

Deep-Ocean Mining—The Next Frontier

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**International Seabed Authority's
Sensitization Seminar at the United Nations
New York City, 16 April 2014**



The Earth's surface is 71% water covered

TOPICS

- Deposit types and locations
- What are the drivers?
- Comparisons with land-based Resources
- Who are the players?

- Dry land 29%
- Ocean 71%

Pacific Ocean
area is greater
than the entire
Earth's land area

Deep-ocean mineral deposits

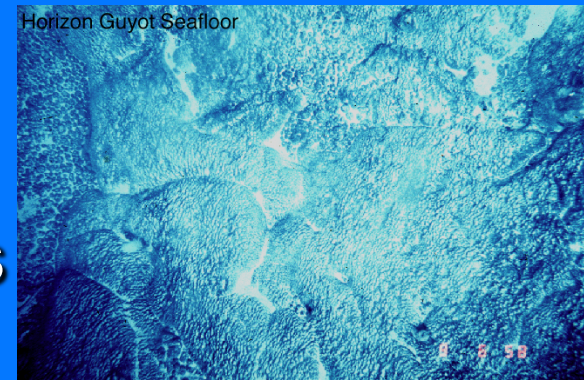
Manganese nodules

- Form on the vast deep-water abyssal plains



Ferromanganese crusts

- Form on 100,000 seamounts



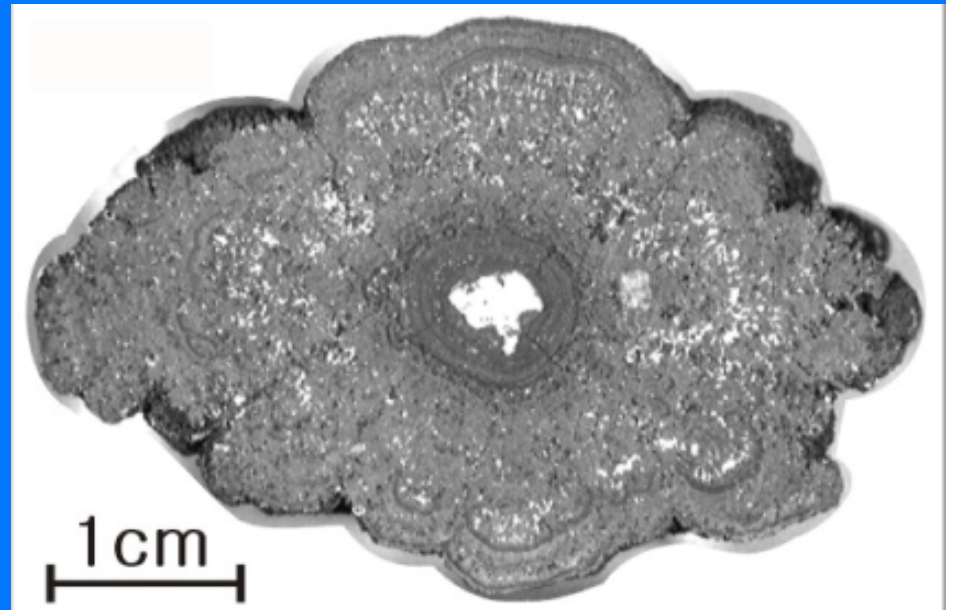
Seafloor massive sulfides

- Form at hydrothermal vents along 89,000 km of ridges

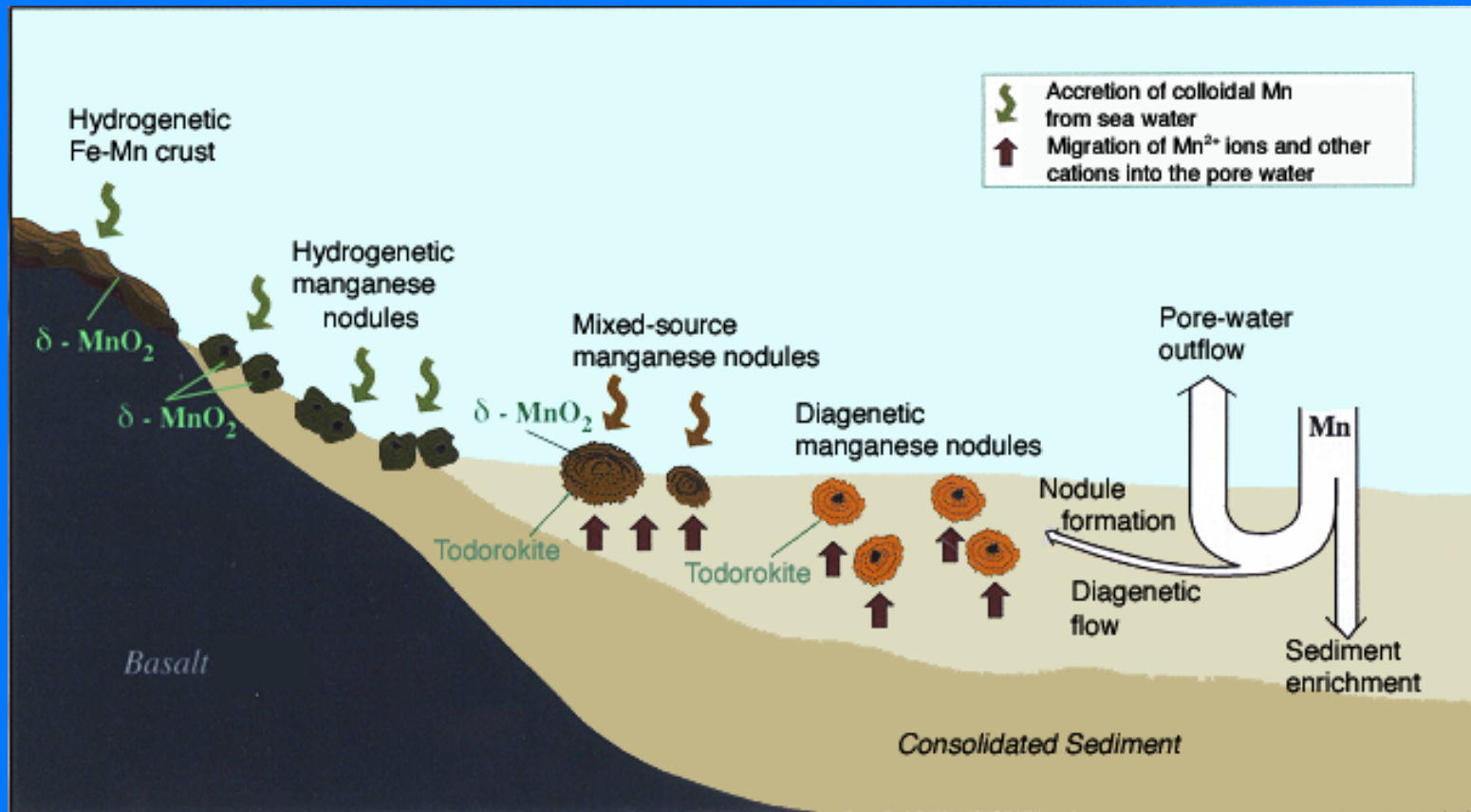


Manganese Nodules

- Form on sediment-covered abyssal plains (4000-6500 meters water depths)
- Composed of manganese and iron oxides, with significant amounts of nickel and copper
- Form by precipitation of metals from cold bottom seawater and from sediment pore fluids

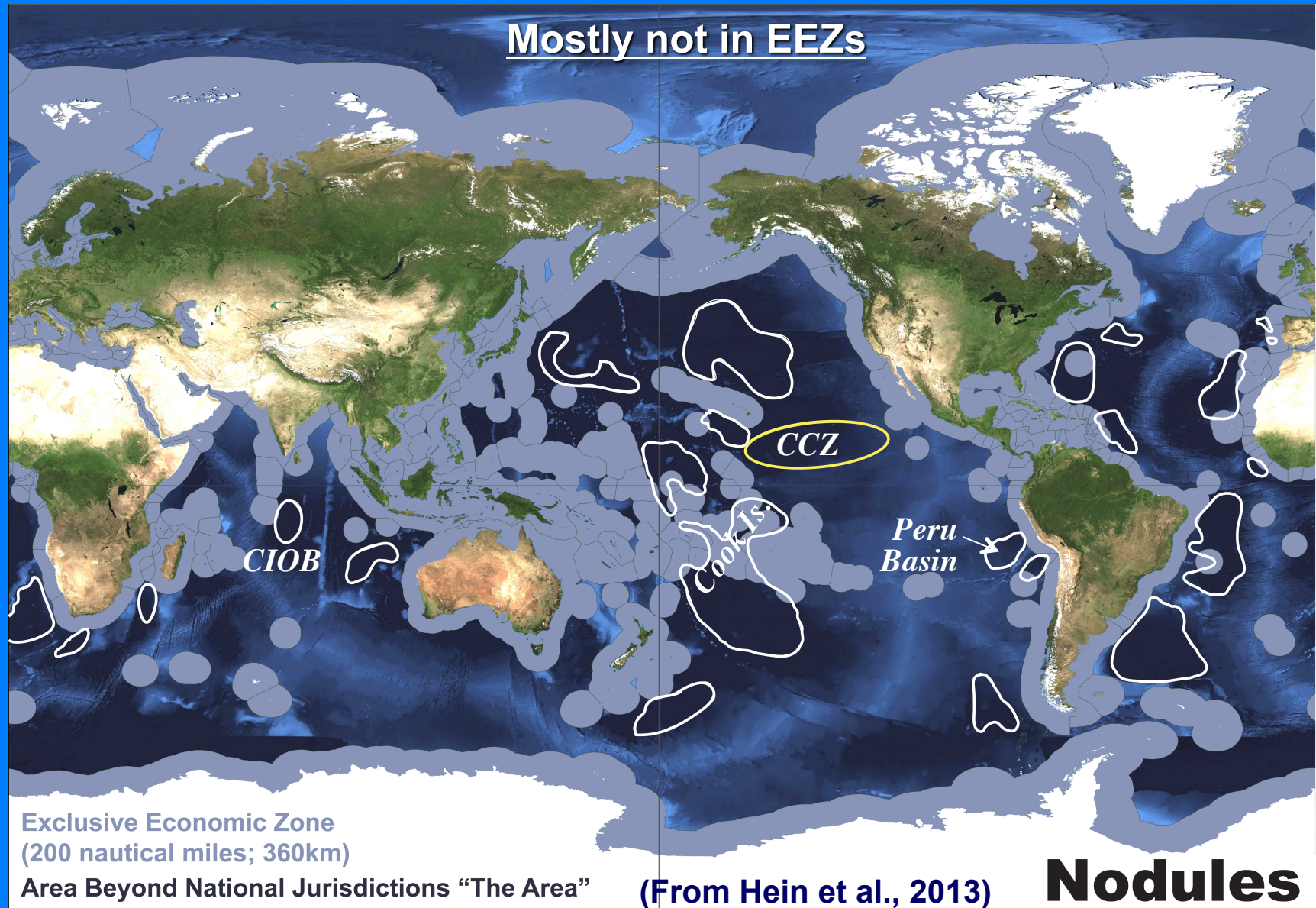


Formation of manganese nodules



(From Hein et al., 2013)

Global Permissive Areas for Manganese Nodules



Four nodule fields are well known: CCZ, CIOB, Peru Basin, and Cook Islands EEZ

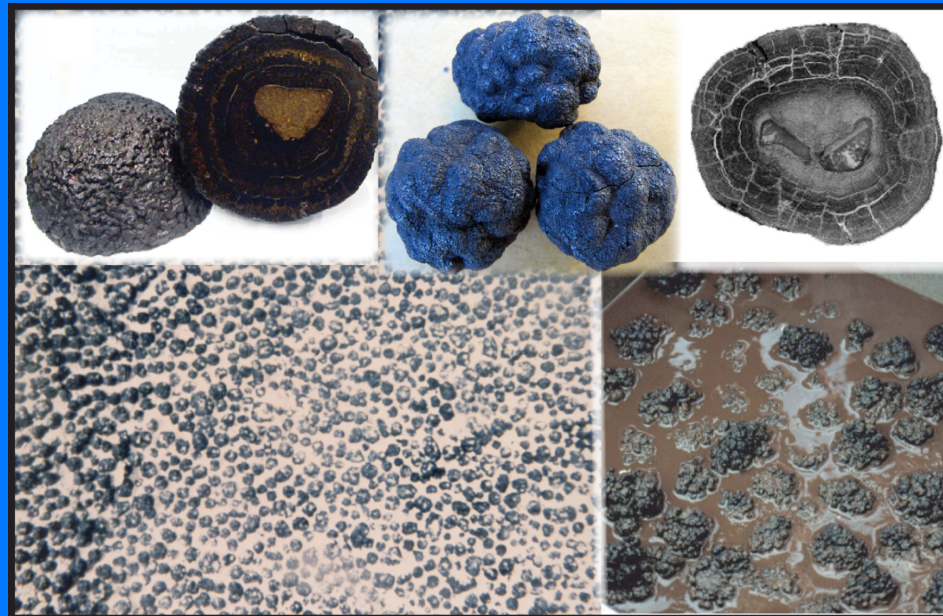
Potential Polymetallic Nodule Ore Deposits

CCZ: Nickel, Copper, Molybdenum, Manganese, Cobalt

CIOB: Nickel, Copper, Molybdenum, Manganese, Zirconium

Peru Basin: Nickel, Manganese, Lithium

Cook Is.: Titanium, Manganese, Scandium, Cobalt, REEs



Deep-ocean mineral deposits

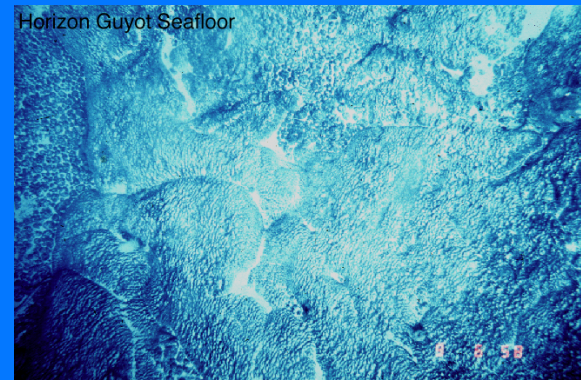
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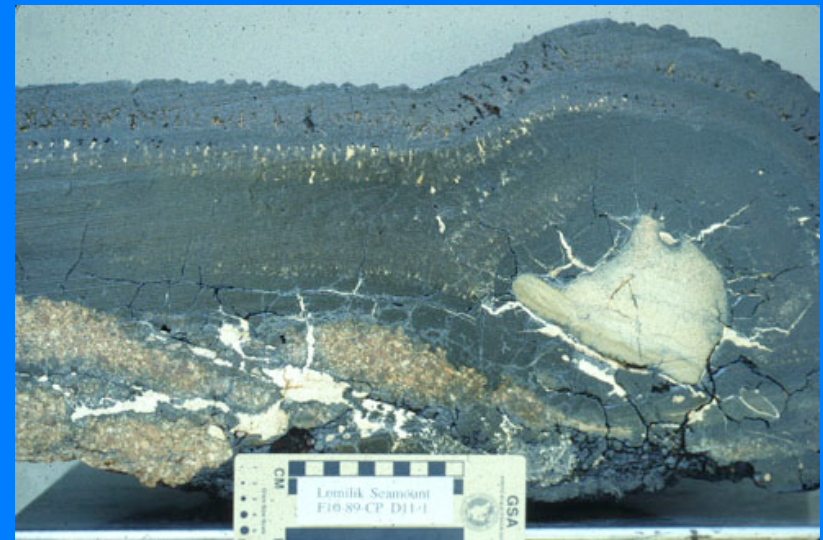
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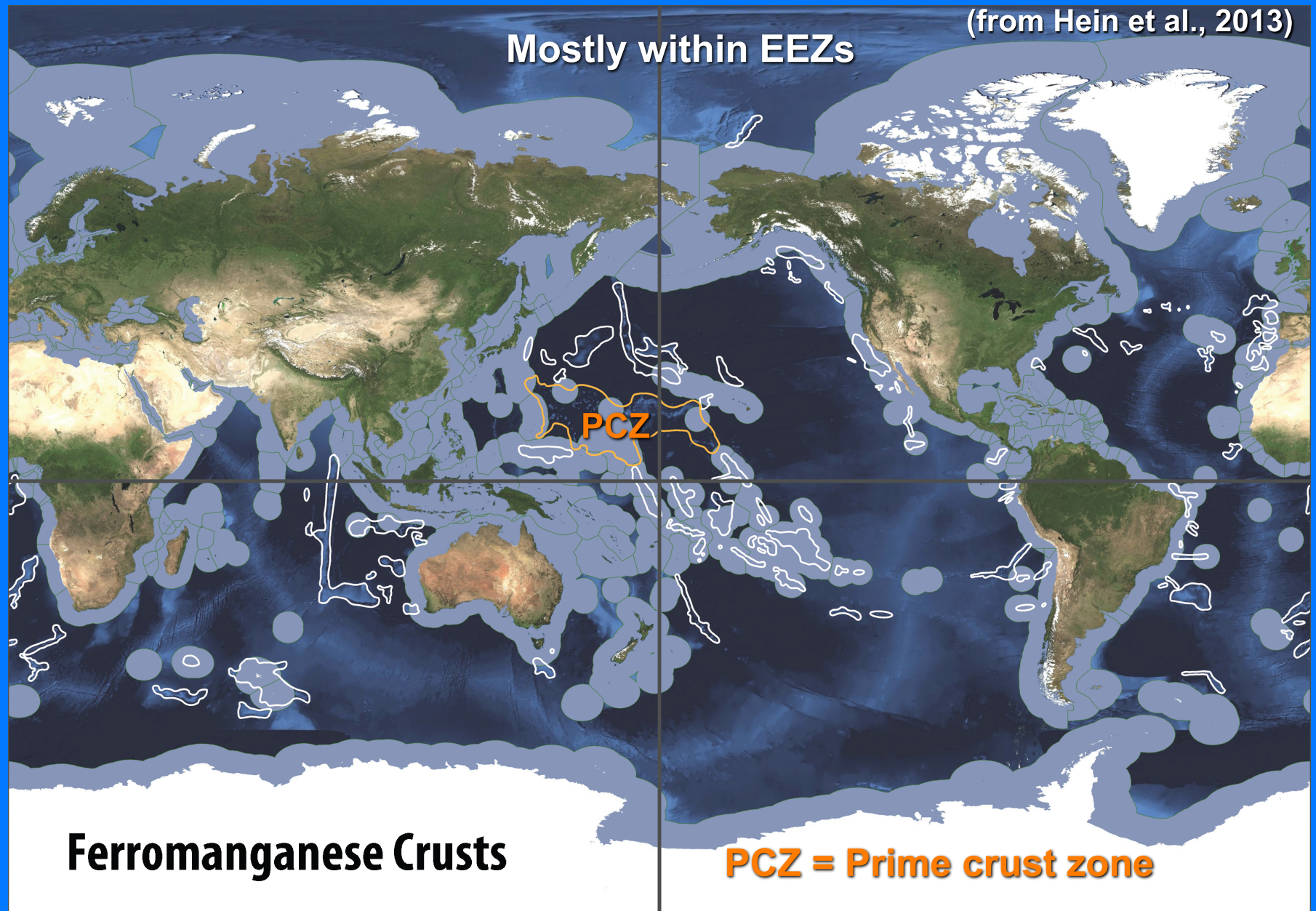


Ferromanganese Crusts

- Grow on hard-rock surfaces on seamounts, ridges, and plateaus
- Found at water depths of ~400-7000 meters
- Thicknesses range from <1 to ~260 millimeters
- Metals precipitate from cold seawater
- Focus metals: Cobalt, Nickel, Manganese



Global Permissive Areas for Ferromanganese Crusts



Rare Metals in Ferromanganese Crusts as Potential Byproducts of Cobalt, Nickel, & Manganese Mining

Rare Earth Elements

Bismuth

Niobium

Molybdenum

Platinum

Scandium

Tellurium

Thorium

Titanium

Tungsten

Zirconium



Scandium-rich crust from the Arctic Ocean

Deep-ocean mineral deposits

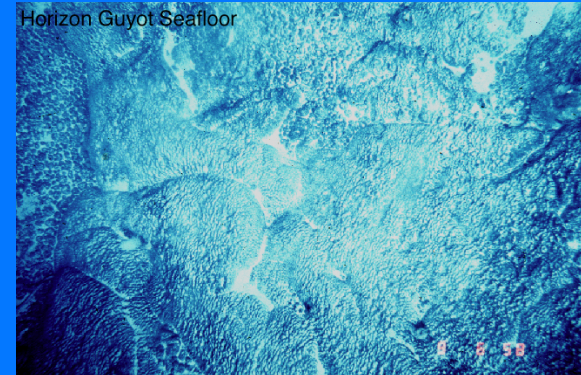
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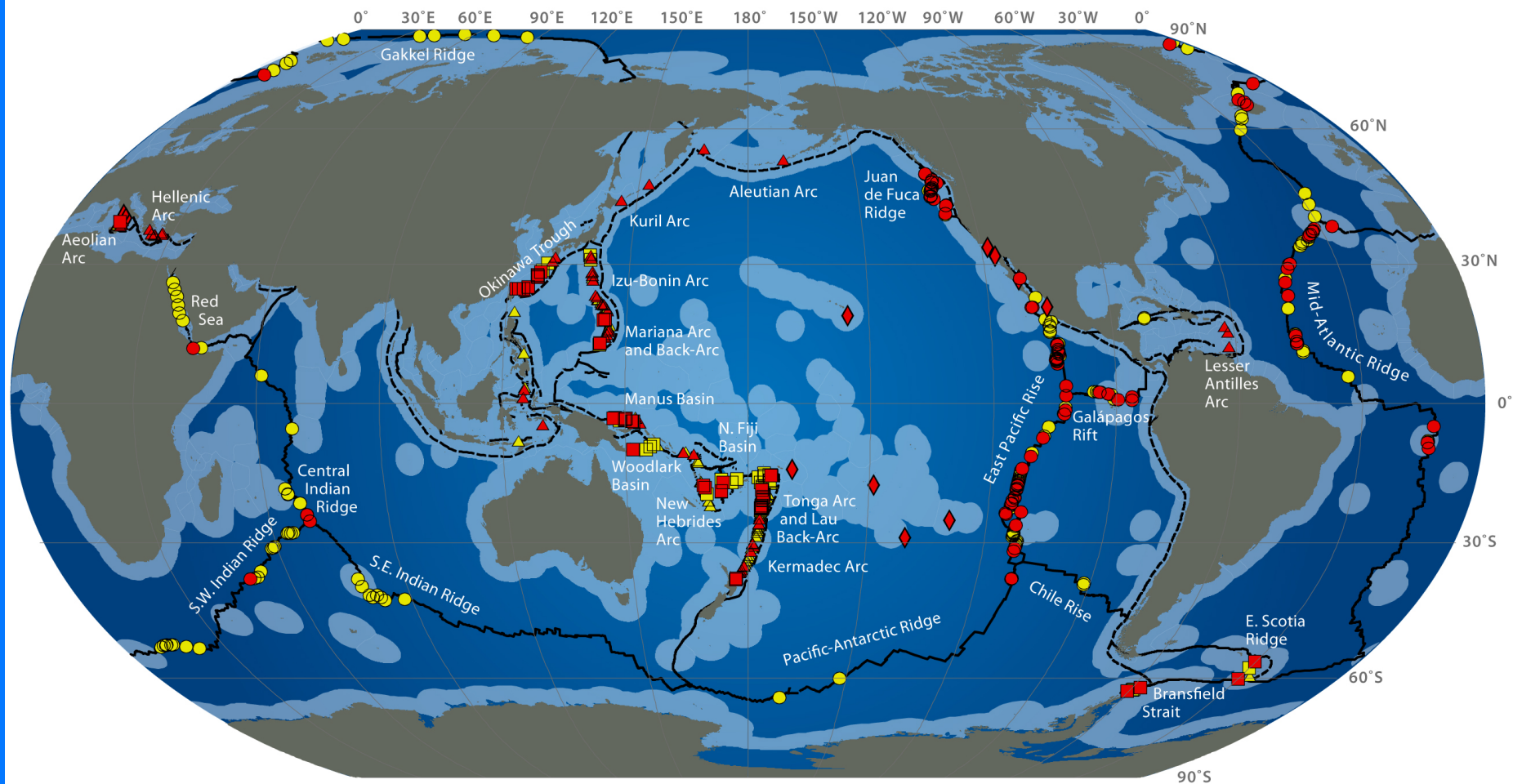
Seafloor Massive Sulfides

- Precipitation from hydrothermal & magmatic fluids
- Black/white smokers produce sulfide/sulfate chimneys and mounds
- Rich in copper, zinc, silver, gold
- Ephemeral vent fields



R787
RX-0012

Global Distribution of Hydrothermal Vent Fields



Mid-ocean ridge

● Active

● Unconfirmed

Arc volcano

▲ Active

▲ Unconfirmed

Back-arc spreading center

■ Active

■ Unconfirmed

**Intra-plate volcano
& Other**

◆ Active

— Ridge & Transform

--- Trench

● Exclusive Economic Zones



64,000 km of oceanic spreading centers
25,000 km of volcanic arc systems

Rare metals in Seafloor Massive Sulfides as Potential Byproducts of Copper or Zinc Mining

Gold
Silver

Antimony
Arsenic
Cadmium
Gallium
Germanium
Indium
Selenium





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**Drivers for Confronting the
Challenges of Mining the
Seabed of the Deep Ocean**



**November 2011, we reached
7,000,000,000
People!**

**2.5 billion live in countries with booming
economies and a rapidly growing
middle class**

**Where will the resources come from to
sustain that growth, and to support
green and emerging technologies?**

Driver: Rare Metals needed for Emerging Technologies

- Tellurium: Photovoltaic **solar cells**; computer chips; thermal cooling devices
- Cobalt: Hybrid & electric car **batteries**, storage of solar energy, magnetic recording media, high-T super-alloys, **supermagnets**, cell phones
- Bismuth: Liquid Pb-Bi coolant for nuclear reactors; Bi-metal polymer bullets, high-T **superconductors**, **computer chips**
- Tungsten: Negative thermal expansion devices, high-T **superalloys**, X-ray photo imaging
- Niobium: High-T superalloys, next generation capacitors, **superconducting** resonators
- Platinum: Hydrogen **fuel cells**, chemical sensors, cancer drugs, flat-panel displays, electronics

Light Rare-Earth Elements

- Lanthanum: FCC catalyst, hybrid car **batteries**, **phosphor green**
- Cerium: Catalytic converters, polishing, water purifier
- Praseodymium: Aircraft engine parts, pigment, CAT scan scintillator
- Neodymium: **High-efficiency** Nd-Fe-B **magnets**, hard disc drives
- Promethium: Portable X-rays and miniature nuclear batteries
- Samarium: Sm-Co magnets, **lasers**, nuclear reactor safety

Heavy Rare-Earth Elements

- Europium: Flat screen displays, lasers, & LCD **phosphors red & blue**
- Gadolinium: Shielding for nuclear reactors, compact discs, MRI
- Terbium: Compact fluorescent lights, mag-optic recording, **phosphor green**
- Dysprosium: Hybrid vehicle motors, Nd-Fe-B magnets
- Holmium: Nuclear control rods, **ultra-powerful** magnets, lasers
- Erbium: Amplifier **high-capacity** fiber-optic data transfer, lasers
- Thulium: Electron beam tubes, medical imaging, microwaves
- Ytterbium: Monitoring equipment for earthquakes, fiber optics
- Lutetium: Oil refining catalyst, X-ray phosphor, PET
- Yttrium: Fluorescent lighting phosphor, YAG laser, displays, radar, alloys

Driver: Green Technology

Rare Earth Elements in Hybrid Cars



10 kg Nickel
65 kg Copper

From EE Times: by Colin Johnson

Driver: Green Technology, 1 Wind Turbine

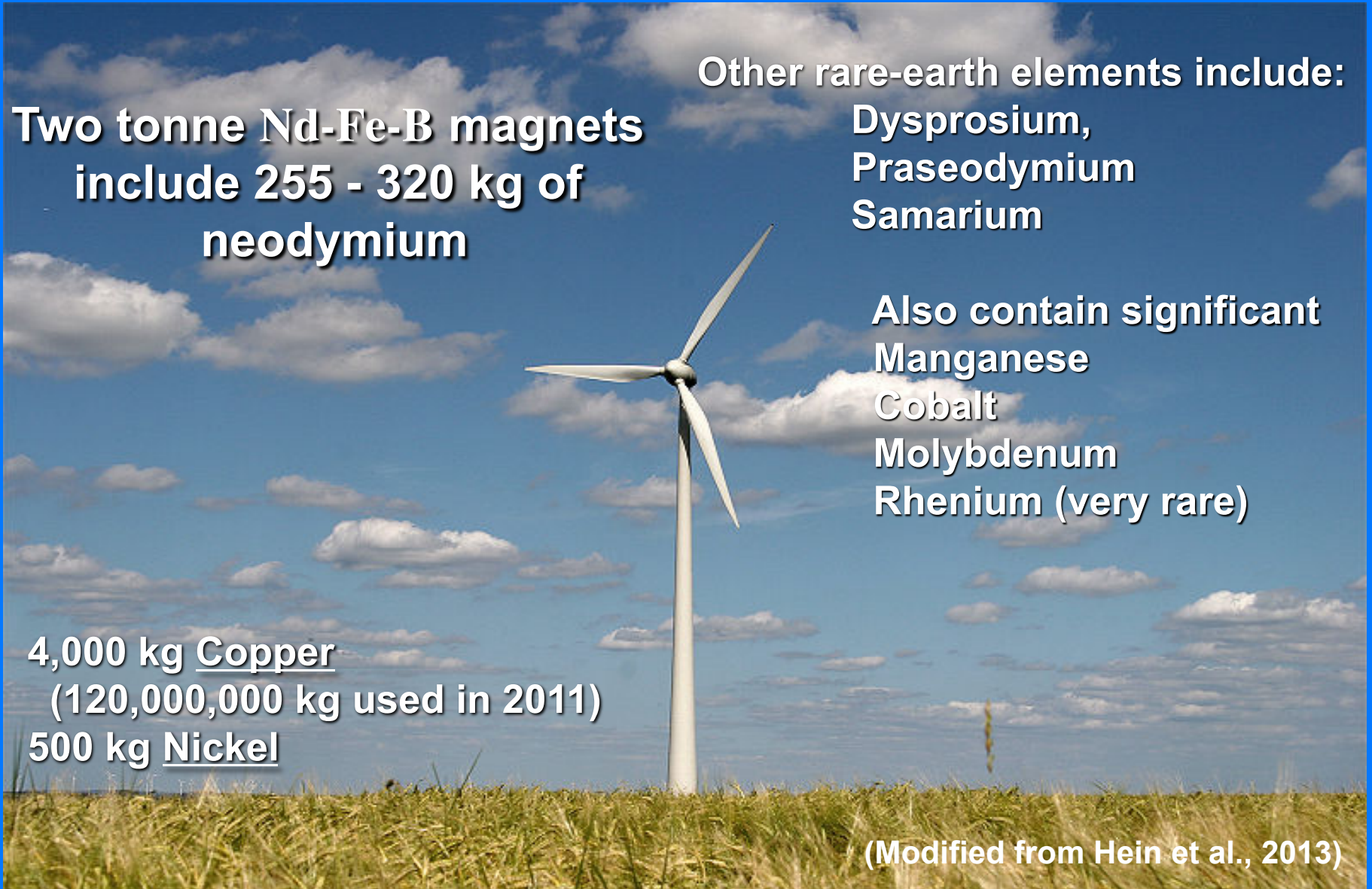
Two tonne Nd-Fe-B magnets
include 255 - 320 kg of
neodymium

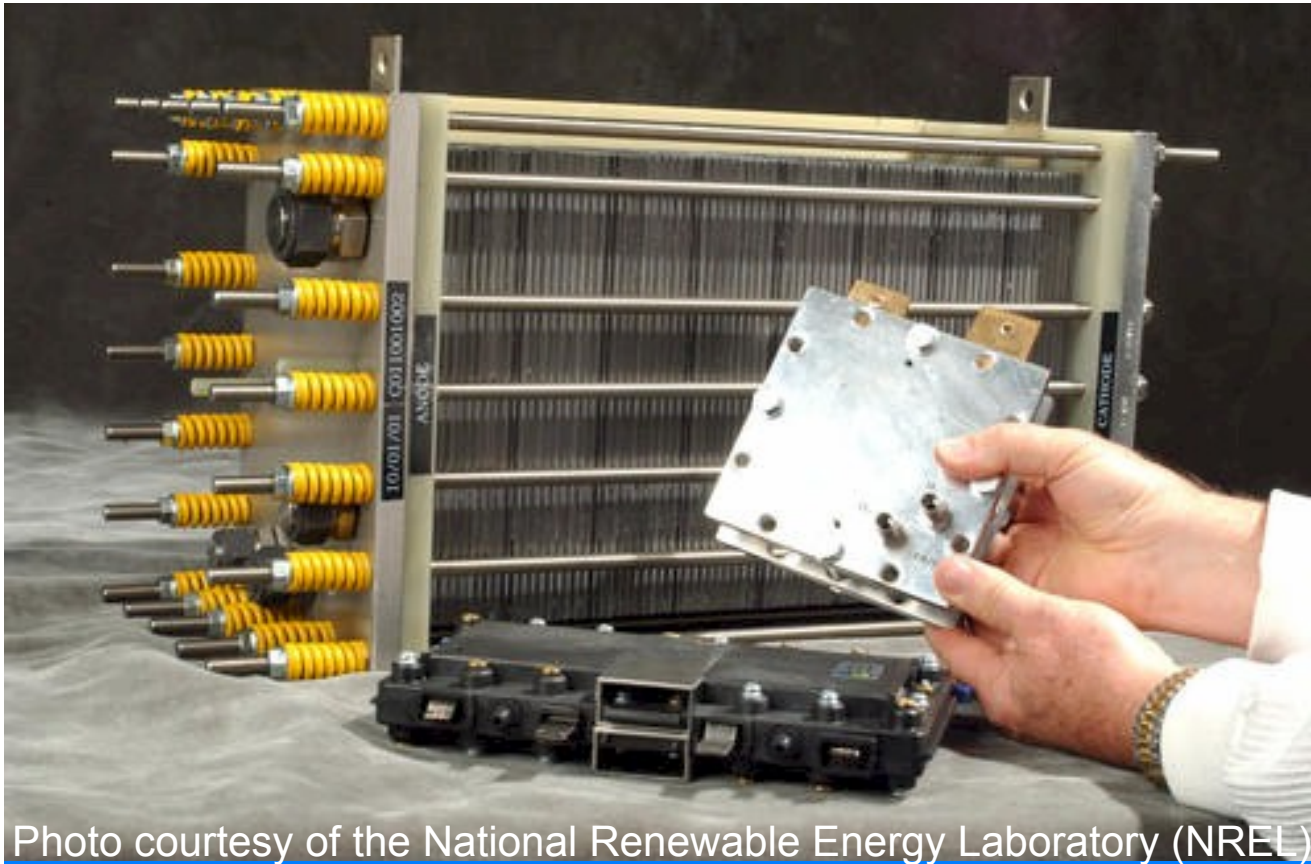
Other rare-earth elements include:
Dysprosium,
Praseodymium
Samarium

Also contain significant
Manganese
Cobalt
Molybdenum
Rhenium (very rare)

4,000 kg Copper
(120,000,000 kg used in 2011)
500 kg Nickel

(Modified from Hein et al., 2013)





Driver: Green Technology FUEL CELLS

Photo courtesy of the National Renewable Energy Laboratory (NREL)

Metals found in deep-sea mineral deposits are essential for fuel cells:

- Platinum, Palladium in Phosphoric Acid Fuel Cells
- Scandium, Lanthanum, Manganese, Nickel, Zirconium, & Cobalt in Solid-Oxide Fuel Cells

Driver: Technology, 25% of a Mobile Phone is Metal

**~1.5 Billion Cell Phones
sold in 2010**



**60 kg Tantalum
510 kg Platinum**

**22.5 tons Palladium
51.0 tons Gold
525 tons Silver
24,000 tons Copper**

**Plus many others e.g.
REEs, Nickel**

There will be only 20 years supply of tantalum if the global per capita use rises to 50% of the current U.S. per capita use; 40 years for copper

(Modified from Hein et al., 2013)

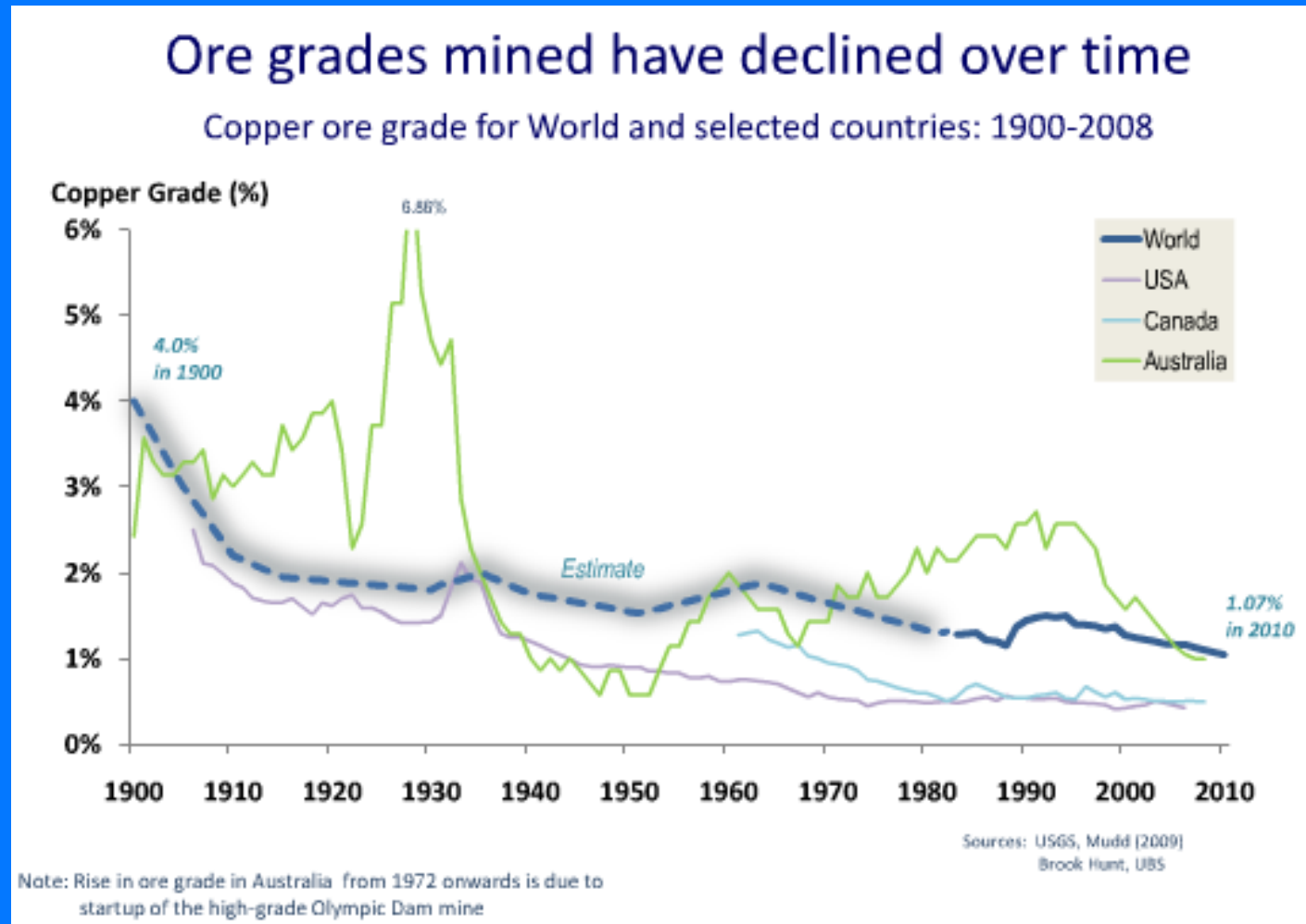
**Driver: Limited
Sources of most
metals**

***China is the Leading
Producer of 30 Critical
Metals***

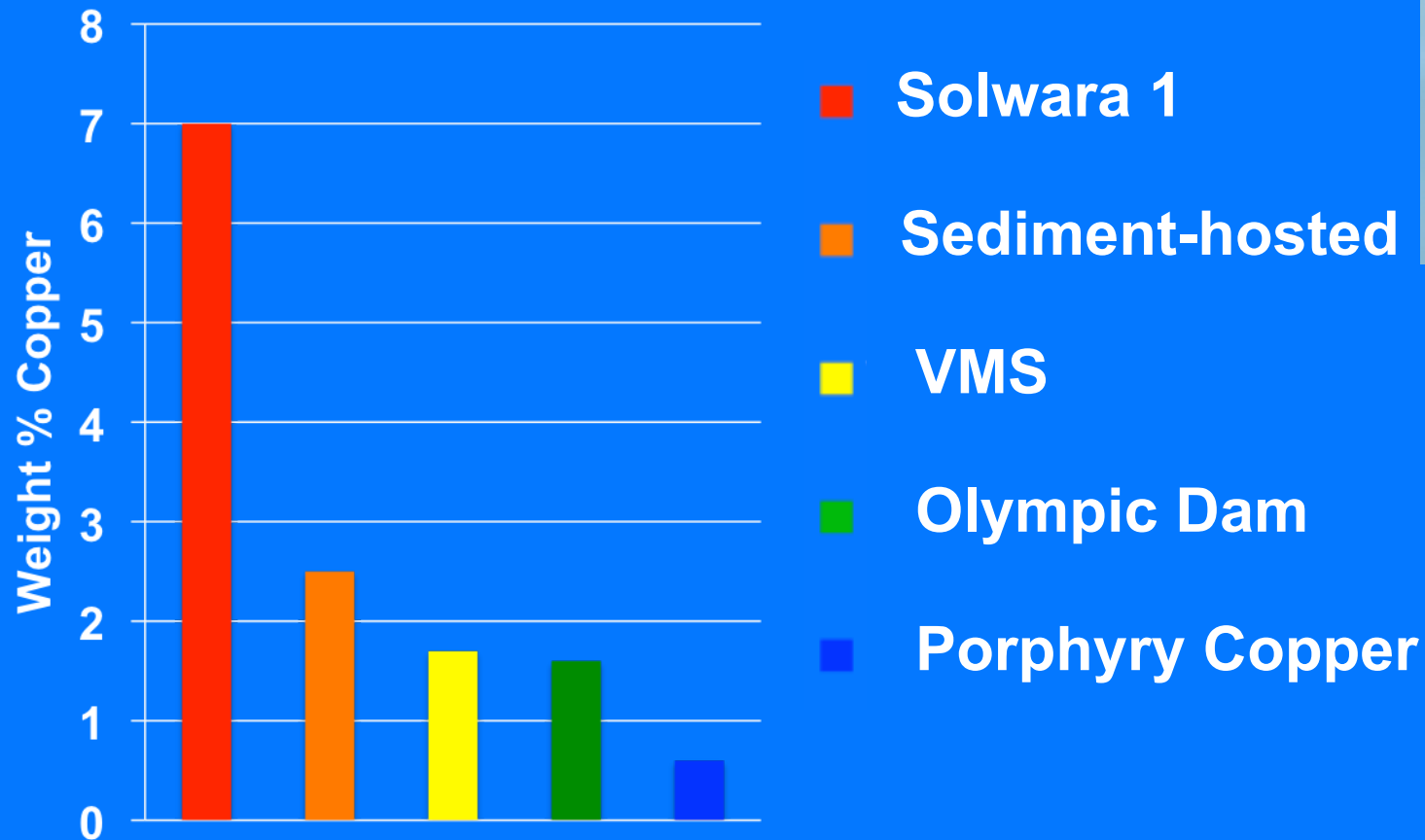
(Modified from Jonathan
Price, SEG Newsletter 82,
July 2010)

Element	Leading Producer	2nd Producer
Arsenic	China (47%)	Chile (21%)
Cadmium	China (23%)	Korea (12%)
Cobalt	Congo (40%)	Australia (10%)
Copper	Chile (34%)	Peru (8%)
Gallium	China	Germany
Germanium	China (71%)	Russia (4%)
Gold	China (13%)	Australia (9%)
Indium	China (50%)	Korea (14%)
Iron	China (39%)	Brazil (17%)
Lead	China (43%)	Australia (13%)
Lithium	Chile (41%)	Australia (24%)
Manganese	China (25%)	Australia (17%)
Molybdenum	China (39%)	USA (25%)
Nickel	Russia (19%)	Indonesia (13%)
Niobium	Brazil (92%)	Canada (7%)
Platinum	South Africa (79%)	Russia (11%)
Rare Earths	China (97%)	India (2%)
Selenium	Japan (50%)	Belgium (13%)
Silver *	Peru (18%)	China (14%)
Tellurium	Chile	USA
Tin	China (37%)	Indonesia (33%)
Vanadium	China (37%)	South Africa (35%)
Zinc	China (25%)	Peru (13%)

Driver: Declining ore grades in land-based mines



Driver: Attractive High Grades for Deep-Ocean Deposits,
e.g. Copper:



Mean composition of Nautilus Solwara 1 marine mine site
compared to all major types of land-based copper deposits

(Modified from Hein et al., 2013)

Driver: Unique characteristics of marine mines

- Marine-based mine sites have no roads, seafloor ore-transport systems, buildings, or other infrastructure
- No overburden to remove, which on land can be 75% of material moved
- Less ore needed to provide the same amount of metal
- Three or more metals can be obtained at one site
- Smaller deposits can be mined



Driver: Rare Earth Elements

The New York Times

September 1, 2009

China Tightens Grip on Rare Minerals

By [KEITH BRADSHER](#)

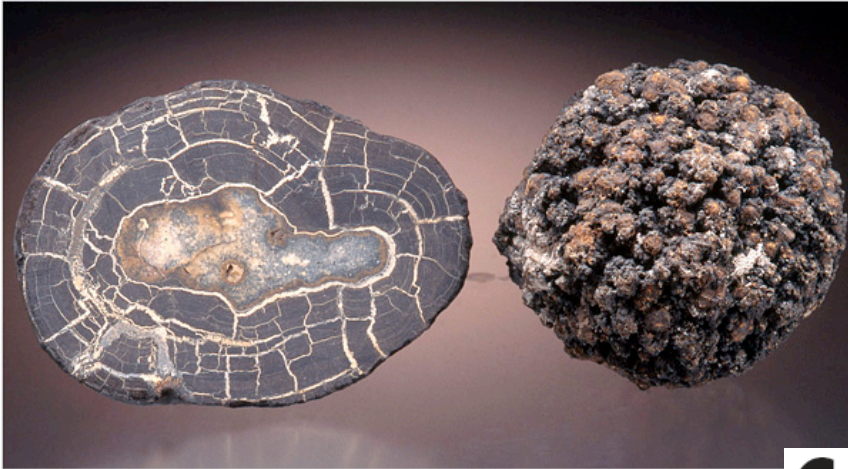
NEWS

Science v. 327 March 26, 2010

Nations Move to Head Off Shortages of Rare Earths

Looming scarcities of a handful of essential elements could shake the electronics industry, unless manufacturers and mining companies develop more sources soon

Mining the Seafloor for Rare-Earth Minerals



Charles D. Winters/Photo

Manganese nodules contain so-called rare-earth minerals, which have commercial and military applications. They are found in disk drives, fluorescent lamps and rechargeable batteries, among other things.

By WILLIAM J. BROAD

Published: November 8, 2010

Concern grows over China's dominance of rare-earth metals

Demand for the elements is expected to surge in tandem with hybrid-electric vehicles, wind turbines, and other green technologies.

BBC Mobile

NEWS

27 October 2010 Last updated at 19:04 ET

Concerns over shortage of rare metals

By Theo Leggett

Business reporter, BBC News

You may never have heard of lanthanum, cerium or neodymium, but these and other so-called "rare earth" metals play a vital role in many modern technologies.

Cerium, for example, is an abrasive used in the manufacture of flat screen televisions.

Lanthanum is a catalyst much prized by the oil industry, while neodymium is found in computer hard drives.



Rare earth metals have vital industrial purposes

Physics
Today May,
2010 David
Kramer

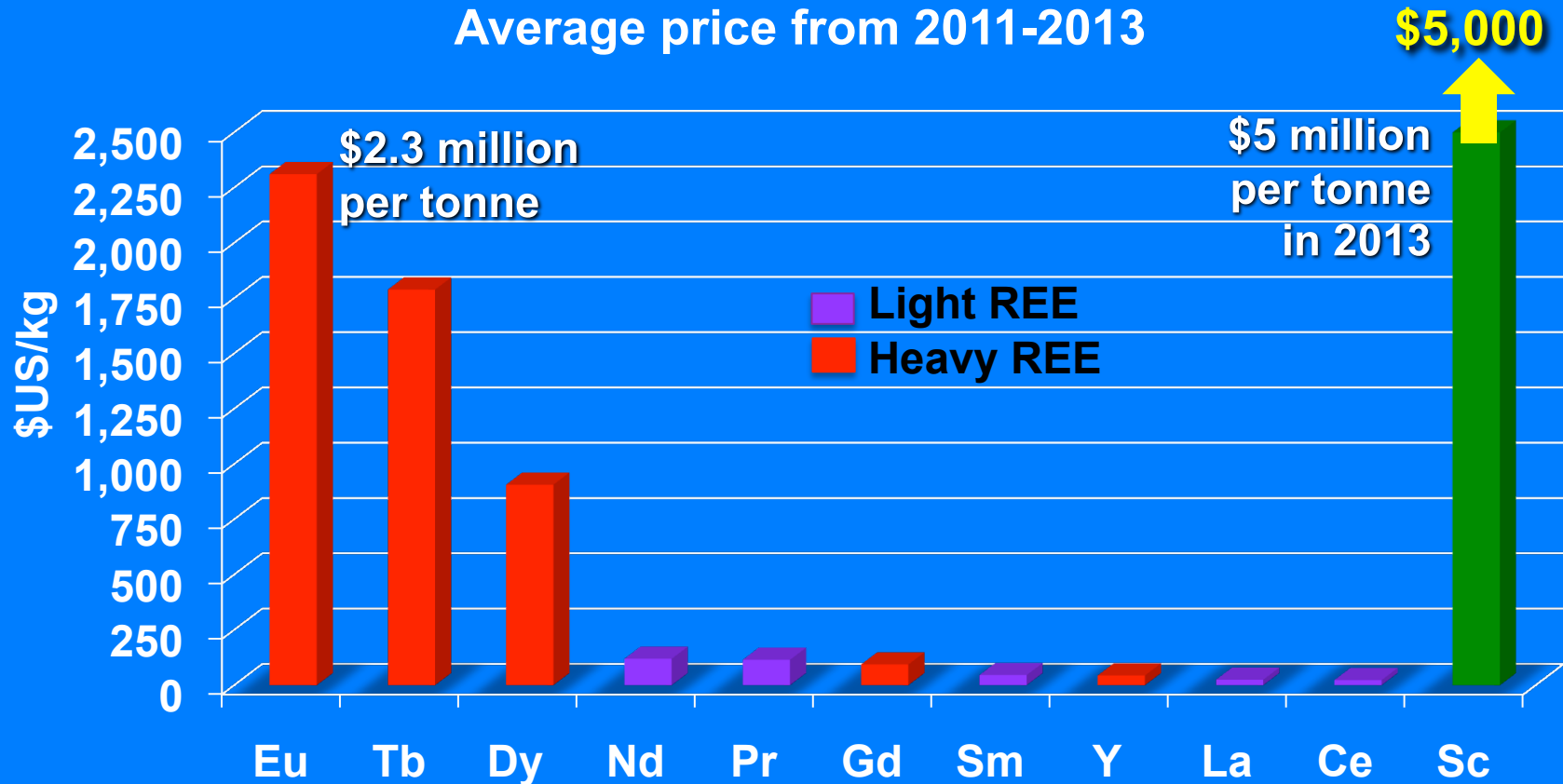
Driver: Light versus Heavy REEs

Large land-based REE deposits average less than 1% HREEs

% HREEs in Marine Deposits

	PCZ Crusts	Arctic Crusts	Cook Is. Nods.	CCZ Nodules
% HREE	18%	23%	16%	26%

Average price from 2011-2013



Driver: Extractive Metallurgy for REEs

Land-based ores require extensive processing, e.g., 1000 steps to isolate ytterbium metal

Marine $\text{FeO}(\text{OH})$ and MnO_2 can be dissolved with simple HCl leach putting all sorbed REEs and other metals into solution

The New York Times

December 15, 2010



David Gray/Reuters



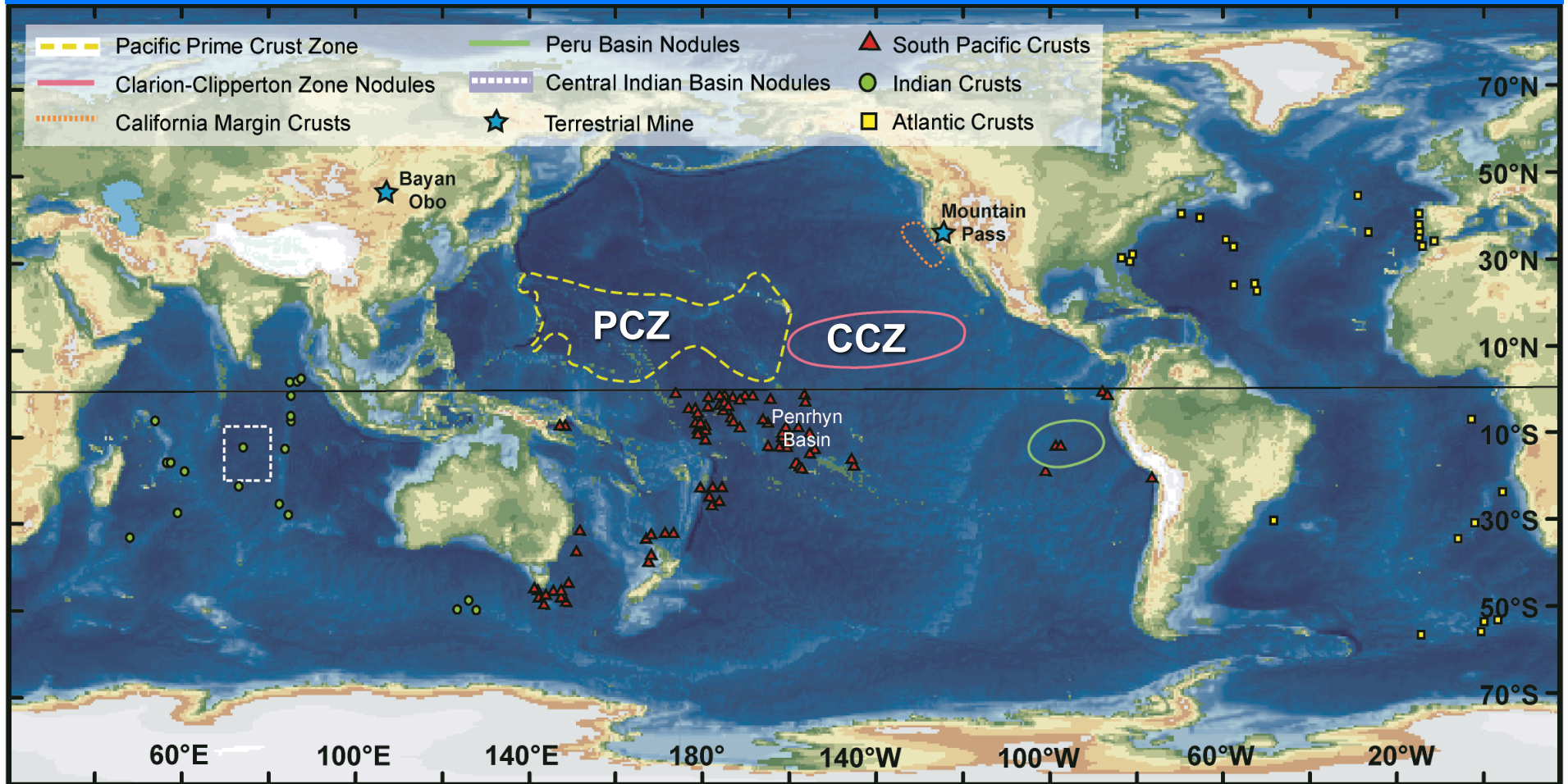


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**Comparisons with Land-Based
Resources**



Comparison of Tonnages of Metals



(From Hein et al., 2013)

Tonnage of nodules in CCZ approximately three times greater than tonnage of crusts in the PCZ

Comparison of tonnages of marine and terrestrial deposits

Contained metal tonnages (x 10⁶ metric tonnes)

Nodule tonnage =
21,100 million dry
tonnes

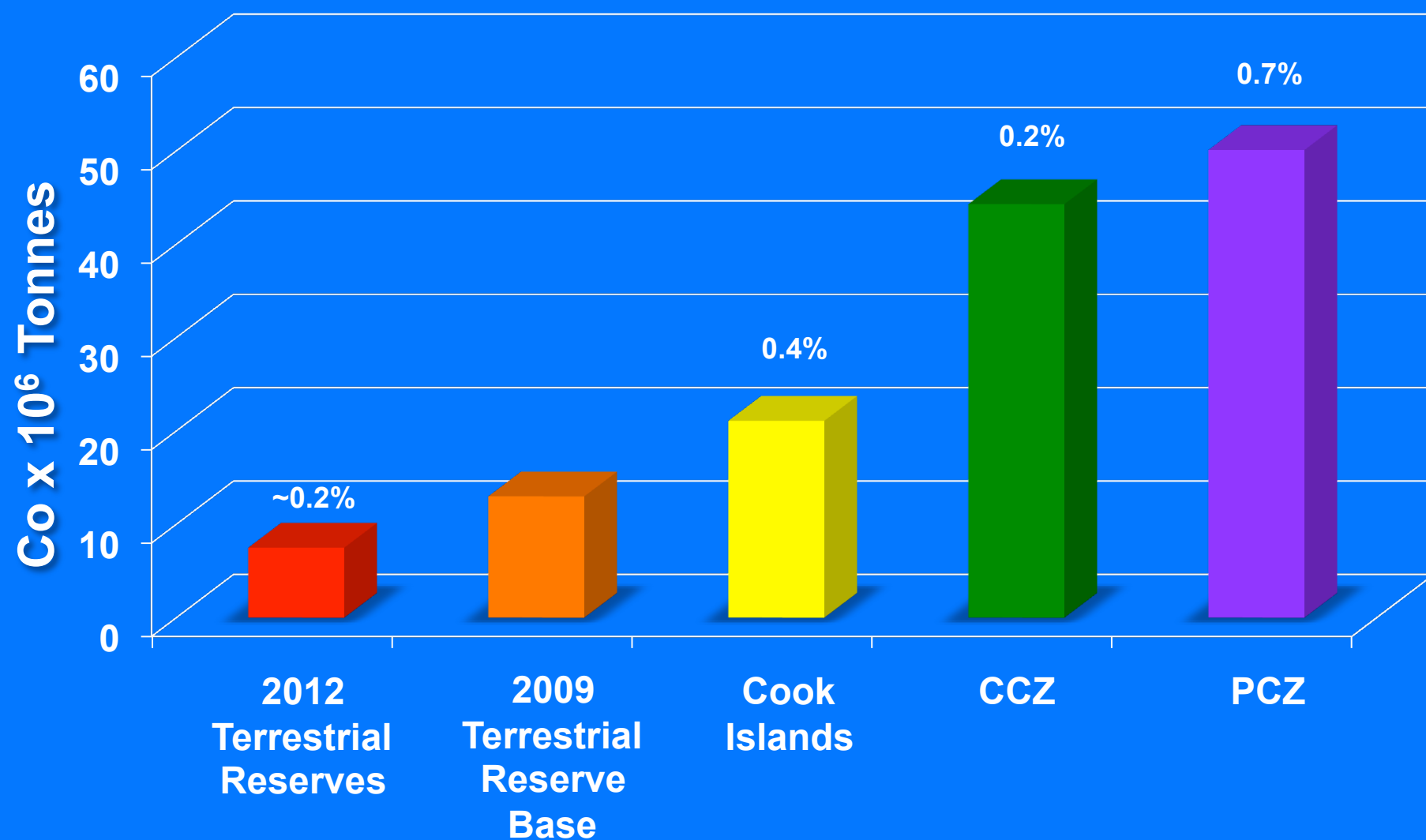
Crust tonnage =
7,533 million dry
tonnes

**CCZ: 15-25%
Economically
mineable**

	CCZ Nodules	Terrestrial Reserve Base	Prime Crust Zone
Manganese	5,992	5,200	1714
Copper	226	1,000+	7.4
TREO	15	150	16
Nickel	274	150	32
Molybdenum	12	19	3.5
Lithium	2.8	14	0.02
Cobalt	44	13	50
Tungsten	1.3	6.3	0.67
Niobium	0.46	3	0.4
Arsenic	1.4	1.6	2.9
Bismuth	0.18	0.7	0.32
Yttrium	2	0.5	1.7
Tellurium	0.08	0.05	0.45
Thallium	4.2	0.0007	1.2

•USGS 2010 reserve base (includes resources that are currently economic (reserves), marginally economic, and subeconomic (from Hein et al., 2013))

Comparison of the Global Cobalt Resource



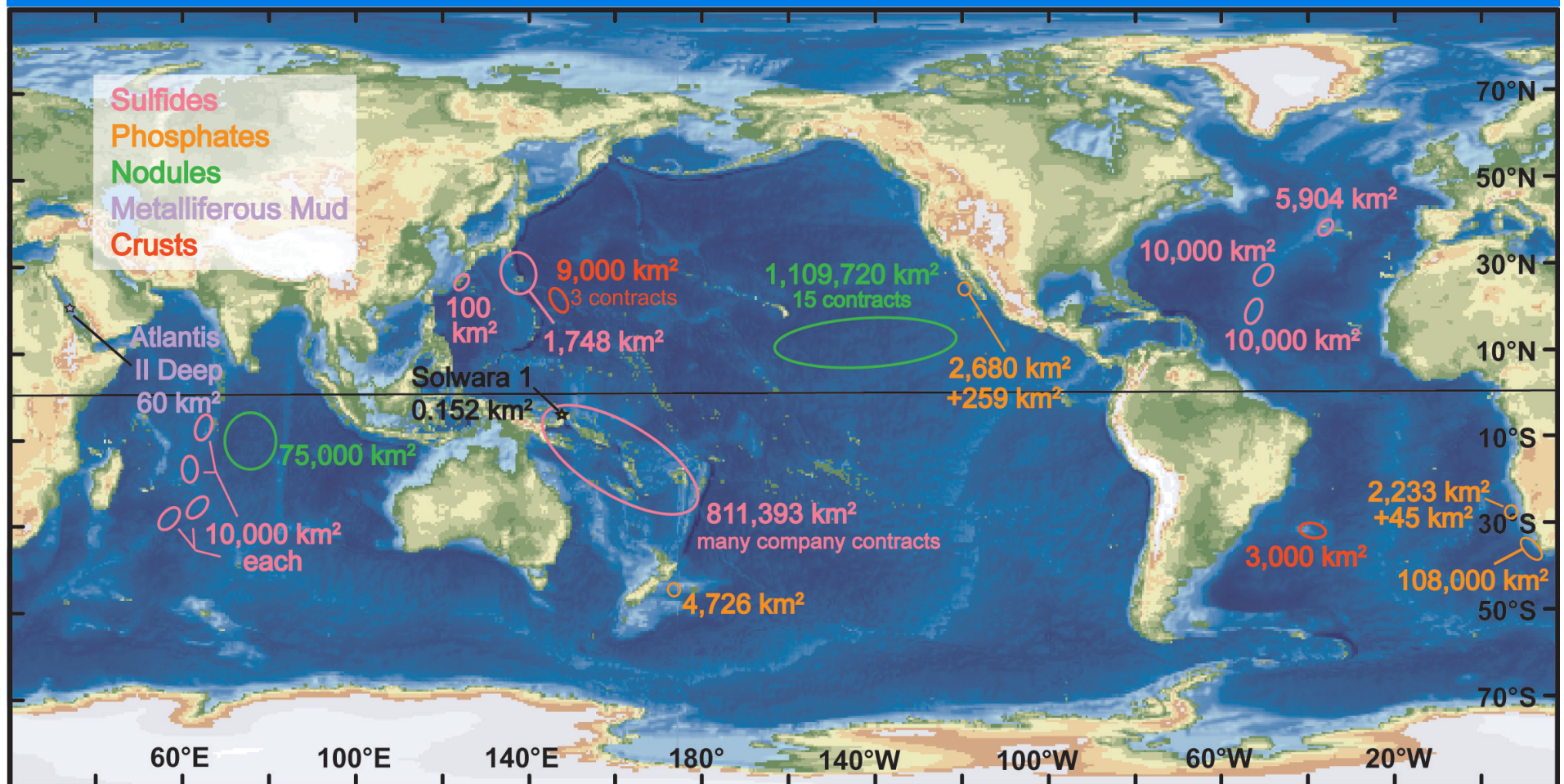


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**Who are the Players and
Where do they Play?**



Contracts for Marine Minerals Exploration Total 2,194,000 km²



(Updated from Hein et al., 2013)

Total contract area is larger than the land area of **Greenland**

Approximately 50% is in EEZs and 50% The Area

States & State Agencies: ISA Deep-Ocean Minerals Contracts

X = APPROVED

X = SUBMITTED

State/State Agency	Nodules	Sulfides	Crusts
China	X	X	X
Russia	X	X	X
France	X	X	
Germany	X	X	
India	X	X	
Japan	X		X
Korea	X	X	
Inter-Ocean Metals ^a	X		
Cook Islands	X		
Brazil			X

^a Bulgaria, Cuba, Czech Republic, Poland, Russia, and Slovak Republic

Companies with deep-ocean minerals contracts

Company	Nodules	Sulfides	Phosphate	Mud
G-TEC Sea Minerals NV	X			
Nauru Ocean Resources	X			
Tonga Offshore Mining Ltd.	X			
UK Seabed Resources Ltd. (2)	XX			
Marawa Research (Kiribati)	X			
Ocean Minerals Singapore Pte.	X			
Nautilus Minerals Inc.		X		
Neptune Minerals		X		
JOGMEC		X		
KORDI (KIOST)		X		
Blue Water Metals Pty Ltd		X		
Odyssey Marine Exploration			X	
Chatham Rock Phosph. Ltd. (2)			XX	
Namibian Marine Phosph. Ltd.			X	
PhosMex Corporation			X	
Green Flash Trading			X	
Diamond Fields Intl. Ltd.				X

ISA
X = APPROVED
X = SUBMITTED

Non-ISA
X = Others

Thank You



Black smoker sulfide chimney, NE Pacific Ocean