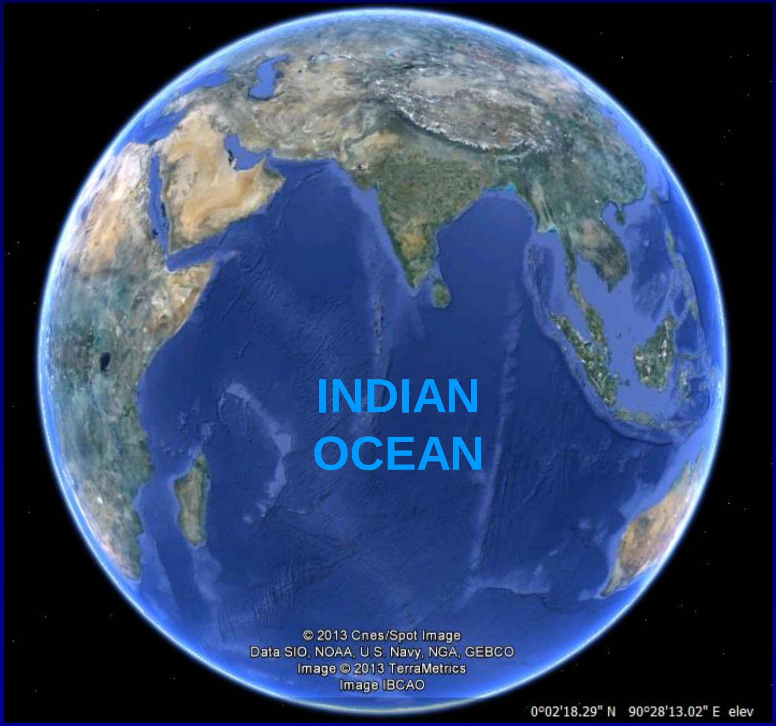
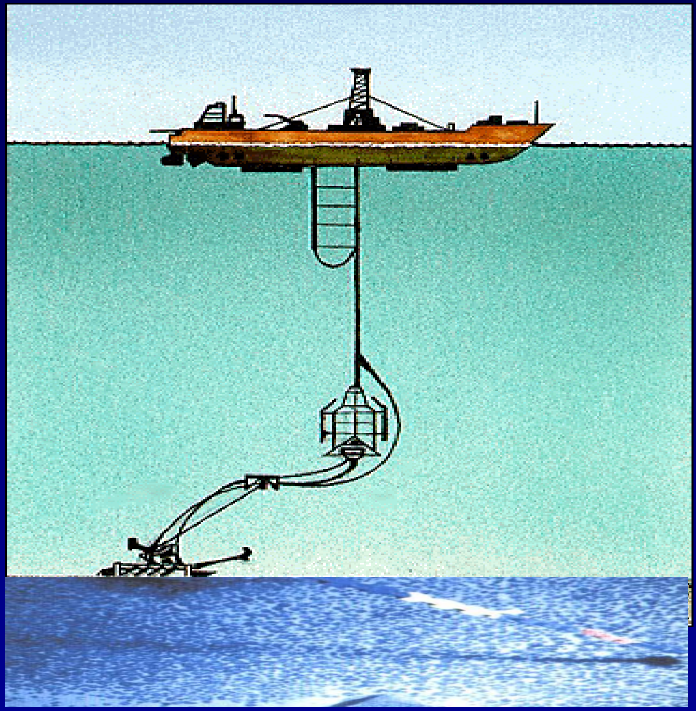
Development of National Capacities for Seabed Mineral Resources – The Indian Experience





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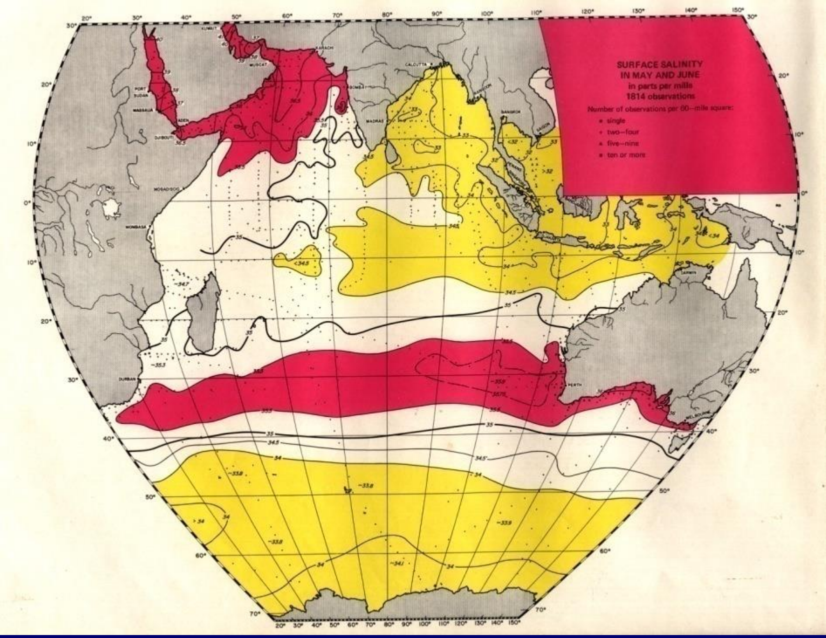
‘Indian Ocean’- ography

International Indian Ocean Expedition (IIOE)

- cooperative multi-ship expedition (1960-65)
- 40 ships participated
- from 20 countries
- data on physical, chemical, biological
- from 270 expeditions



Lead to formation of National Institute of Oceanography (1966) for

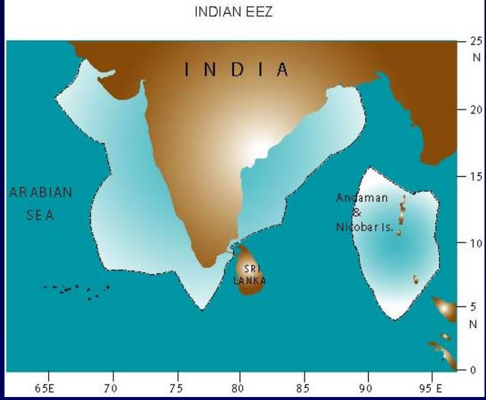
- Multi-disciplinary oceanographic research
- Services to offshore industry
- One of the objectives is ‘to explore marine mineral resources’
- Staff : Permanent ~500, Temporary ~300

Map showing surface salinity (May-June)

1614 Observations

(Source : IIOE, 1971)

Economic and social dependence on oceans



Coastline : ~ 7,500 km

EEZ : ~ 2 mi. km^2 (~ 2/3 of land area)

Islands : 36 in Lakshadweep (10 inhabited)
554 in Andaman (36 inhabited)

Occupations in coastal areas :
Fishing, shipping, ship building, ports

Marine resources :
(fishery, petroleum, minerals) of EEZ and beyond

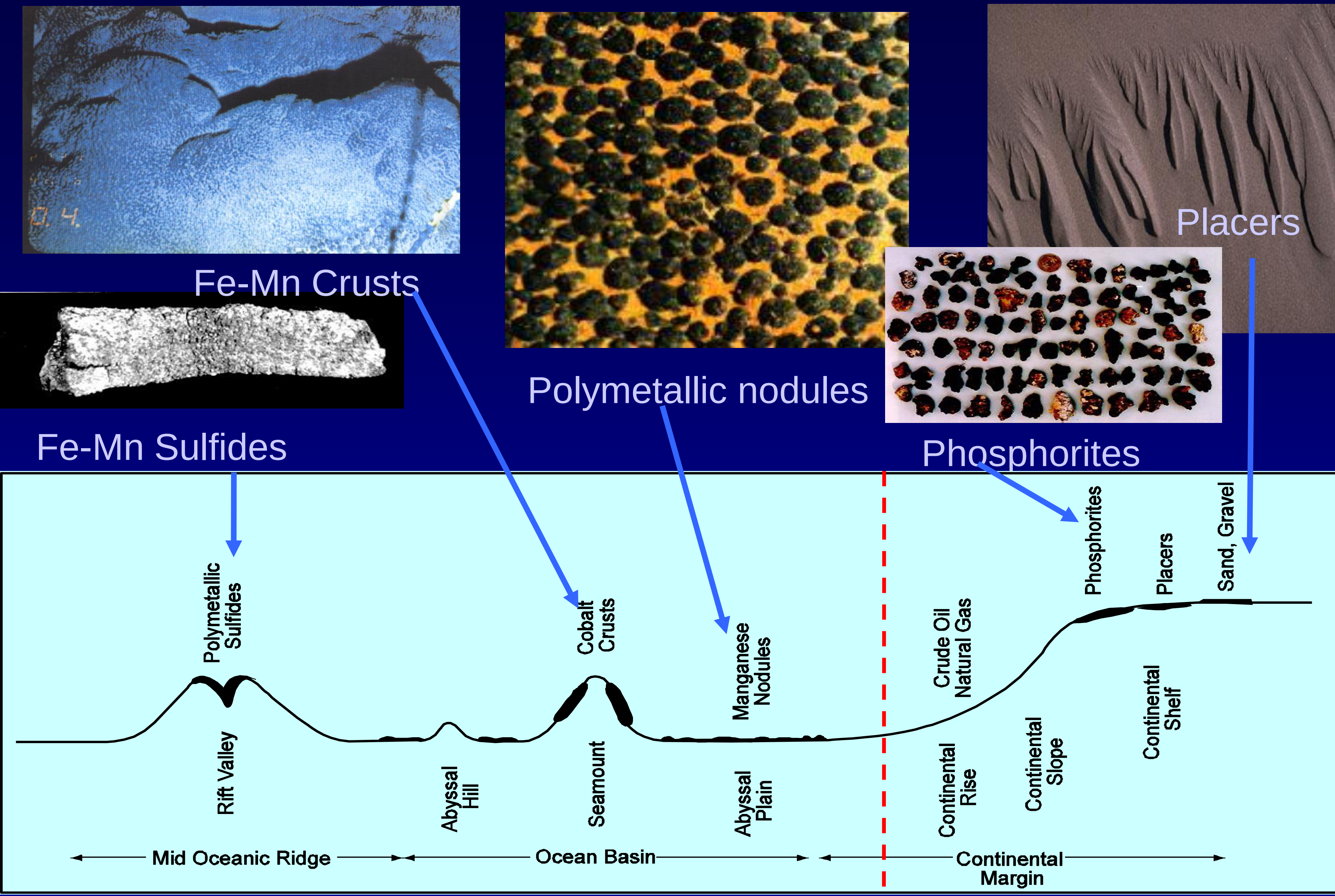
Agriculture based economy :
Monsoons (that originate from the ocean) play an important role

Key metals from deep-sea minerals – their uses and status

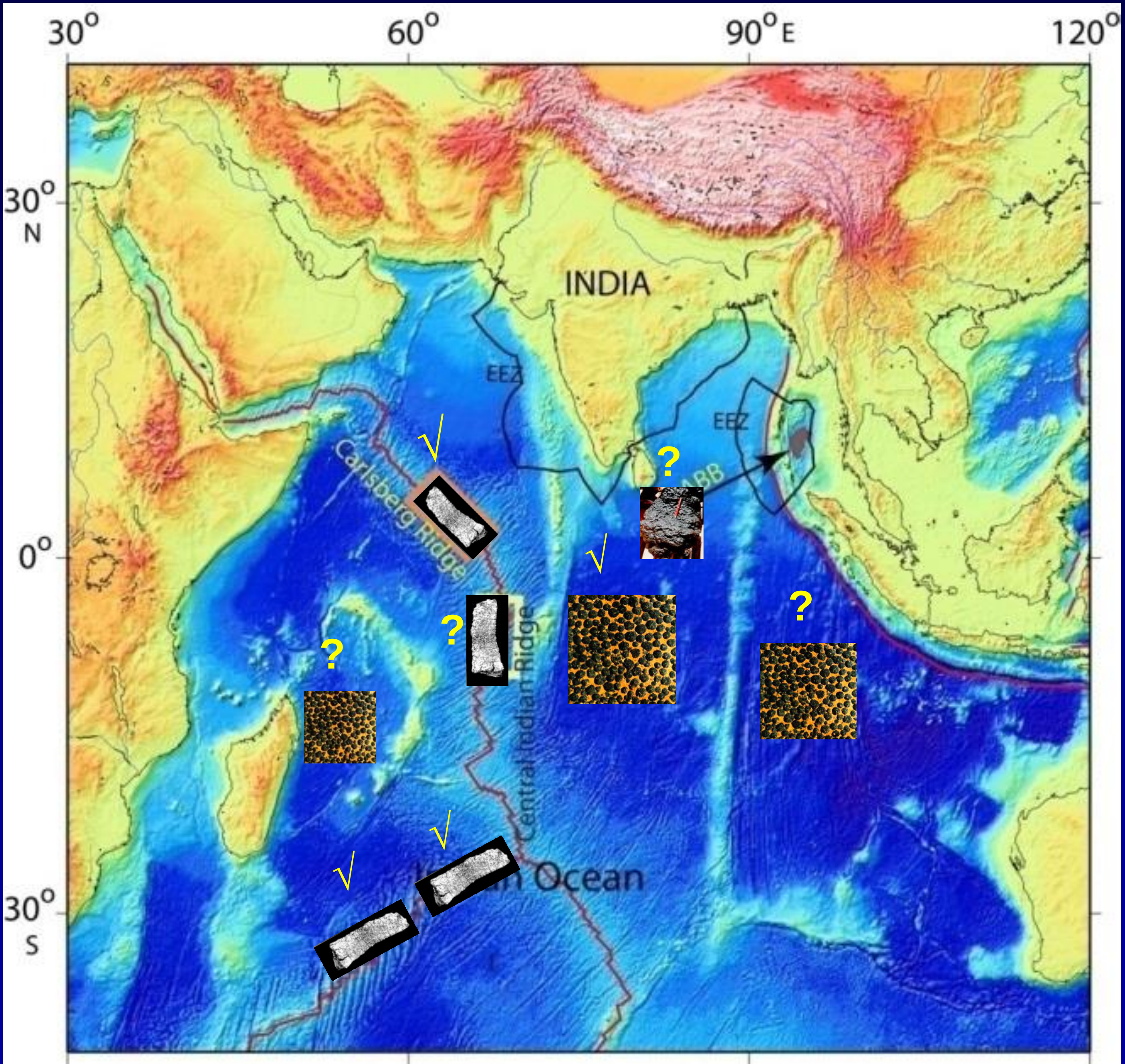
Metal	Used in*	Reserves on land & status**	
		In India	In World
Nickel	Making steel (46%) , nonferrous alloys and superalloys (34%); electroplating (11%) , coins, ceramics, batteries, hard discs	Nil, totally depend on imports	71 mi. t
Cobalt	Alloys, magnets, batteries, catalysts, pigments and coloring, radio-isotopes, electroplating	Nil, totally depend on imports	6.6 mi. t (52% in Congo)
Copper	Electrical, telecom and electronic applications such as generators, transformers, motors, PCs, TVs, mobile phones (65%), automobile (7%), anti-bacterial agent and consumer products (coins, musical instruments, cookware)	4.3 mi. t	140 mi. t (low grade)
Manganese	Steel production (> 85% of ore used for this), corrosion resistant alloys (cans), additive in unleaded gasoline, paint, dry cell and alkaline batteries, pigments, ceramic & glass industry	142 mi. t (ore)	540 mi. t (metal)
Iron	Pig iron / sponge iron / steel (>90%), alloys, automobiles, ships, trains, machines, buildings, glass	8.09 bi. t (ore), Rich reserves available	160 bi. t (ore) and 77 bi. t (metal)

* Wikipedia, ** IBM year book 2010

Distribution of marine minerals



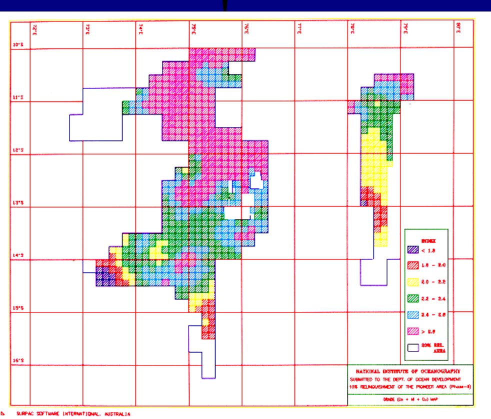
Potential deep-sea mineral areas in Indian Ocean



Components of deep-sea mining program

Ministry of Earth Sciences (Govt. of India)

- **Exploration**
- **Mining**
- **Metallurgy**
- **EIA**



NIO, Goa

NIOT, Chennai

IMMT, Bhubaneswar
NML, Jamshedpur

NIO, Goa

Criteria for nodule mining

(Source: UNOET, 1987)

- Cut off grade : 1.8 % Ni + Cu
- Cut off abundance : 5 kgm^{-2}
- Topography : acceptable
  (< 3º slope)
- Life of a mine site : 20 years
- Annual recovery rate : 1.5 - 3 mi.t y^{-1}

Pluses : International waters - don't belong to anyone
Loosely strewn on the seafloor – easy to mine

Minuses : Extreme conditions – 500 bars, 2º C, no light
Distance from the shore – 1000s of kms
Working depths -- > 5 km

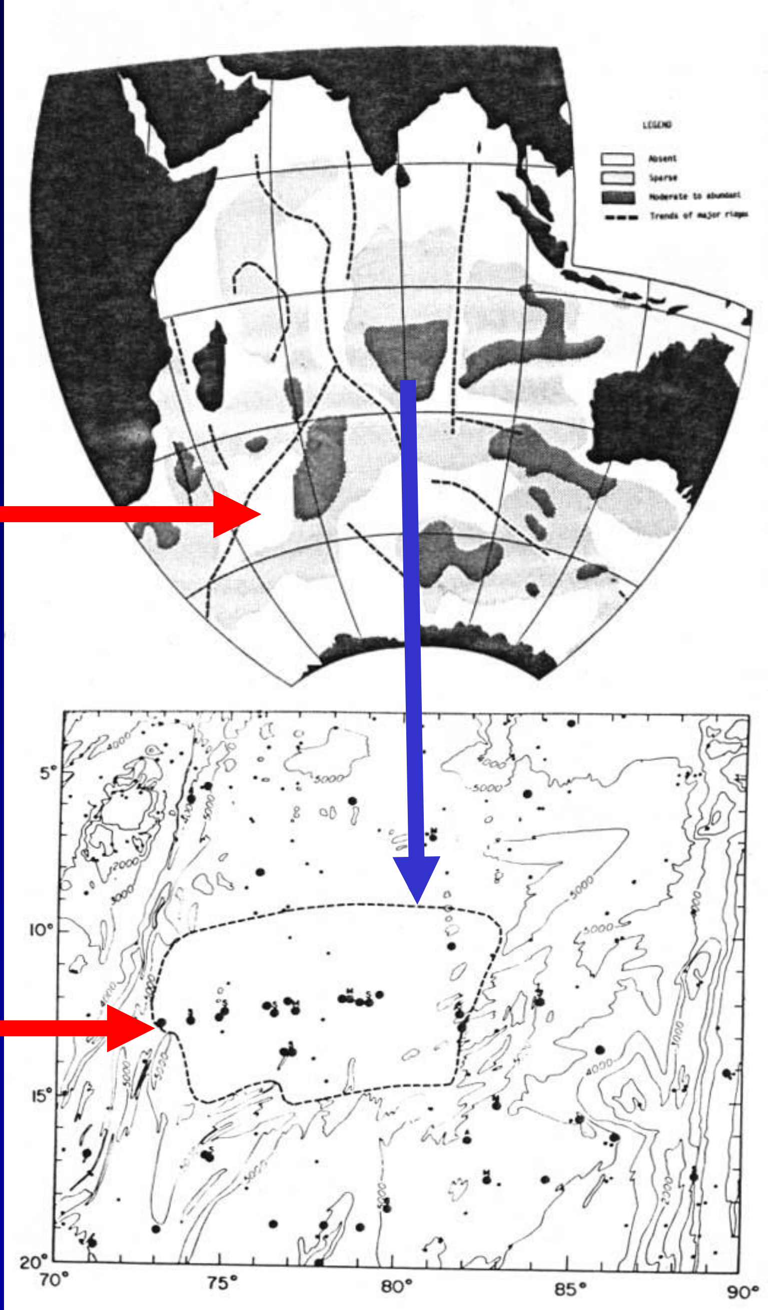
Initial reports on Indian Ocean nodules

- Glasby (1972) – Geochemistry of manganese nodules from NW Indian Ocean

- SIO (Scripps Institution of Oceanography, 1978) report – Availability of Cu, Ni, Mn from Ocean Fe-Mn nodules

- Frazer and Wilson (1980) – identified 5 regions of potential manganese nodule resources in Indian Ocean based on
  - 7000 samples, 700 analyses
  - criteria : average 2.4 % Cu+Ni+Co
    cutoff grade 1.8 % Cu+Ni+Co
    cutoff abund. 5 kg/sqm.

  - Concluded that CIOB offered potential sites for mining between 10-16ºS, that has
    - o Low sedimentation rate (< 3 mm/ 1000 years, Udintsev, 1975)
    - o High Cu, equal or more than Ni, low Co



Indian 'site' is located in this area

Nodule program launched

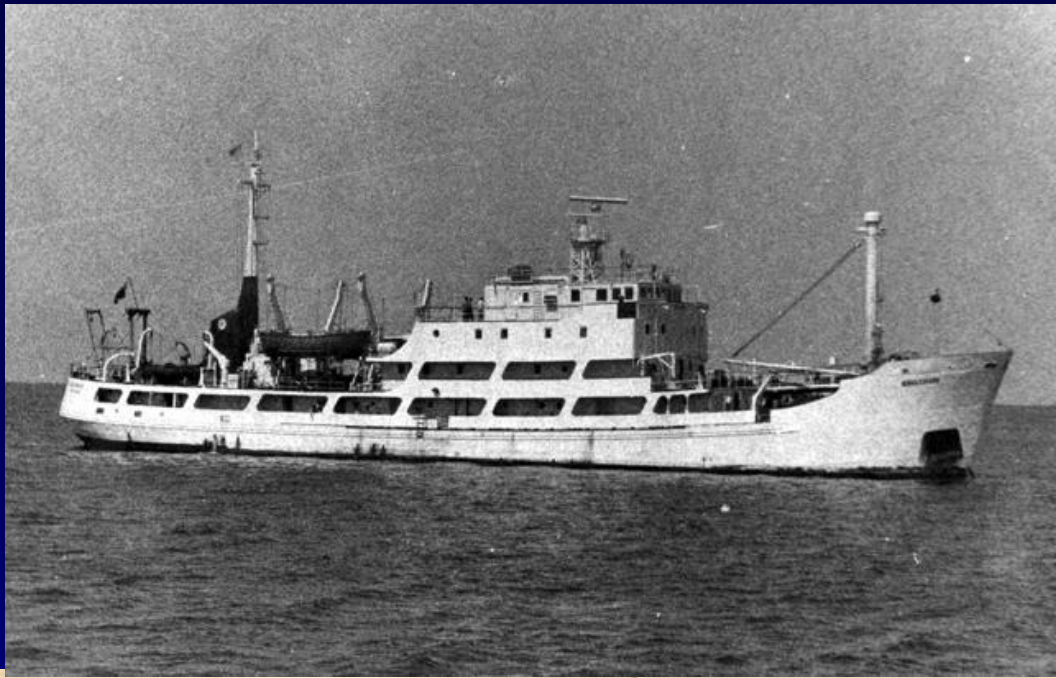
RV Gaveshani (1900 tonne)

Cruise 86-87

First nodule recovered

On 26 January 1981

From Equatorial Indian Ocean



(Source : Qasim and Nair, 1988; Photos: AV Sonawane)

State of the art technology / ships utilisation

RV Skandi Surveyor (Norway)

RV Farnella (UK)

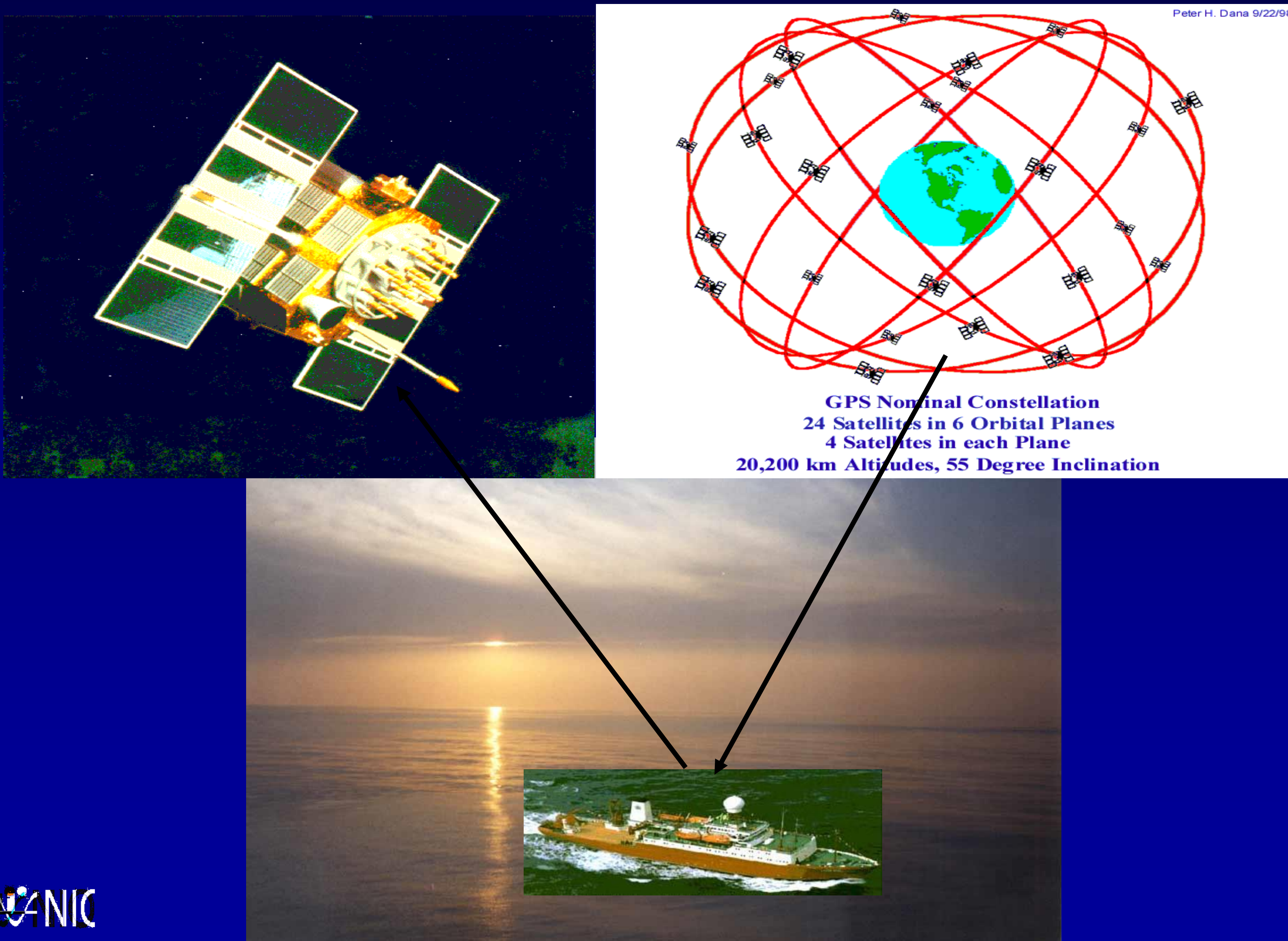
RV AA Sidorenko (Russia)

ORV Sagar Kanya (India)

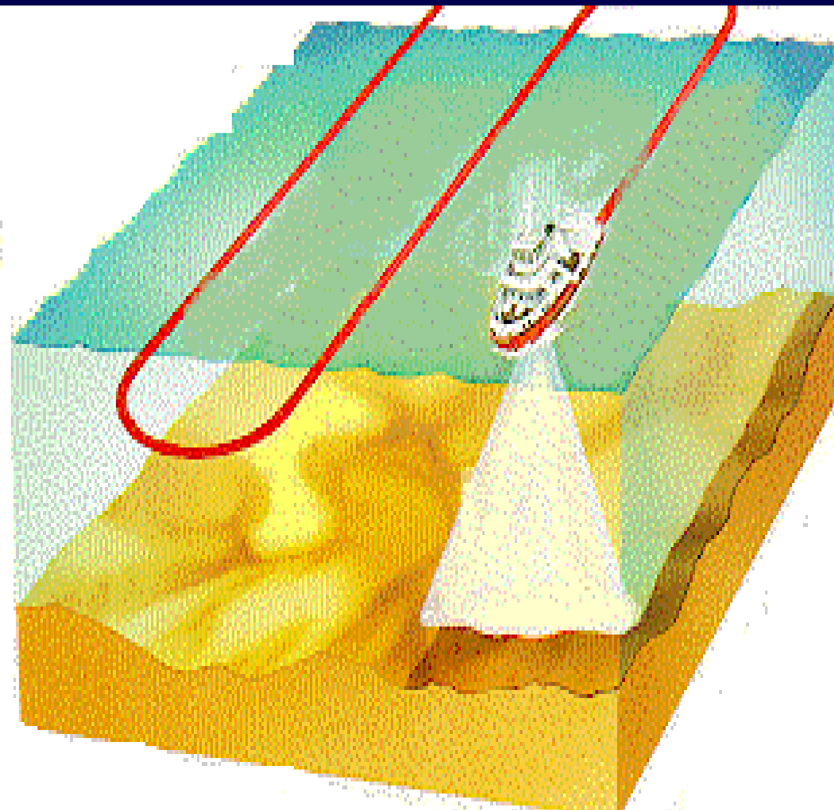
No. of expeditions = 72 x 35 days = 2520 days = 7 years at sea

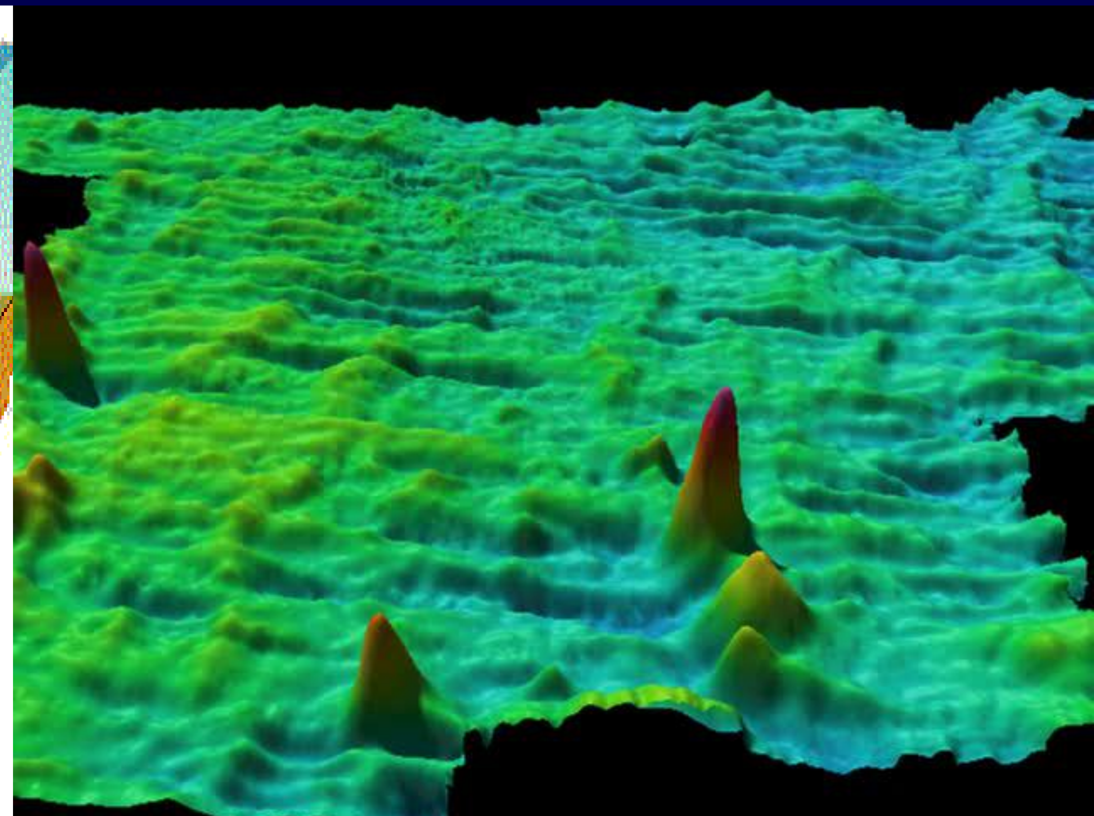
(Source: NIO/PMN data bank)

Satellite navigation and position fixing



Multibeam Bathymetry System



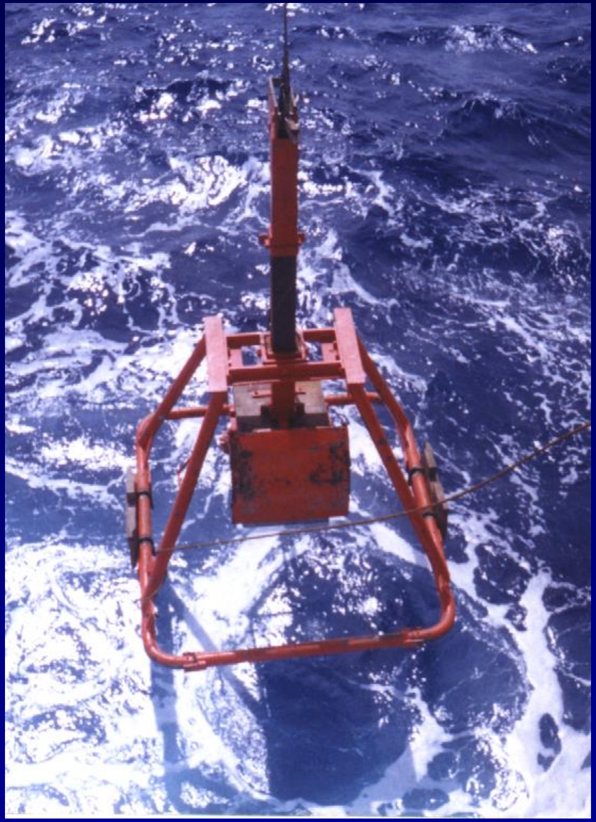


Total bathymetry Survey (30,000 km x ~10 km swath)

(Source: NIO/PMN data bank)

Underwater sampling equipments

Freefall grab



Box corer

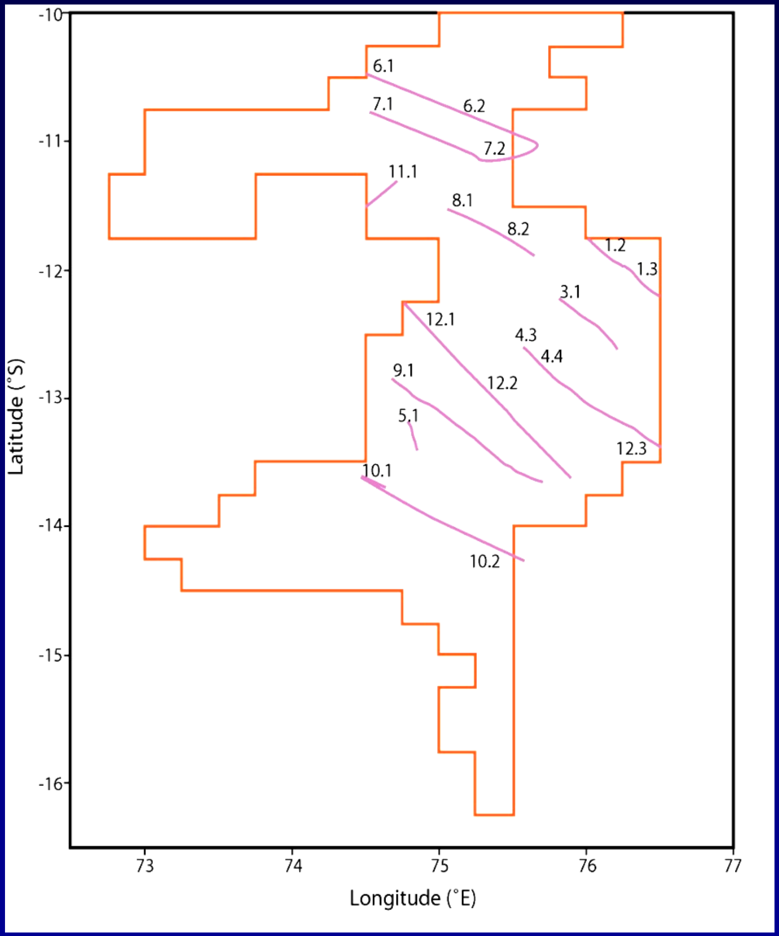
Dredge

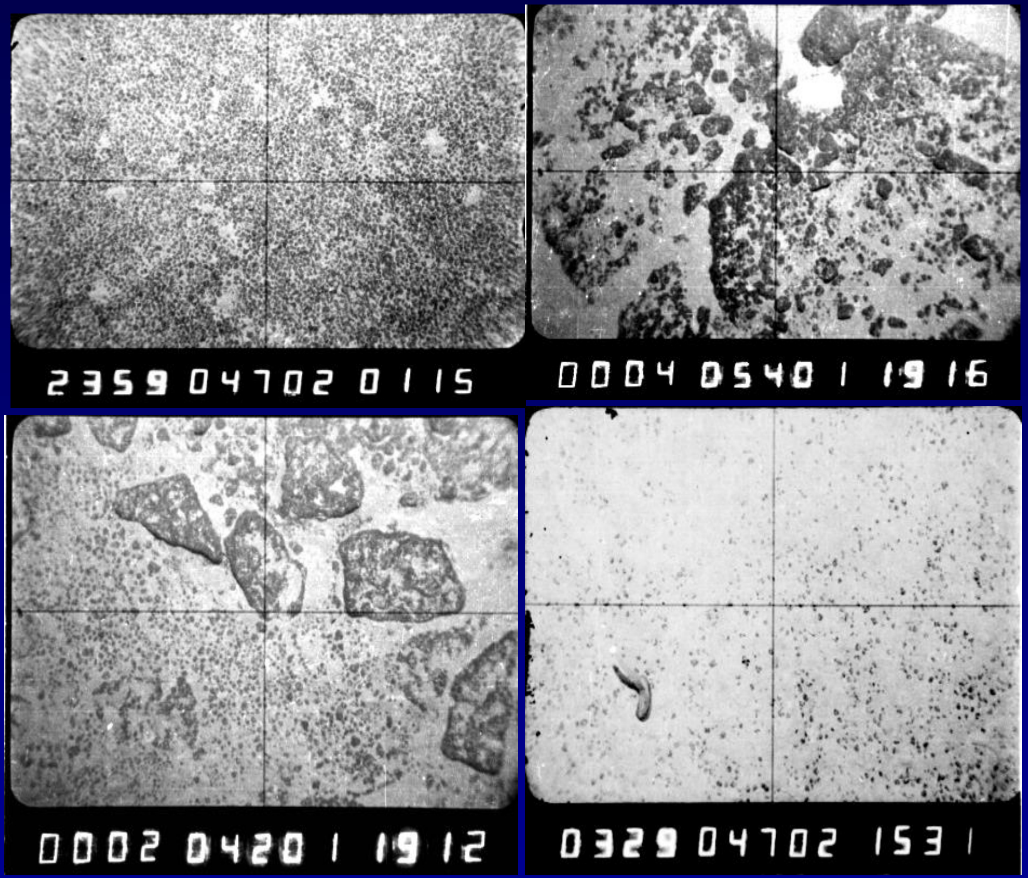
Total locations sampled = 2500

Total samples collected = 11000

(Source: NIO/PMN data bank)

Underwater photography





Profiles : 19
Photos : > 50,000

Distribution of minerals and seafloor features

Nodule morphology and size

4-6 cm

2-4 cm

< 2 cm

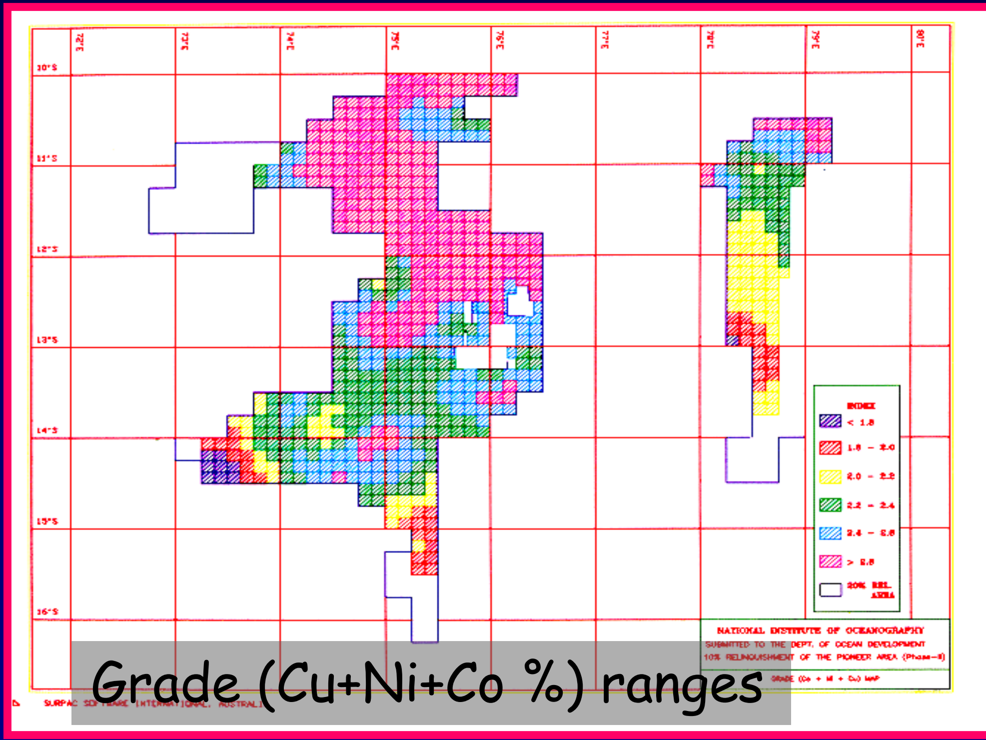
Nodule composition from Central Indian Ocean Basin

Element	No. of samples	Max	Min	Mean
Fe	1119	20.5	2.4	7.1
Mn	1119	48.6	6.5	24.4
Cu	1108	2.73	0.13	1.04
Ni	1108	2.21	0.18	1.10
Co	1108	0.43	0.07	0.11

Source: Jauhari and Pattan, 2000, In:Cronan (ed), Marine Mineral Deposits

First nodule to first mine-site

- Jan, 1981 : First nodule picked from Eq. Indian Ocean
- April, 1982 : India recognised as Pioneer Investor
- August 1987: Area allocated to India (150,000 sq. km.)
- July 1994 : 20% area relinquished
- October '96 : 10 % area relinquished
- May 2002 : 20% relinquishment
- August 2007: Retained area (75,000 sq.km.)
- Sept. 2013 : First generation mine-site identified



Wet Nodules	457.00 MMT
Dry Nodules	365.00 MMT
Manganese	91.52 MMT
Nickel	4.37 MMT
Copper	4.23 MMT
Cobalt	0.50 MMT
Total Metals	**100.62 MMT**

Total metals in retained area (75,000 km^2)

(Source: NIO/PMN data bank)

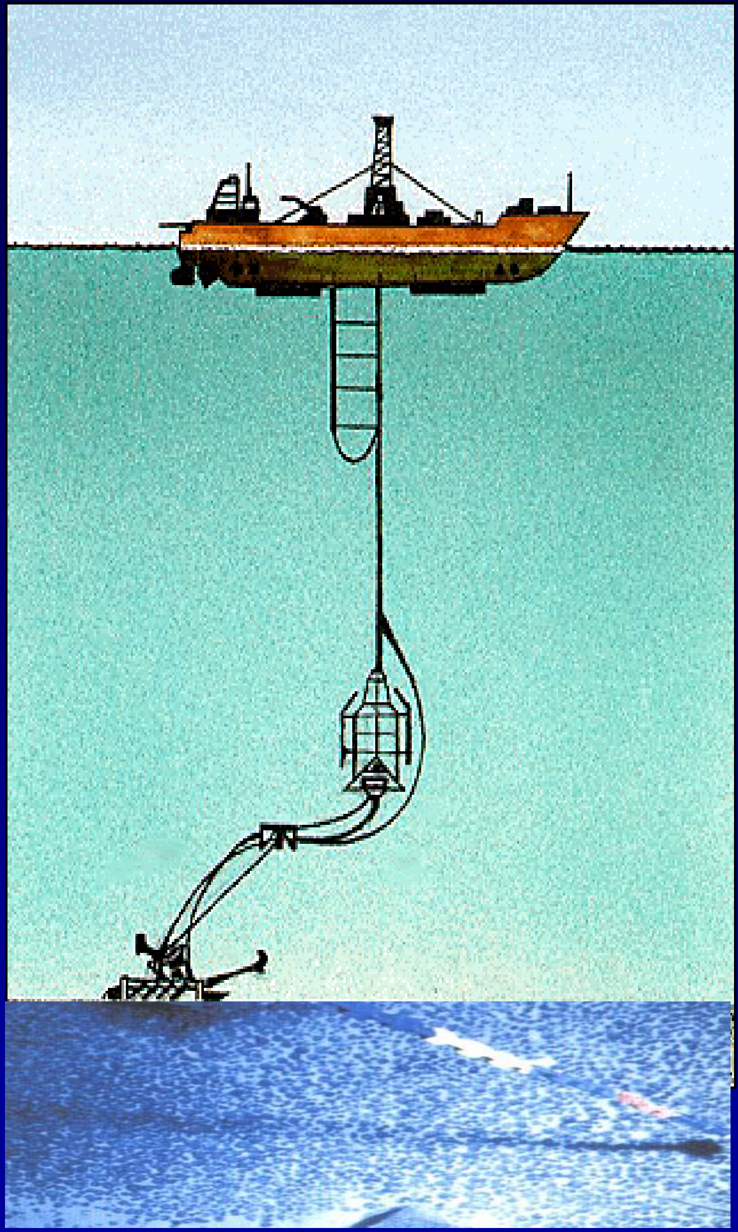
Marine Mining System – schematic

Surface components

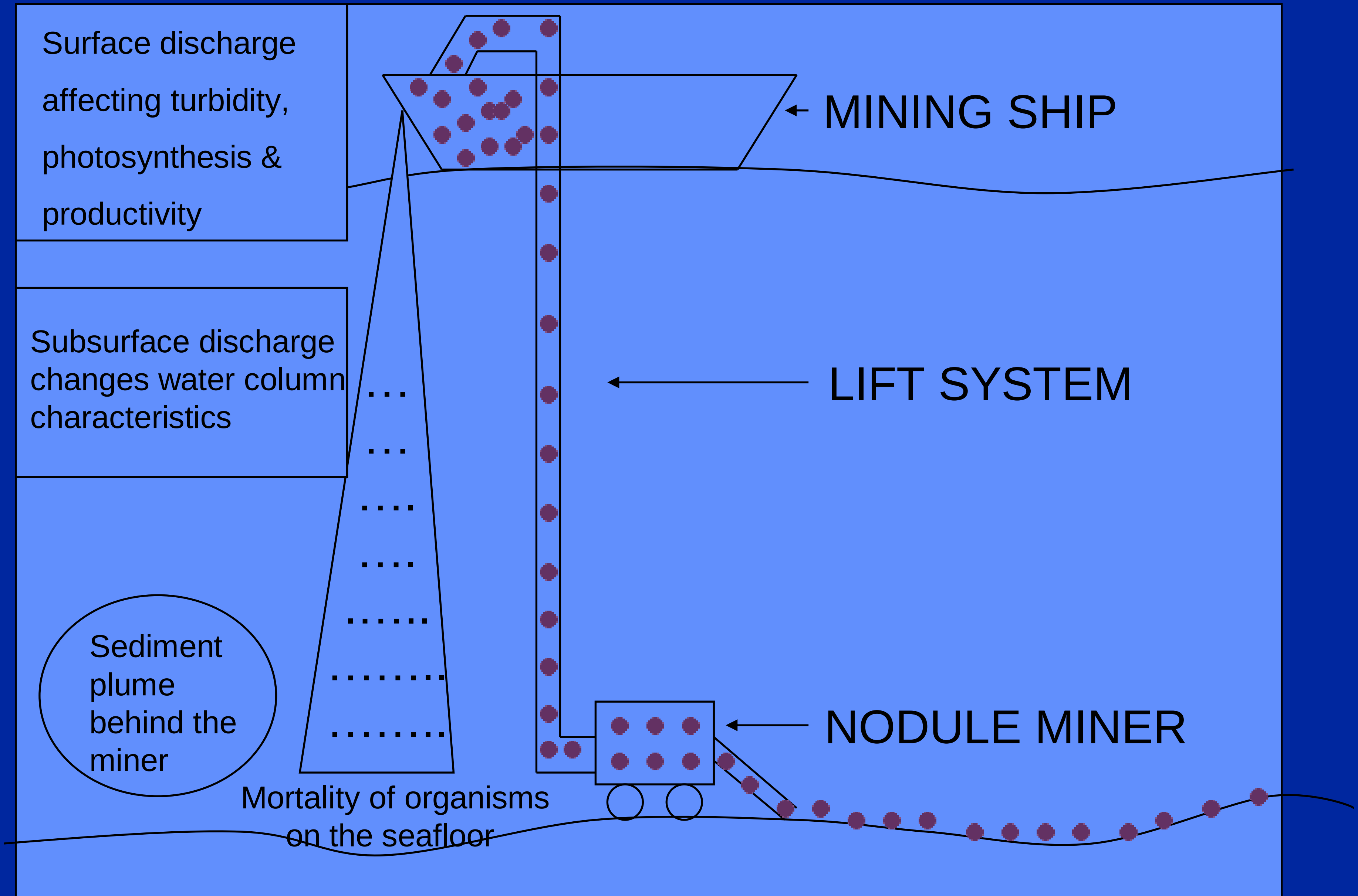
1. Surface platform
2. Storage and handling
3. Power generation
4. Processing plant
5. Transport vessels

Sub-surface components

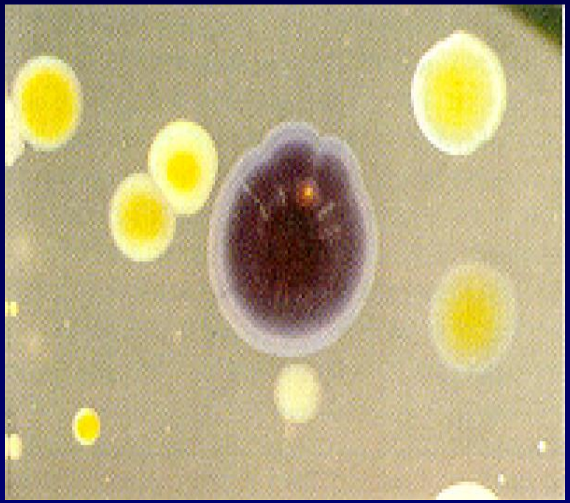
1. Collector mechanism
2. Ore lifting mechanism
3. Navigation device
4. Propulsion devices
5. Obstacle avoidance mechanism
6. Rescue/recovery devices

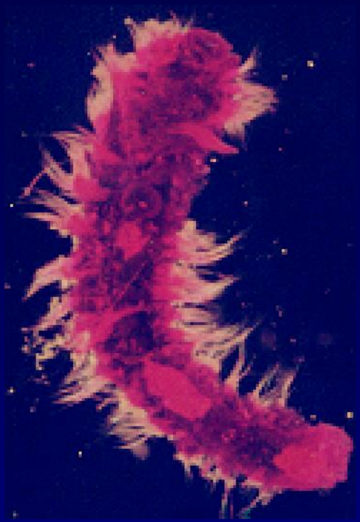


MINING IMPACTS

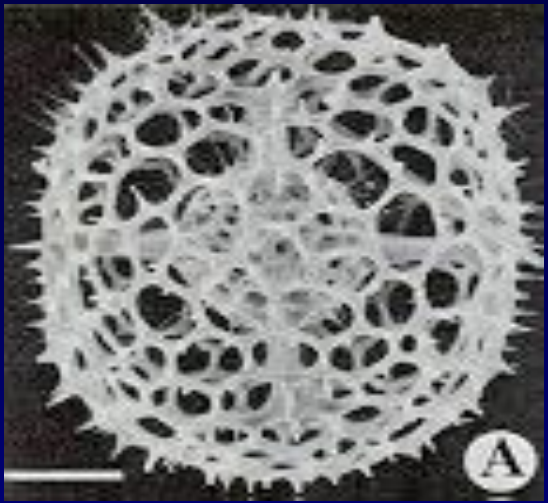


Types of marine organisms (micro to mega)



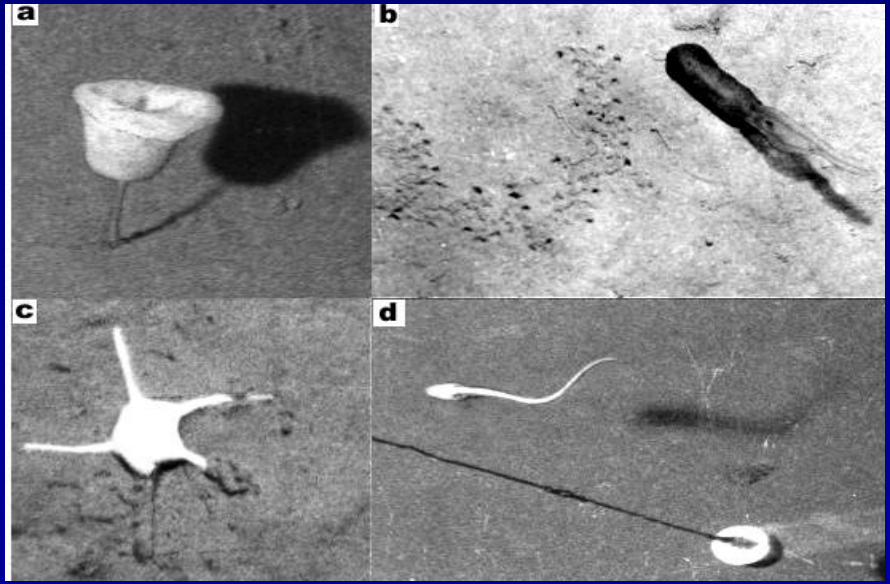


< 50 μ

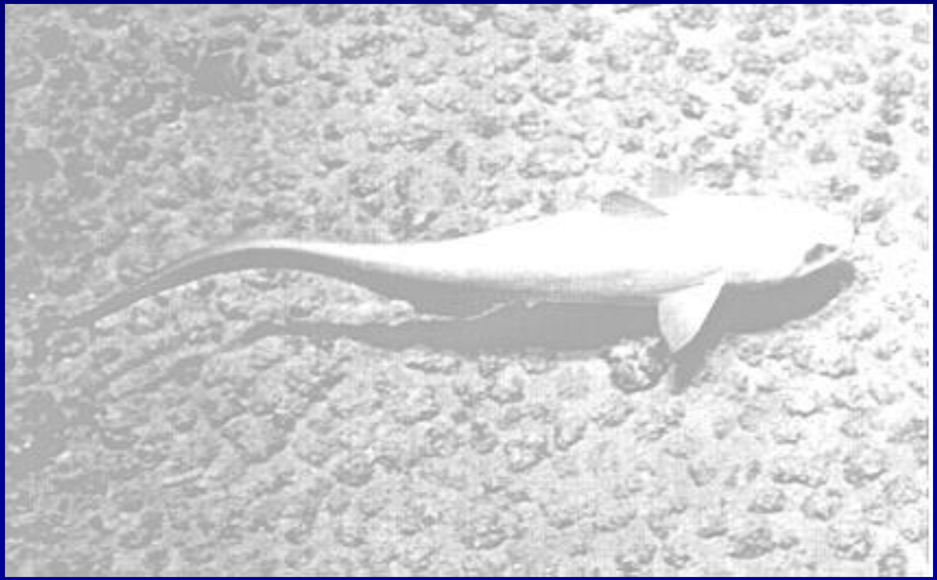


50-500μ

0.5 - 3 cm



10-100 cm



> 100 cm

International Seabed Authority
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Kingston
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Statement of environmental impact assessment from the contractor:

Recommendations for guidance of the contractors for assessment of possible environmental impacts arising from exploration for marine minerals in the Area

ISBA/18/LTC/CRP.2
6 July 2012

- Baseline data in the proposed mining area
- Test and reference sites for env. monitoring
- Results of simulated impact experiment
- Expected environmental impact due to mining
- Critical parameters for monitoring impacts
- Proposed measures to minimize the effects

Environmental studies for deep-sea mining

1. Mining impact experiment (1997-2005)

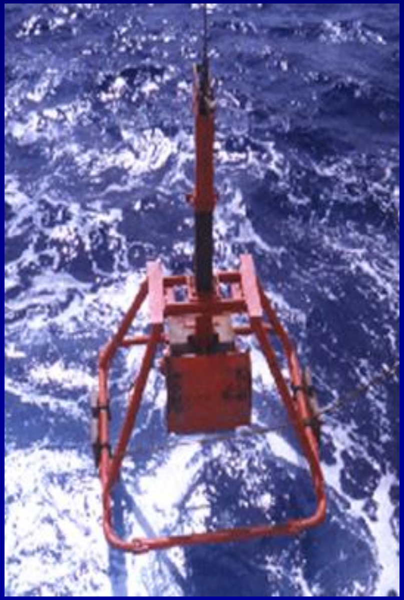
- No. of tows : 26 tows
- No. of days : 9
- Operation time : 47 hrs
- Operation distance : 88 km
- Sediment resuspended : 580 t (dry)

Impact assessment and restoration evaluation for 7 years

2. Assessment of environmental baselines (1996-2012)

<u>Water column</u> : 34 stations

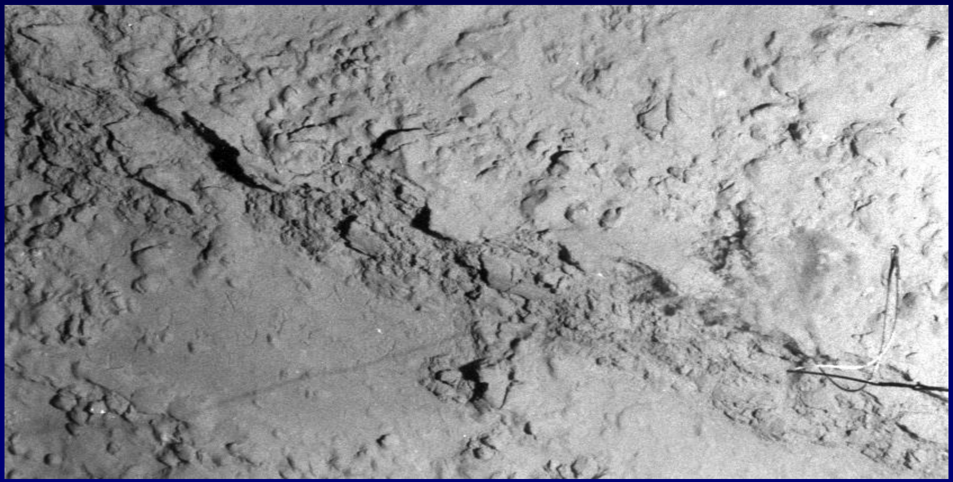
- **Temperature, salinity : 600x900 km**
- **Currents (3 levels/locations) : ~200 days**
- **Bottom currents in test area : ~200 days**
- **Productivity and chlorophyl : 600x900 km**
- **Chemical characteristics : 600x900 km**

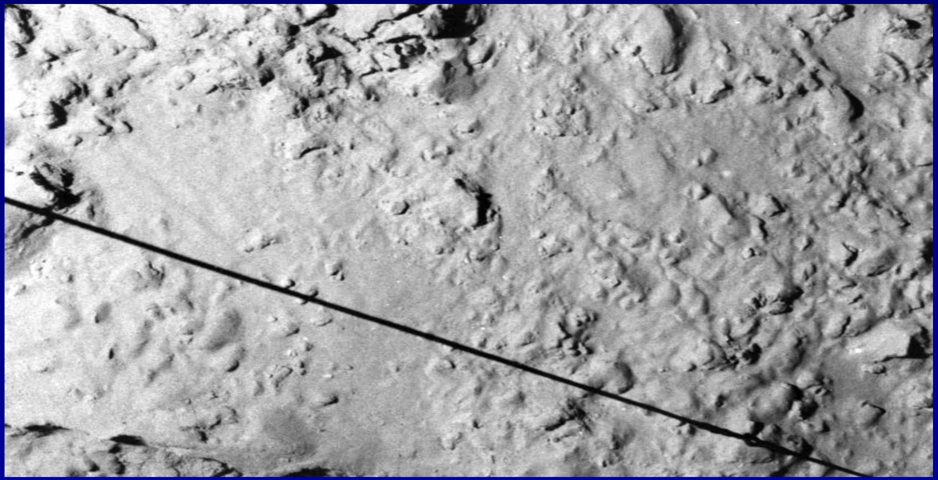


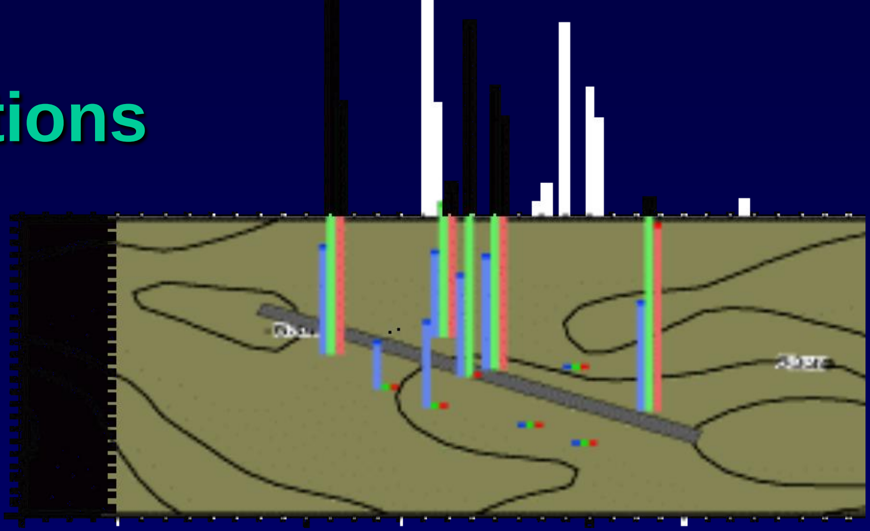
<u>Benthic data : 26 stations x 4 observations</u>

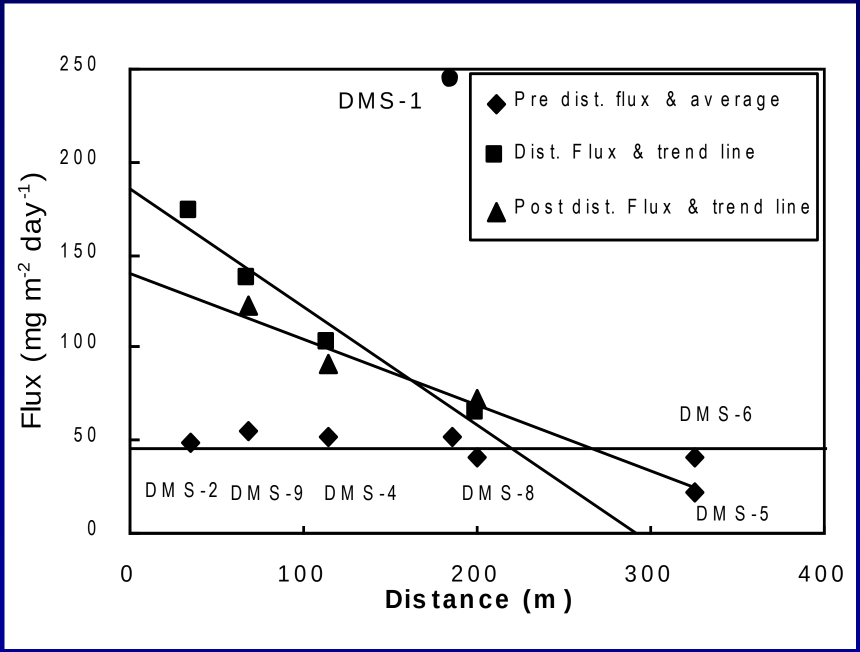
- **Sediment size, thickness and mineralogy**
- **Shear strength and water content**
- **Sediment and porewater geochemistry**
- **Sediment microbiology and biochemistry**
- **Meiofaunal and macrofaunal diversity**

Alterations in seafloor conditions





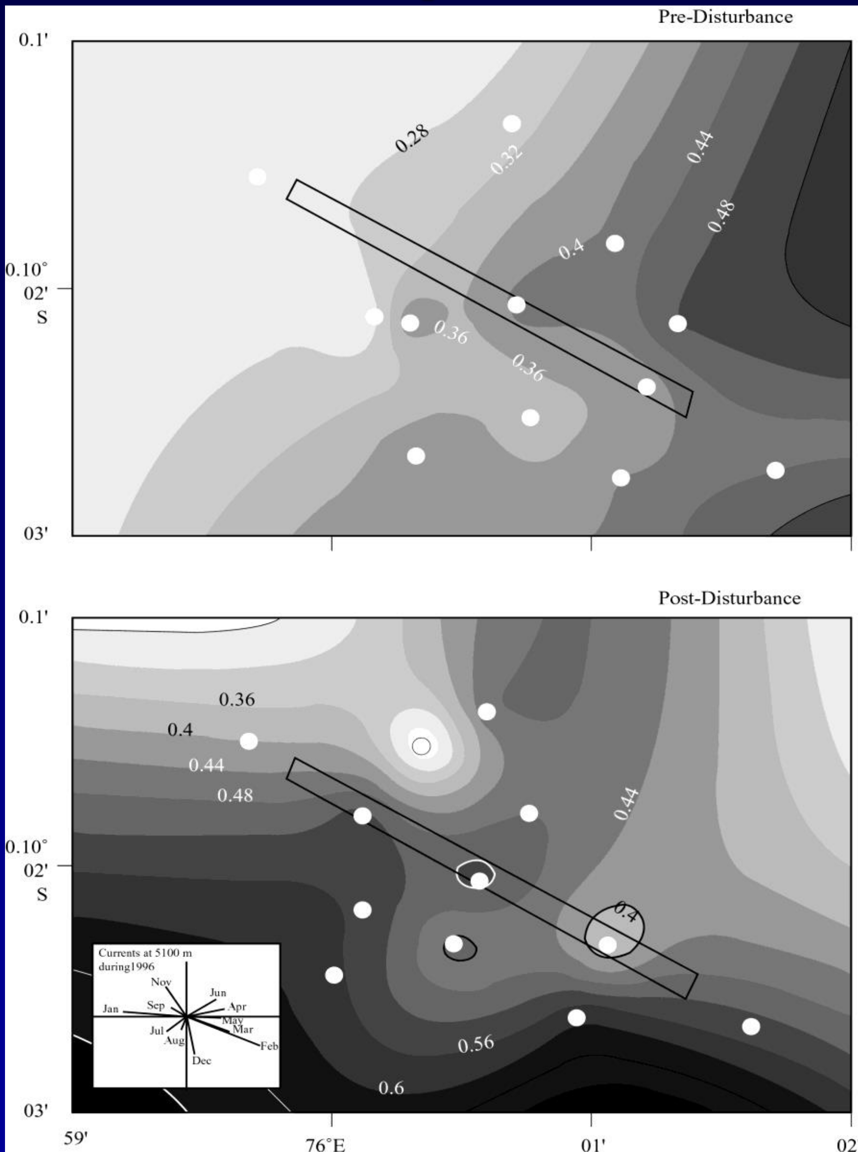


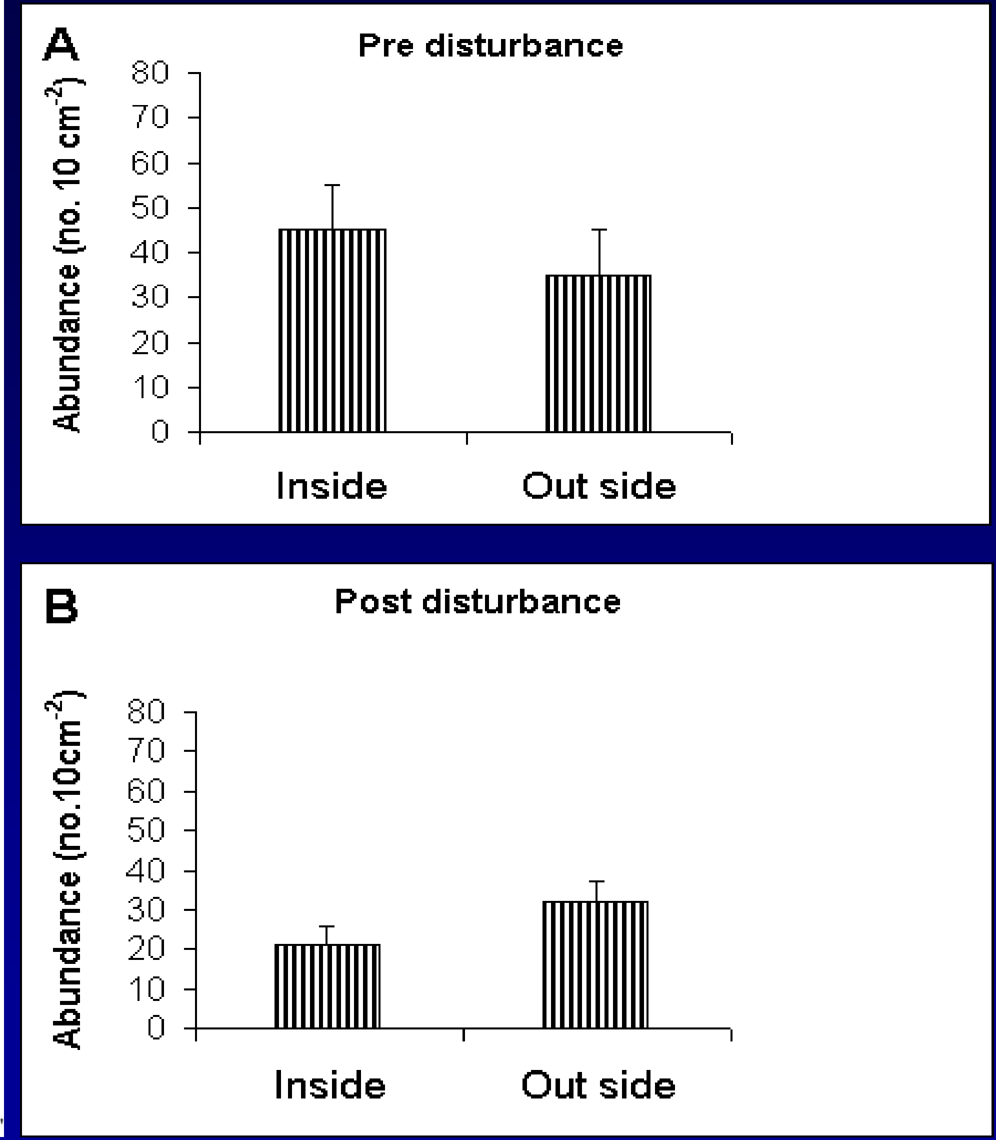


Vertical mixing of sediment

Lateral migration of sediment

Impacts of benthic disturbance





Changes in physico-chemical conditions

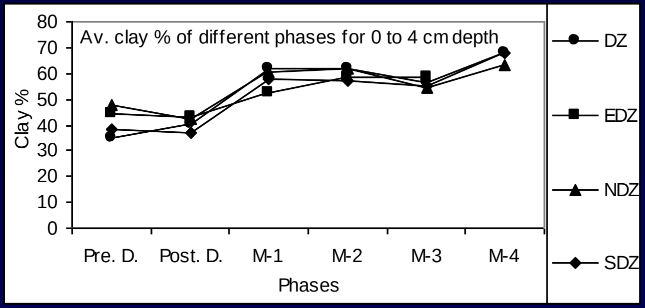
Overall reduction in biomass

Findings after 7 years of monitoring

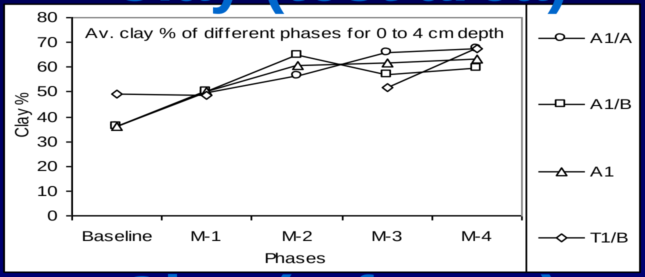
	Parameter	Indication
1.	Clay content	Natural influx
2.	Geotech	Fresh sediment supply
3.	Nutrients & OC	Recovered partially
4.	Protiens, CHO	Conditions recovering
5.	Meiofauna	Slow recolonisation
6.	Macrofauna	More burrowing

Conclusions

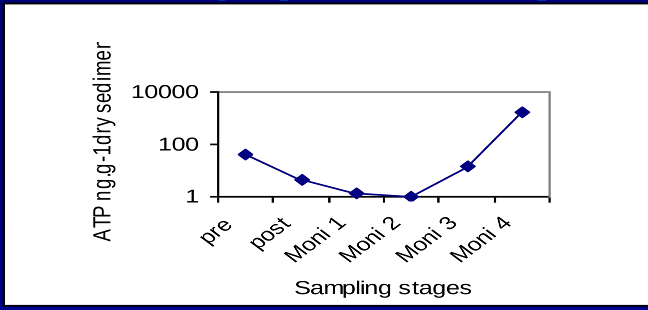
1. Benthic conditions getting restored
2. Degree of restoration is different
3. Natural variability taking over



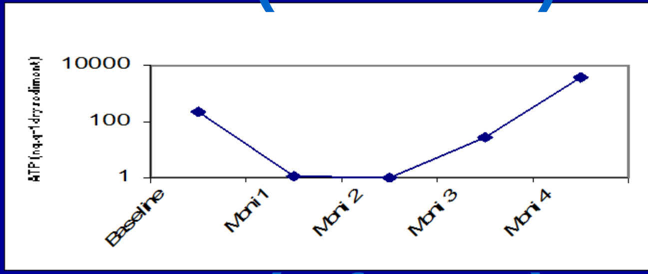
Clay (test area)



Clay (ref. area)



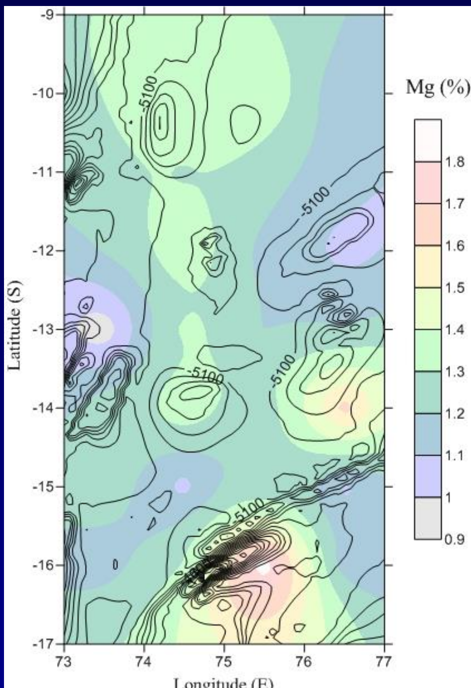
ATP (test area)

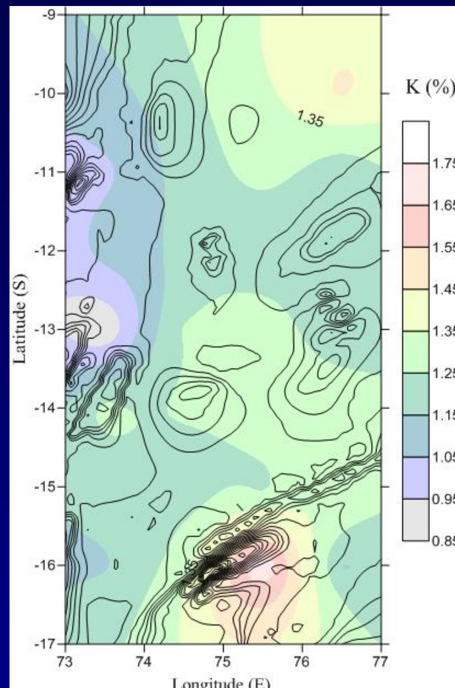


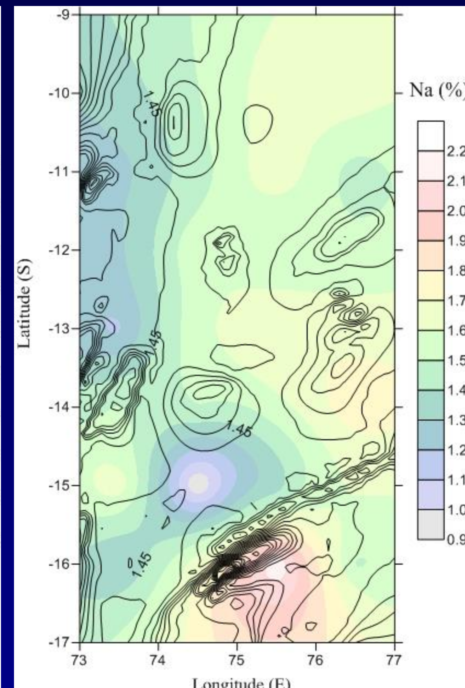
ATP (ref. area)

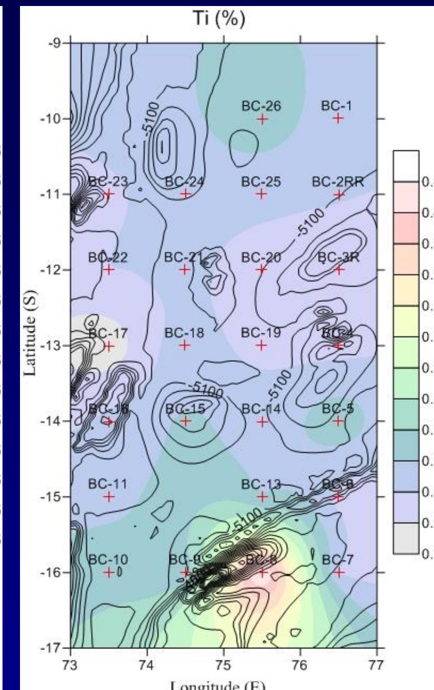
Mapping of elemental distribution in the surface sediments

Mg **K** **Na** **Ti**









- High concentration in the north of the study area indicated a terrigenous influence mainly by the terrestrial sources
- High concentration in the southern part of the basin indicated an additional source such as MORB and local volcanic rocks.
- Al, Ti, Nb and Zr were useful to trace the detrital signature in the basin.
- Distribution pattern of Rb/Sr was useful as an indicator of transportation pathways of fine–grained fractions of sediments on the bottom.

Deep sea faunal assemblages from polymetallic nodule area

- Box core sub-sampled with PVC corer & preserved with (10%) formalin.
- Sieved on 37-µm mesh.
- Sorted & Identified.

Box-coring

Box-core

Sampling

Sub-sampling

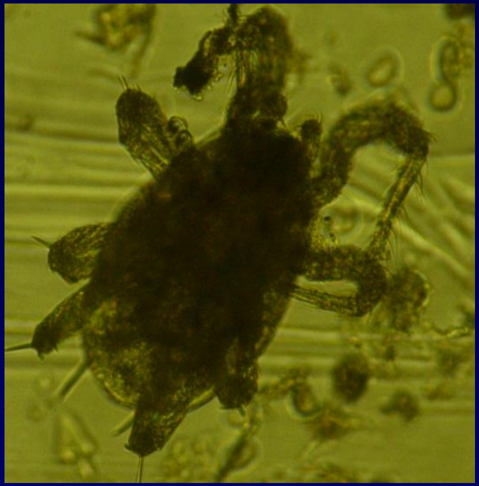
Seiving

Nodule associated faunal communities

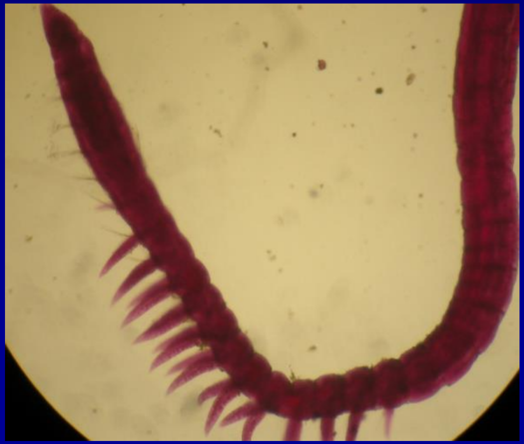
Tanaid

Nematoda

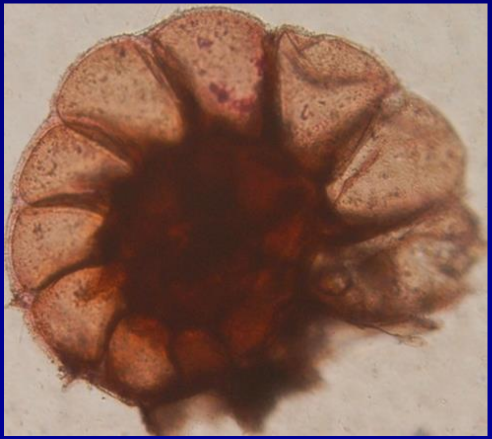
Harpacticoida



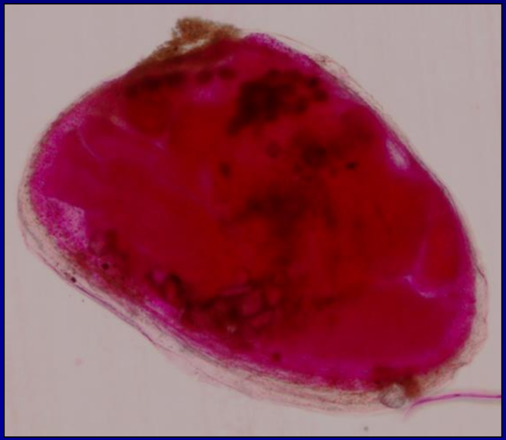
Orbitadea



Polychaeta

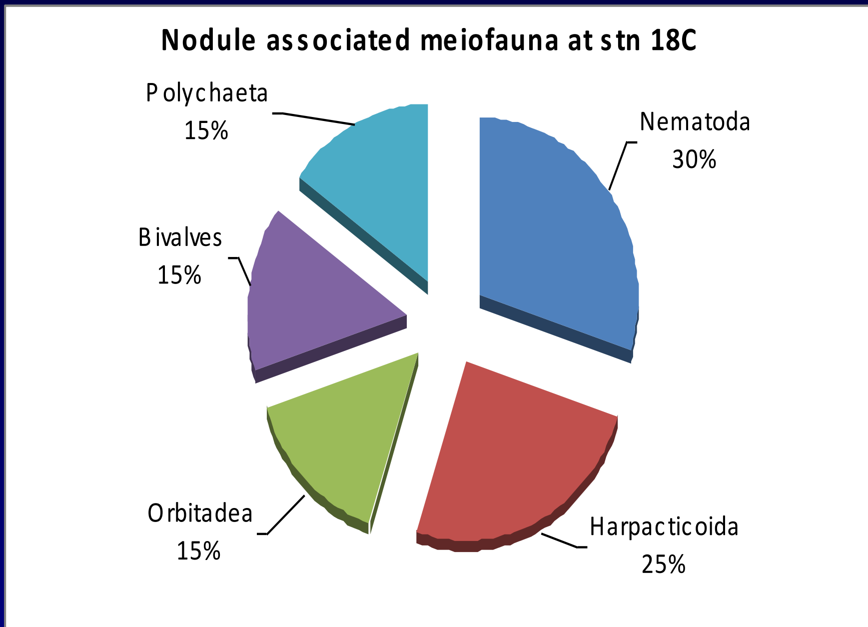


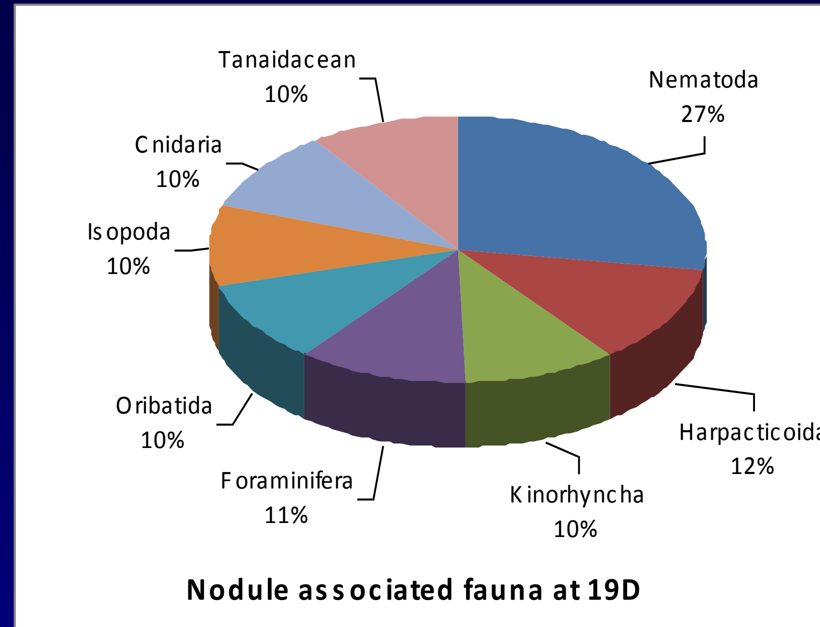
Foraminifera

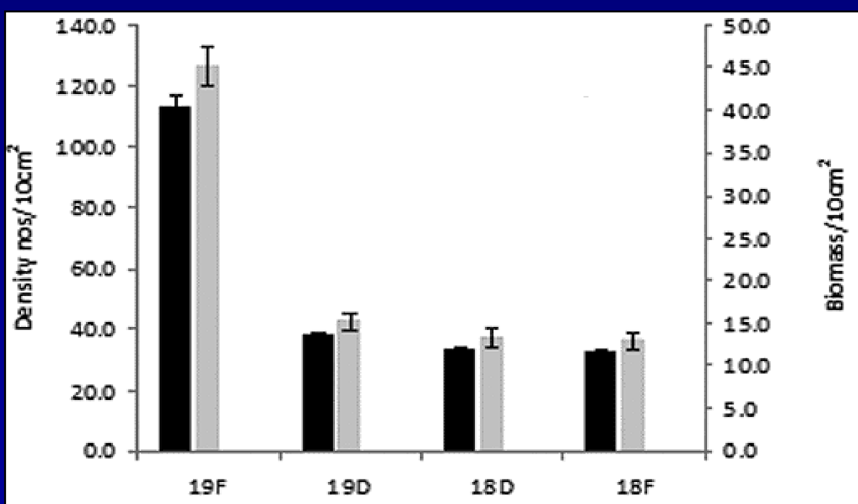


Ostracoda

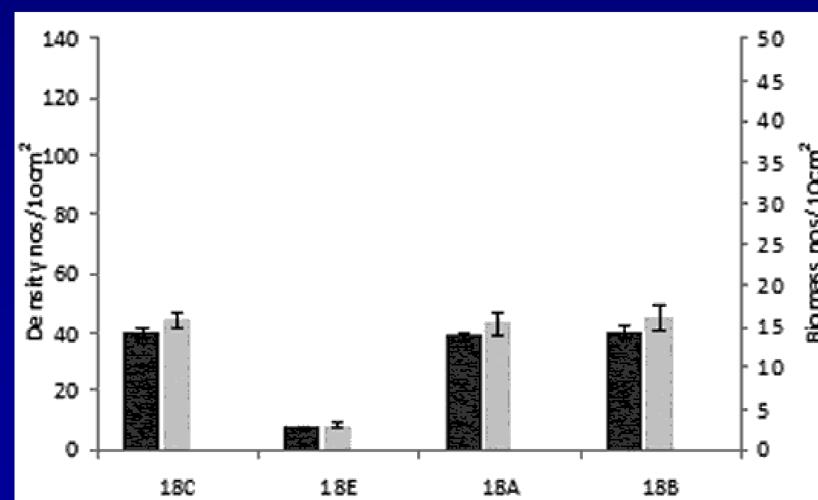
Density and diversity of faunal communities





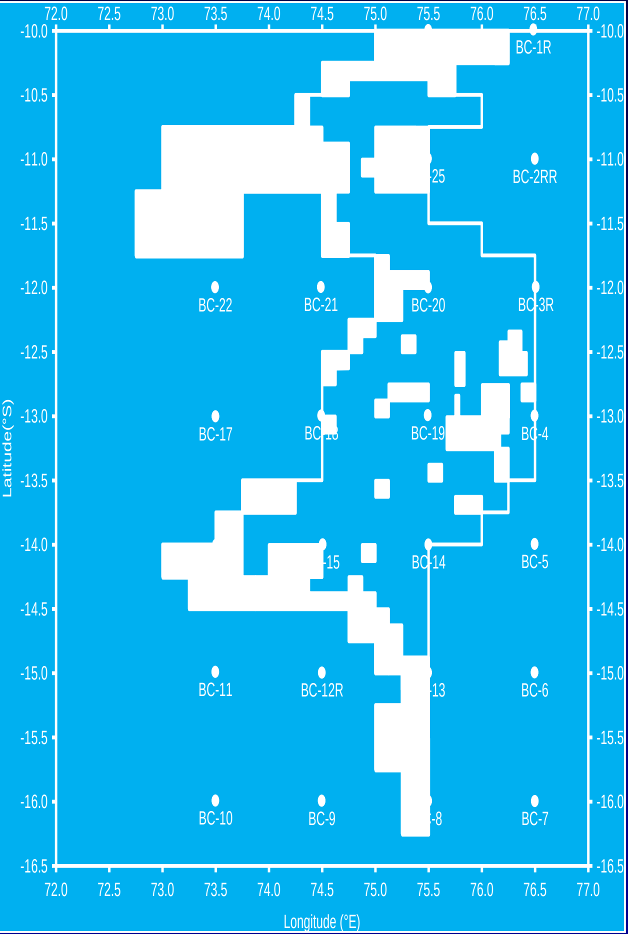


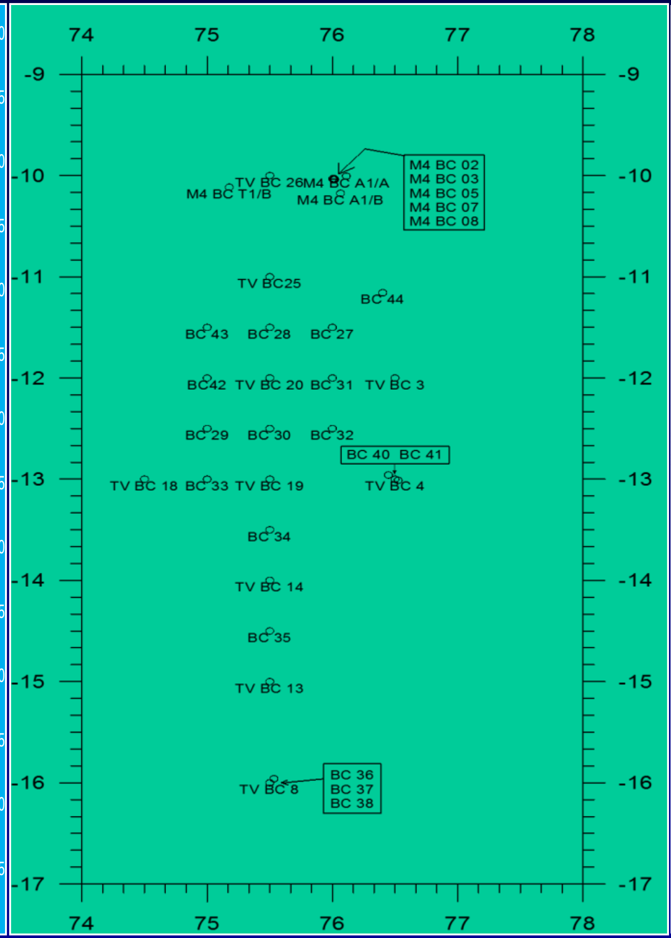
Density (gray lines) and biomass (black lines) of sediment meiofauna from nodule associated sediment from CIB.

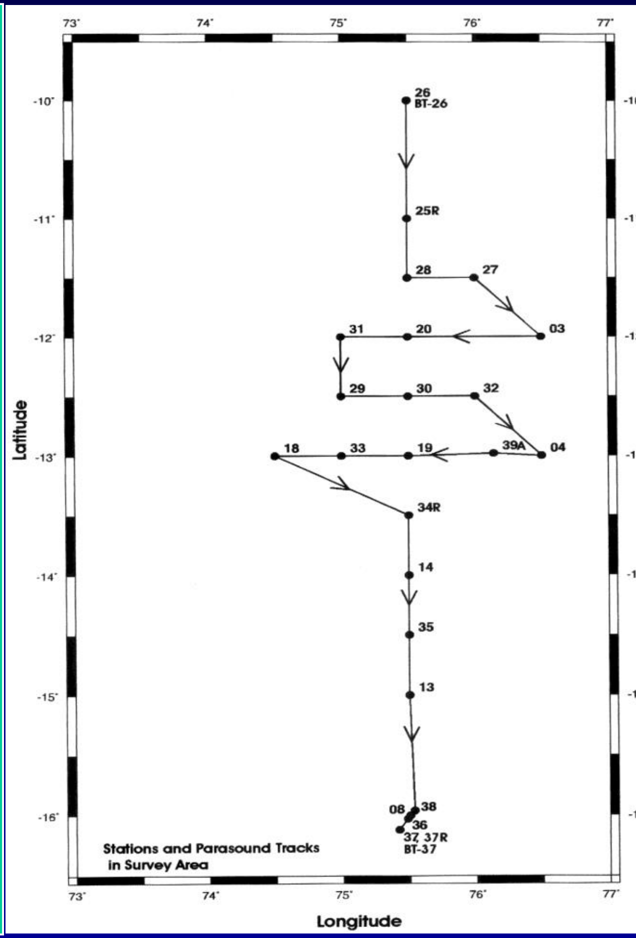


Density (gray lines) and biomass (black lines) of sediment meiofauna without nodule

Spatial, temporal & seasonal variability of environmental parameters







EVD-I: April-May 2003
26 locations

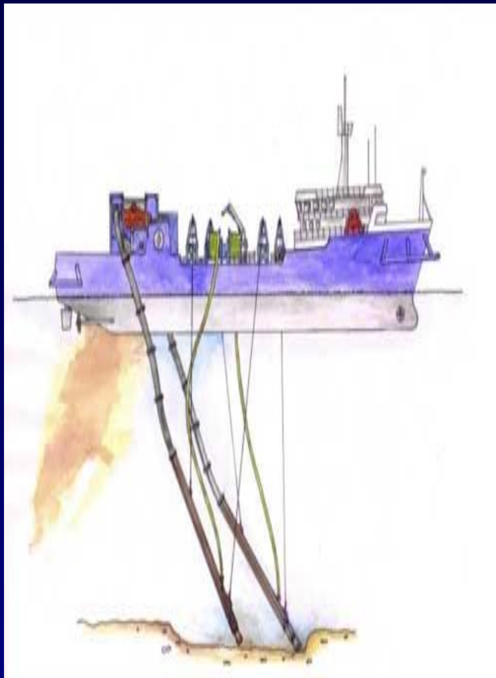
EVD-II: April-May 2005
22 locations

EVD-III: December 2006
20 locations

Major outcomes of EIA studies

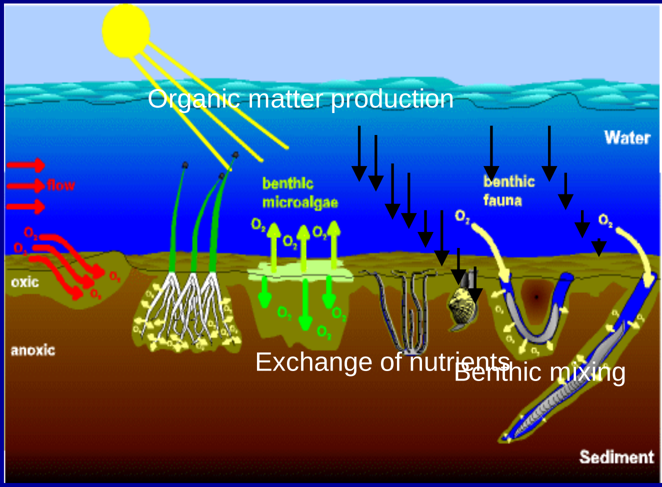
Environmental data for nodule mining

Atmospheric	- wind, rainfall, cyclone
Surface	- waves, temperature, currents
Water column	- currents, temperature, pressure
Seafloor	- topography, micro-topography, slopes
Sub-seafloor	- sediment thickness, shear strength
Mineral characteristics	- abundance, grade, size
Associated substrates	- sediments, rocks, crusts



Measures for environmentally 'safe' mining

- Minimize sediment penetration
- Restrict sediment dispersal to seafloor
- Minimize nodule-sediment transport on surface
- Discharge tailings below oxygen minimum zone
- Treat tailings before discharging
- Induce high rate of sedimentation



Impact of deep-sea mining on environment

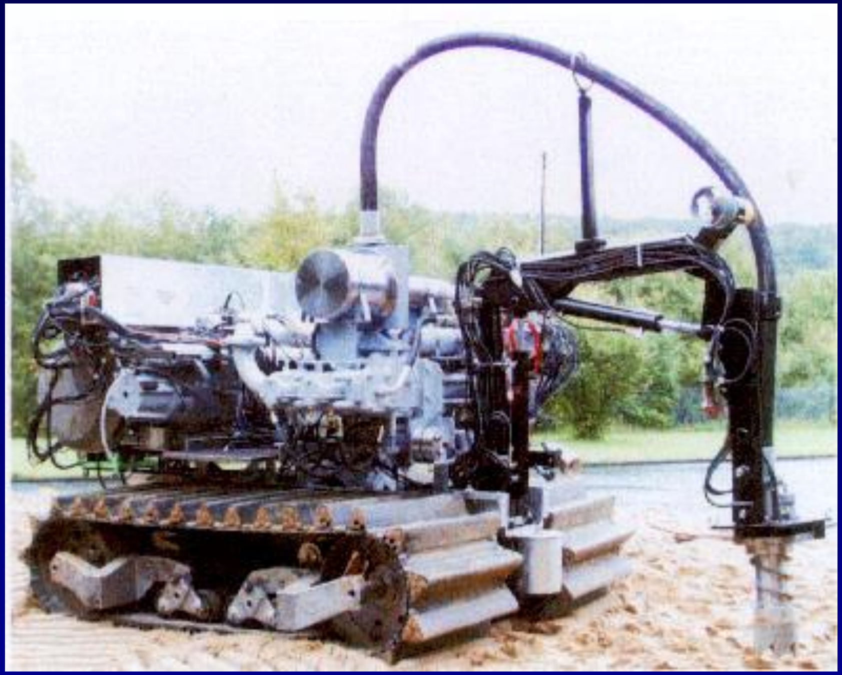
Activity	Seafloor	Water Column	Surface	Land
Collection				
Separation				
Lifting				
Washing				
At-sea processing				
Transport				
Extraction				
Tailing discharge				

Indicates likely impact

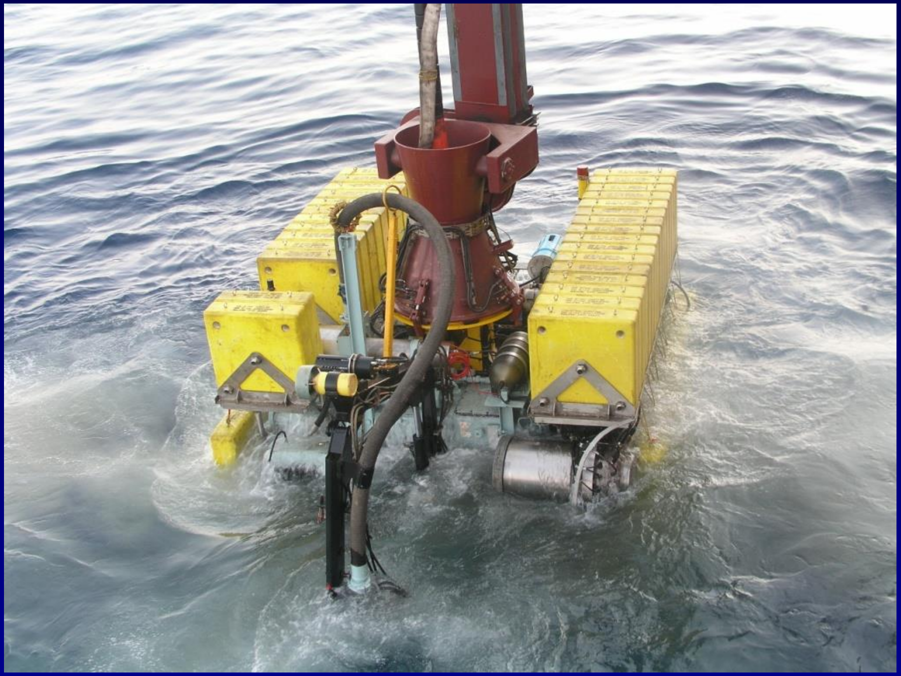
Indicates impact not known

(Courtesy: PMN-EIA, NIO)

Technology Development for Deep-sea Mining



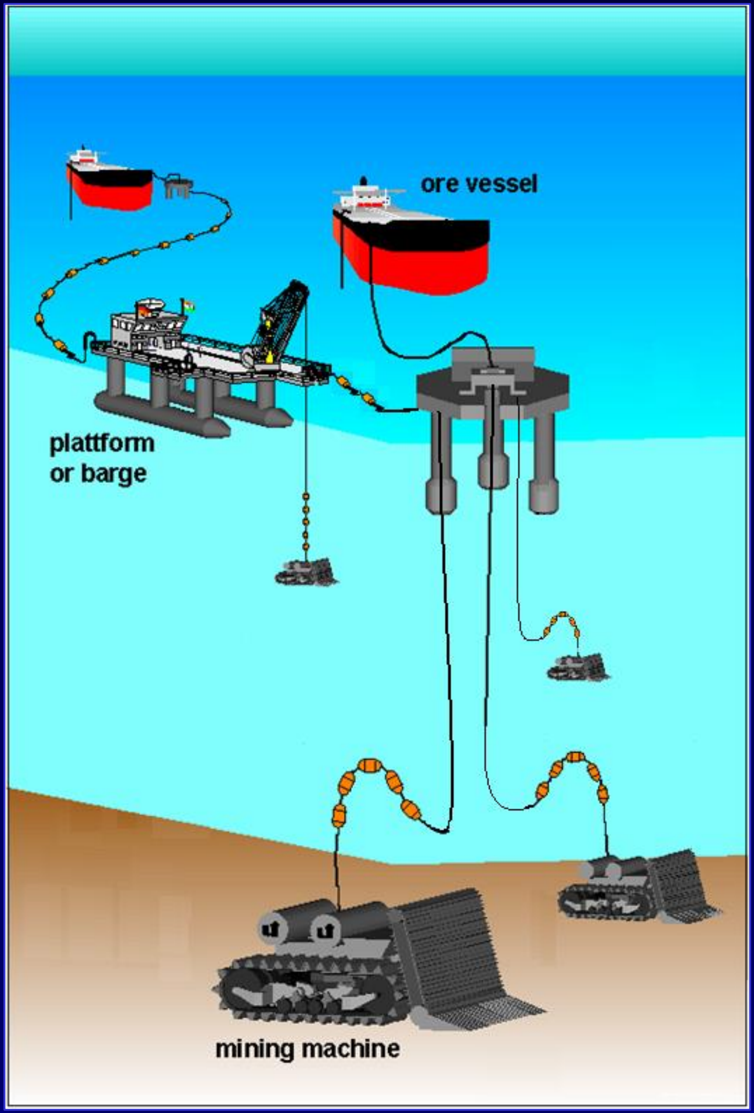
Onshore testing of Mining System



Offshore (440 m) testing of Mining System

Source: NIOT, Chennai

Conceptual design



Salient features

- Multiple Self propelled mining vehicles collect, crush and pump polymetallic nodules
- Flexible riser is mounted on the vehicle to pump nodules to platform
- A small semi-submersible platform pumps the mined nodules to ore-ship or storage mother station

Advantages

- Failure in one system will not affect total operations
- Less cost intensive
- Ease in deployment, retrieval

Source: NIOT, Chennai

Development of metallurgical extraction process

1983- 1986 : Lab scale work with different routes

1987 : Three routes chosen

- NML - Reduction-roasting-ammonia-ammonium carbonate leaching
- RRL - NH_3-SO_2
- HZL - Acid pressure leaching

2006 : Pilot plant established with 500 kg/day capacity

Source: HZL, Udaipur

Economics of deep-sea mining

Nodule / Metal	Mean concentr-ation[a]	Resource potential t (mi.t)[b]	Metal production per year t (mi.t) @1.5 mi.t/y	@ 3 mi. /y	Price of metal ($/Kg)[c]	Gross in-place value of metal $/year @ 1.5 mi. t/y	@ 3 mi. t/y	Gross in-place value of metal $/20 years @1.5 mi. t/y	@ 3 mi. t/y
Wet nodules	-	375,000,000 (375)	-	-	-	-	-	-	-
Dry nodules	55% of wet nodules	206,250,000 (206.25)	-	-	-	-	-	-	-
Manga-nese	24% of dry nodules	49,500,000 (49.5)	360,000 (0.36)	720,000 (0.72)	1.32	475,200,000 (475.2 million)	950,400,000 (950.4 million)	9.504 billion	19.008 billion
Nickel	1.1% of dry nodules	2,268,750 (2.26875)	16,500 (0.0165)	33,000 (0.033)	23.00	379,500,000 (379.5 million)	759,000,000 (759 million)	7.59 billion	15.18 billion
Copper	1.04% of dry nodules	2,145,000 (2.145)	15,600 (0.0156)	31,200 (0.0312)	8.30	129,480,000 (129.48 million)	258,960,000 (258.96 million)	2.5896 billion	5.1792 billion
Cobalt	0.1% of dry nodules	206,250 (0.20625)	1,500 (0.0015)	3,000 (0.003)	39.20	58,800,000 (58.8 million)	117,600,000 (117.6 million)	1.176 billion	2.352 billion
Total (metals)	26.24%	54,120,000 (54.12)	393,600 (0.3936)	787,200 (0.7872)	-	1042,980,000 (1042.98 million)	2085,960,000 (2085.96 million)	20.8596 billion	41.7192 billion

[a] Source: Jauhari and Pattan, 2000

[b] @5 kg/sqm for 75,000 sq km (75×10^9 sqm)

[c] Average metal prices for the period from July 2010 to January 2011 (source: www.metalprices.com)

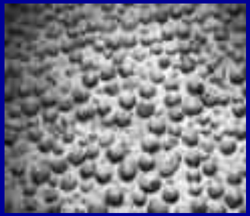
(Sharma, 2011)

Estimated capital and operating expenditures for polymetallic nodules mining (for 1.5 mi. t./year)

Item	Capital expenditures	Operating expenditures	Total
Mining system	$ 550 mi.* ($ 372-562 mi.)	$ 100 mi/y* ($ 69-96 mi.) x 20 years = $ 2.0 billion	$ 2.55 billion
Ore transfer	$ 600 mi.* ($ 495-600 mi.)	$ 150 mi/y* ($ 93-132 mi/yr) x 20 years = $ 3.0 billion	$ 3.60 billion
Processing plant	($ 750 mi.)	($250 mi/y) x 20 years = $5.0 billion	$ 5.75 billion
Total	$ 1.90 billion	$ 10.0 billion	$ 11.90 billion

(Sharma, 2011)

* Rounded off to nearest fifty of the highest value
( ) figures in brackets show the range for different systems (Source: ISA, 2008)



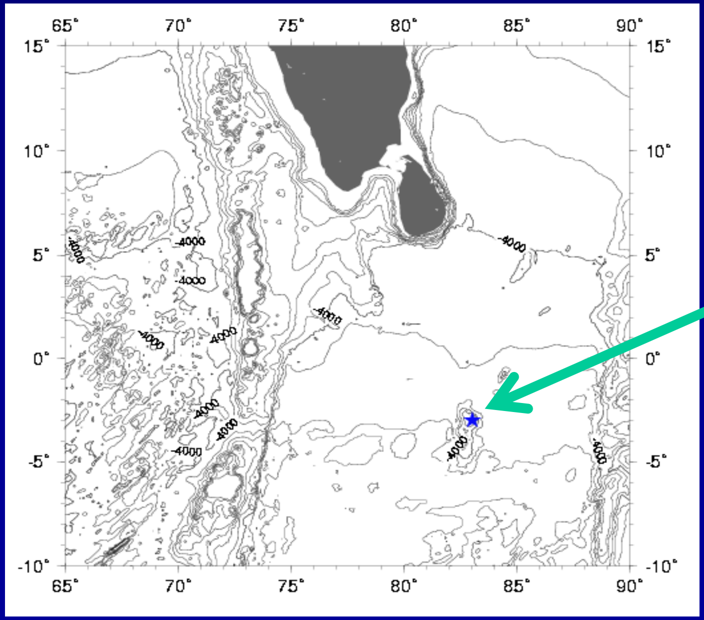
Metals worth $ 21 billion can be extracted with an investment of $ 12 billion

Estimates for mining of polymetallic nodules at different mining rates

Estimates for operation of 300 days year^{-1}	Mining rate					Remark
	1.0 Mt y^{-1}	1.5 Mt y^{-1}	2.0 Mt y^{-1}	2.5 Mt y^{-1}	3.0 Mt y^{-1}	
Area (Size) of mine-site #	4267 Km^2	6,400 Km^2	8533 Km^2	10,667 Km^2	12,800 Km^2	Negligible with respect to area covered by ocean basins
Area of contact per year #	200 Km^2	300 Km^2	400 Km^2	500 Km^2	600 Km^2.	i.e. 0.66-2 km^2 day^{-1}
Ore production/day	3333.3 t day^{-1}	5,000 t day^{-1}	6666.6 t day^{-1}	8333.25 t day^{-1}	10 000 t day^{-1}	Proportionate storage and transport facility required
Volume of sediment disturbed at seafloor	60 000 m^3 day^{-1}	90 000 m^3 day^{-1}	120 000 m^3 day^{-1}	150 000 m^3 day^{-1}	180 000 m^3 day^{-1}	Major source of environmental impact
Wt. of disturbed sediment (wet) (@1.15 g cm^{-3} density)	69 000 t day^{-1}	103 500 t day^{-1}	138 000 t day^{-1}	172 500 t day^{-1}	207 000 t day^{-1}	In slurry form that can travel with bottom currents to adjacent areas
Wt. of disturbed sediment (dry) (@ 80 % water content)	13 800 t day^{-1}	20 700 t day^{-1}	27 600 t day^{-1}	34 500 t day^{-1}	41 400 t day^{-1}	Dominant (50-60 %) fine clays, may remain suspended for longer periods
Unwanted material to be disposed off (@ 26 % of metal content)	0.74 Mt y^{-1}	1.11 Mt y^{-1}	1.48 Mt y^{-1}	1.85 Mt y^{-1}	2.22 Mt y^{-1}	Find constructive use or environment friendly disposal mechanism

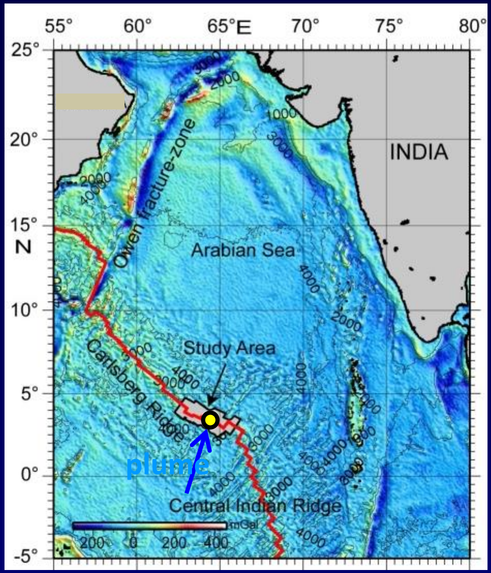
Ferro-manganese Cobalt-rich crusts

- Ferromanganese crusts are rich in cobalt, platinum besides iron and manganese.
- Found on hard-rock substrates mainly on the flanks and summits of seamounts, ridges,
- Unlike nodules they are ‘fixed’ or ‘stuck’ to the rock outcrop below.
- They are formed as layers of oxides and generally found at the contact of the rock outcrops with water column.

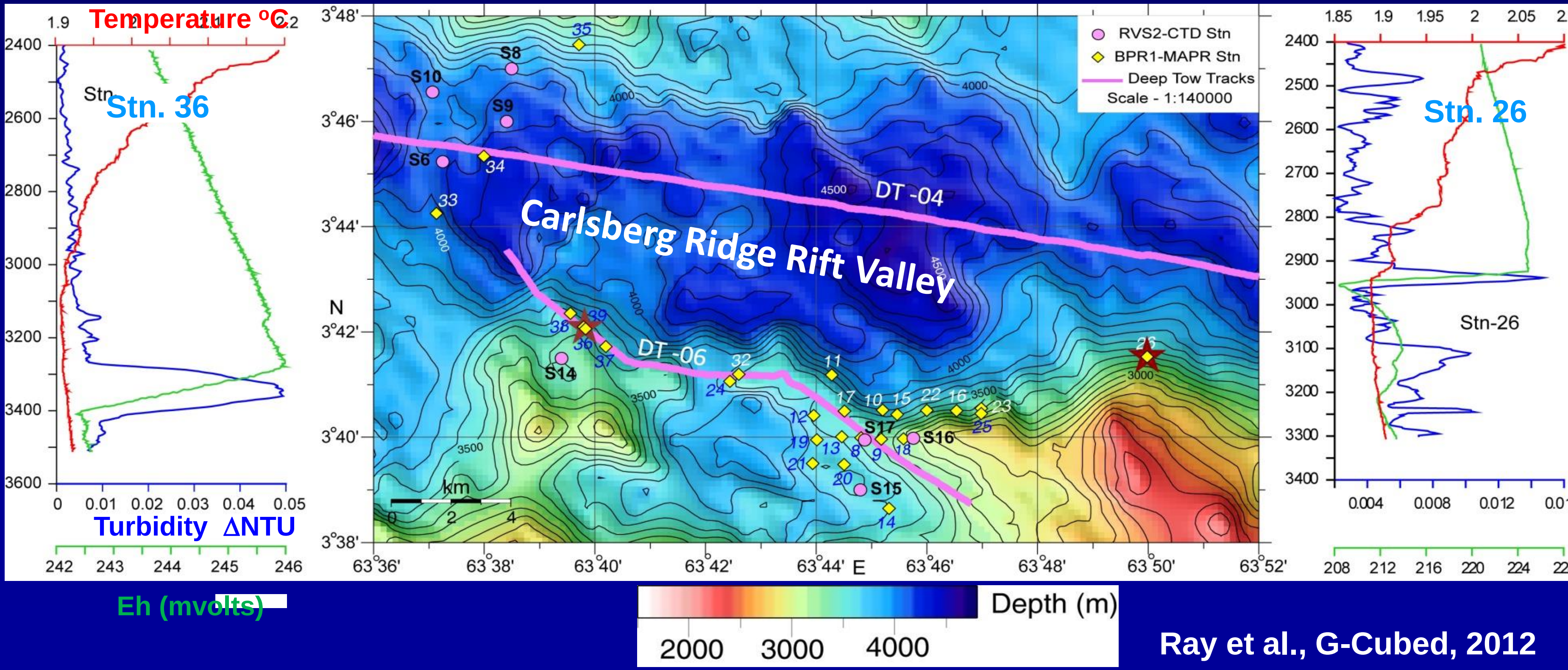


In Indian Ocean region, they are found on Afanasiy-Nikitin seamount in the Equatorial Indian Ocean with Co contents up to 0.8% (Banakar et al., 2007)

Hydrothermal Plumes indicative of new Vent fields over the Carlsberg Ridge



Identification of prominent Hydrothermal Plumes over the Carlsberg Ridge (CR) in the Indian Ocean suggest the presence of two active hydrothermal vent fields over the CR at water depths 3500-3800 m.



Ray et al., G-Cubed, 2012

Nodules in EEZ of island countries

Seychelles (1984)

- Around Seychelles islands - 4000 km survey done
- Geological, chemical, biological, physical data collected
- Sediments, nodules and biological samples analysed
- Report on data and samples giver to Seychelles govt.

Mauritius (1987)

- Polymetallic nodules in Mascarene Basin (~11,900 sq. km. area)
- Morphology, internal structures, composition, growth rates
- 1-10 kg / sq. m abundance, rich in Fe and Co.

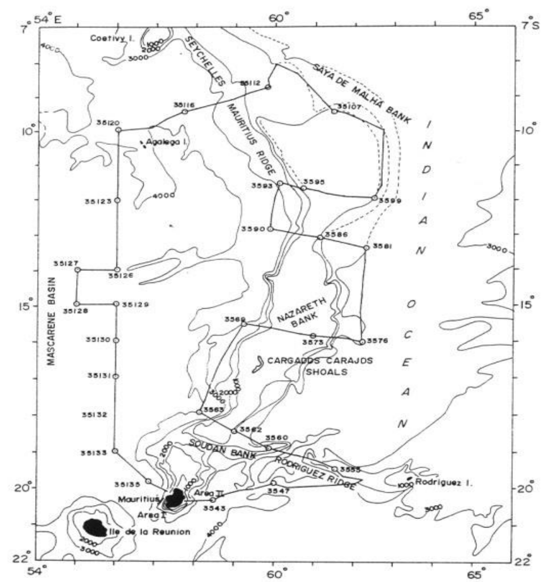


Figure 1. Cruise track and stations occupied for sampling during the reconnaissance survey in the waters around Mauritius (Cruise 35 of ORV *Sagar Kanya*). The figure also shows the physiographic setting of the area surveyed.

(Source: Nagender Nath and Shyam Prasad, NIO, India - 1991)

Key to success- Multi-agency networking

Survey and data collection

- Nat. Inst. of Oceanography

Chemical & mineralogical analysis

- Geological Survey of India
- Indian Bureau of Mines
- Hindustan Zinc Ltd.

Metallurgical processing

- Regional Research Lab.
- Nat. Metallurgical Lab.

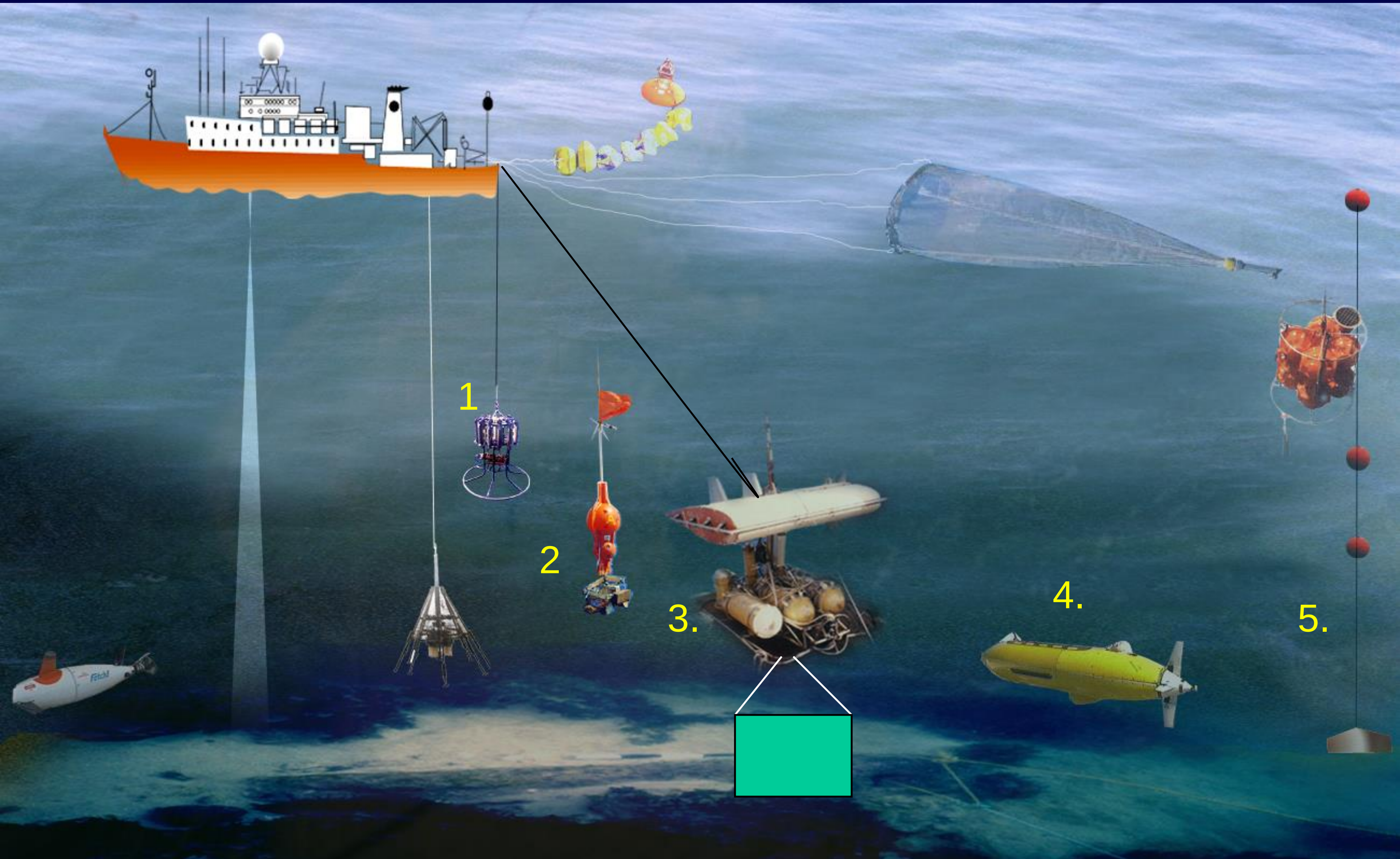
Mining technology Development

- Central Mech. Engg. Res. Inst.
- Central Mining Research Inst.
- Nat. Inst. Of Ocean Tech. (later)

Data processing

- Engineers India Limited

Key to success - Creating required infrastructure



1. Tethered 2. Freefall 3. Deep towed 4. AUV/ROV 5. Moored

Key to success - Mixing experience with youth

Discipline	Experienced personnel	Young recruits	Total
Geology / Geophysics	15	23	38
Mech/Elec Instrumentation	7	11	18
Marine Survey	3	7	10
Physics	0	6	6
Biology	2	2	4
Chemistry	0	2	2
Ocean Engineering	0	2	2
Total	27	53	80
Average Age (Years)	35	25	-
Extent of involvement	Shortterm/Partial	Longterm/Complete	-

- **Training in new instruments to young recruits**
- **Very few had any background of oceanography**

(Source : Qasim and Nair, 1988)

Key to success – Emphasis on high quality research

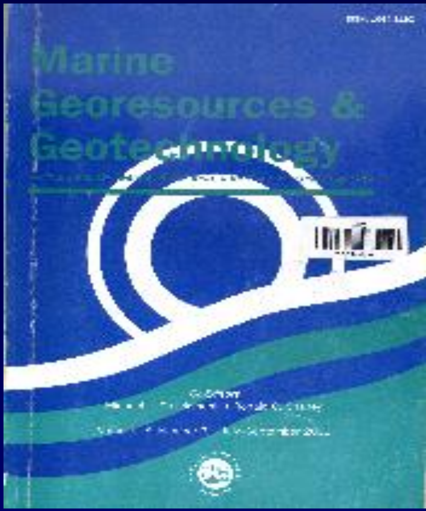
Publications : Over 350 in SCI Journals

Patents : 2 International Patents

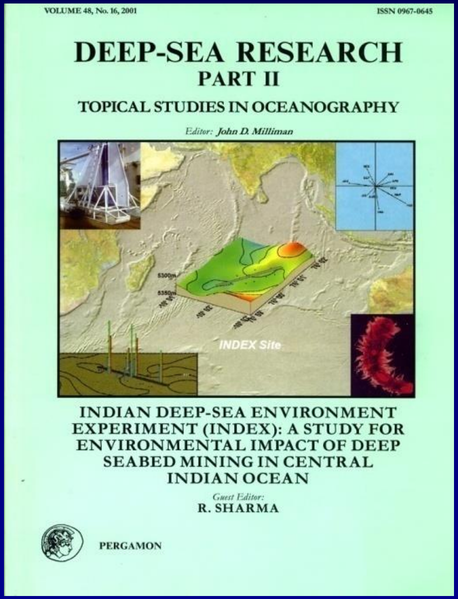
Areas of Research :

- Nodule Geochemistry
- Sediment Geochemistry
- Micropaleontology/Paleoceanography
- Volcanology
- Marine Acoustics
- Geophysics, Plate tectonics
- Planetary Geology
- Geotechnical properties
- Biological diversity

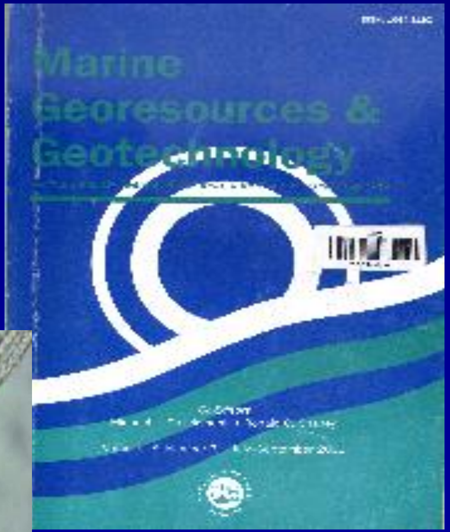
Special issues : 3 international journals



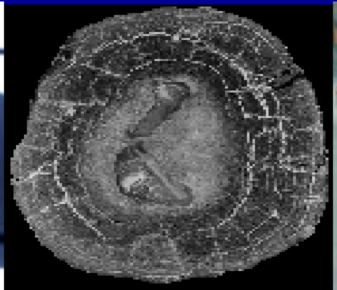
2000

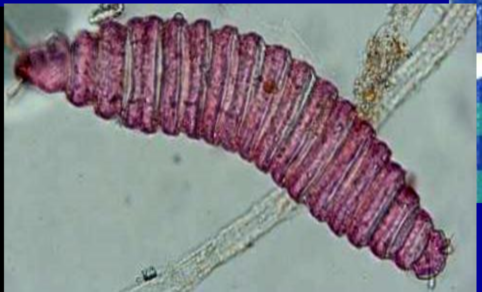


2001



2005





Inter-governmental collaborations

Indian –Myanmar joint oceanographic studies (2002~)

- Training of scientists from Myanmar
- Joint cruises for sample collection, data analysis, interpretation
- Geological, Geophysical, chemical, biological data
- Exchange visits and Joint publications

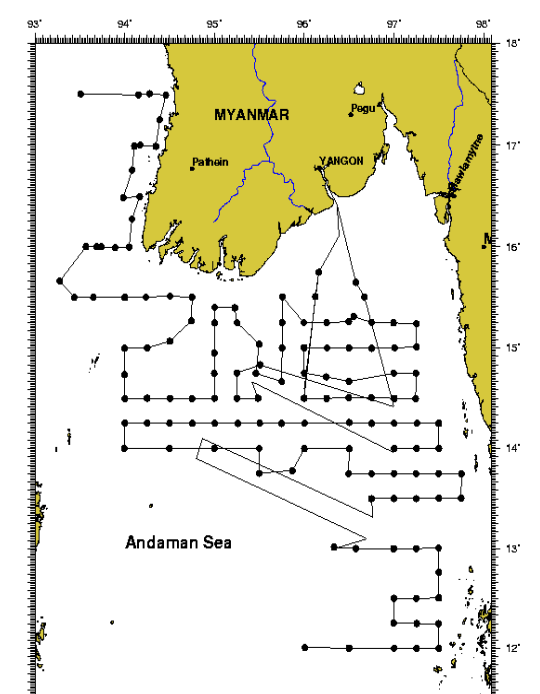


Fig.2 Sample locations and geophysical lines

India- Iran cooperation (2006~) between NIO and

- Marine Geology Division, Geological Survey of Iran, Tehran.
- Iranian National Center for Oceanography, Tehran, Iran

For training of scientists and Joint cruises in Gulf of Oman and Persian Gulf

(Source: V. Ramaswamy, NIO, India)

Hands on training in marine scientific research for professionals from

Vietnam Egypt Sri Lanka France Saudi Arabia Germany Ghana

Dynamics of the Indian Ocean: Perspective and Retrospective

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