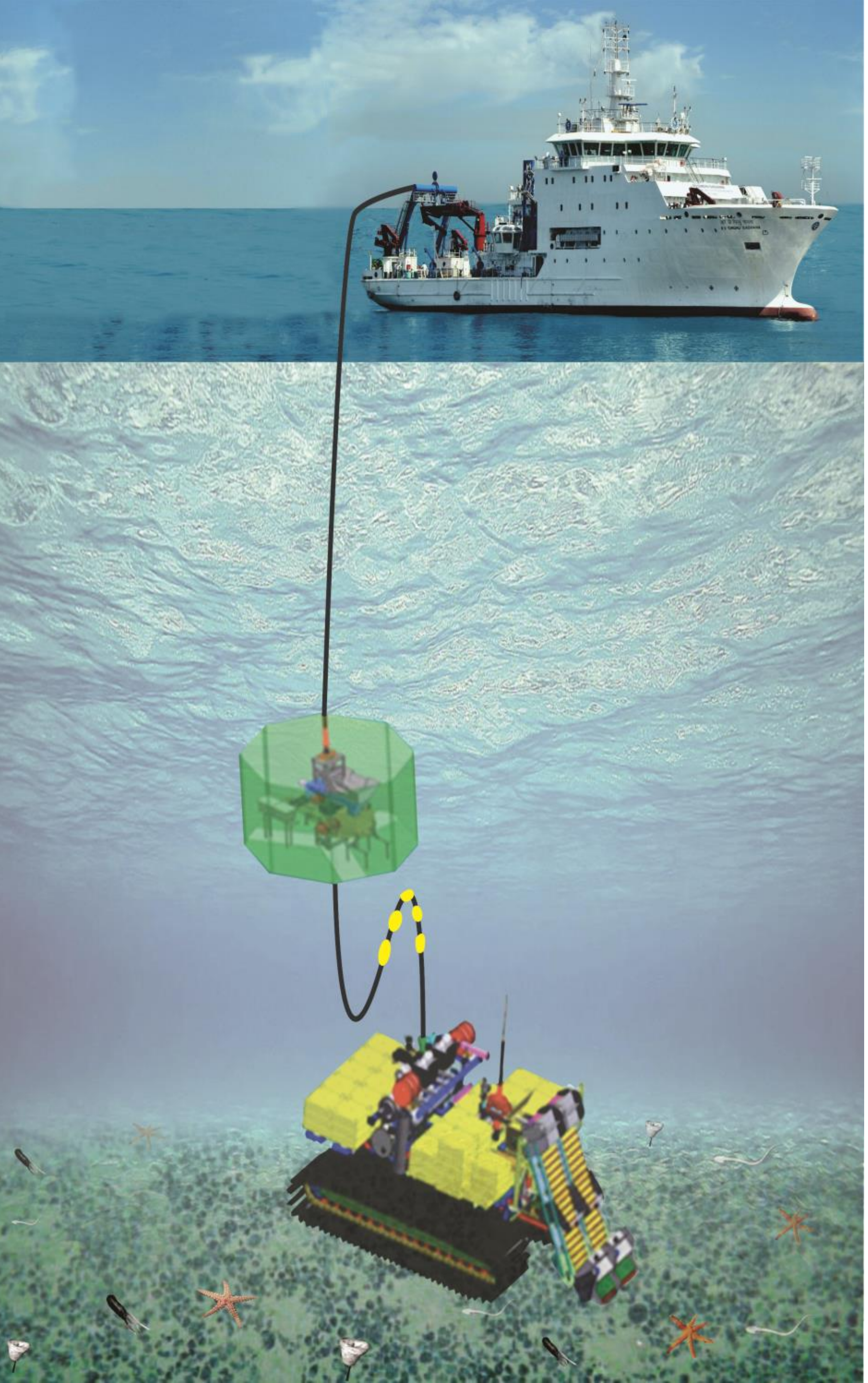

Techno-Economic Assessment of Deep-sea mining

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Why switch to deep-sea minerals

- Land reserves depleting, need alternative metal sources
- Increase in annual production rate (Au -1.1% to Co - 8.3%)
- Metals from deep-sea minerals can be used for a variety of applications (eg. Machines, electric transmission; alloys)
- Some are key for transition to green and renewable energy (high capacity batteries, solar and wind farms)

(Source: Hein et al., 2020; Cronan, 2022)

Why switch to deep-sea minerals

- Will require millions of tons of metals (Mn, Ni, Cu and Co) that can be derived from deep-seabed
- Some of these are controlled by few countries

  -60% of raw Co comes from Congo - critical for lithium-ion batteries

  - 80% of refined Co comes from China
- So, several countries have embarked upon exploration for deep-sea minerals to become self reliant.

(Source: Al Barazi et al, 2018, Hein et al., 2020).

Statements on global metal demand

EU and USGS	**Identified 27 and 50 CRMs (critical raw materials) - for economic and sustainable development**
International Energy Agency	'**Looming mismatch**' between the world's climate ambitions and the availability of critical minerals'
World Bank	**Co, Cu, Ni, Mn, Pb, Li, Pt, Zn, REEs** - critical for green technology **Will need over three billion tonnes of critical metals** to deploy the wind, solar and energy storage technologies to limit climate change to below 2°C

(Hein et al, 2020, www.rechargenews.com, www.mineralsindepth.org)

Status of key metals found in deep-sea minerals

Metal	World reserves on land in 2018 (www.usgs.gov)	Production rate in 2016 (www.usgs.gov)	Increase in production rate/year (%)	No. of years for which land reserves will last
Mn	680 mill t (Mn content in ore)	15,700,000 t	4.3	23
Cu	790 mill t	20,100, 000 t	3.1	24
Ni	74 mill t	2 090 000 t	3.7	21
Co	7 100 000 t	111 000 t	8.3	21
Pb	88 mill t	4,710,000 t	2.6	14
Zn	230 mill t	12,600,000 t	2.9	13

Unless

1. New technology for processing the low grade minerals is developed
2. Recycling of metals with improved technology is available
3. New resources are found or known resources can be converted to reserves

Estimated area under exploration contracts

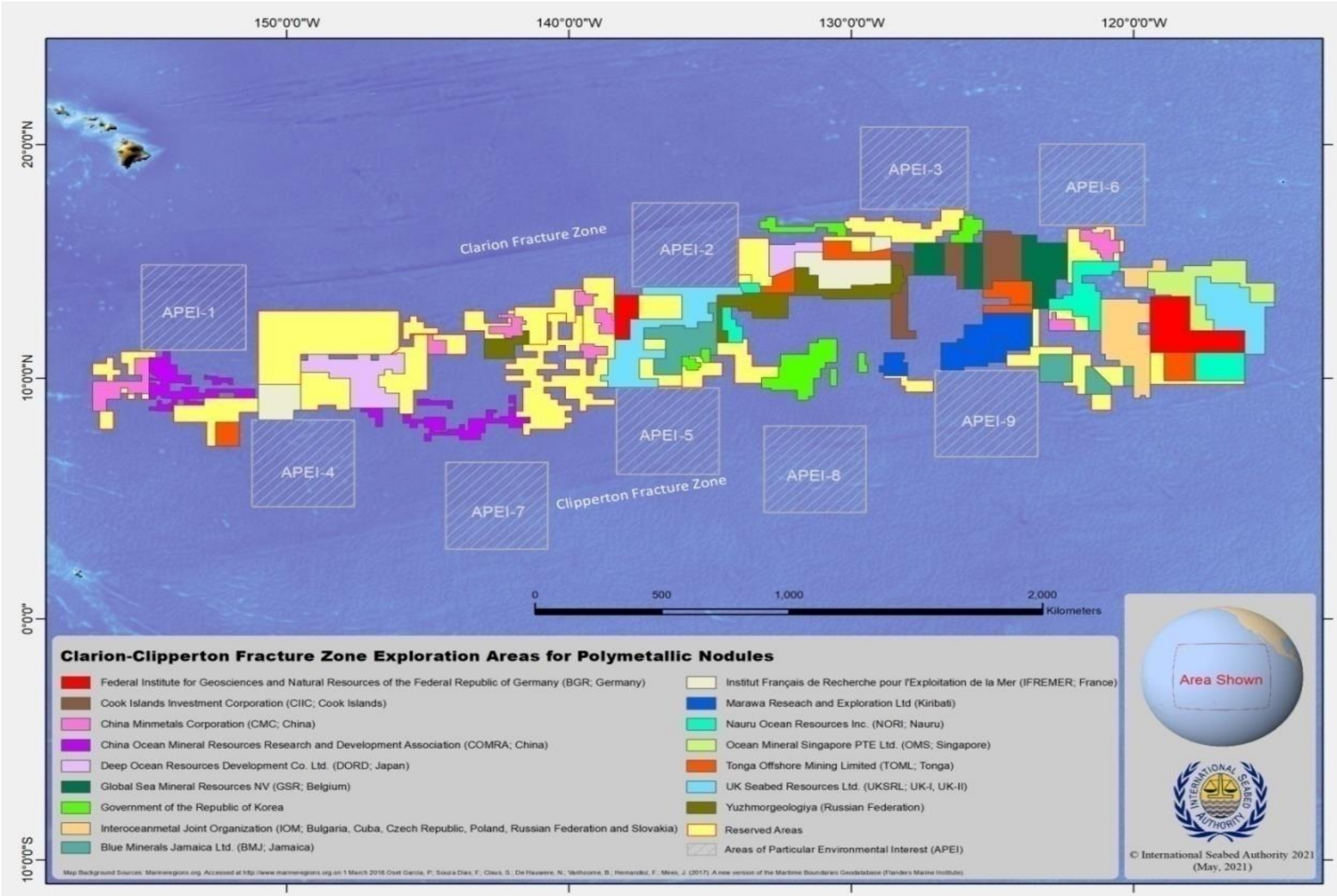
Mineral type	Area (km²) / contract	Total contracts	Total area (km²)
Nodules	75,000	19	1,425,000
Sulfides	2500	7	17,500
Crusts	1000	5	5,000
	Total	**31#**	**1,447,500***

(#In international waters as of 2022, Sharma 2022) *(0.45% of total area of all oceans)

Key points

- Four fold increase in no. of Contractors from 8 (2001 - 2010) to 31 (2011 -2021).
- A typical nodule area of 75,000 km^2 contains at least 375 MT (wet) or 281.25 MT (dry) nodules (@ 5 kg/m^2 abundance)
- This can be mined for 187 years (at 1.5 MT/y) or 93.5 years (at 3 MT/y).
- Mining in ~3 to 4 areas could meet global demand for critical metals initially.

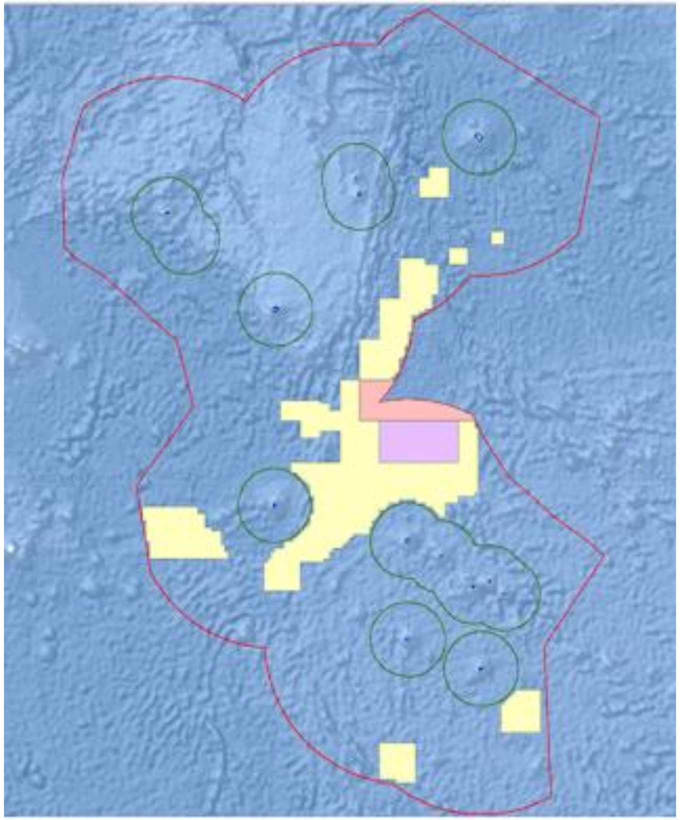
Potential in International Area



CCZ alone has metals such as Mn, Ni, Co, Y that are 1.15 to 3.4 times higher than the entire global resources on land (Hein et al., 2020)

Potential within EEZ

- Approx. 650,000 sq.km. is covered by exploration contracts within EEZs of different coastal states
- Large metal resources found in the national jurisdictions of Japan, Kiribati and others
- Cook islands has issued exploration licences within EEZ
- New Zealand government has issued prospecting licences for hydrothermal sulfides rich in silver and gold in its EEZ.
- Minamitorishima island has 1.2 Mt of rare earths that account for 32 to 62 years of annual global demand of different REEs



Exploration Areas for polymetallic nodules in Exclusive Economic Zone, Cook Islands

(SPC, 2013; Petersen et al., 2018, Hein et al, 2005; Hein et al 2015, Boschen-Rose et al. 2022,Takaya et al, 2018).

Estimated metal production (Mt) for different mining rates

Metal	Mining rate of dry nodules									
	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}**	
	Pacific	Indian	Pacific	Indian	Pacific	Indian	Pacific	Indian	Pacific	Indian
Mn	0.22	0.24	0.33	0.36	0.44	0.48	0.55	0.6	0.66	0.72
Ni	0.01	0.011	0.015	0.165	0.02	0.022	0.025	0.0275	0.03	0.033
Cu	0.0078	0.0104	0.0117	0.0156	0.0156	0.0208	0.0195	0.0260	0.0234	0.312
Co	0.0023	0.001	0.00345	0.0015	0.0046	0.002	0.00575	0.0025	0.0069	0.0030
Total /year	0.2401	0.2624	0.36015	0.3936	0.4802	0.5248	0.60025	0.6560	0.7203	0.7872
Total (in 20 yrs)#	4.802	5.248	**7.203**	**7.872**	9.604	10.496	12.005	13.120	**14.406**	**15.744**

Note:
Metal concentrations for Pacific Ocean Mn=22%, Ni=1.0%, Cu=0.78%, Co=0.23% (Morgan, 2000)
Metal concentrations for Indian Ocean Mn=24%, Ni=1.1%, Cu=1.04%, Co=0.1% (Jauhari&Pattan, 20
As life of a mine-site is expected to be 20 years (UNOET, 1987)

(Sharma et al., 2019)

Estimated metal values (mi. US$[@]) for different mining rates

Metal	Mining rate of dry nodules									
	1.0 Mt/y		**1.5 Mt/y**		**2.0 Mt/y**		**2.5 Mt/y**		**3.0 Mt/y**	
	Pacific	Indian	Pacific	Indian	Pacific	Indian	Pacific	Indian	Pacific	Indian
Mn	343.2	374.4	514.8	561.6	686.4	748.8	858.0	936.0	1029.6	1123.2
Ni	179.75	197.72	269.63	296.58	359.5	395.45	449.37	494.31	539.25	593.17
Cu	78.21	104.29	117.32	156.43	156.43	208.58	195.54	260.72	234.65	312.87
Co	103.87	45.16	155.82	67.74	207.75	90.33	259.69	112.91	311.63	135.49
Total /year	705.02	721.57	1057.5	1082.3	1410,08	1443.16	1762.60	1803.94	2115.13	2164.73
Total (in 20 years) #	14100 (14.1 billion)	14431 (14.431 billion)	**21150 (21.15 billion)**	21646 (21.646 billion)	28201 (28.201 billion)	28863 (28.863 billion)	35252 (35.252 billion)	36078 (36.078 billion)	**42302 (42.302 billion)**	43294 (43.294 billion)

@ Average metal prices as of May 2021 : Mn = $1560/t, Ni = $17975/t, Cu = $10028/t, Co = $45165/t (source: www.lme.com for Ni, Cu, Co; Kirchain et al., 2020 for Mn)

as life of a mine-site is expected to be 20 years (UNOET, 1987)

Estimated CAPEX / OPEX for nodule mining (@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* $ 2.34 billion#	$ 10.0 billion* $ 12.30 billion#	$ 11.90 billion **$ 14.64 billion#**

(Sharma 2022)

* Figures taken from ISA report (ISA, 2008a) and rounded off to nearest fifty of the highest value.
• Figures in brackets () show the range for different systems.
Recalculated cumulative inflation rate @ 23 % for 2021 (inflation calculator.com)

Metals worth $ 21.15 billion can be mined for an investment of $ 14.64 billion (Taxes, royalties not included)

Financial assessments for nodule mining (@~3 mi. t./year)

Agency	Mining rate	Ships	OPEX	CAPEX
GSR (Belgium)	3 Mt / year	Two vessels	Offshore $ 325×10^6 annually x 20 years = $ 6500×10^6 **($ 6.5 billion)** Onshore $ 688.7×10^6 annually x 20 years = $ $13,774 \times 10^6$ **($ 13.774 billion)**	-
MIT (USA)	3.86 Mt / year	Two vessels	**$ 840 million**	**$ 2730 million**

(Van Nijen et al. 2018; Kirchain et al, 2020)

1. **Major capital cost is for the processing plant (40-60%) - onshore component**
2. **Operational costs on processing plant are also the highest (50-70%)**
3. **CAPEX and OPEX are not linear functions of the mining rate, but also vary with the number of vessels / collectors and other infrastructure**

Beyond Four Metal Recovery Route

- World demand for rare-earth elements and the metal yttrium—which are crucial for electronic equipment and green-energy technologies is increasing rapidly. These can be derived from seafloor sediments.

  (Yasihuro et al. 2011).

- REE supplies can come from very large tonnage of deep-ocean mineral deposits, specifically polymetallic nodules and cobalt rich crusts (which can be extracted) as a byproduct of Cu, Ni, Co, and Mn Processing

  (Hein, 2012).

- Considering resource crunch of REE from terrestrial resources, the recovery of rare earth from sea nodules will enhance the sustainability of the sea bed deposits

  (Sen, 2017).

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	1.5 Mt/y	2.0 Mt/y	2.5 Mt/y	3.0 Mt/y	
Area (Size) of mine-site #	4267 Km^2	6,400 Km^2	8533 Km^2	10,667 Km^2	12,800 Km^2	5.6-17% of contract area
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
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

for cutoff abundance of 5 kg m^{-2} (minimum required for nodule mining, UNOET, 1987),
Contract (mining) area of 75,000 km^2, mining for 20 years for 300 days of operation per year

(Sharma 2017a)

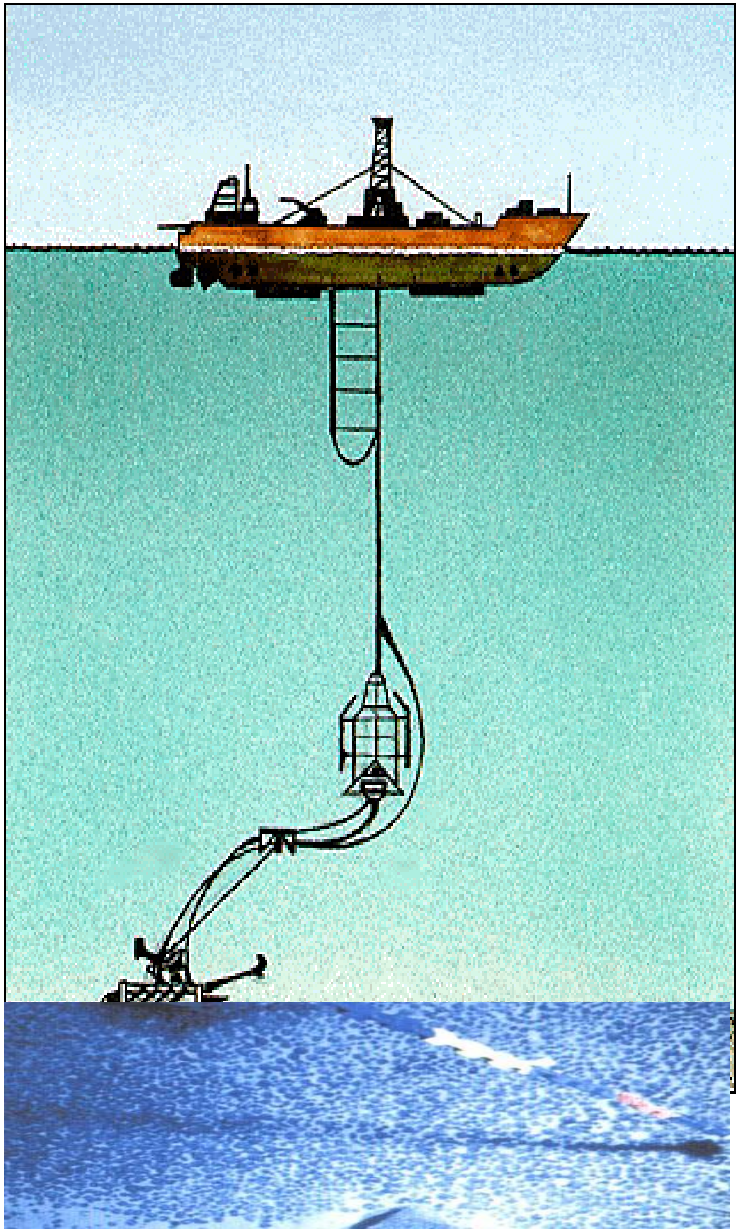
Deep-sea mining challenges

- Up-scaling from prototypes to commercial mining systems

- Operation under extreme conditions -
  - 250-300 days/year,
  - 1-2^0 C temperature,
  - 300-500 bars pressure,
  - cross cutting currents,
  - uneven topography and
  - heterogeneous distribution of minerals

- Self-propelled mining device
  - to detect promising areas and avoid unfavourable areas
  - for better power consumption and saving of time and cost
  - stand alone systems to avoid redundancy

Solution – Robotics???



Sunset at Miramar beach, Goa