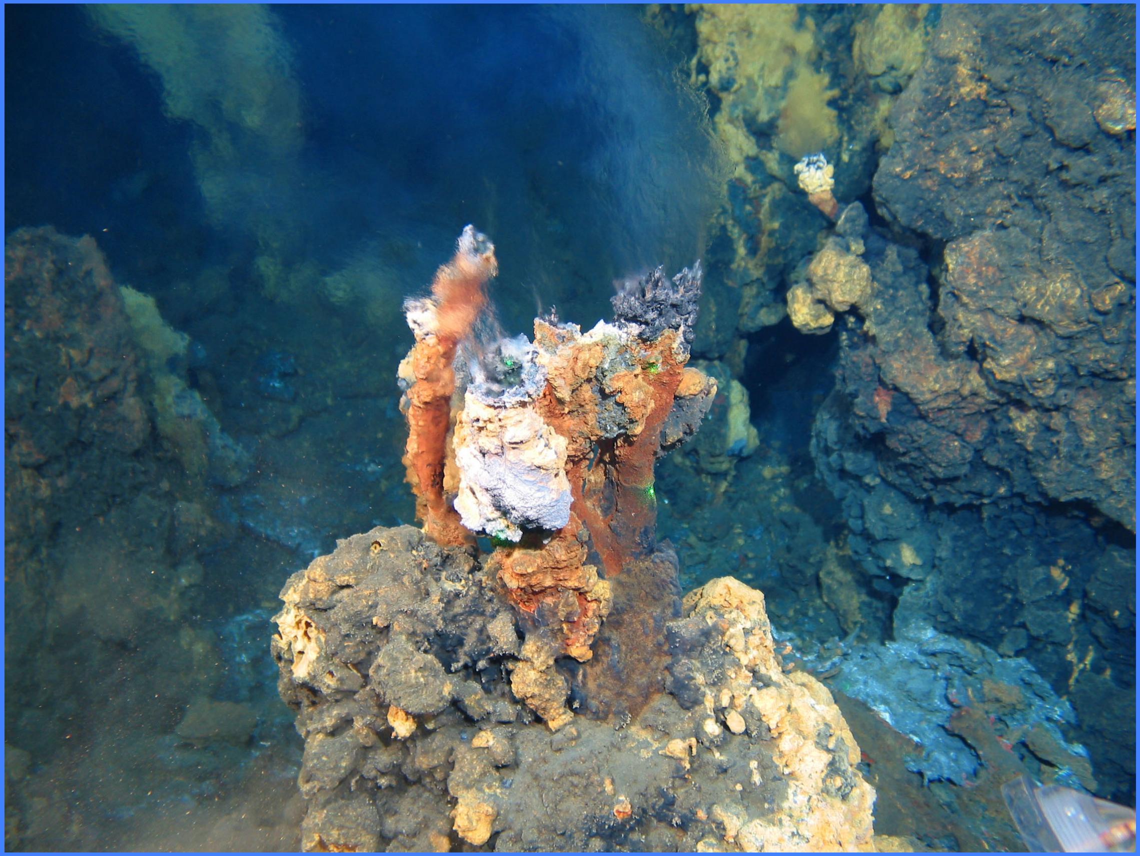
Rare Metals and Rare-Earth Elements in Deep-Ocean Mineral Deposits



James R. Hein
U.S. Geological Survey, Santa Cruz, CA, USA

International Seabed Authority Seminar on Deep Seabed Mining
United Nations, New York, 16 February 2012

Last November, 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?

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The New York Times

September 1, 2009

China Tightens Grip on Rare Minerals

By KEITH BRADSHER

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
in disk drives, fluorescent lamps and rechargeable batteries, among other things.

By WILLIAM J. BROAD
Published: November 8, 2010

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

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.

Physics Today May, 2010 David Kramer

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.

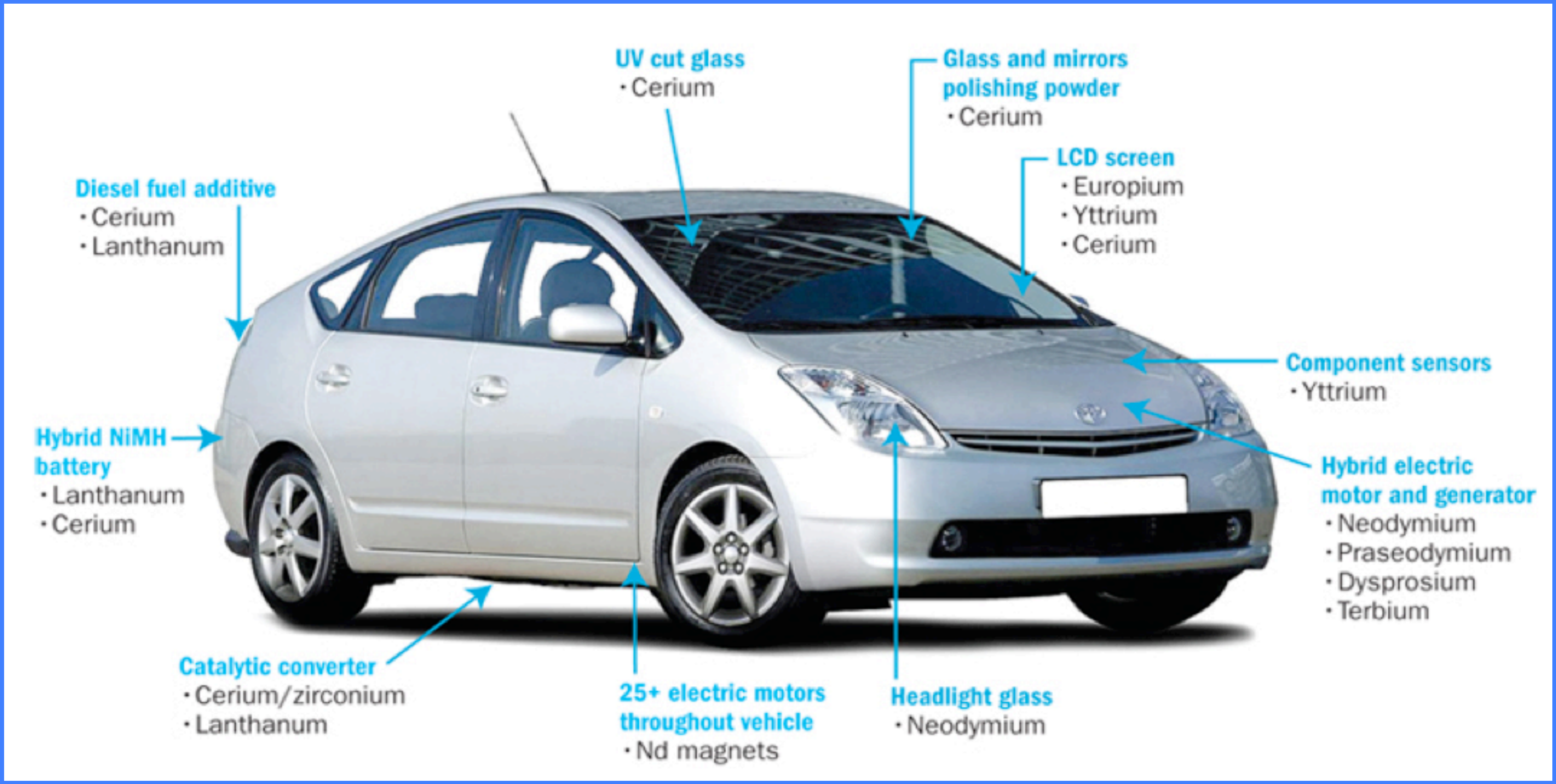
Lanthanum is a catalyst much prized by the oil industry, while neodymium is found in computer hard drives.

Rare earth metals have vital industrial purposes

Road Bump? President Obama's efforts to promote electric-car production may be stymied by getting access to rare-earth elements

Science v. 329 July 23, 2010

Variety of REEs in hybrid cars



From EE Times: Rare earth supply chain: Industry's common cause by Colin Johnson

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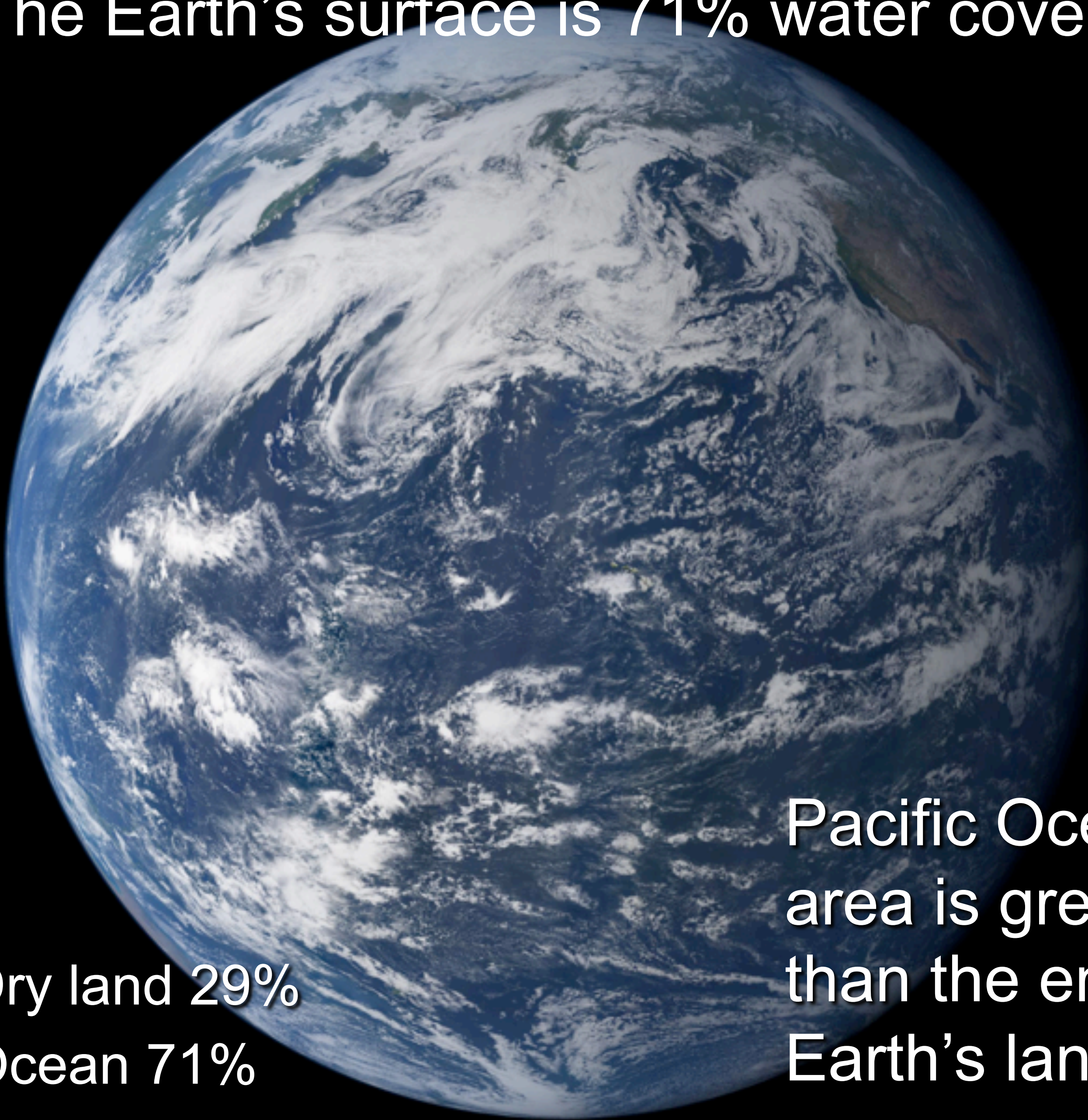
The U.S. imports >90% of 26 strategic and critical metals

China is the leading producer of 28 metals essential for high-tech and green-tech applications

2010 U.S. NET IMPORT RELIANCE FOR SELECTED NONFUEL MINERAL MATERIALS

Commodity	Percent	Major Import Sources (2006-09)[1]
ARSENIC (trioxide)	100	Morocco, China, Belgium
ASBESTOS	100	Canada
BAUXITE and ALUMINA	100	Jamaica, Brazil, Guinea, Australia
CESIUM	100	Canada
FLUORSPAR	100	Mexico, China, South Africa, Mongolia
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
INDIUM	100	China, Canada, Japan, Belgium
MANGANESE	100	South Africa, Gabon, China, Australia
MICA, sheet (natural)	100	China, Brazil, Belgium, India
NIOBIUM (columbium)	100	Brazil, Canada, Germany, Estonia
QUARTZ CRYSTAL (industrial)	100	China, Japan, Russia
RARE EARTHS	100	China, France, Japan, Austria
RUBIDIUM	100	Canada
STRONTIUM	100	Mexico, Germany
TANTALUM	100	Australia, China, Kazakhstan, Germany
THALLIUM	100	Russia, Germany, Netherlands
THORIUM	100	United Kingdom, France, India, Canada
YTTRIUM	100	China, Japan, France
GALLIUM	99	Germany, Canada, China, Ukraine
GEMSTONES	99	Israel, India, Belgium, South Africa
BISMUTH	94	Belgium, China, United Kingdom, Mexico
PLATINUM	94	South Africa, Germany, United Kingdom, Canada
ANTIMONY	93	China, Mexico, Belgium
GERMANIUM	90	Belgium, China, Russia, Germany
IODINE	88	Chile, Japan
RHENIUM	86	Chile, Netherlands
DIAMOND (dust, grit and powder)	85	China, Ireland, Russia, Republic of Korea
STONE (dimension)	85	Brazil, China, Italy, Turkey
POTASH	83	Canada, Belarus, Russia
COBALT	81	Norway, Russia, China, Canada
TITANIUM MINERAL CONCENTRATES	81	South Africa, Australia, Canada, Mozambique
SILICON CARBIDE	77	China, Venezuela, Netherlands, Romania
ZINC	77	Canada, Peru, Mexico, Ireland
BARITE	76	China, India
TIN	69	Peru, Bolivia, China, Indonesia
VANADIUM	69	Rep. of Korea, Czech Republic, Canada, Austria
TUNGSTEN	68	China, Canada, Germany, Bolivia
SILVER	65	Mexico, Canada, Peru, Chile
TITANIUM (sponge)	64	Kazakhstan, Japan, Ukraine, Russia
PEAT	59	Canada
PALLADIUM	58	Russia, South Africa, United Kingdom, Belgium
CHROMIUM	56	South Africa, Kazakhstan, Russia, China
MAGNESIUM COMPOUNDS	53	China, Austria, Canada, Brazil
BERYLLIUM	47	Kazakhstan, Kenya, Germany, Ireland
SILICON (ferrosilicon)	44	China, Russia, Venezuela, Canada
LITHIUM	43	Chile, Argentina, China
NICKEL	43	Canada, Russia, Australia, Norway
NITROGEN (fixed), AMMONIA	43	Trinidad and Tobago, Russia, Canada, Ukraine
ALUMINUM	38	Canada, Russia, China, Mexico
MAGNESIUM METAL	34	Canada, Israel, China, Russia
GOLD	33	Canada, Mexico, Peru, Chile
COPPER	30	Chile, Canada, Peru, Mexico

The Earth’s surface is 71% water covered



- Dry land 29%
- Ocean 71%

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

Potential Deep-Ocean Metal Resources

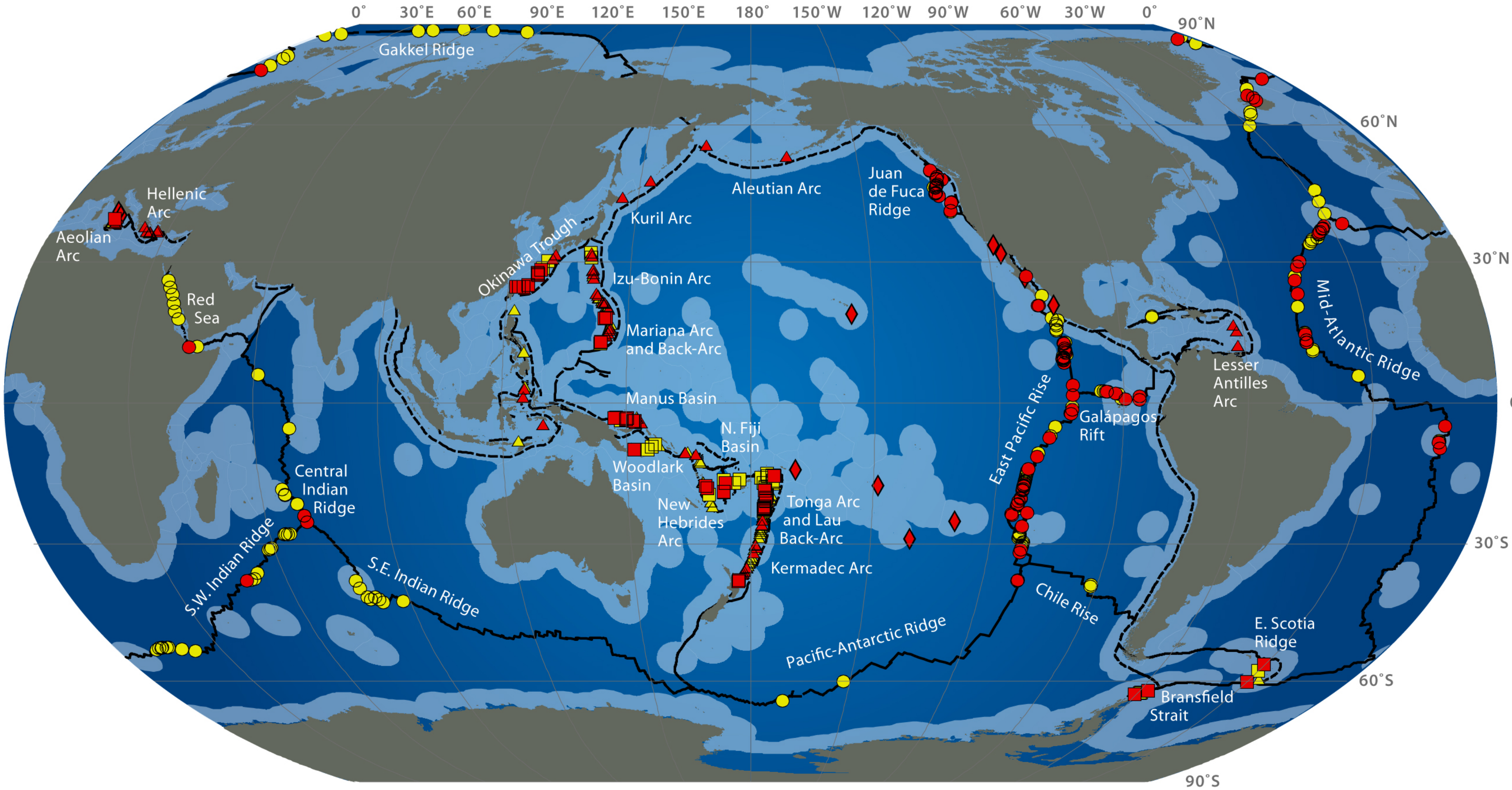
	Sulfides/ Sulfates	Fe-Mn Crusts	Manganese Nodules
Antimony	G	--	--
Bismuth	--	G	--
Cadmium	G	--	--
Cobalt	--	**G**	**G**
Copper	**G**	L	**G**
Gallium	G	--	--
Germanium	L	--	--
Gold	**G**	--	--
Indium	G	--	--
Lithium	--	--	G
Manganese	--	**G**	**G**
Molybdenun	L	G	G
Nickel	--	**G**	**G**
Niobium	--	G	--
Platinum	--	L	--
REEs	--	**G**	G
Selenium	L	--	--
Silver	**G**	--	--
Tellurium	L	**G**	--
Thorium	--	G	--
Titanium	--	G	L
Tungsten	--	G	G
Zinc	**G**	--	--
Zirconium	--	L	--

G = Good Potential L = Longer term Potential

Emerging and Next Generation 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

Global Distribution of Hydrothermal Vent Fields



Mid-ocean ridge	Arc volcano	Back-arc spreading center	Intra-plate volcano & Other	
Active	Active	Active	Active	Ridge & Transform
Unconfirmed	Unconfirmed	Unconfirmed		Trench
				Exclusive Economic Zones

64,000 km of spreading centers & intercontinental rifts
25,000 km of volcanic arcs & back-arc-basin spreading centers

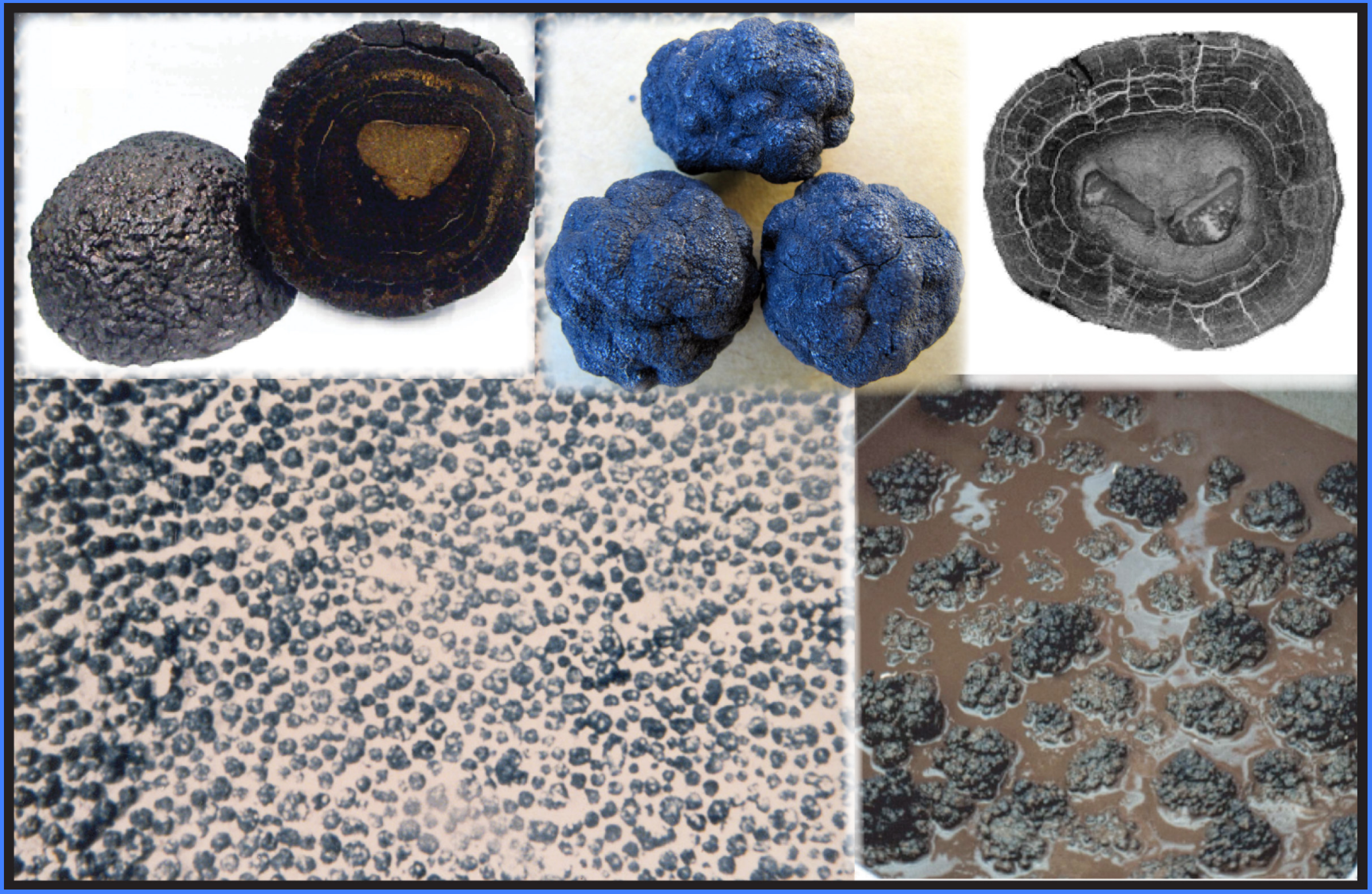
Rare metals in Seafloor Massive Sulfides

Gold
Silver

Antimony
Cadmium
Gallium
Germanium
Indium
Selenium

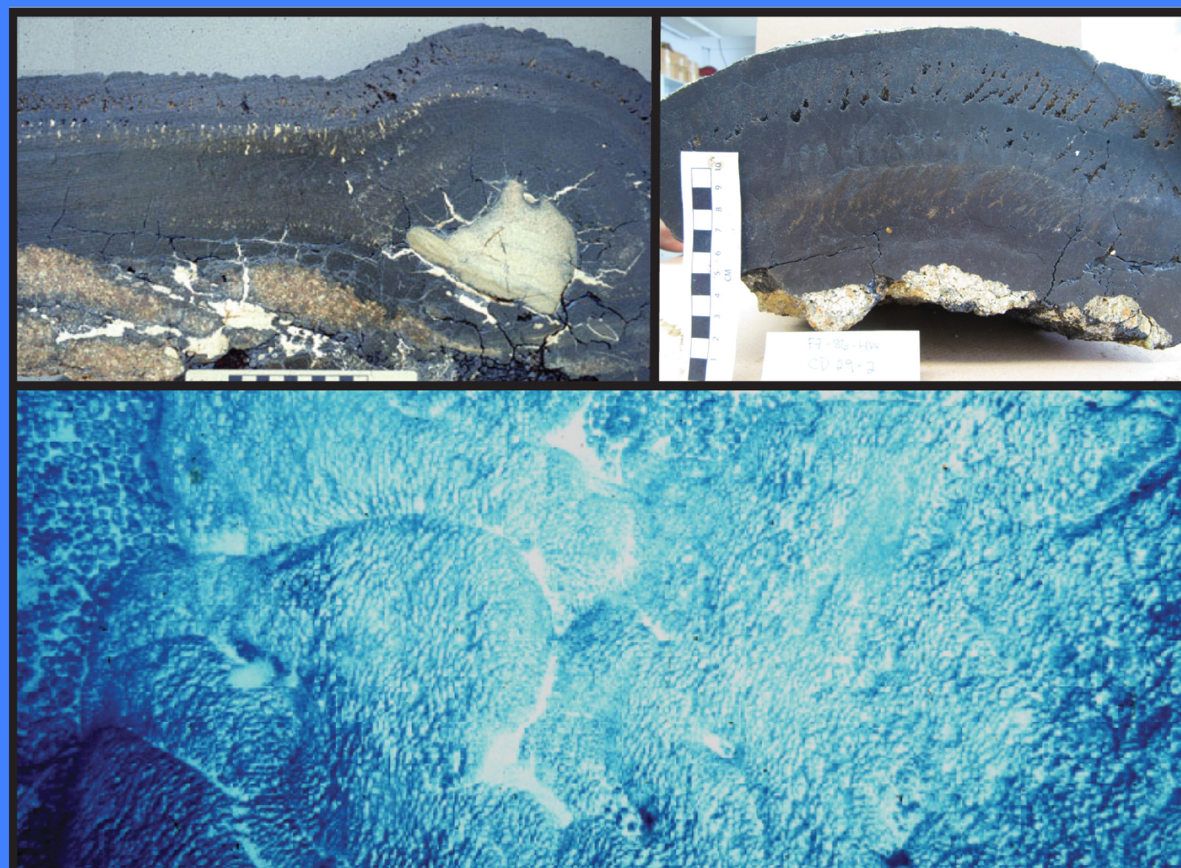
Rare Metals in Manganese Nodules

Rare-Earth Elements,
Lithium, Molybdenum, Zirconium



Rare Metals in Ferromanganese Crusts

Rare-Earth Elements
Bismuth
Niobium
Molybdenum
Platinum
Tellurium
Thorium
Zirconium



Challenges to Fe-Mn Crust Mining

- The largest impediment to exploration for Fe-Mn crusts is the real-time measurement of crust thicknesses with a deep-towed instrument

- The largest physical impediment to ore recovery is separation of Fe-Mn crusts from substrate rock that occurs on an uneven and rough seabed

Ferromanganese crusts provide the richest source of tellurium (Te) known (Hein et al., 2003)

"Finding enough Te for CdTe is the largest barrier to the multi-terawatt use of CdTe for solar-cell electricity. It is widely regarded as the lowest cost photovoltaic technology with the greatest potential. This is important to the US and the world" (Ken Zweibel, National Renewable Energy Laboratory)

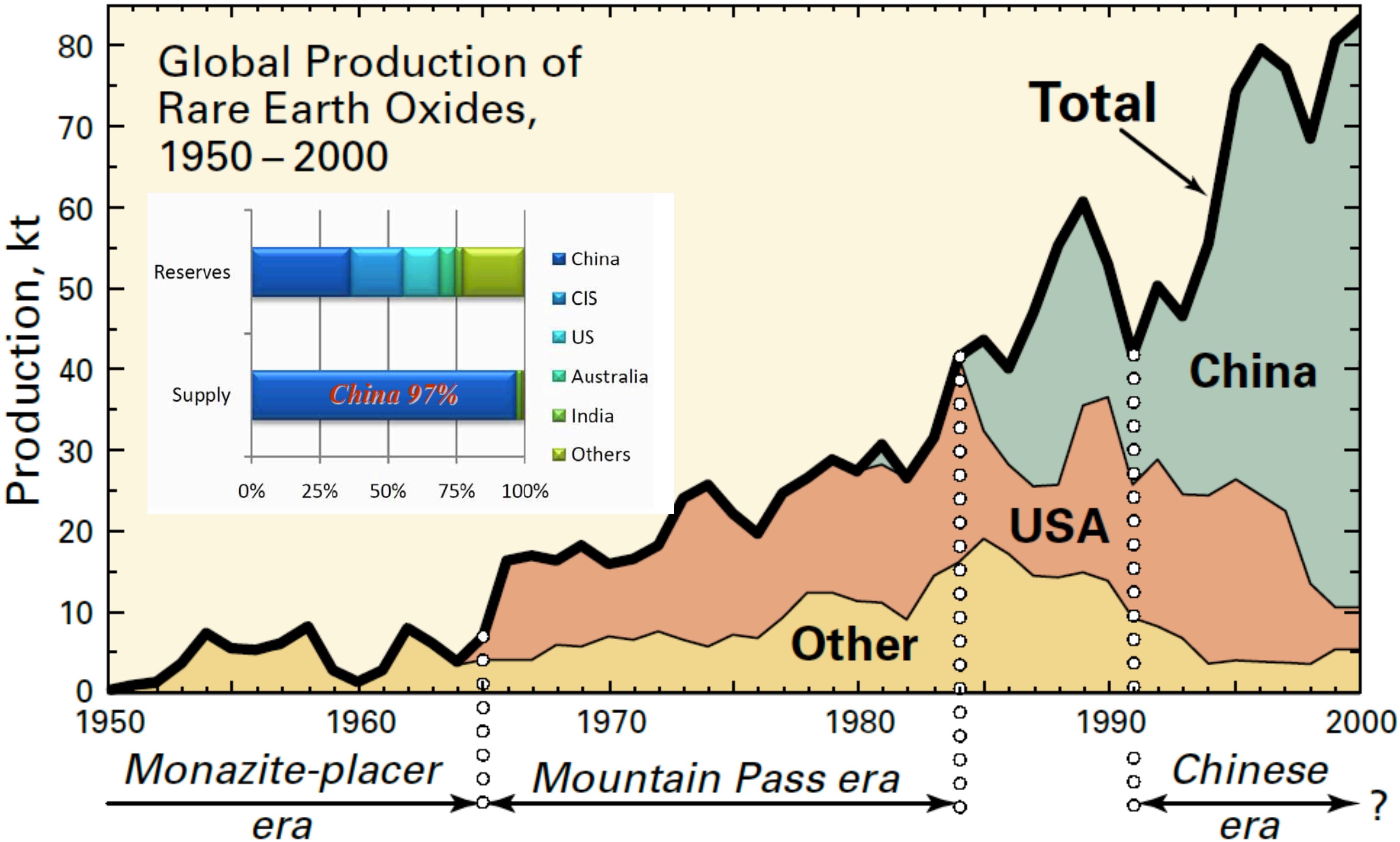
Light Rare-Earth Elements

- Lanthanum: FCC catalyst, hybrid car batteries, green phosphor
- 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

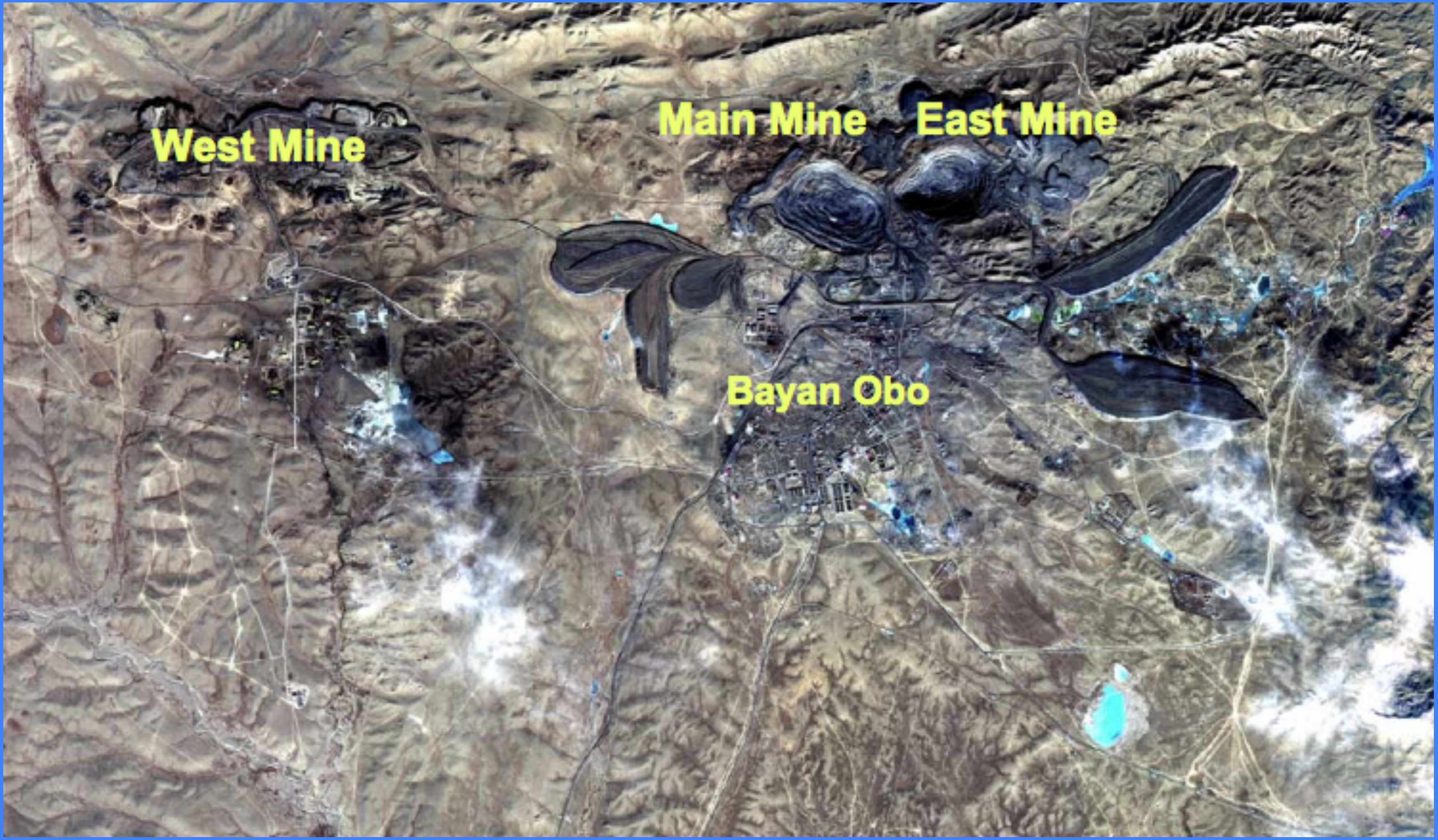
- Europium: Flat screen displays and lasers, fluorescent phosphors: red & blue
- Gadolinium: Shielding for nuclear reactors, compact discs, MRI
- Terbium: Compact fluorescent lights, magneto-optic recording
- Dysprosium: Hybrid vehicle motors, Nd-Fe-B magnets
- Holmium: Nuclear control rods, ultra-powerful 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

Global Production of REEs



From USGS REE fact sheet

Mine Site is 18 km long and 2-3 km wide; note waste-rock dumps



Light versus Heavy REEs

Bayan Obo & Mountain Pass average less than 1% HREEs

PCZ averages 7.0% HREEs
CCZ averages 10% HREEs

Primary Ore Versus Byproduct Production

Land-based: REE predominantly primary ore

PCZ: Byproduct of Co and Ni mining

CCZ: Byproduct of Ni and Cu mining

Thorium Concentrations

Bayan Obo and Mountain Pass contain 100s ppm Th

PCZ averages 11 ppm Th

CCZ averages 14 ppm Th

Extractive Metallurgy

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

Marine FeO(OH) and MnO_2 can be dissolved with simple HCl leach putting all sorbed REEs into solution

SCIENTIFIC AMERICAN

Sea Holds Treasure Trove of Rare-Earth Elements

Survey reveals wealth of important metals in ocean floor mud.

| July 3, 2011 | 4

July 3, 2011

The Ocean Law Daily

"Security, Sovereignty, Sustainability - the Law of the Sea Convention"

July 8, 2011

Here We Go Again: Riches in the Mud?

Wishful Thinking: the Deep Seabed and Rare Earth Mud

July 9, 2011

SCIENTIFIC AMERICAN

Experts Skeptical about Potential of Rare-Earth Elements in Seafloor Mud

BBC NEWS

BBC Home > BBC News > Asia-Pacific

Menu

Japan finds rare earths in Pacific seabed

04 July 11 00:58 ET

Japanese researchers say they have discovered

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nature geoscience

LETTERS

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

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]

Is there a resource Potential?

Highly unlikely!

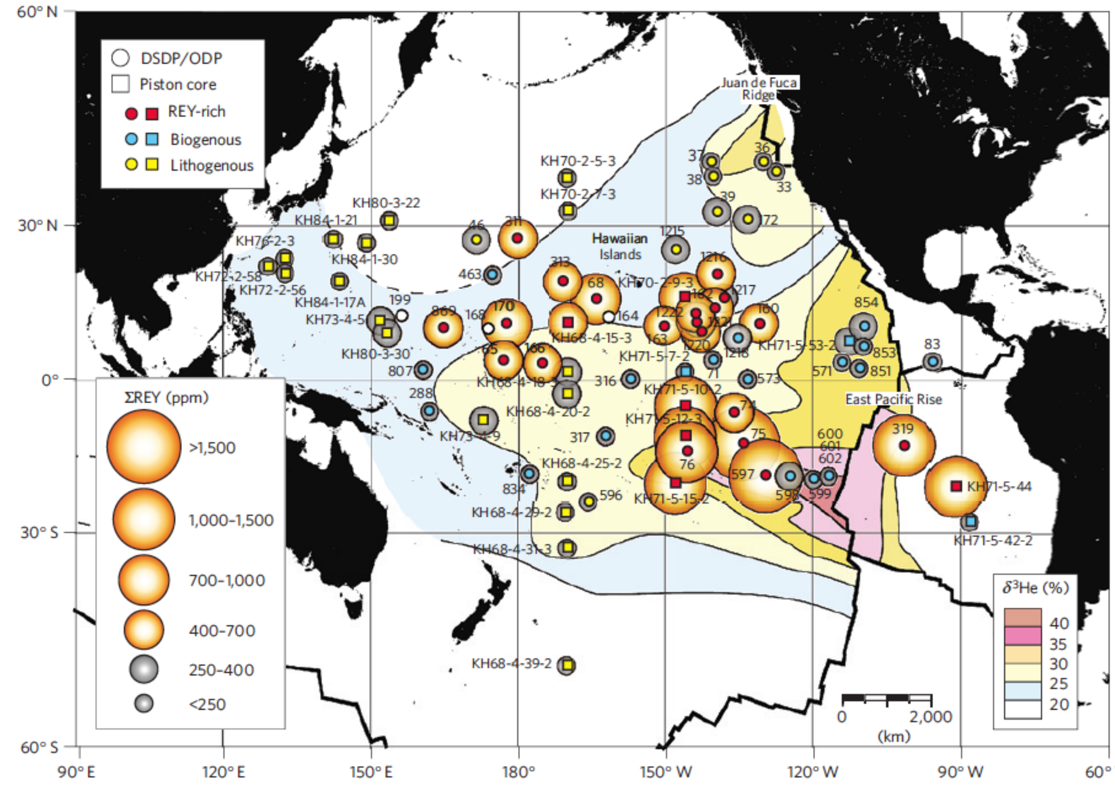

Figure 1 | Distribution of average ΣREY contents for surface sediments (<2 m in depth) in the Pacific Ocean. Circles represent DSDP/ODP sites and

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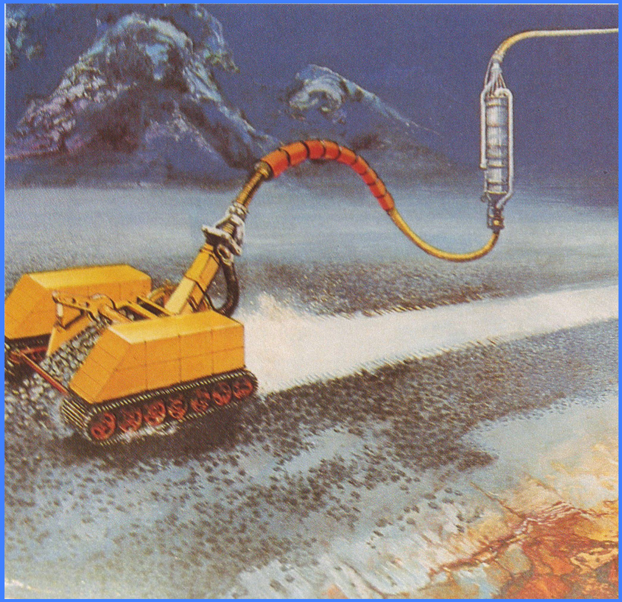
Potential social and environmental advantages for recovery of deep-ocean minerals



- **Land-based mines leave a substantial footprint, impacted waterways, carbon emissions from heavy machinery, and millions to tons of waste rock**
- **Marine-based mine sites have no roads, surface ore-transport systems, buildings, or other infrastructure**

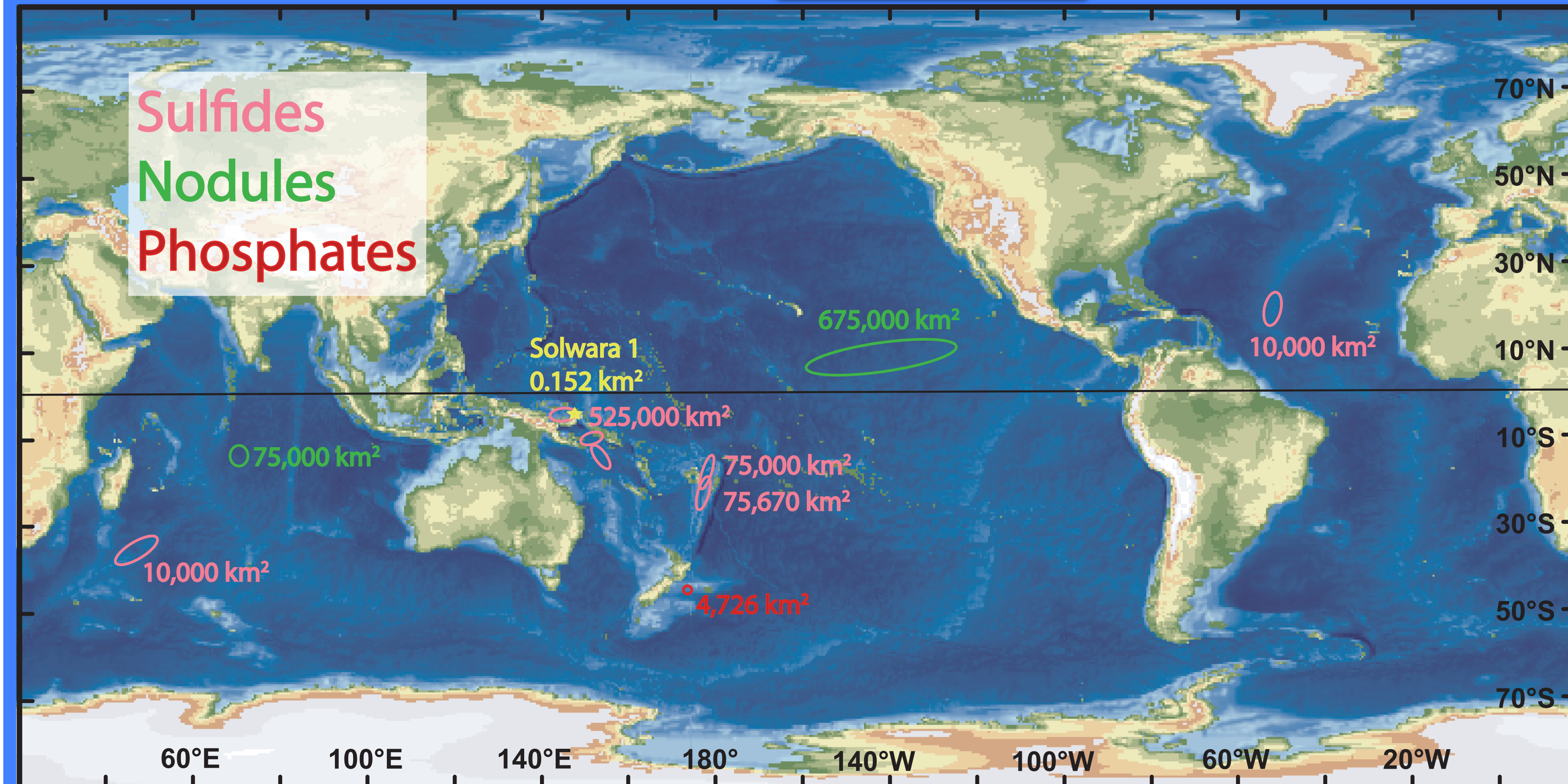
Potential social and environmental advantages for recovery of deep-ocean minerals

- 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
- No indigenous or native populations to disrupt
- Ecosystems with generally low population densities and low diversity

Potential cconomic advantages to companies

- Lower capital start-up costs
- Moveable mining platform
- Smaller deposits can be mined
- High metal grades

Licenses for Marine Minerals Exploration Total 1,450,000 km²



Total lease area equivalent to 3.4 Californias

Yellow shows the location of the only mining license

All SW Pacific licenses in EEZs, all others in The Area

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