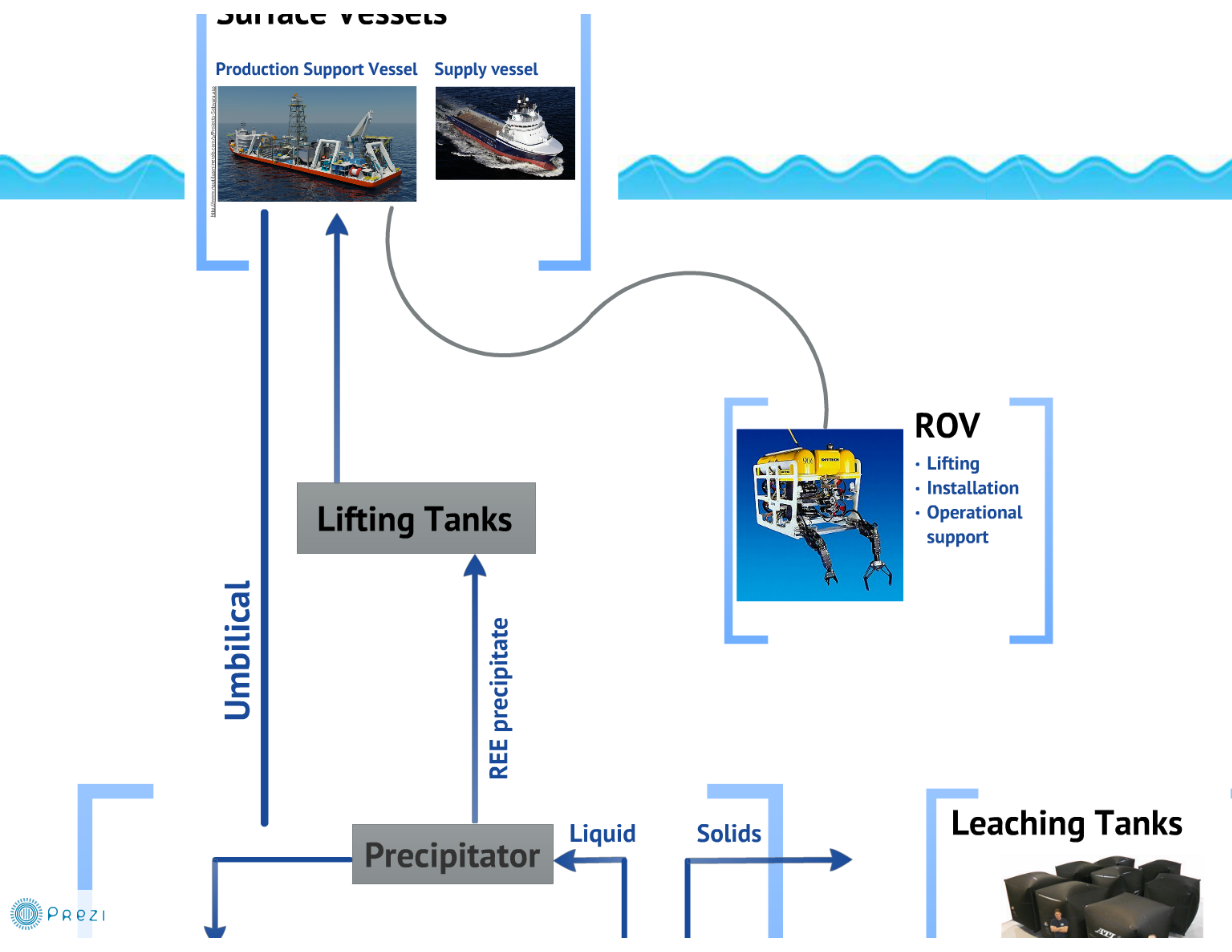
Production Support Vessel
Supply vessel
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Lifting Tanks
REE precipitate
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• Lifting
• Installation
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Precipitator
Liquid
Solids
Leaching Tanks

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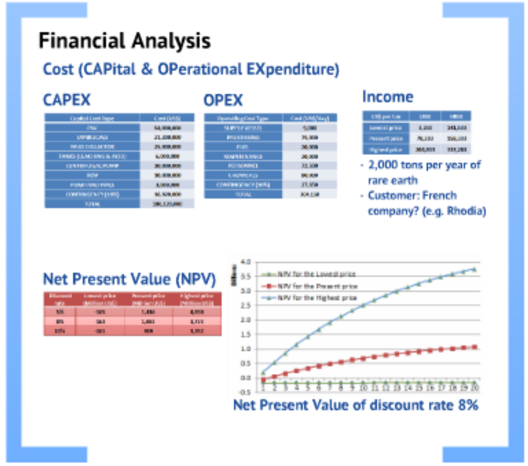
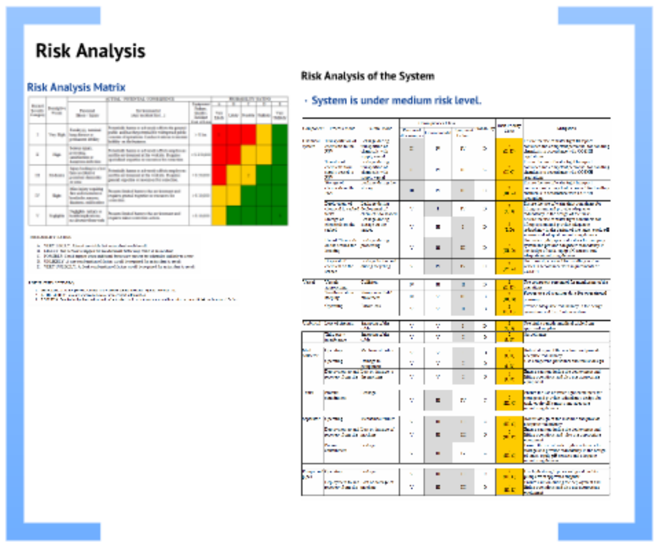
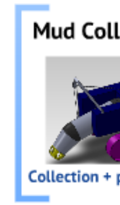


Finance & Risk





Financial Analysis

Cost (CAPital & OPerational EXpenditure)

CAPEX

Capital Cost Type	Cost (US$)
PSV	94,000,000
UMBILICALS	21,200,000
MUD COLLECTOR	25,000,000
TANKS (LEACHING & ACID)	6,000,000
CENTRIFUGAL PUMP	10,000,000
ROV	10,000,000
PUMP AND PIPES	3,000,000
CONTINGENCY (10%)	16,920,000
TOTAL	186,120,000

OPEX

Operating Cost Type	Cost (US$/day)
SUPPLY VESSEL	9,000
PROCESSING	75,000
FUEL	20,000
MAINTENANCE	20,000
PERSONNEL	72,500
CHEMICALS	80,000
CONTINGENCY (10%)	27,650
TOTAL	304,150

Income

US$ per ton	LREE	HREE
Lowest price	3,233	141,533
Present price	78,333	158,333
Highest price	204,833	337,284

- 2,000 tons per year of rare earth
- Customer: French company? (e.g. Rhodia)

Net Present Value (NPV)

Discount rate	Lowest price (Million US$)	Present price (Million US$)	Highest price (Million US$)

CENTRIFUGAL PUMP	10,000,000
ROV	10,000,000
PUMP AND PIPES	3,000,000
CONTINGENCY (10%)	16,920,000
TOTAL	186,120,000

PERSONNEL	72,500
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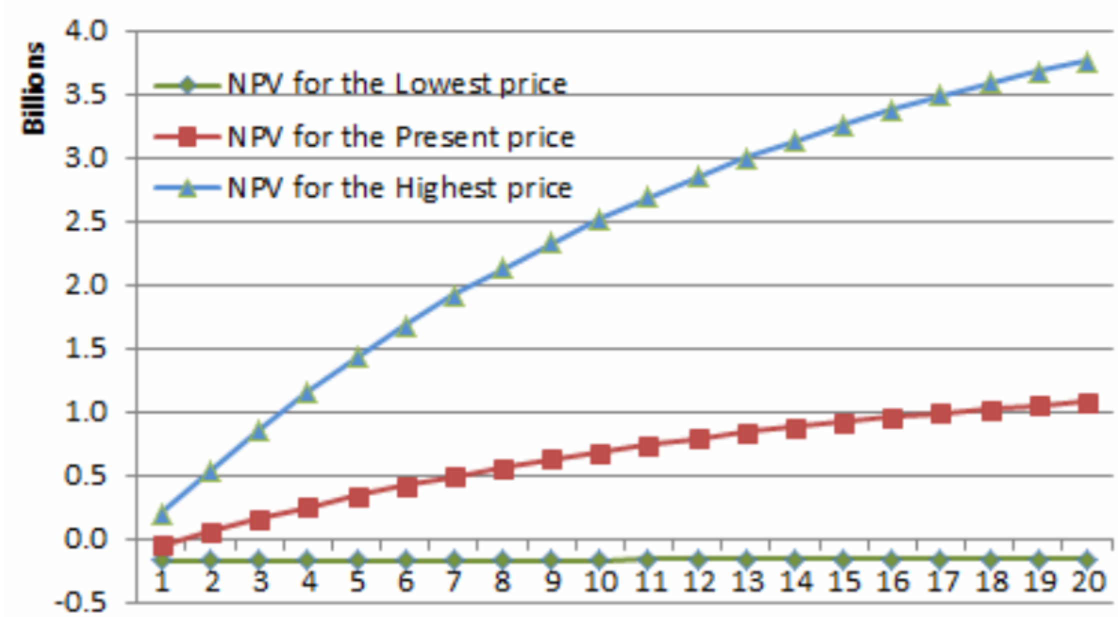
CONTINGENCY (10%)	27,650
TOTAL	304,150

- 2,000 tons per year of rare earth
- Customer: French company? (e.g. Rhodia)

Net Present Value (NPV)

Discount rate	Lowest price (Million US$)	Present price (Million US$)	Highest price (Million US$)
5%	-165	1,416	4,830
8%	-163	1,083	3,773
10%	-161	919	3,252



Net Present Value of discount rate 8%

Risk Analysis

Risk Analysis Matrix

Hazard Severity Category	Descriptive Words	ACTUAL / POTENTIAL CONSEQUENCE			PROBABILITY RATING				
		Personnel Illness / Injury	Environmental (Any incident that…)	Equipment Failure; Quality; Incident Cost of Loss	A Very Likely	B Likely	C Possible	D Unlikely	E Very Unlikely
I	Very High	Fatality(s), terminal lung disease or permanent debility	Potentially harms or adversely affects the general public and has the potential for widespread public concern of operations. Can have serious economic liability on the business.	> $ 1m	1				
II	High	Serious injury, poisoning, sensitisation or dangerous infection	Potentially harms or adversely affects employees and the environment at the worksite. Requires specialised expertise or resources for correction.	> $ 250,000					
III	Moderate	Injury leading to a lost time accident or persistent dermatitis or acne	Potentially harms or adversely affects employees and the environment at the worksite. Requires general expertise or resources for correction.	> $ 50,000			2		
	Slight	Mino injury requiring first aid treatment or headache, nausea,	Presents limited harm to the environment and requires general expertise or resources for	> $ 10,000					

Equipment Failure; Quality; Incident Cost of Loss	Very Likely	Likely	Possible	Unlikely	Very Unlikely
> $ 1m	1				
> $ 250,000					
> $ 50,000			2		
> $ 10,000					
< $ 10,000					3

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t to see if risk can be reduced further.

Component	Process Mode	Failure Mode	Consequences Class			Probability	Risk Priority Code	Mitigation
			Personnel illness/injury	Environmental	Equipment Failure			
Chemical system	Transportation of chemicals to the PSV	Leakage during transportion of chemicals with supply vessel	II	IV	IV	D	2 (II, D)	Ensure the use of water tight transport container and competent personnel for handling chemicals in accordance with COSHH regulations
	Transfer of chemicals from supply vessel to PSV	Leakage during transportion of chemicals with supply vessel	II	IV	III	C	2 (II, C)	Ensure the use of water tight transport container and competent personnel for handling chemicals in accordance with COSHH regulations
	Storage of chemicals on the PSV	Leakage during the storage	III	IV	III	C	2 (III, C)	Ensure the use of water tight transport container and competent personnel for handling chemicals in accordance with COSHH regulations
	Deployment of chemical to seabed tanks	Leakage during deployment of chemicals to seabed	V	I	IV	D	2 (I, D)	Ensure the use of water tight containers for lifting system and provide adequacte redundancy in the design of the tanks
	Storage of chemicals on the seabed	Leakage during storage on the seabed	V	III	I	D	2 (I, D)	Ensure the use of water tight containers for lifting system and provide adequacte redundancy in the design of the tanks, equip pH sensors and adequate monitoring devices
	Use of Chemicals on the seabed for leaching	Leakage during processing	V	III	III	D	2 (III, D)	Use water tight pipes and valves for pumping system and provide adequacte redundancy in the design of tank, equip pH sensors and adequate monitoring devices
	Disposal of chemical on the seabed	Leakage before and during recycling	V	IV	IV	C	2 (IV, C)	Use trained personnel for handling acid on vessel in accordance with requirements of COSHH
Vessel	Vessels approaching	Collision	IV	III	II	D	2 (II, D)	Use competent personnel for monitoring of the operations
	Weather/station keeping	Strong wind/tidal movement	IV	V	III	B	2 (III, B)	Proper use of weather data for operational planning
	Operating	Power loss	V	V	II	D	2 (II, D)	Provide adequacte redundancy in the design generation and distribution system
Umbilical	Loss of strength	Snapping of the cable	V	V	I	D	2 (I, D)	Use high strength umbilical cable from approved supplier
	Third party interference	Snapping of the cable	V	V	I	D	2 (I, D)	Surveillance
Mud collector	Operating	Mechanical failure	V	V	I	D	2 (I, D)	Robust design of the machine and provide adequate redundancy
	Operating	Damage to component	V	V	I	D	2 (I, D)	Use competent personnel and robust design
	Deployment to and recovery from site	Lost or damage to the machine	V	V	I	D	2 (I, D)	Ensure caution during the deployment and lifting operations and also use appropriate equipment
Tanks	Product containment	Leakage	V	III	IV	C	2 (III, C)	Ensure the use of water tight containers for storage and provide redundancy design for tank, equip pH sensors and adequate monitoring devices
Separator	Operating	Mechanical failure	V	III	III	C	2 (III, C)	Robust design of the machine and provide adequate redundancy
	Deployment to and recovery from site	Lost or damage of machine	V	III	III	D	2 (III, D)	Ensure caution during the deployment and lifting operations and also use appropriate equipment
	Pressure containment	Leakage	V	III	IV	C	2 (III, C)	Ensure the use of water tight containers for storage and provide redundancy in the design of tanks, equip pH sensors and adequate monitoring devices
Pumps and pipes	Operating	Leakage	V	III	III	C	2 (III, C)	Use high strength pipes and good quality pumps from approved supplier
	Deployment to and recovery from site	Lost or damage of machine	V	III	III	D	2 (III, D)	Ensure caution during the deployment and lifting operations and also use appropriate equipment

Risk Analysis of the System

- **System is under medium risk level.**

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Musa Bashir

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- University of Southampton
- Prof Ian Croudace
- Dr Koichiro Fujinaga
- Dr Maaten Furlong
- Dr Kelsey Jordahl
- Prof Rachel Mills

Conclusions & Recommendations

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- Feasibility will depend on individual REE concentrations and future prices
- Exploration in French Polynesia is worthwhile; low radioactivity, potentially large resource, high HREE, land supply uncertain
- New concept: riserless seabed REE processing system has potential to make seabed REE mining cheaper/more feasible

Recommendations

- Further exploration of REE in this region needed; we suggest some innovative methods
- Detailed processing technology development required
- More environmental study required

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A Concept for Seabed Rare Earth Mining in the Eastern South Pacific

Lloyd's Register Educational Trust

Group A
6th September 2012

University of Southampton

Musa Bashir
Sung-Hee Kim
Evangelia (Lila) Kiosidou
Hugh Wolgamot
Wei Zhang

Introduction

Rare Earth Elements

REE Resources

REE Locations: Core samples

- Water depth: ~4500m
- Site 76: 0-5 mbsf avg ≈1300ppm
- HREE ~200ppm (high)
- Site KH 71-5-15-2: 0-0.72 mbsf avg ≈1000ppm.

More data required.

Environment & Politics

Exploration

New Concept

Finance & Risk

Conclusions & Recommendations

Prezi