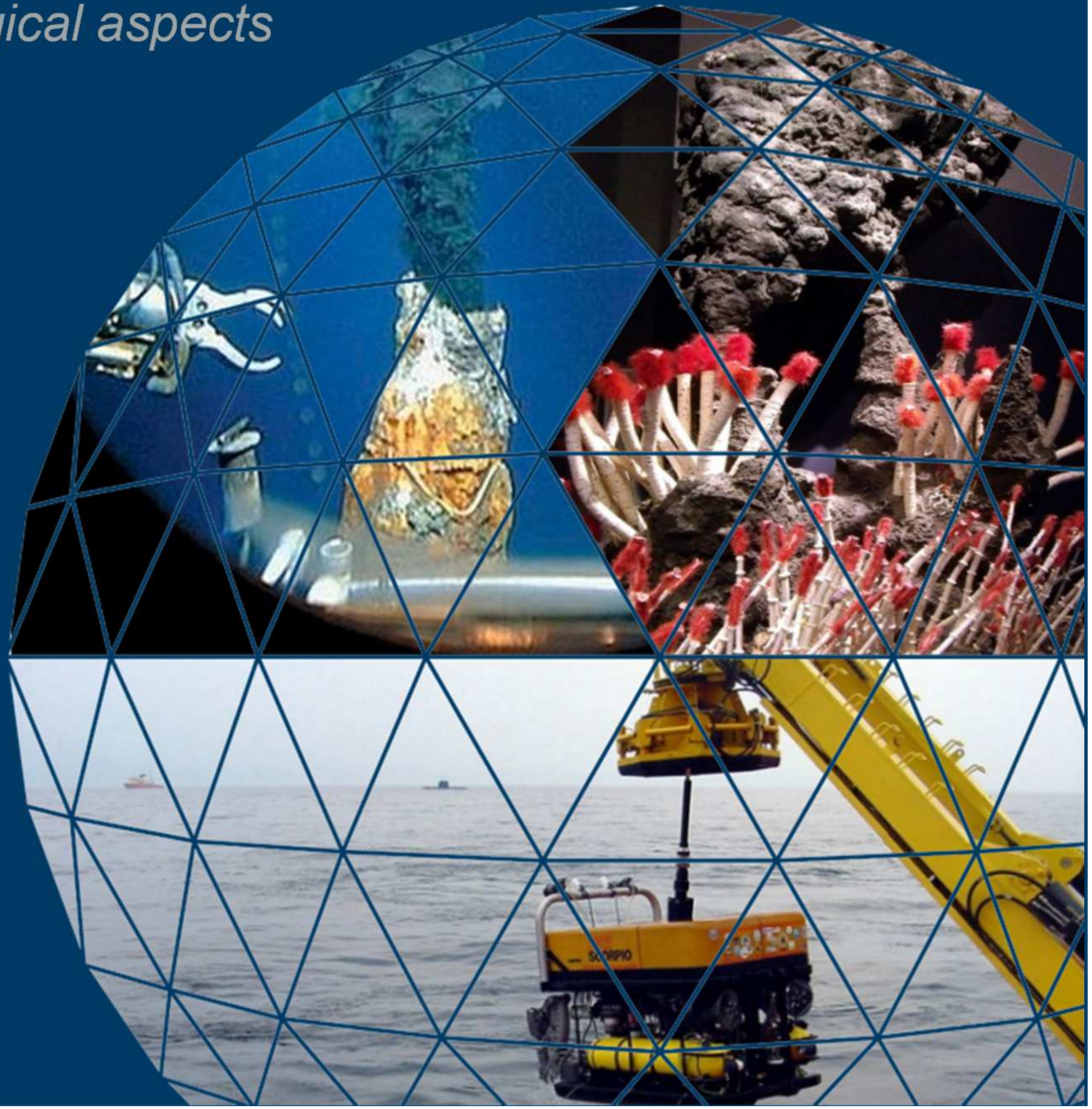
STUDY TO INVESTIGATE THE STATE OF KNOWLEDGE OF DEEP SEA MINING

Workshop on the technological aspects of Deep Sea Mining

Plenary session



Mike Buxton & Joerg Benndorf
(Resource Engineering, TU Delft)
Brussels, 29 April 2014

ECORYS

Purpose of today's workshop

1. Presenting and validating the **Value Chain** of DSM
2. Presenting an validating the different **technologies** per activity
3. Cross-checking the relevant **companies** active in the field
4. Determining the **importance and potential for EU suppliers**
5. Validating the **technology readiness levels** per technology

Remark: the findings presented are preliminary – ample room for discussion

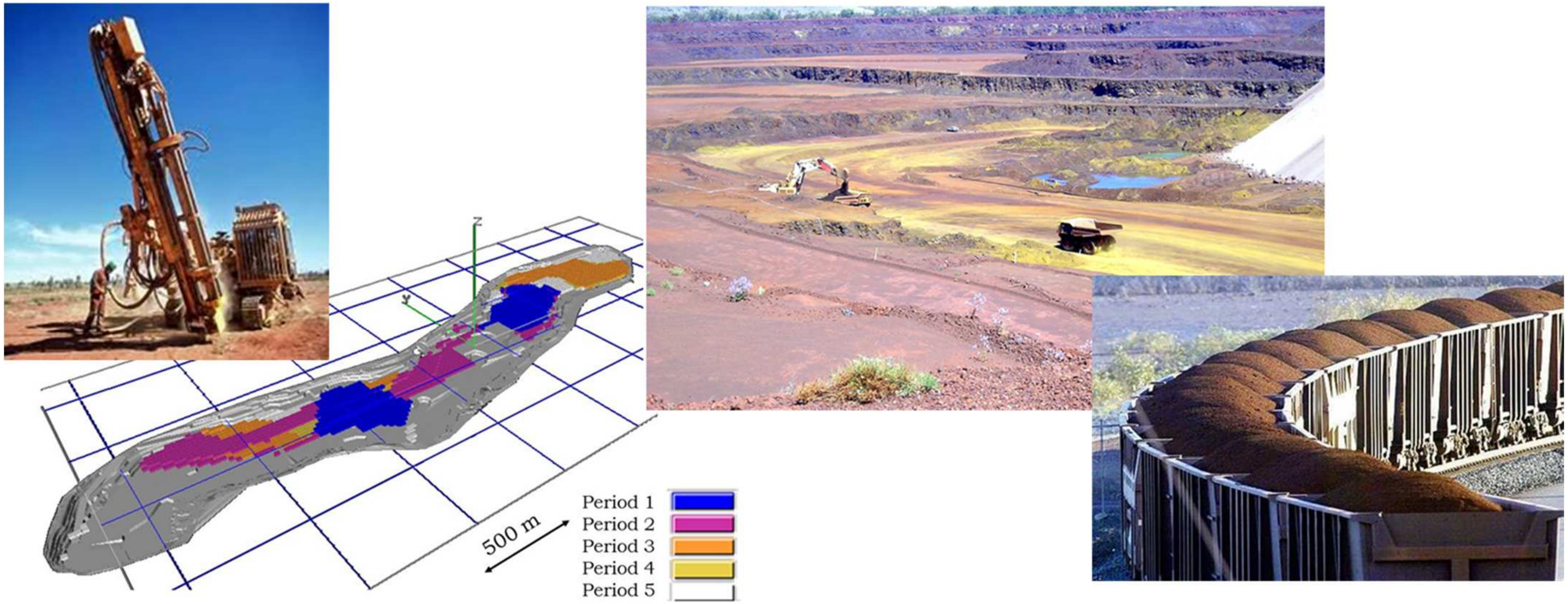
Mapping the state of play for DSM technology: Technology Readiness Levels (TRL)

Table 3.1 Technology readiness levels

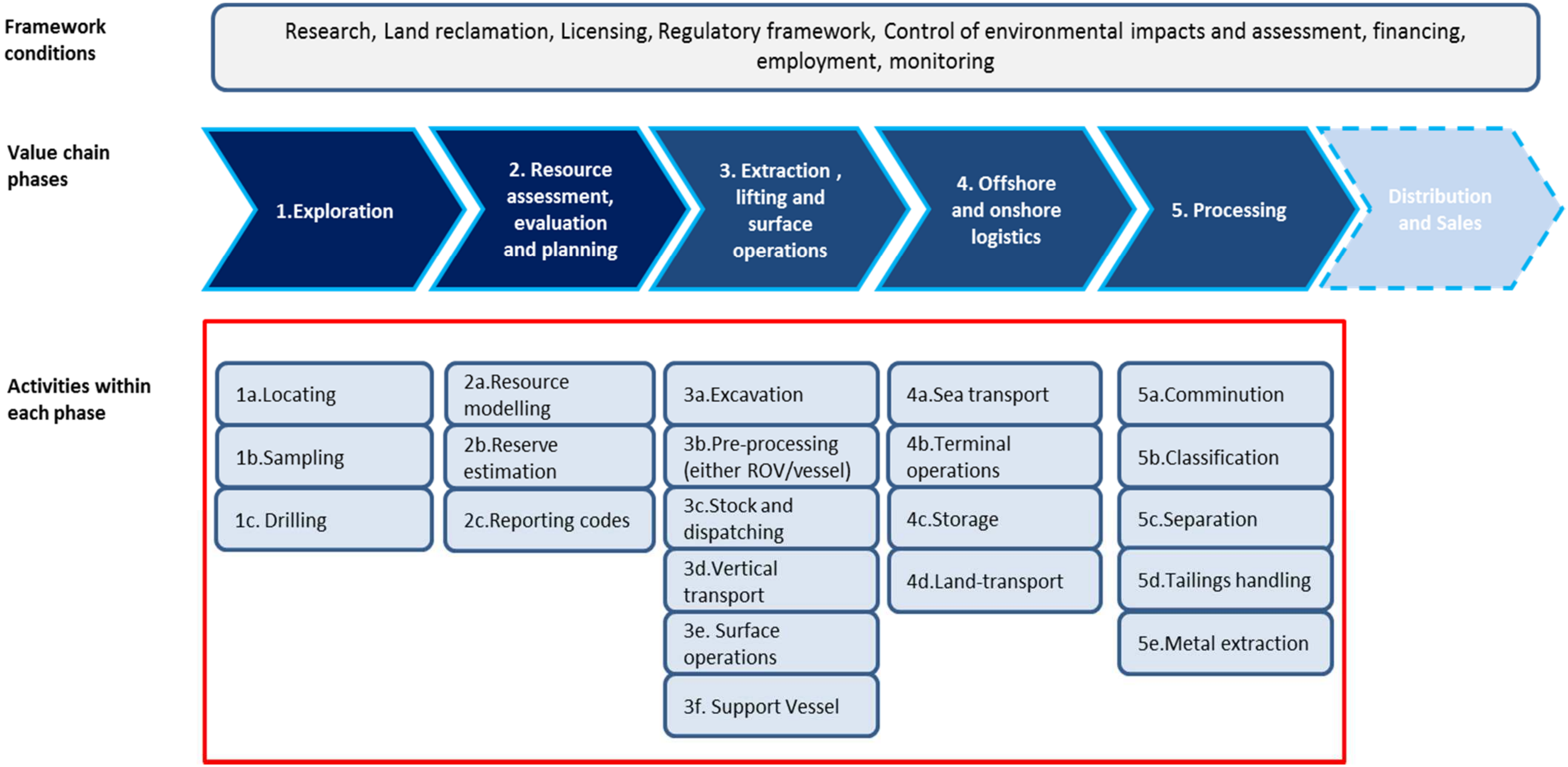
TRL	Definition
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment[5]
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment

Source: European Commission (2013) Horizon 2020 Work programme

The Mining-Value-Chain



1. The value chain activities



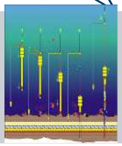
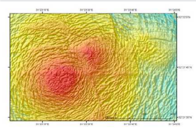
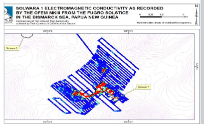
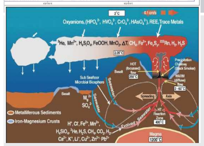
ECORYS

Phase 1. Exploration

Value chain phase: 1. Exploration

Value chain activities: 1a. Locating → 1b. Sampling → 1c. Drilling

Technologies:

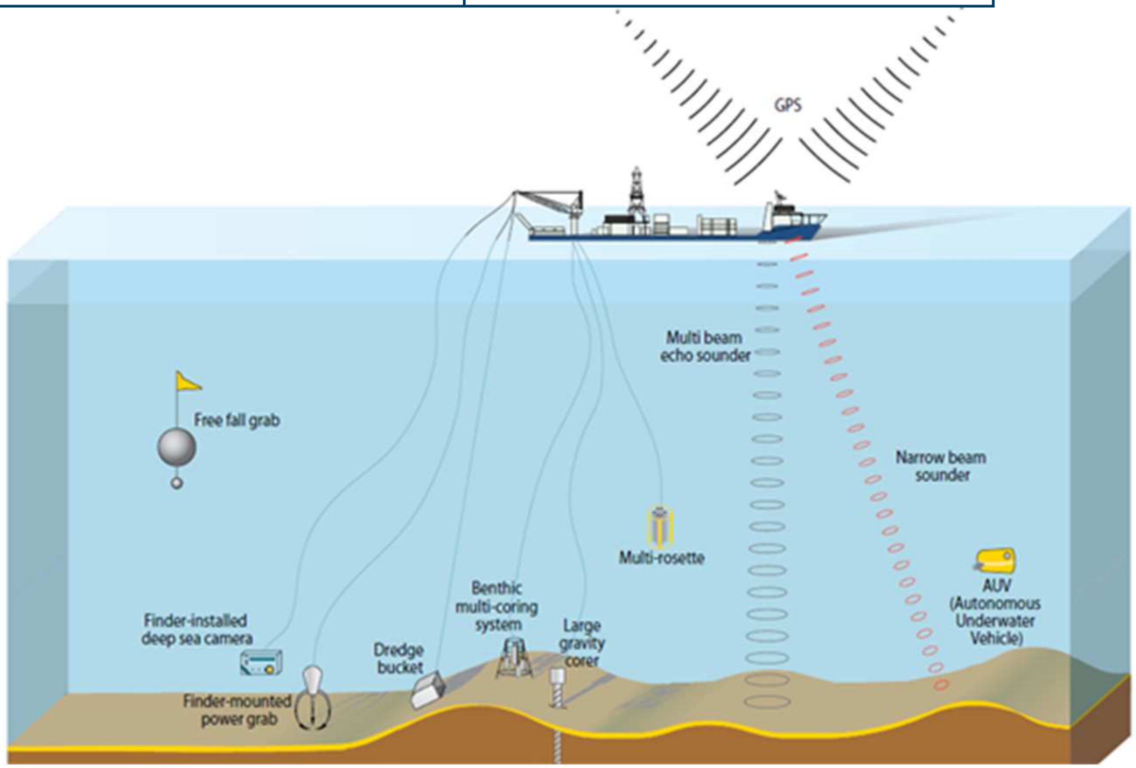
1a. Locating	1b. Sampling	1c. Drilling
 Research vessels	Free-fall devices	 Piston corers
 Echo sounder Bathymetry	Grab-Samplers	 Vibro-coring
 Electromagnetics	Cable-operated grabs and camera's	…
 Water chemistry testing	…	…
 ROV's	…	…
 AUV's	…	…

1. Exploration

Technology	Identified companies (country)	Experience? Gaps? Issues?
Research vessels	Various yards in Europe (NO, GE, NL) capable of manufacturing; however main asset is technology on board.	Only a few European ships, mostly owned/operated by research institutions
Echo sounder bathymetry (single beam, multi beam and side scan)	Edgetech (US) Kongsberg (NO) L-3 Klein Associates (US) Teledyne Reson (US) C-Max (UK) Tritech (UK)	Already widely used
Electromagnetics		
Water-chemistry testing		
ROV		
AUV	Kongsberg (NO) Teledyne Benthos (US) Bluefin Robotics (US) International Submarine Engineering (ISE) Ltd (CAN) FESTO (DE) Evologics (DE)	

1. Exploration - Sampling

Technology	Companies (country)	Experience? Gaps? Issues?
Free fall devices		Local scale
Grab samplers		Local scale
Cable-operated grabs and cameras		Local scale



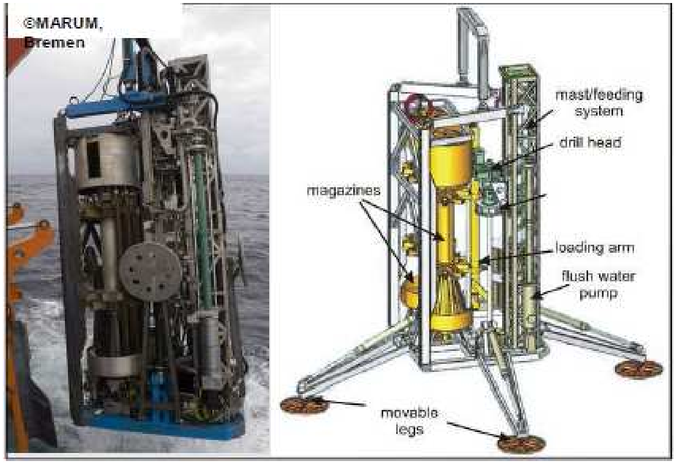
ECORYS

1. Exploration - Drilling

Technology	Companies (country)	Experience? Gaps? Issues?
Piston corers		
Vibrocoring		

- **Challenge**:
  deposits can only be evaluated, if drilling indicates presence of subbottom resources.
- **Problem**:
  too deep to use existing devices

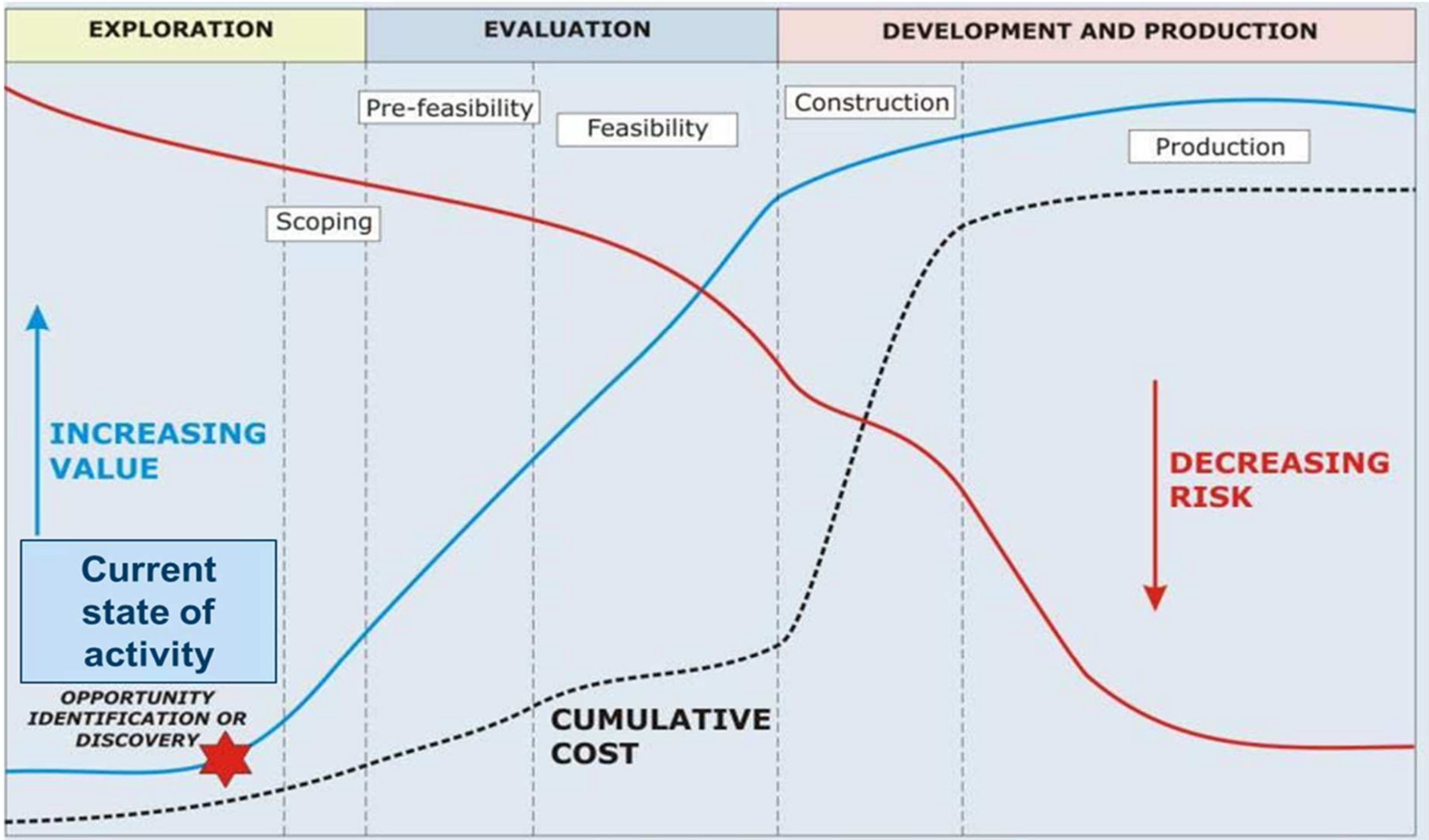
Drilling device From ROVDRILL (see SEAFLOOR Geoservices)



Wiedicke, BGR

ECORYS

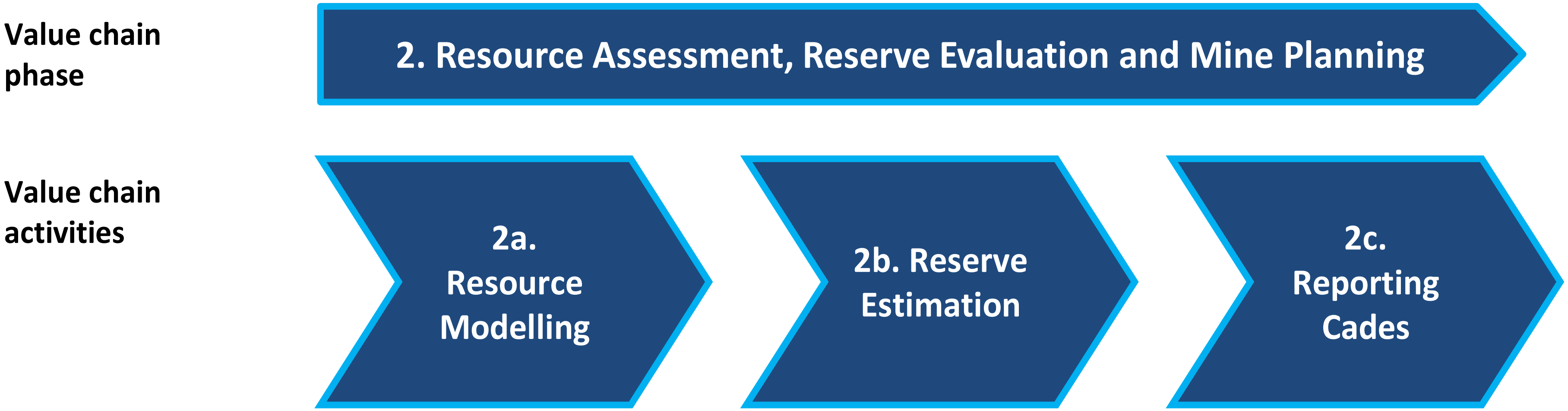
1. Exploration - Conclusion



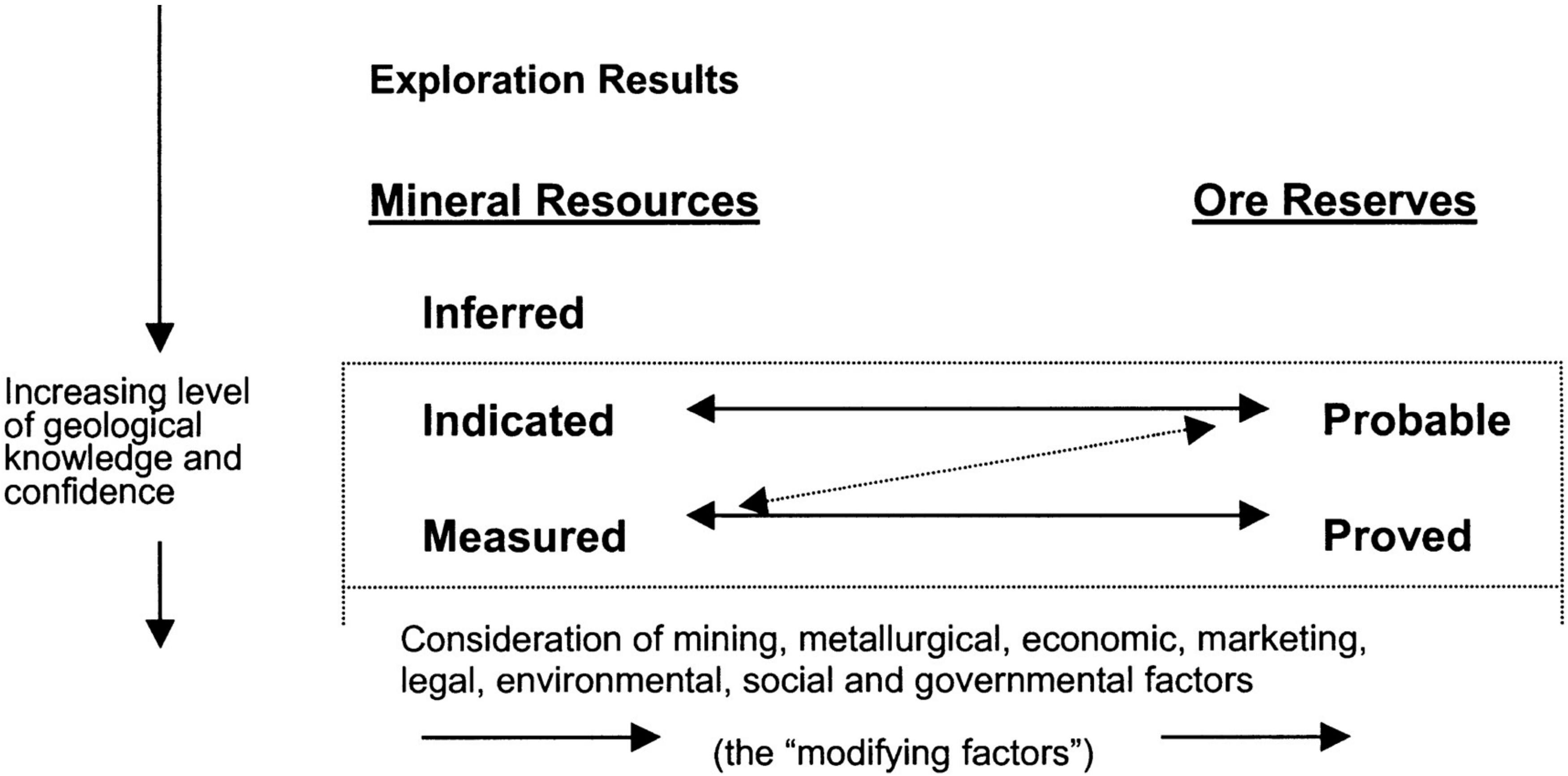
Current deep sea exploration technology allows for scientific prospecting, not for resource evaluation

ECORYS

Phase 2. Resource assessment, reserve evaluation and mine planning



Phase 2a. Resource assessment, reserve evaluation and mine planning



ECORYS

Example: JORC Code, produced by the Australasian Joint Ore Reserves Committee (2012)

Phase 2a. Resource assessment, reserve evaluation and mine planning

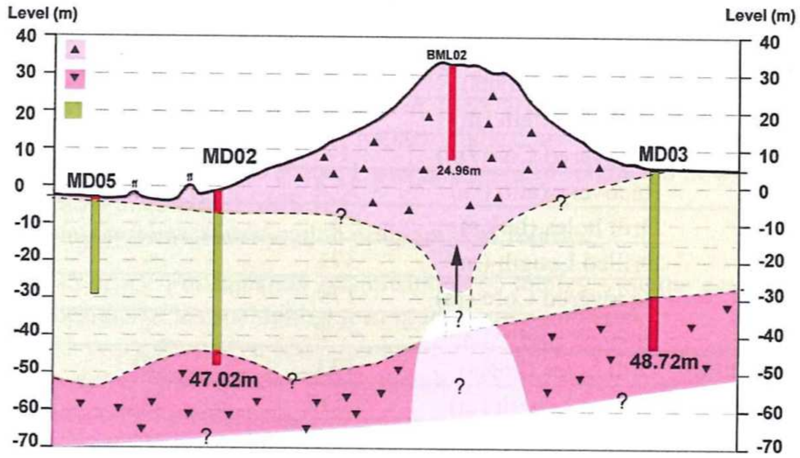
Resource Exploration

Land-based Deposits

- **Mainly Drill-core Sampling**
- **Typical 50m x 50m horizontal spacing**
- **Vertical as variability requires**
- **85% to 95% core recovery**
- **Intersecting whole deposit**

Seabed Deposits

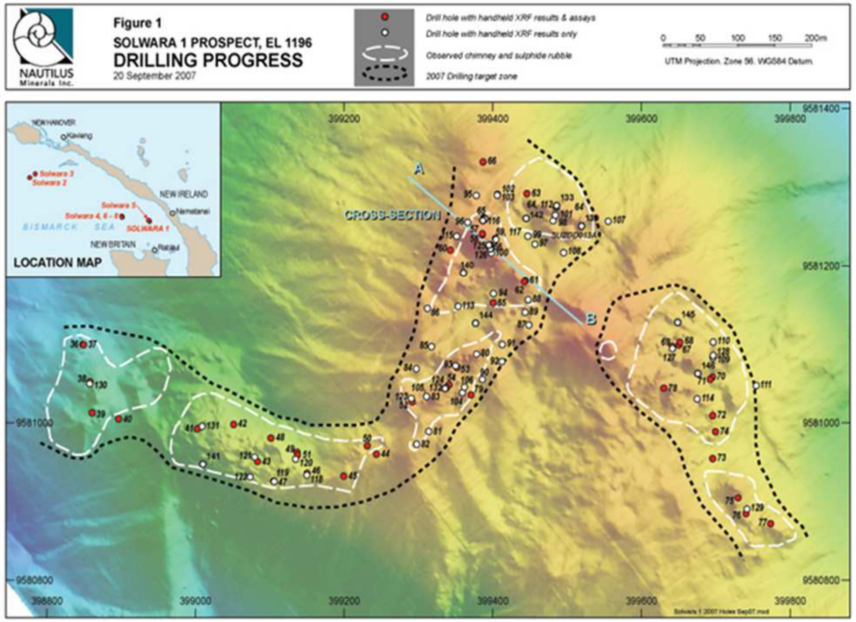
- **Scarce Drill-core Sampling**
- **Average length of drill cores: 11m**
- **Average recovery ratio: 41%**
- **Supported by surface geophysics**

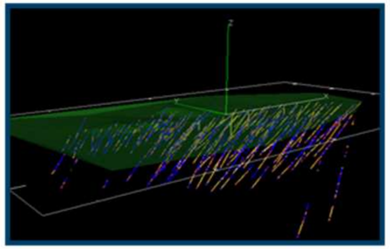


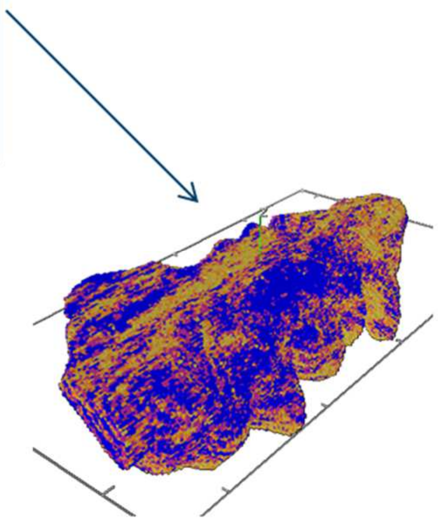
Nobuyuki, M., Nobuyuki, O., Takahiro, K., 2013, Sea-Floor Massive Sulfide Mining – Its Possibility and Difficulties to Emerge as a Future Business, In: Proceedings of the 22nd MPES Conference, Dresden, Germany, 14th – 19th October 2013, [pdf]

Phase 2a. Resource assessment, reserve evaluation and mine planning

Technology	Companies (country)	Experience? Gaps? Issues?
3D geometallurgical modelling (for polymetallic sulphides)	Geovariances (France) gOcad (France) Dessault/Geovia (UK)	Companies for implementing modelling techniques in commercial software
2D multivariate modelling (for nodules and cobalt-rich crusts)	Geovariances (France) gOcad (France) Dassault/Geovia (UK)	Companies for implementing modelling techniques in commercial software







Copper grade in %

0.00-0.07
0.07-0.14
0.14-0.33
> 0.33

Technological Readiness Level

TRL - 1	TRL - 2	TRL - 3	TRL - 4	TRL - 5	TRL - 6	TRL - 7	TRL - 8	TRL - 9

Phase 2b. Resource assessment, reserve evaluation and mine planning

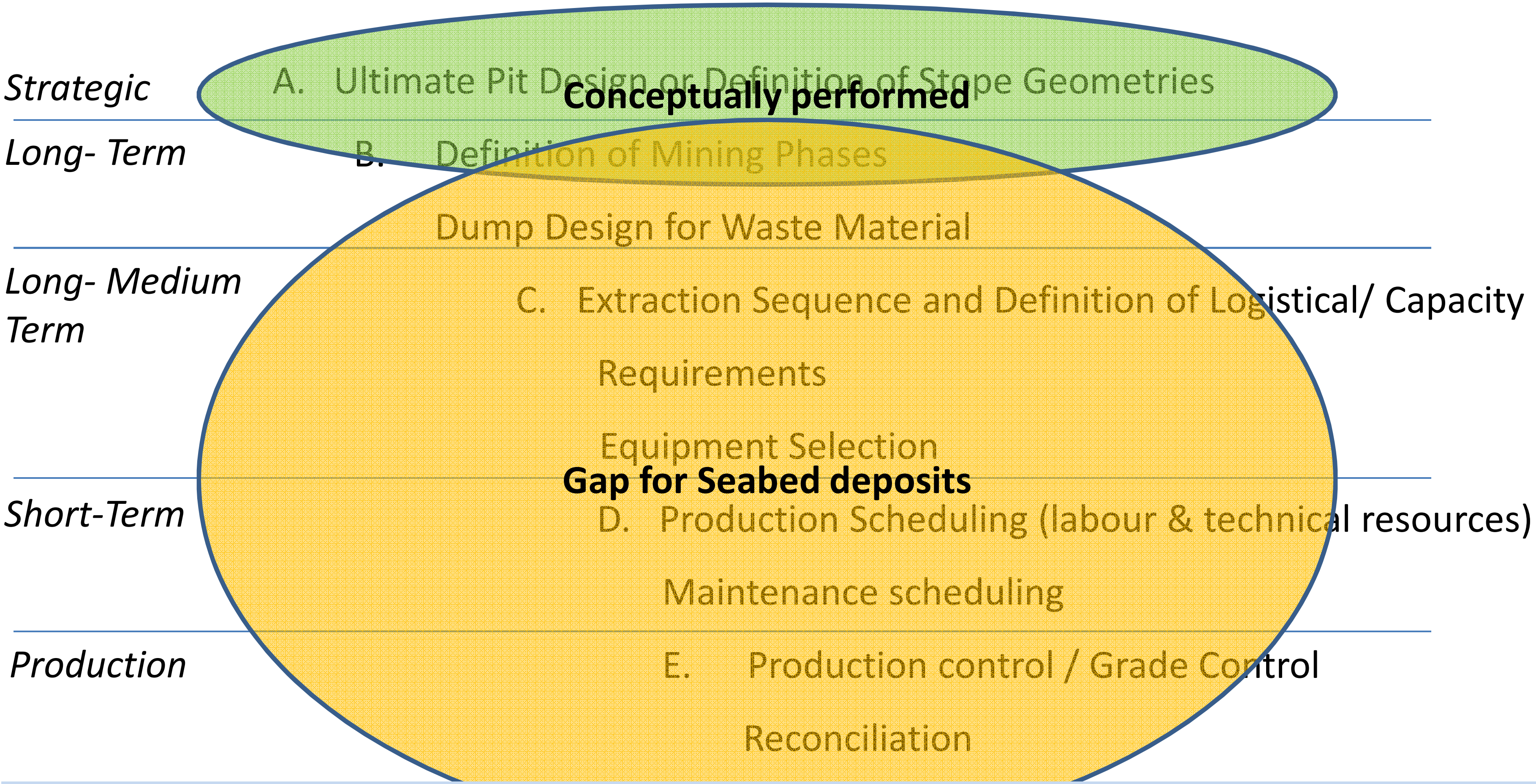
Technology	Companies (country)	Experience? Gaps? Issues?
Long-term Mine Planning	Established Consultants	Long-term DSM planning is not possible at the moment
Short-term and Operational Planning	Established Consultants	Medium- and short-term DSM planning: effective production rate and effective operating time are understood only with a very low level of confidence

For a comprehensive long-term mine planning process all boundary conditions including

- mining license area;
- mining technology;
- processing technology;
- available space for waste disposal;
- environmental impact;
- capital and operational expenditures;
- necessary permits;

ECORYS

Phase 2b. Resource assessment, reserve evaluation and mine planning



TRL 1: Currently not possible to undertake long term planning leading to proven reserves.

In combination with resource modelling mine planning standards for DSM have to be developed.

Phase 2c. Resource assessment, reserve evaluation and mine planning

Framework conditions

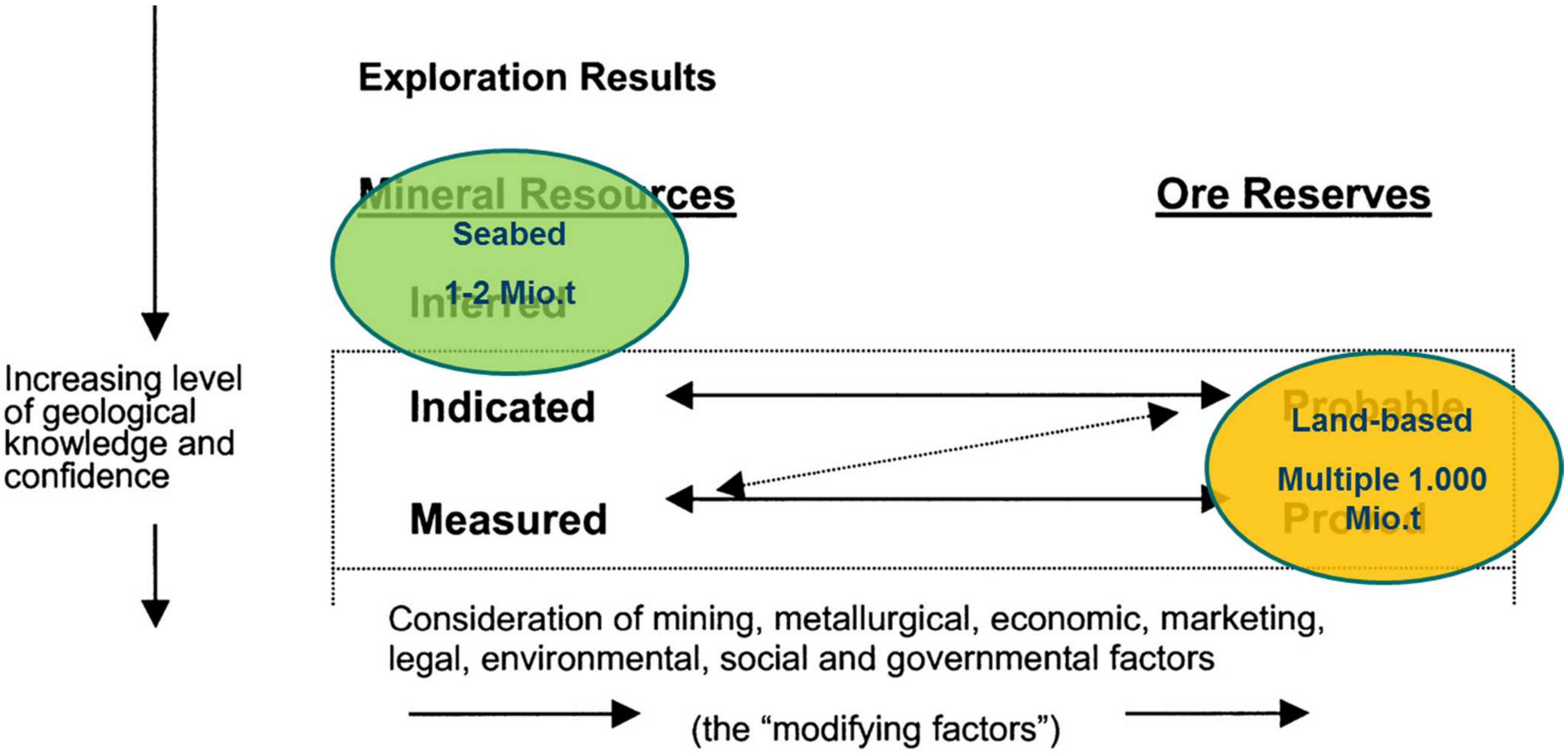
Research, Land reclamation, Licensing, Regulatory framework, Control of environmental impacts and assessment, financing, employment, monitoring

Consideration of mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors

→ (the "modifying factors") →

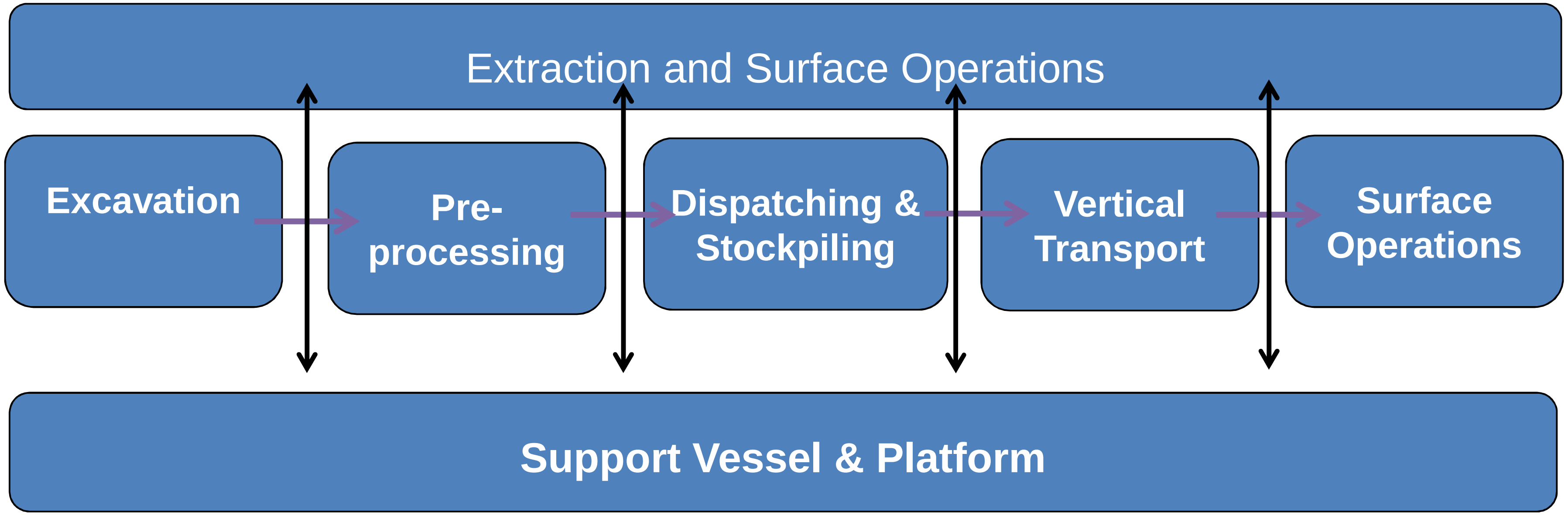
- Without an agreed international regulatory framework, no bankable reserves can be defined
- Therefore there is no business case

Phase 2c. Resource assessment, reserve evaluation and mine planning



Example: JORC Code, produced by the Australasian Joint Ore Reserves Committee (2012)

Phase 3. Extraction, lifting and surface operations



Phase 3. Extraction, lifting and surface operations

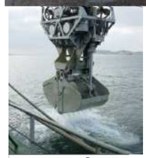
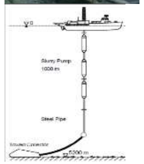
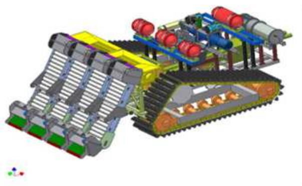
Value chain phase: 3. Extraction and Surface operations

Value chain activities: 3a. Excavation | 3b. Pre-processing | 3c. Dispatching | 3d. Vertical material Transport | 3e. Surface operations

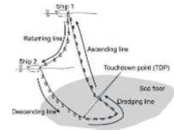
3f. Support vessel

Technologies:

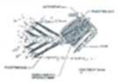
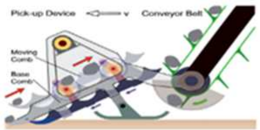


Drum-cutter ROV	Identification – sensors and sampling	??	Continuous line bucket	Dewatering
Rotating-cutter head ROV	Separation		Air lift system	Dewatering + concentrating
ROV Clamshell grap	Size Reduction – crushing	…	Hydraulic pump system	Dewatering + concentrating + metallurgical processing
Passive collectors	Concentration – gravity, Magnetic and sensor	…	Batch cable-lifting	
Active Collectors & crusher-collectors	…	…		
…	…	…		




3. Extraction, lifting and surface operations: Excavation

Technology	Company (country)	Experience? Gaps? Issues?
Drum-cutter ROV **TRL 2** (based on terrestrial coal mining) 	SMD (UK) Nautilus Minerals (CA) Placer Dome (CA) Perry Slingsby Systems (USA) Voest Alpine (A)	SMS Terrestrial cutter head mounted on ROV and tested at 1600m depth: no collection of material
Rotating-cutter head ROV **TRL 2** 	SMD (UK) Nautilus Minerals (CA) De Beers Group (L) Perry Slingsby Systems (USA) Voest Alpine (A)	SMS Used on dredgers and marine diamond mining (150m water depth)
ROV Clamshell grab **TRL 2** 	Neptune minerals Plc (UK) IHC Merwede (NL)	SMS Used for soft soils/gravel: applicability to rock collection is uncertain
Passive collectors **TRL 5** 	Abandoned method	Polymetallic Nodules
Active collectors **TRL 4/5** 	Aker Wirth (DE) NIOT (IN)	Polymetallic Nodules

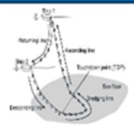
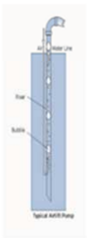
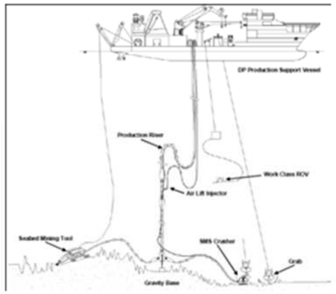
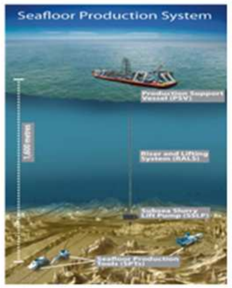
3. Extraction, lifting and surface operations – Stock & dispatch systems

Technology	Company (country)	Experience? Gaps? Issues?
Collector ROV **TRL 1/2**	Nautilus	

- **Ore needs to be transported to surface.**
- **For processing efficiency, require a continuous predictable flow of material**
- **Reality: Fluctuating production rates & inherent variability in grade:**
    - **May require stockpiling to permit blending to ensure constant grade**
        - **Seabed ?**
        - **Ship/Platform ?**
    - **Or, episodic discontinuous batch transport**

Major knowledge gap in development of Deep Sea Mining Concepts

3. Extraction, lifting and surface operations – Vertical material transport

Technology	Company (country)	Experience? Gaps? Issues?
Continuous line bucket **TRL 5** 	Abandoned method	Lack of manoeuvrability, lack of production control, low cutting efficiency
Air lift system **TRL 5**  	Aker Wirth (DE) IHC Merwede (NL)	Vulnerable to clogging, high energy requirements, piloted for nodules. Depth limitation (need to send air down to great depth) Proven method to transport slurry in a vertical riser pipe. Applied in dredging operations within limited depths. Validated in transportation of nodules from 5000m
Hydraulic pump system **TRL 3** 	GE oil and gas (USA) Part of planning for Nautilus Solwara 1	Successfully applied in deep water oil & gas drilling (size of drill cuttings vs ore particles ? High potential wear due to continuous transport ?). Equipment at surface allows ease of maintenance
Batch cable-lifting **TRL 2**	Siemag (DE) Investigated for Nautilus	Limitations in hoisting speed: limits capacity. Simple system

3. Extraction, lifting and surface operations – Pre-processing

Technology	Companies (country)	Experience? Gaps? Issues?
Identification – sensors and sampling **TRL 4 ?**	Tomra (Norway) for terrestrial ores	Land-based experiences, measuring tools could be implemented on AUV/ROV Use of X – ray techniques uncertain
Separation **TRL 3**	Tomra (Norway), Steinert (Germany) Terrestrial ores	Experiments done; wet versus dry ? Particle by particle ? Bulk separation ?
Size reduction – crushing **TRL 2**		For sea floor operation still in conceptual phase (routinely applied in terrestrial operations)
Concentration – gravity, magnetic and sensor **TRL 1**		Successful applications on land-based mining facilities, uncertain if transfer to seabed is feasible

Excavating/Cutting - Vertical transport ore/waste to surface

Subsequent separation of ore from waste, disposal of sediments.

Transportation of ore to shore for further processing.

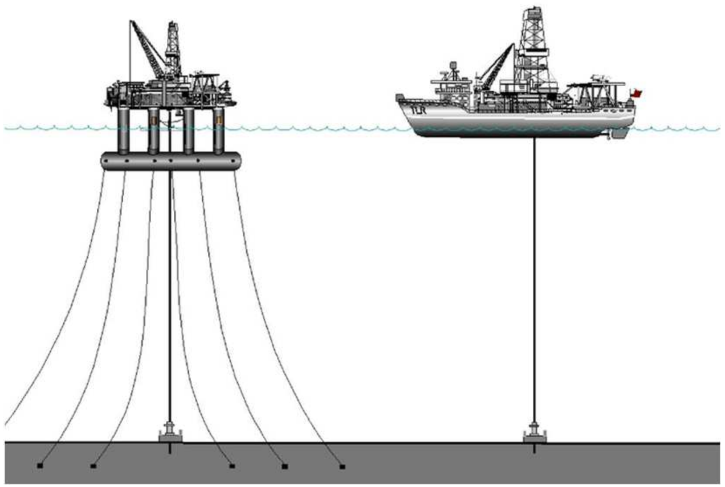
Pre-processing of excavated material prior to vertical transportation could significantly reduce costs & increase the value of the mined material.

3. Extraction, lifting and surface operations – Surface operations

Technology	Companies (country)	Experience? Gaps? Issues?
Dewatering (Shipping of raw product) **TRL 9**	Ausenco Minerals (for Nautilus Project)	Known from sand & gravel dredging. Should be applicable to sea based platform
Dewatering + concentrating (Shipping of ore concentrate) **TRL 3**		Uncertain how equipment will react to salty water; impact of disposal on the environment to be investigated. Space constraints on ship/platform ?
Dewatering + concentrating + metallurgical processing (shipping of final product) **TRL 1**		Processing on land known; currently unlikely for offshore applications due to size & energy consumption

3. Extraction, lifting and surface operations – Support vessel

Technology	Company (country)	Experience? Gaps? Issues?
Vessel	Nautilus Minerals (CA)	Deep sea cable laying
Platform	N/A	Oil & Gas Industry

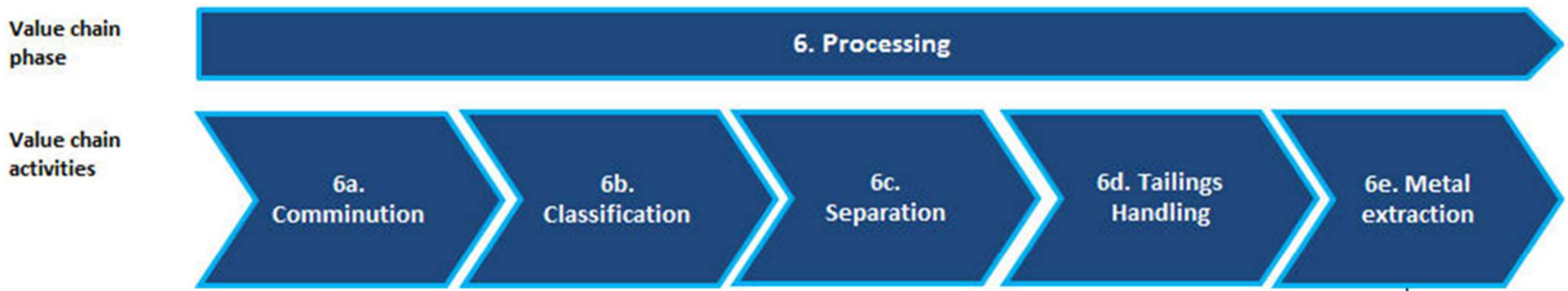


Semi-submersible platforms: widely used in deep water oil & gas applications:

- more space for processing equipment.
- stable and are very seaworthy

ECORYS

Phase 4. Processing



Technologies:

Jaw crusher	Hydrocyclone	Gravity Tables	N/A	Pyrometallurgy
Impact crusher	Screening	Froth Flotation		Hydrometallurgy
Cone crusher		Jigging		
Gyratory crusher		Spiral separators		
Roll crusher				

4. Processing techniques – Comminution: Crushing

Technology	Company (country)	Experience? Gaps? Issues?
Jaw crusher	Numerous suppliers (UK, other EU mining countries; US, China)	Land-based mining experience
Impact crusher	Numerous suppliers identified globally	Land-based mining experience
Cone crusher	Idem	Land-based mining experience
Gyratory crusher	Idem	Land-based mining experience
Roll crusher	Idem	Land-based mining experience

Well developed for terrestrial mining: TRL 9

For DSM: **TRL 2.** Seabed ? ship/platform based ? Transport to shore ?

Efficiency is poorly known for wet or moist material

ECORYS

4. Processing techniques – Comminution: Grinding

For further size reduction, the milling process is used.

Technology	Company (country)	Experience? Gaps? Issues?
Rod Mills	Numerous suppliers (UK, other EU mining countries; US, China)	Land-based mining experience Wear of the rods may lead to fracturing
Ball Mills	Numerous suppliers identified globally	Land-based mining experience. Large equipment size.
Semi-Autogenous Grinding (SAG Mills)	Idem	Land-based mining experience. Common.
Autogenous Grinding (AG Mills)	Idem	Land-based mining experience
-	-	-

Well developed for terrestrial mining: TRL 9

For DSM: **TRL 2.** Seabed ? ship/platform based ? Transport to shore ?

ECORYS

Efficiency is poorly known for wet or moist material

4. Processing techniques - Classification

Technology	Company (country)	Experience? Gaps? Issues?
Hydrocyclone, screening, sieving **TRL 7**	Multiple in the EU (UK, GE, ES), US, Asia	Well-known in land-based applications

Well known process in dry & wet mining environments

- Screening is routinely used in offshore diamond mining

- Hydrocyclones: likely to be suitable for shipboard application, although currently untested.

ECORYS

4. Processing techniques - Separation

Technology	Company (country)	Experience? Gaps? Issues?
Spiral concentrators	Various (China, US, some EU, South America)	Techniques well understood & applied in land-based mining; Location of technique: ship/platform or land based ? Spirals & Mag Sep: Shipboard application feasible Gravity tables: space consuming Froth flotation: toxic waste water
Gravity separation		
Jigging		
Magnetic separation		
Froth flotation		
Sensor based Sorting	Tomra (Norway), Steinert (Germany) Terrestrial ores	Experiments done; wet versus dry ? Particle by particle ? Bulk separation ?

TRL 4 Technology is mature & routinely applied in terrestrial applications

Need to assess what combination is most suitable for the

mineral compositions found on the sea bed.

ECORYS

4.. Processing techniques - Separation

- Application of separation technologies offshore

Ores	Separation Techniques					
	Spirals	**Shaking Tables**	**Hydro-cyclones**	**Froth Flotation**	**Jig**	**Magnetic Separation**
Poly-metallic sulphides	*To be investigated*	*Unpractical*	*Possible*	*Unpractical*	*To be investigated*	*Not possible. Sulphides are in general non-magnetic**
Poly-metallic nodules	*To be investigated*	*Unpractical*	*Possible*	*Unpractical*	*To be investigated*	*Depending on mineral content*
Cobalt-rich crusts	*To be investigated*	*Unpractical*	*Possible*	*Unpractical*	*To be investigated*	*Depending on mineral content*

For DSM, TRL 4: application specific research is required

4. Processing techniques – Tailings handlings

- Separation – Every separation technique produces tailings, which in most cases must be discarded.

- Issues at stake:

    - Separation offshore or onshore
    - Chemicals applied or not
    - Discharge from surface to seabed
        - Damages to the sea bed vs the water column

- **TRL 1.** Any sea-based mineral processing will produce tailings.

Is sea based processing realistic and/or practical given this constraint ?

ECORYS

4. Processing techniques – Metal extraction

- Well-known for land based applications

  - Pyrometallurgical (heat extraction) – high temp
  - Hydrometallurgical (chemical leaching) – hazardous chemicals
  - Electrometallurgical (wet chemistry + electrowinning) – power

Ores:	Identified Concentrating techniques		
Polymetallic sulphides	Flotation + Smelting	Magnetic Separation + Smelting	
Polymetallic nodules	Cuprion process	Sulphuric leaching	Smelting
Cobalt-rich crusts	Gravity Separation + Smelting		

Proven but application/deposit specific research is needed

Metal extraction techniques are either not possible or impractical on a seagoing vessel or on a platform.

THANK YOU!