THE UNIVERSITY OF TOKYO

Current status of rare earth production in China and recycling in Japan

Institute of Industrial Science,
The University of Tokyo
Toru H. Okabe

'Current status of rare earth production in China and recycling in Japan', Toru H. Okabe:
REE4EU Project
REE4EU Exploitation Workshop
Presentation in the exploitation workshop with external industry and EU-policy participation, Wednesday 24th April, (45 min)
[April 22-25, 2019, Stakeholders workshop, 24 April 2019, Avenue de la joyeuse Entrée 1, 4thfloor, 1040 Brussels, Belgium] (2019. 4. 24).
[Invited presentation]

Recovery of Rare Metals at Okabe's Group-University of Tokyo

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[Invited presentation]

Current Status on Resource and Recycling Technology for Rare Earths

OSAMU TAKEDA and TORU H. OKABE

The development of recycling technologies for rare earths is essential for resource security and supply stability because high-quality rare earth mines are concentrated in China and the demand for rare earth metals such as neodymium and dysprosium, used as raw materials in permanent magnets (neodymium magnet), is expected to increase rapidly in the near future. It is also important to establish a recycling-based society from the perspective of the conservation of finite and valuable mineral resources and the reduction of the environmental load associated with mining and smelting. In this article, the current status of rare earth resource as well as that of recycling technology for the magnets is reviewed. The importance of establishing an efficient recycling process for rare earths is discussed from the characteristics of supply chain of rare earths, and the technological bases of the recycling processes for the magnet are introduced. Further, some fundamental researches on the development of new recycling processes based on pyrometallurgical process are introduced, and the features of the recycling processes are evaluated.

DOI: 10.1007/s40553-014-0016-7

Osamu Takeda and Toru H. Okabe,
'Current Status on Resource and Recycling Technology',
METALLURGICAL AND MATERIALS TRANSACTIONS
E, vol. 1A, June (2014) pp.160-173.

I. INTRODUCTION

PROBLEMS related to, for example, economy and resource supply are generally the focus of studies on material flow and the recycling of metal resources. Rare metals, especially rare earths (or rare earth elements) are often a major topic in discussions of trade and economic challenges because they are intricately related to resource nationalism, territorial disputes, business issues in venture speculation, foreign and domestic affairs, and environmental burden.

In recent years, the heightened general interest in rare metals, which are often essential resources in high-tech industries, has led to rapid progress in quantity-based

materials. Some of these waste materials are recycled and reused when they possess economic efficiency. However, it is often economically unfeasible to recycle rare metals from waste products, and these materials are frequently disposed of in landfills.

"Economic value" is typically used to evaluate the value of metals, particularly in countries that prioritize economic principles. As a result, rare earths contained in industrial products are typically not recycled. However, the environmental cost generated through the production of metal and the "fundamental value" (or value of nature) of the finite mineral resources from which those metals were initially produced should be considered. Therefore, fundamental issues, including the essential

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IOM3 The Institute of Materials, Minerals and Mining

AusIMM THE MINERALS INSTITUTE

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Bottlenecks in rare metal supply and the importance of recycling – a Japanese perspective

Toru H. Okabe

Integrated Research Center for Sustainable Energy and Materials, Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

ABSTRACT
Rare metals are less common metals that are generally perceived to be scarce. The media often presents one-track thinking on the depletion of mineral resources. Despite this common notion, the supply of most rare metals – including rare earth metals (REMs) – in terms of the amount of minerals available in known deposits is not a serious problem. Key factors that determine the supply of rare metals are the costs of mining and smelting and related environmental destruction. These are the major practical constraints, rather than the amount of mineral deposits in the earth. When extracting rare metals from recycled feed material, harmful wastes generated from natural ore processing can be avoided. This is the primary advantage of the cyclical use of rare metal resources. In this article, bottlenecks of rare metal supply, and the importance of recycling, are discussed, using REMs as an example.

ARTICLE HISTORY
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KEYWORDS
Rare metals; REMs; bottlenecks; supply chain; recycling; environmental destruction

'Bottlenecks in Rare Metal Supply and the Importance of Recycling - a Japanese Perspective', Toru H. Okabe:
Mineral Processing and Extractive Metallurgy, vol.126, no.1-2, (2017) pp.22-32.

1. Introduction

Most of the things that generate wealth, including rare metals, have good and bad aspects: light and shadow.

2. Misconceptions of the general public about rare metals

From the words 'rare metals', the majority of the public

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[Invited presentation]

Why do we have to recycle rare metals?

Current status of rare earth production in China and recycling in Japan

NORM:
Naturally Occurring Radioactive Materials

Goldschmidt's classification of elements

Relationship between main products and by-products.

Value of nature

Why do we have to recycle rare metals?

What will be the bottlenecks of rare metal supply?

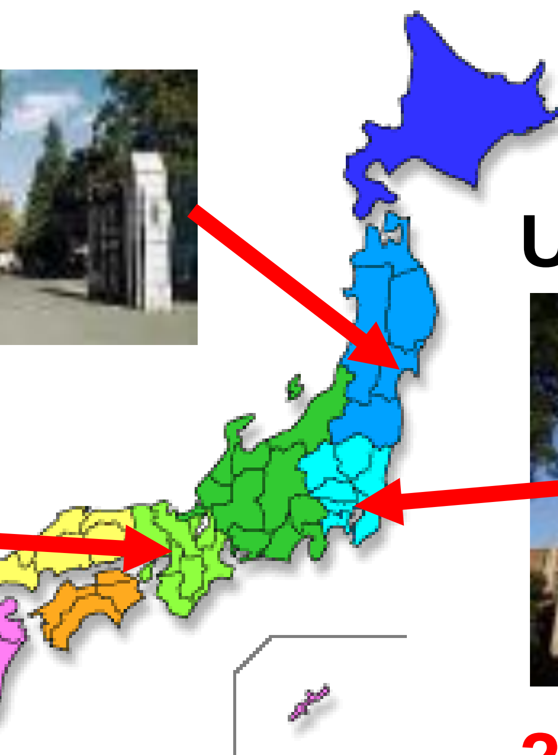
Dr. Toru H. Okabe's footmark

MIT, Boston

1993～1995

Tohoku University

1995～2000



University of Tokyo

Kyoto University

1984～1993

2001～

1984～1993 Kyoto Univ. (Student)

B: Ti

M: Ti

D: Nb, Ta, (Ti, Y, …)

1993～1995 MIT (Postdoc)

Ta, (Al, …)

30 years of refining and recycling research on rare metals or minor metals

1995～2000 Tohoku University (Res. Assciate)

Waseda Lab: Ti, Nb, Ta, REMs (La, Pr, Dy, Tb…)

Umetsu Lab: Mo, Re, Ag, Cu, Ti, REMs (Nd) …

2001～ Univ. of Tokyo (Assoc. Prof. → Prof.)

Initial: Nb, Ta, PGMs (Pt, Rh)

Currently: Ti, Sc, V, PGMs (Pt, Rh, Ru, Ir, …)

Nb, Ta, REMs (Nd, Dy, …), W, Re…

The University of Tokyo

The University of Tokyo, established in 1877

Faculty: 2,429

Staff: 5,779

Students: 28,753

Undergraduates: 14,274

Postgraduates: 13,732

Doctoral students: 6,022

11 research institutes

Institute of Medical Science, Earthquake Research Institute, Institute of Oriental Culture, Institute of Social Science, Institute of Industrial Science, Historiographical Institute, Institute of Molecular and Cellular Biosciences, Institute for Cosmic Ray Research, Institute for Solid State Physics, Ocean Research Institute, Research Center for Advanced Science and Technology

Institute of Industrial Science
The University of Tokyo

Institute of Industrial Science
The University of Tokyo

東京大学　生産技術研究所

One of the biggest research institute in Japan:

Consisted of one hundred independent Labs.





Okabe Lab.

Resource Recovery and Materials Process Engineering Laboratory

Process development of value added inorganic materials.

Development of new titanium production process

Production of rare metal powder (Nb, Ta) production for electronic application

Recycling of valuable metals (e.g. PGMs)

http://www.okabe.iis.u-tokyo.ac.jp/

New production process of less-common metals

$$TiO_2 + 4\,e^- \xrightarrow[\text{molten salt}]{} Ti + 2\,O^{2-}$$

$$TiCl_2 + Mg \rightarrow Ti + MgCl_2$$

$$Nb_2O_5 + 5\,Mg \xrightarrow[\text{with flux}]{} 2\,Nb + 5\,MgO$$

$$Sc_2O_3 + Al + 6\,e^- \xrightarrow[\text{molten salt}]{} Al\text{-}Sc + 3\,O^{2-}$$

Resource Recovery and
Materials Process Engineering Laboratory

Future Materials: Titanium / Rare Metals

未来材料：チタン･レアアメタル

Process research on new materials with full of dream

夢とロマンに満ちた新素材プロセスの研究

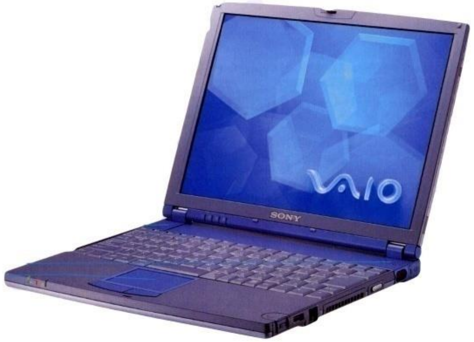
http://www.okabe.iis.u-tokyo.ac.jp

Environmental problems related to rare metals, and importance of recycling

Institute of Industrial Science,
The University of Tokyo
Toru H. Okabe

"Environmental problems related to
rare metals, and importance of recycling"
Toru H. Okabe,
Lecture at Apple, Building 5, Infinite Loop, Cupertino,
[11:00-12:00] (2016.12.1) [Invited lecture]

Recently less-common metals (or, rare metals) are getting important



REMs (Nd, Dy, Sm, ...):
Hard disk for PCs, vibrators of mobile phones, motors for hybrid vehicles

PGMs (Pt, Rh, Pd,…):
Catalyst for automobile, and fuel cells

In: Transparent electrodes for displays

Ga: Blue diodes

Ta: High performance capacitors

Li: High performance batteries

Definition of less-common metals (or rare metals) is….

Metal with rare resources (an element with a little abundance)

→**PGMs, In, Ga, Ta, Dy, …**

Metal difficult to produce even with rich mineral abundance

→**Ti, Si, Mg, Li, (Nb)…**

Metal obtained from extremely low grade ore even with rich elemental abundance

→**Sc, V, …**

What is less-common metals (, or rare metals) ?

The Periodic Table of the Elements

Rare Metals

Rare Metals (Broad category)

Elements studied at Okabe lab.

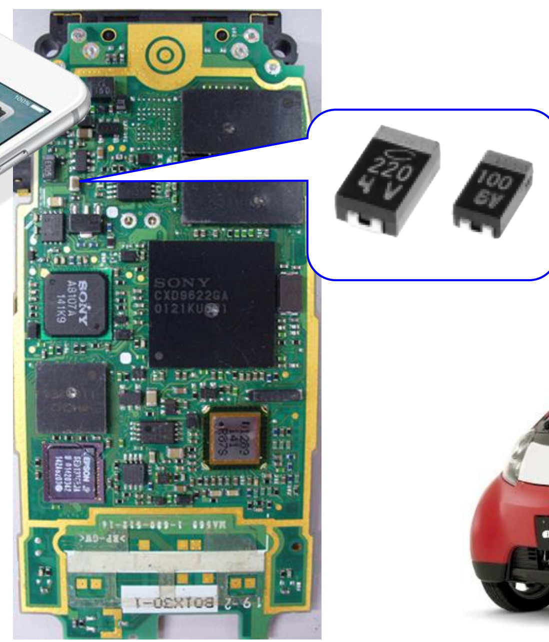
I A	II A	III B	IV B	V B	VI B	VII B	VIII B			I B	II B	III A	IV A	V A	VI A	VII A	VIII A
Hydrogen 1 H 1.008																	Helium 2 He 4.003
Lithium 3 Li 6.941	Beryllium 4 Be 9.012											Boron 5 B 10.81	Carbon 6 C 12.01	Nitrogen 7 N 14.01	Oxygen 8 O 16.00	Fluorine 9 F 19.00	Neon 10 Ne 20.18
Sodium 11 Na 22.99	Magnesium 12 Mg 24.31											Aluminium 13 Al 26.98	Silicon 14 Si 28.09	Phosphorus 15 P 30.97	Sulfur 16 S 32.07	Chlorine 17 Cl 35.45	Argon 18 Ar 39.95
Potassium 19 K 39.10	Calcium 20 Ca 40.08	Scandium 21 Sc 44.96	Titanium 22 Ti 47.87	Vanadium 23 V 50.94	Chromium 24 Cr 52.00	Manganese 25 Mn 54.94	Iron 26 Fe 55.85	Cobalt 27 Co 58.93	Nickel 28 Ni 58.69	Copper 29 Cu 63.54	Zinc 30 Zn 65.39	Gallium 31 Ga 69.72	Germanium 32 Ge 72.61	Arsenic 33 As 74.92	Selenium 34 Se 78.96	Bromine 35 Br 79.90	Krypton 36 Kr 83.80
Rubidium 37 Rb 85.47	Strontium 38 Sr 87.62	Yttrium 39 Y 88.91	Zirconium 40 Zr 91.22	Niobium 41 Nb 92.91	Molybdnum 42 Mo 95.94	Technetium 43 Tc (99)	Ruthenium 44 Ru 101.1	Rhodium 45 Rh 102.9	Palladium 46 Pd 106.4	Silver 47 Ag 107.9	Cadmium 48 Cd 112.4	Indium 49 In 114.8	Tin 50 Sn 118.7	Antimony 51 Sb 121.8	Tellurium 52 Te 127.6	Iodine 53 I 126.9	Xenon 54 Xe 131.3
Caesium 55 Cs 132.9	Barium 56 Ba 137.3	Lutetium 71 Lu 175	Hafnium 72 Hf 178.5	Tantalum 73 Ta 180.9	Tungsten 74 W 183.8	Rhenium 75 Re 186.2	Osmium 76 Os 190.2	Iridium 77 Ir 192.2	Platinum 78 Pt 195.1	Gold 79 Au 197.0	Mercury 80 Hg 200.6	Thallium 81 Tl 204.4	Lead 82 Pb 207.2	Bismuth 83 Bi 209.0	Polonium 84 Po (210)	Astatine 85 At (210)	Radon 86 Rn (222)
Francium 87 Fr [illegible]	Radium 88 Ra [illegible]	Lawrencium 103 Lr [illegible]	Rutherfordium 104 Rf [illegible]	Dubnium 105 Db [illegible]	Seaborgium 106 Sg (263)	Bohrium 107 Bh [illegible]	Hassium 108 Hs [illegible]	Meitnerium 109 Mt [illegible]									

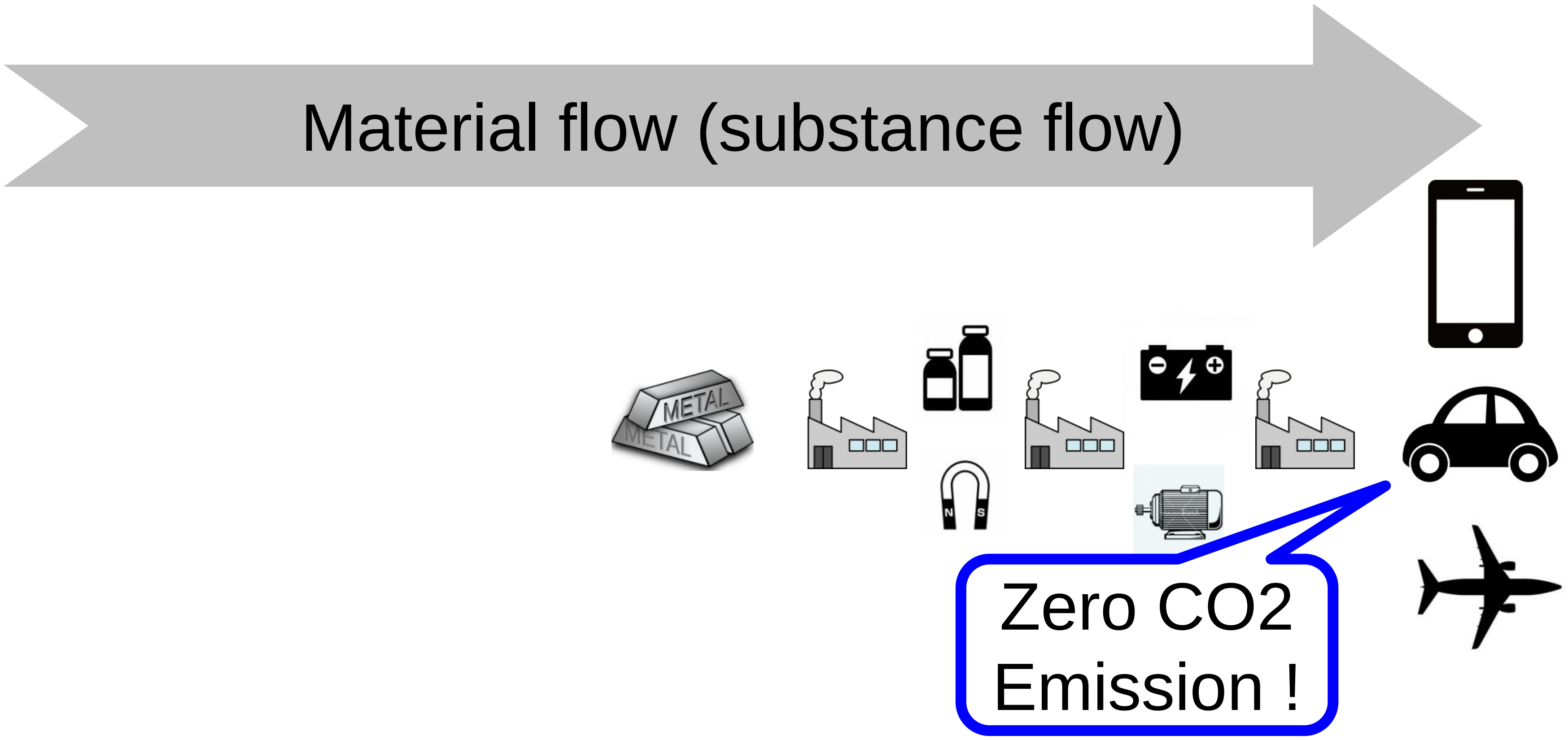
Most of the elements are rare metals

Lanthanide	Lanthanum 57 La 138.9	Cerium 58 Ce 140.1	Praseodymium 59 Pr 140.9	Neodymium 60 Nd 144.2	Promethium 61 Pm (145)	Samarium 62 Sm 150.4	Europium 63 Eu 152.0	Gadolinium 64 Gd 157.3	Terbium 65 Tb 158.9	Dysprosium 66 Dy 162.5	Holmium 67 Ho 164.9	Erbium 68 Er 167.3	Thulium 69 Tm 168.9	Ytterbium 70 Yb 173.0
Actinide	Actinium 89 Ac (227)	Thorium 90 Th 232.0	Protactinium 91 Pa 231.0	Uranium 92 U 238.0	Neptunium 93 Np (237)	Plutonium 94 Pu (239)	Americium 95 Am (243)	Curium 96 Cm (247)	Berkelium 97 Bk (247)	Californium 98 Cf (252)	Einsteinium 99 Es (252)	Fermium 100 Fm (257)	Mendelevium 101 Md (258)	Nobelium 102 No (259)

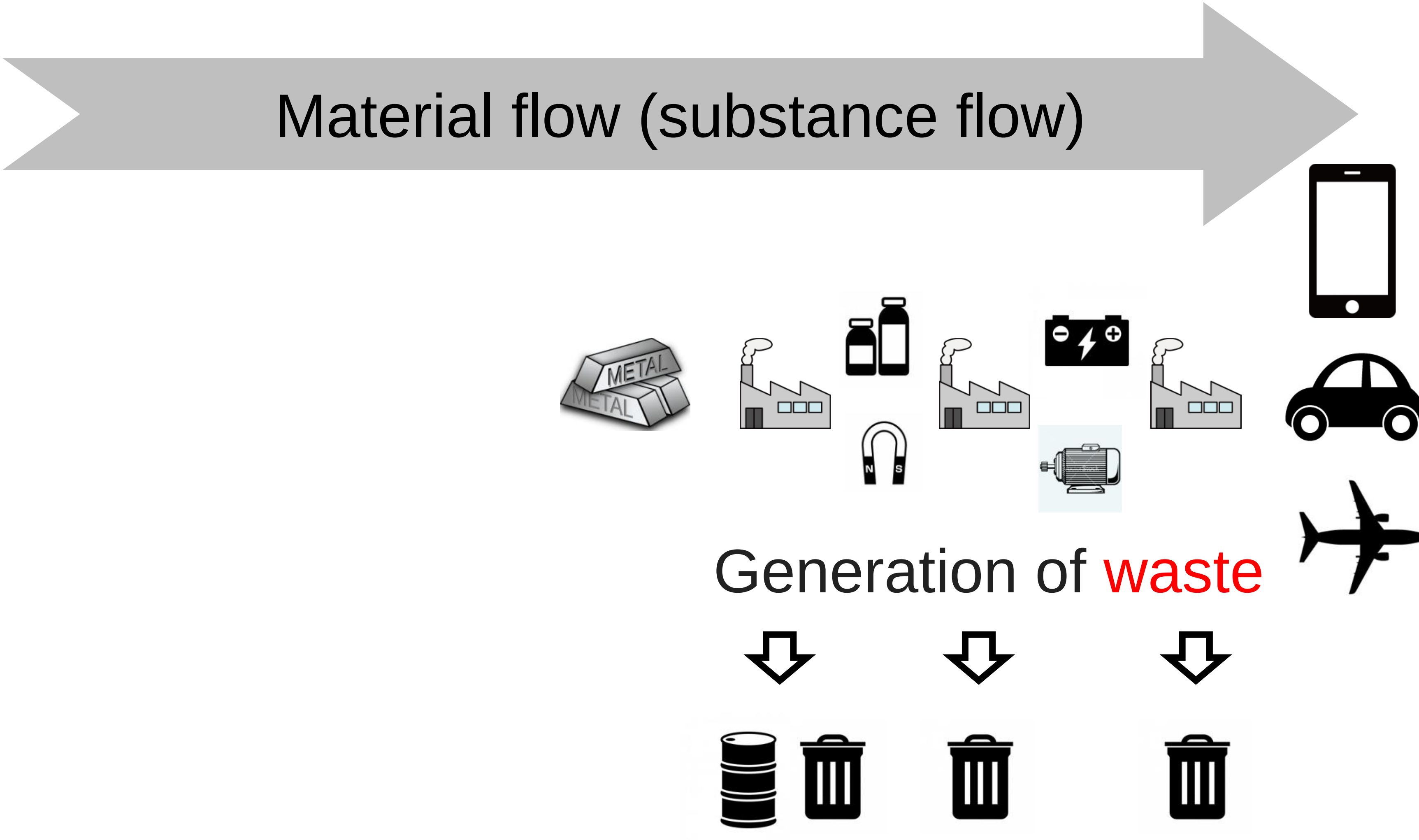
Rare Metals

PGMs, REMs, Ga, Ta…

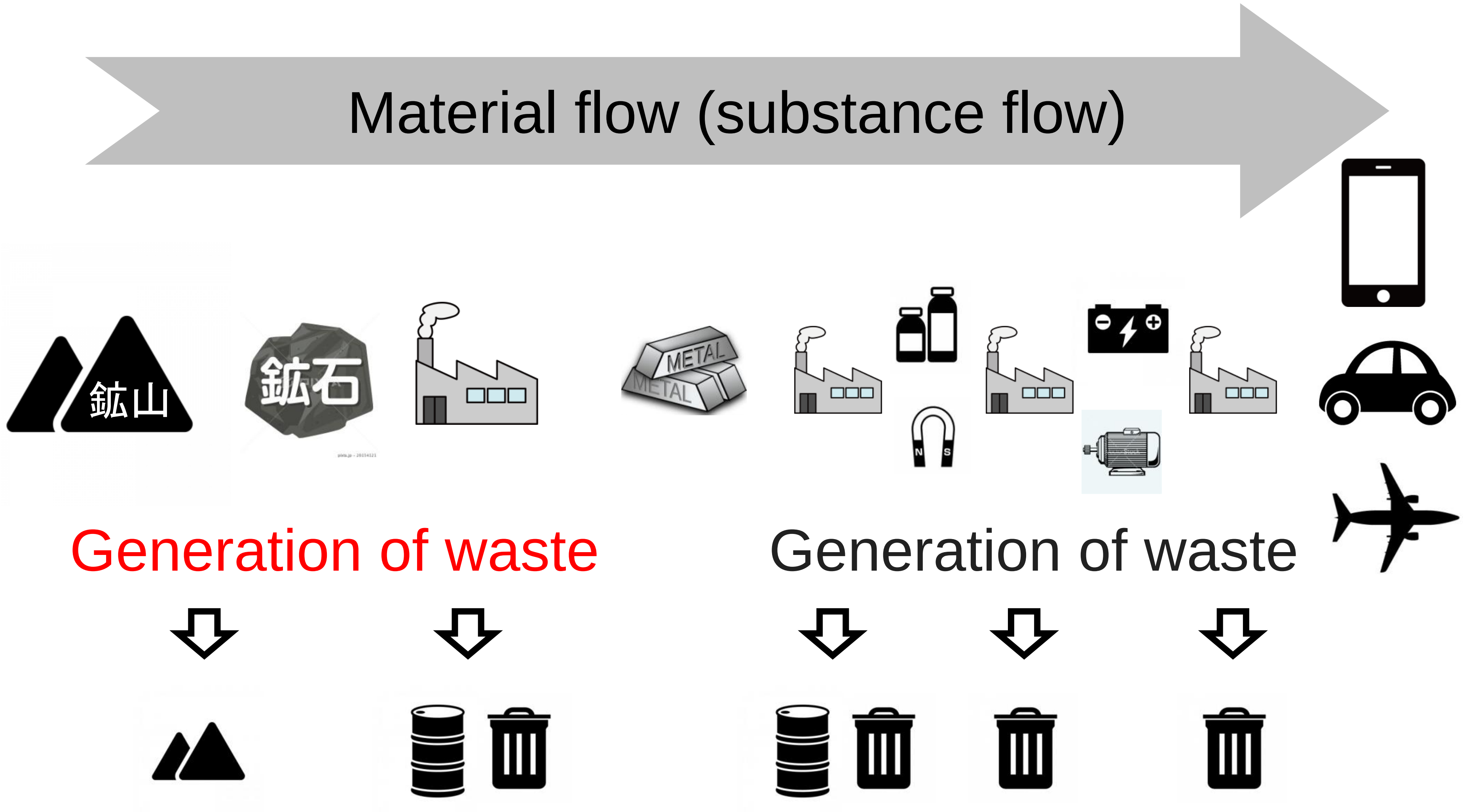




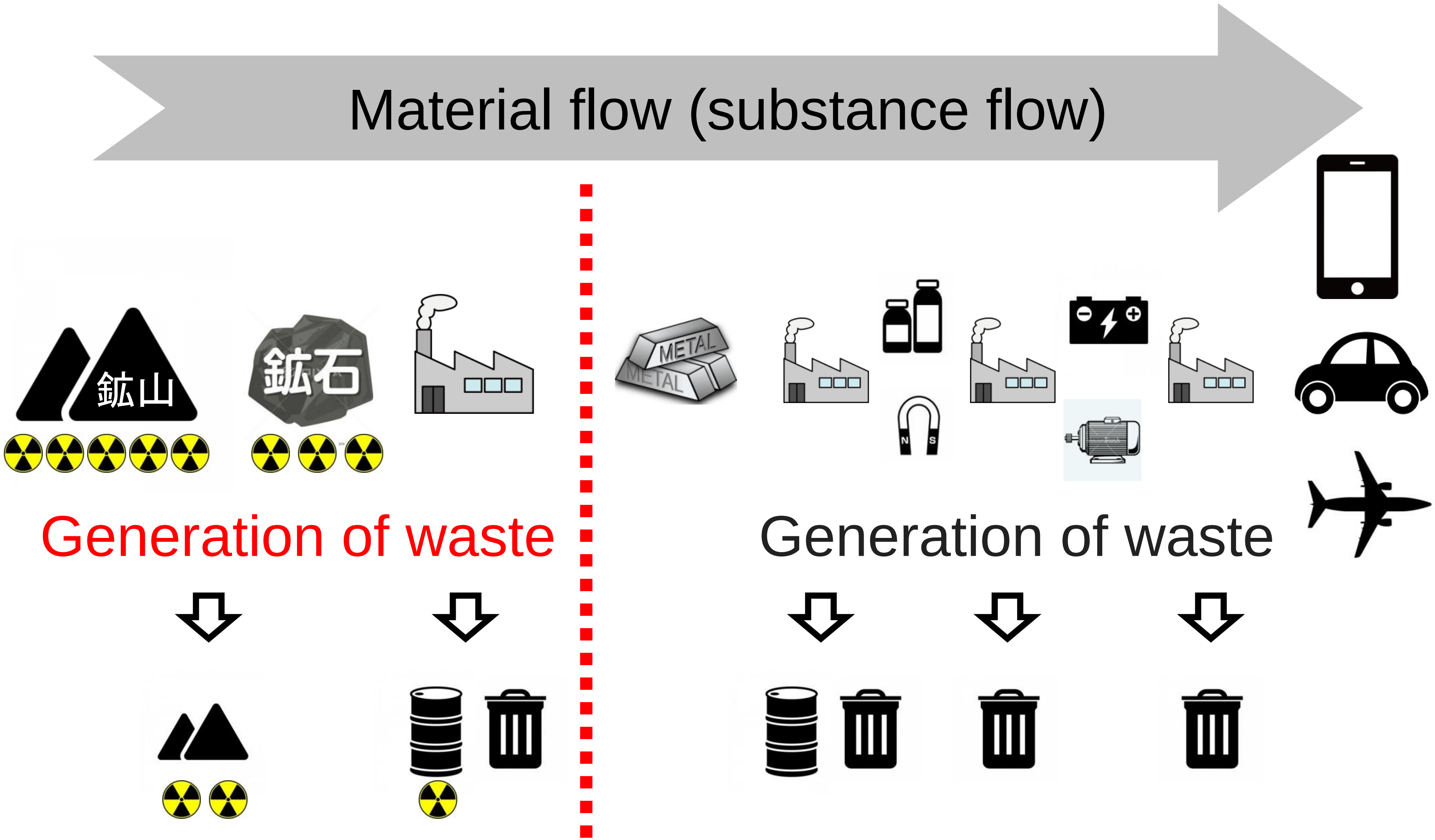
People in developed countries import rare metals from overseas, and produce high-performance or high-tech products. They believe that it contributes to the environment…



People also know that wastes are generated when making things.



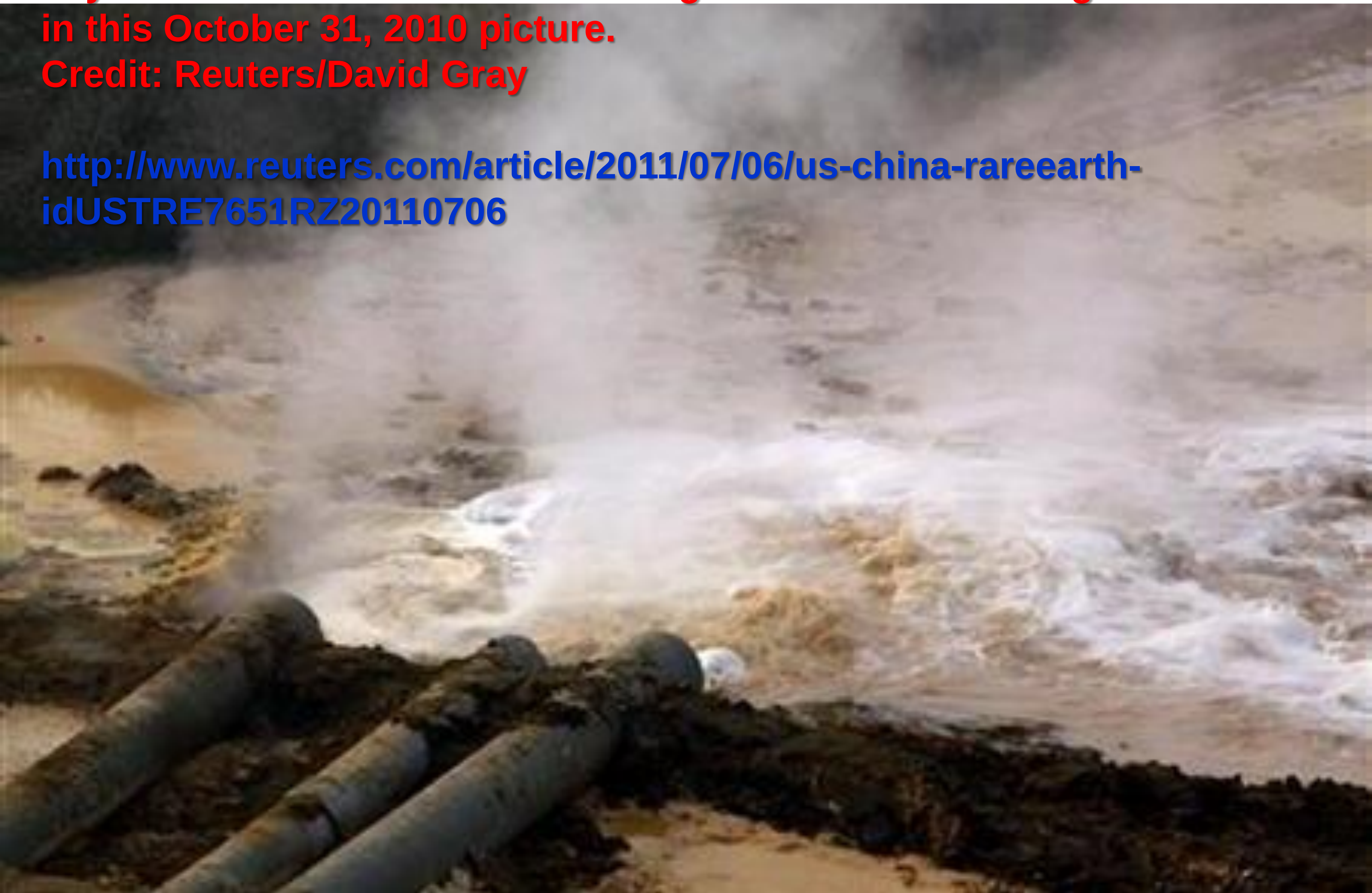
Some people can imagine that an enormous amount of waste is generated in mining and smelting



Most of the people do not know that serious environmental destruction occurs when mining or smelting.

Pipes coming from a rare earth smelting plant spew polluted water into a vast tailings dam near Xinguang Village, located on the outskirts of the city of Baotou in China's Inner Mongolia Autonomous Region in this October 31, 2010 picture.
Credit: Reuters/David Gray

http://www.reuters.com/article/2011/07/06/us-china-rareearth-idUSTRE7651RZ20110706

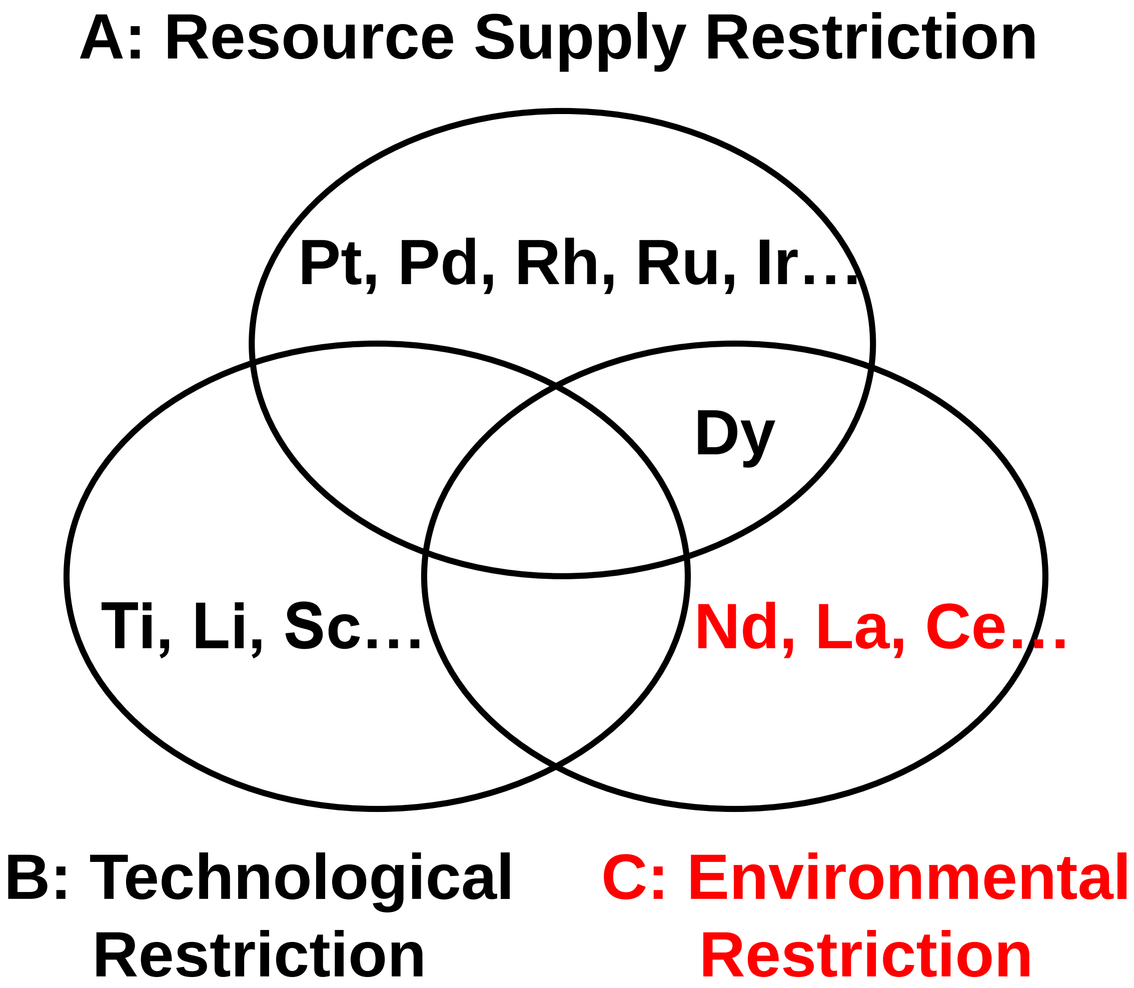


**Regarding the production and supply of rare metals,
the main three items to consider bottlenecks are as follows:**

A: Resource Supply Restriction

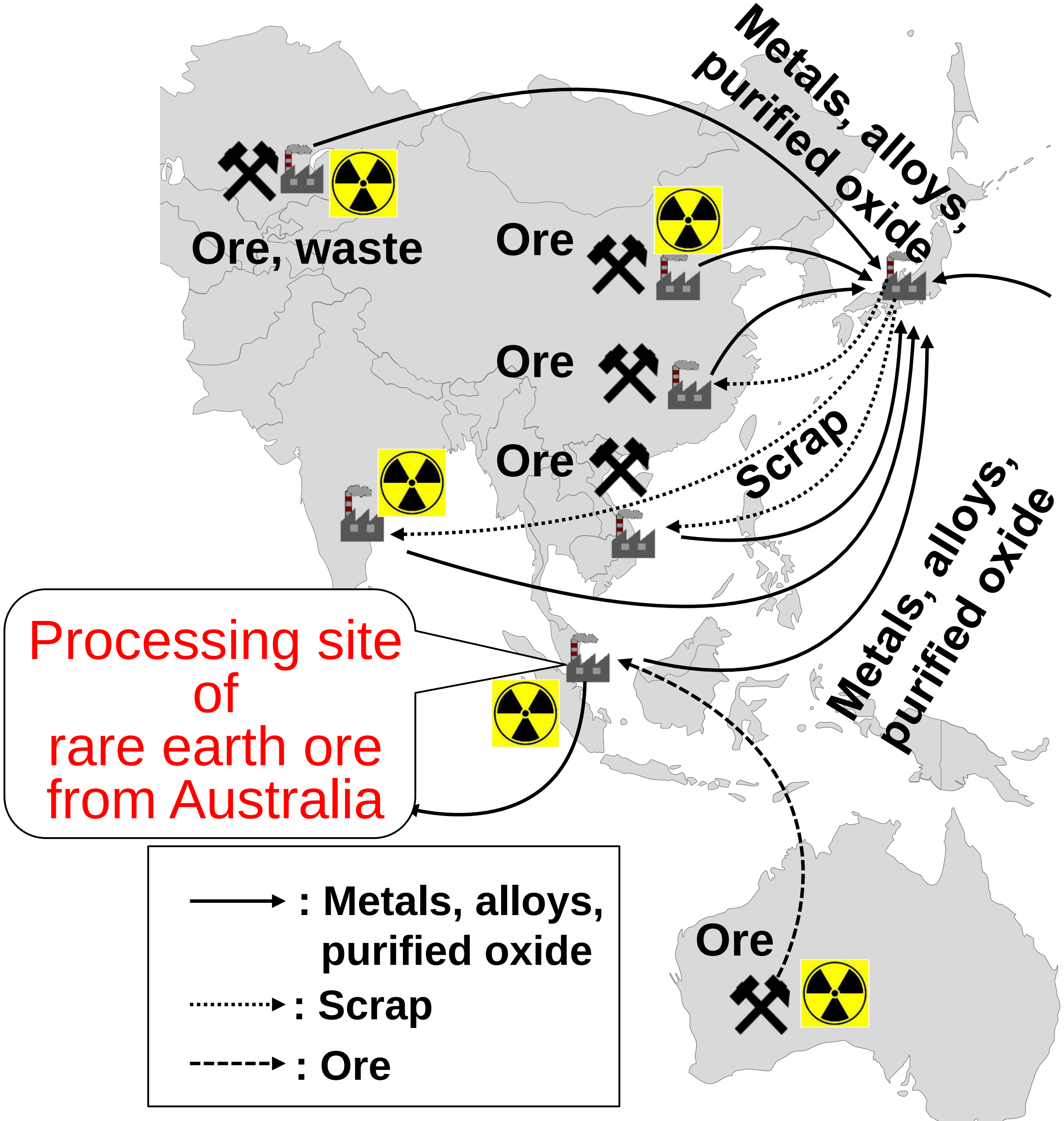
B: Technology Restriction

C: Environmental Restriction



← Only this item "A" attracts attention in the media, and the technical and environmental restrictions are not reported much. (Business companies also often have trouble with "B" and "C" if they are reported.)

Fig. Key factors that determine rare metal supply.
Environmental and technological restrictions are the major practical constraints, not the resource supply restriction, especially for rare earth metals and many other rare metals.



Supply problems for rare metals depending on the ubiquity of the country of supply and region.

However, this is not a resource problem, but rather an environmental issue.

Fig. Global material flow for production of metals and alloys of rare earth metals and waste treatment of the scrap.

Recent projects:
Development of new recovery process of rare metals from scraps

Rare Metals

Environmentally sound technology for producing and recycling less-common metals

What is your interest?

1. Environmental problems related to metal production?
2. Mining / Smelting situation in China?

3. Recycling technologies related to metal?
4. Japanese companies' R&D activities?
5. Okabe's recent research ?

6. Future trends on recycling of metals and environmental issues?

More questions…

1. Have you visited metal mine?

    (e.g. Bingham Mine, Mt. Pass, …)

2. Have you visited metal smelting/refining plant?

3. Have you seen waste dumping site?

4. Are there any one who visited metal recycling plant?

Recently less-common metals (or, rare metals) are getting important



REMs (Nd, Dy, Sm, ...):
Hard disk for PCs, vibrators of mobile phones, motors for hybrid vehicles

PGMs (Pt, Rh, Pd, ...):
Catalyst for automobile, and fuel cells

In: Transparent electrodes for displays

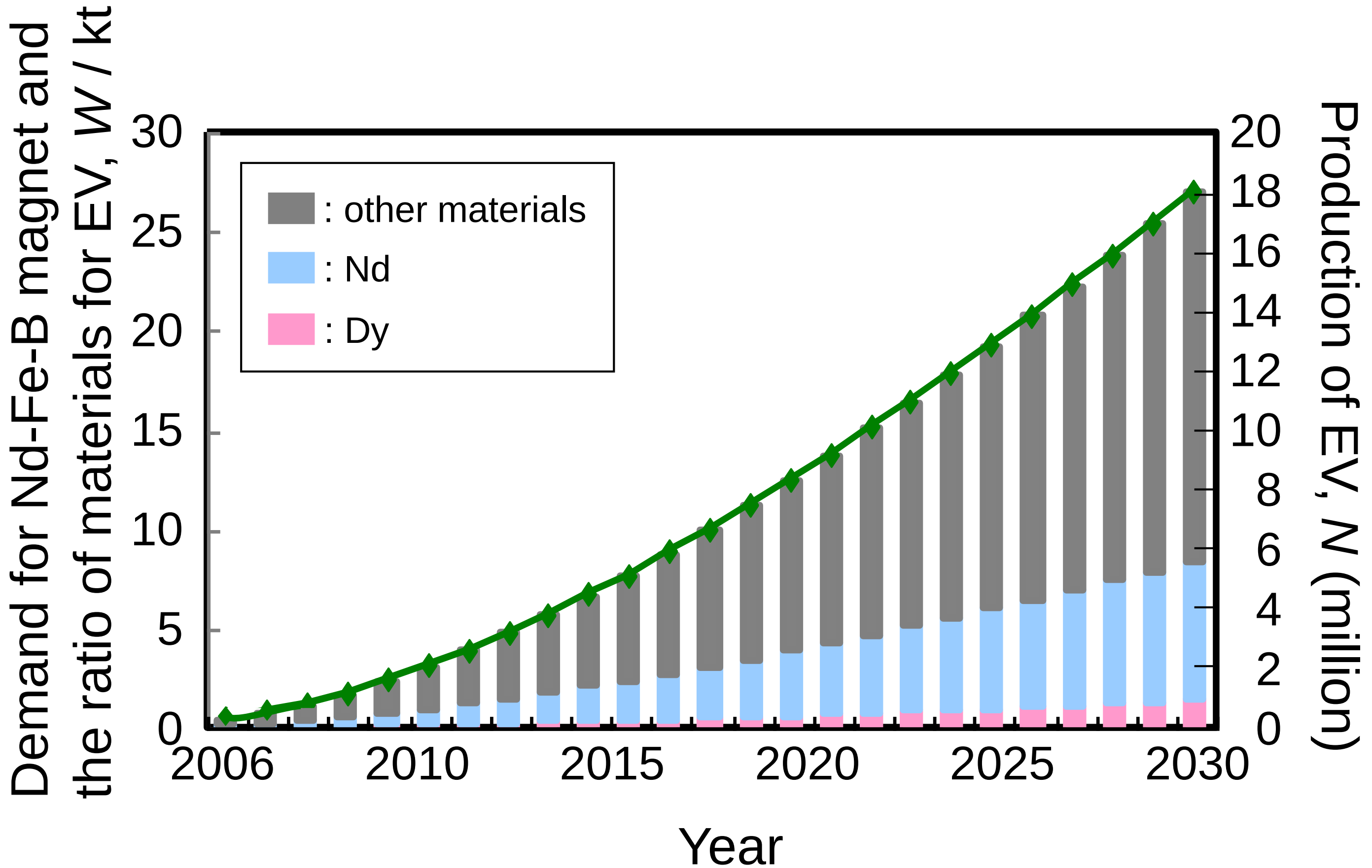
Ga: Blue diodes

Ta: High performance capacitors

Li: High performance batteries

Demand of Nd and Dy will be quintupled over the next 20 years.

Demand for Nd and Dy in the future



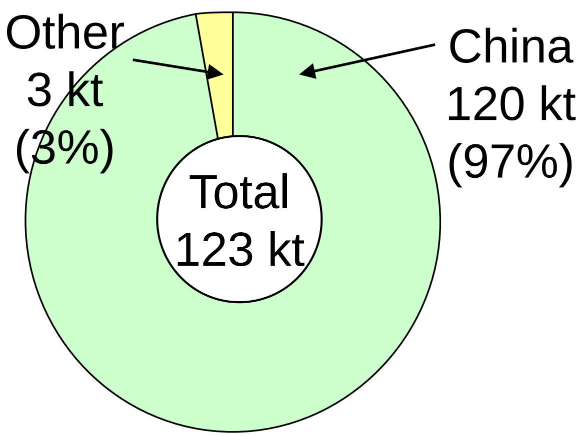
★ Large amount of magnet scrap will be produced in the future.

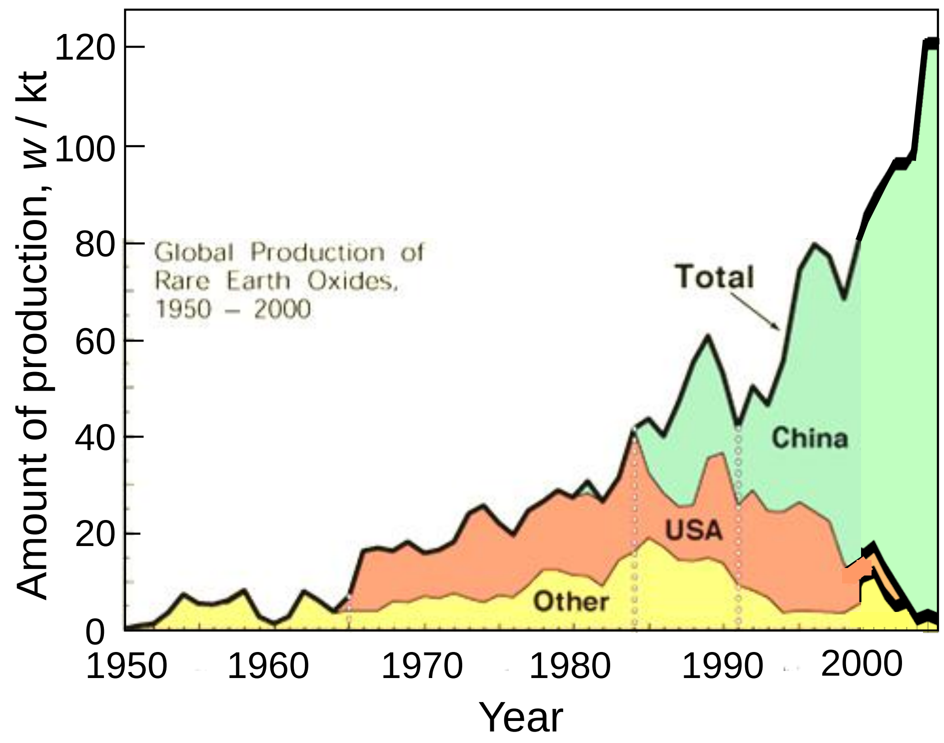
(Annual Energy Outlook 2008: US DOE EIA, http://www.eia.doe.gov/oiaf/ieo/)

China has extremely high quality mineral resource and cheep labor.

Worlds’ 97 % supply is dominated by China.

Problems in supply of REE

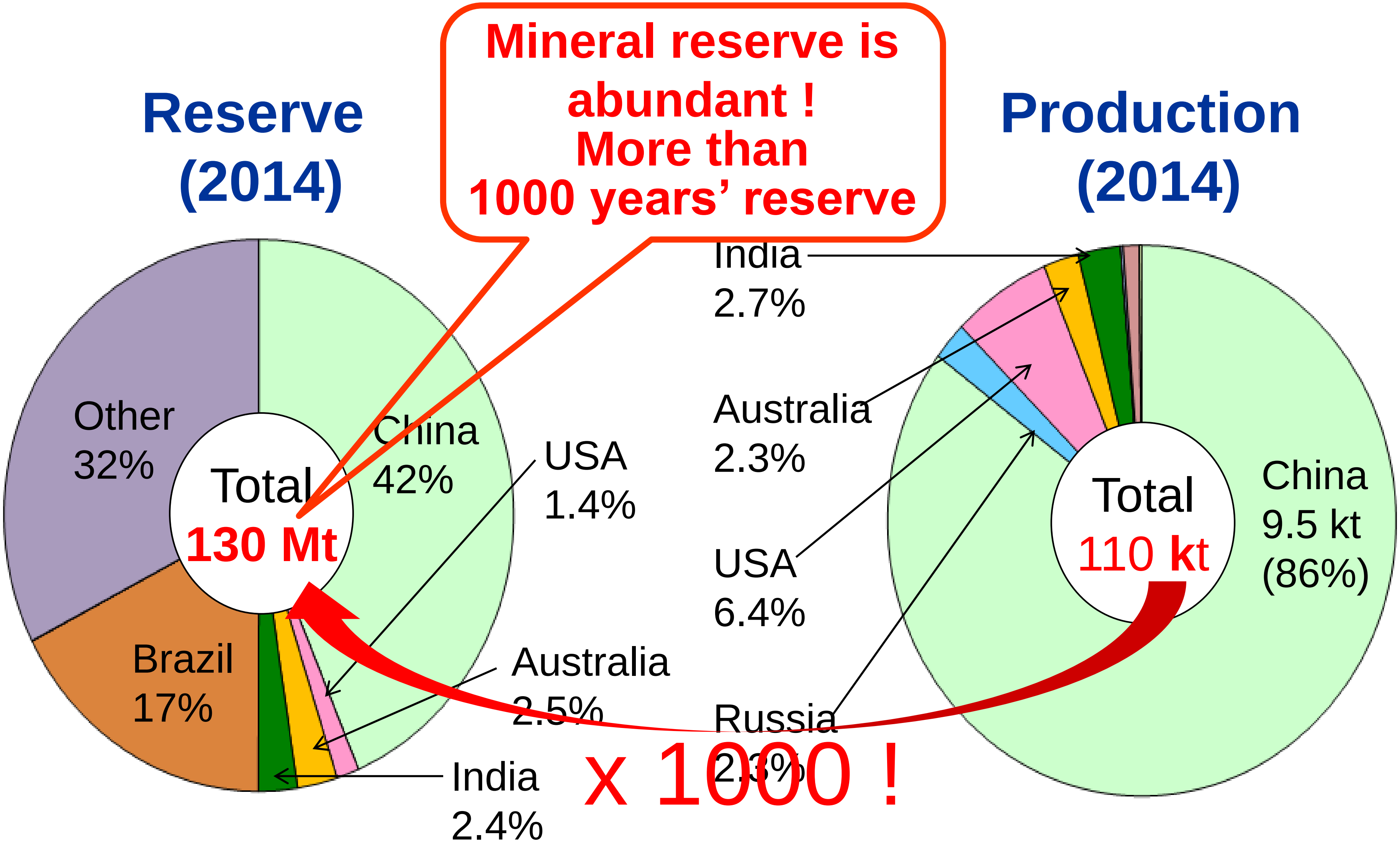




Change in amount of production of REE, and share in supply of REE in 2006.
(USGS Mineral Commodity Summaries (2007))

Supply of REE

- Worlds' 86 % supply is dominated by China.



USGS Mineral Commodity Summaries (2015)

Courtesy of Prof. Osamu Takeda / Tohoku University

Why do we have to recycle rare metals?

Development of new recovery process of rare metals from scraps

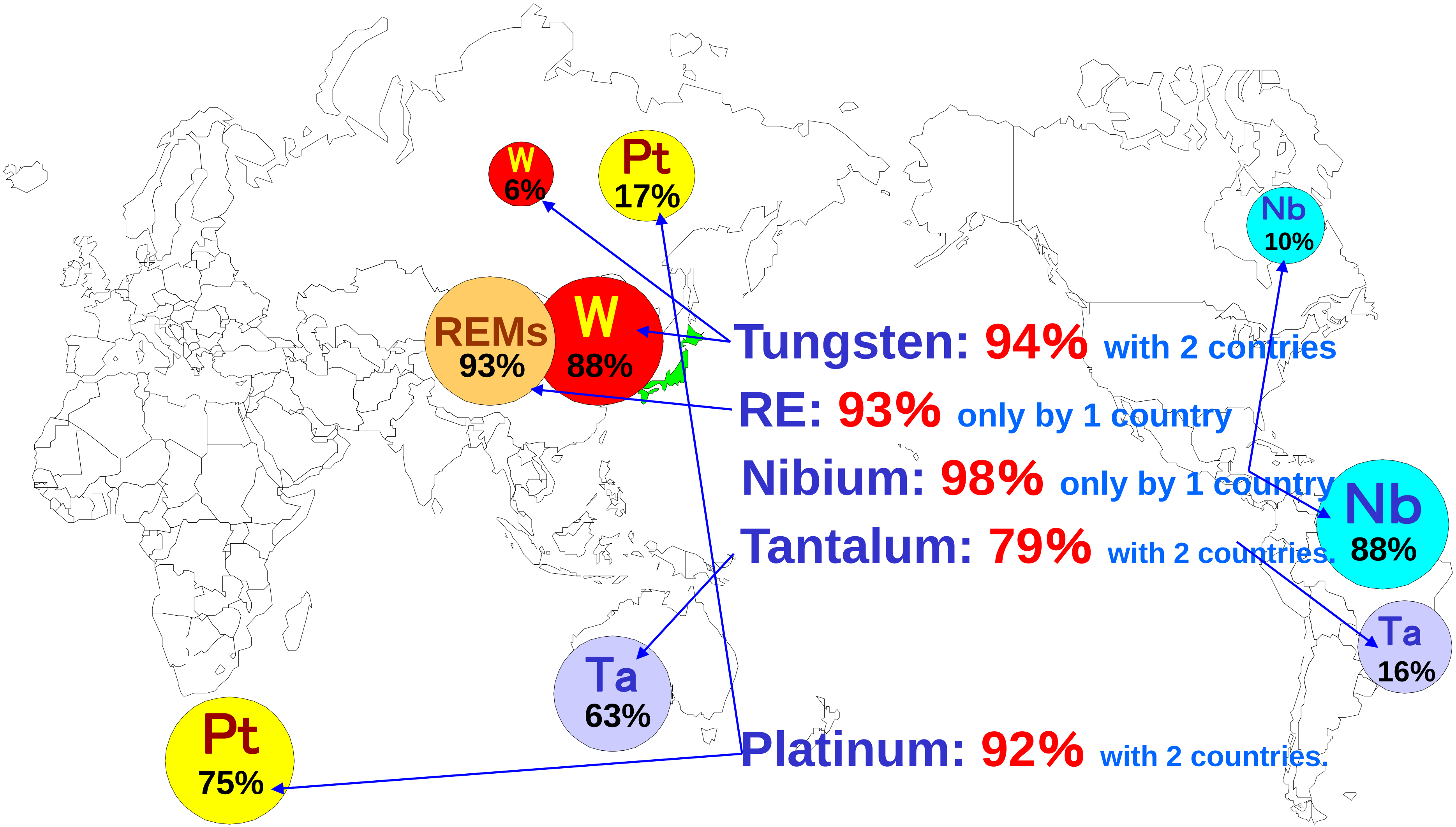
Rare Metals

Environmentally sound technology for producing and recycling less-common metals

Rare Metals

PGMs, REMs, Ga, Ta…

Uneven distribution and segregation of rare metals



※経済産業省非鉄金属課資料より (docs from METI)

More questions…

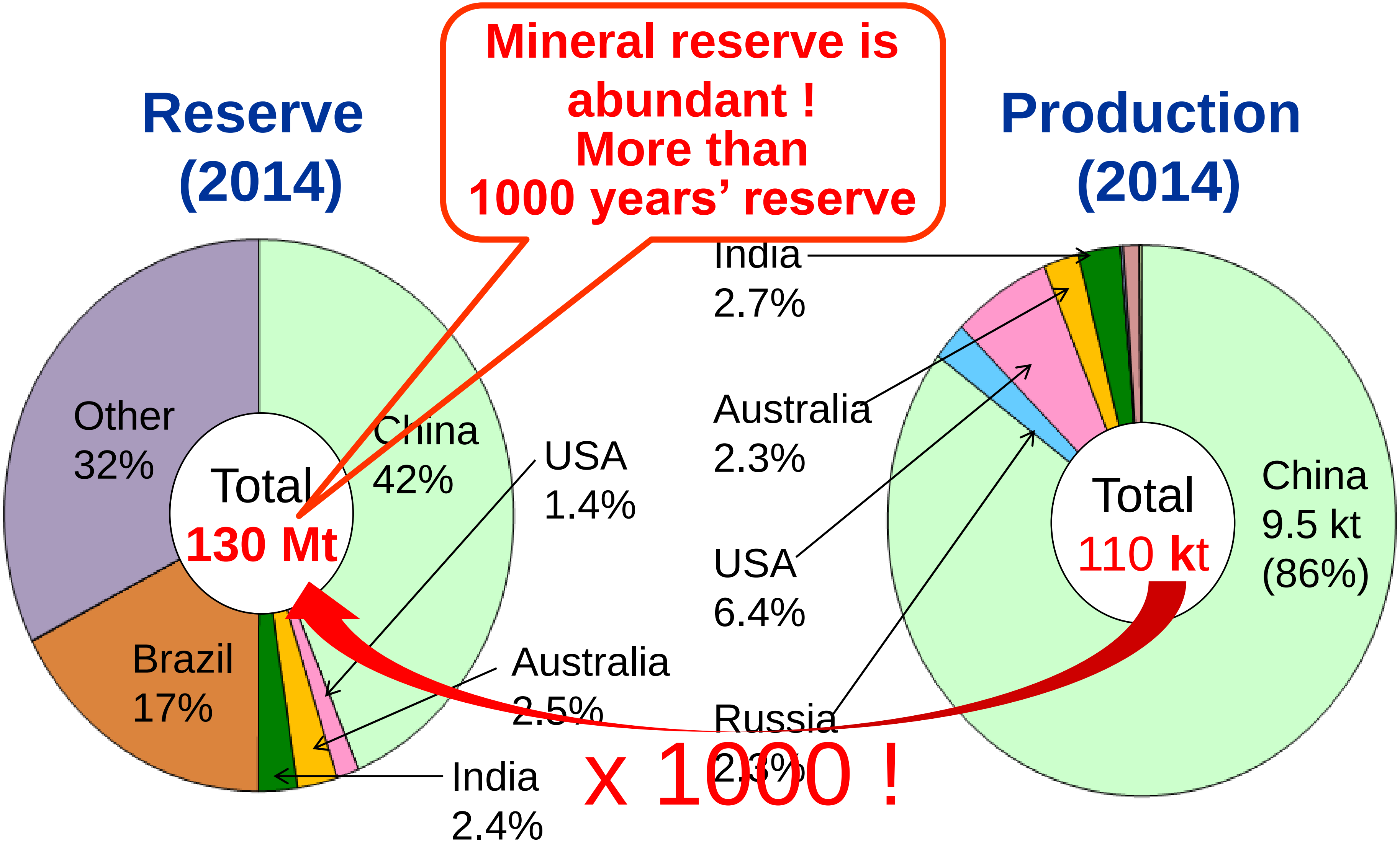
1. Why China monopolized rare earth production?

2. What will be problems in the future?

3. How about other rare metals?

Supply of REE

- Worlds' 86 % supply is dominated by China.



USGS Mineral Commodity Summaries (2015)

Courtesy of Prof. Osamu Takeda / Tohoku University

Before starting the talk on the real problems, following topics has to be introduced…

1. NORM

   (Naturally Occurring Radioactive Materials)

2. Goldschmidt's classification of elements

3. Relationship between main products and by-products.

NORM：

Naturally Occurring Radioactive Materials

自然起源放射性物質

NORM：Naturally Occurring Radioactive Materials

Natural radioactive elements existed since the generation of the Earth (Terrestrial NORM)

K-40
Rb-87
La-138
Sm-147
Lu-176
Th-232 system
U-238 system
etc. (their decay products)

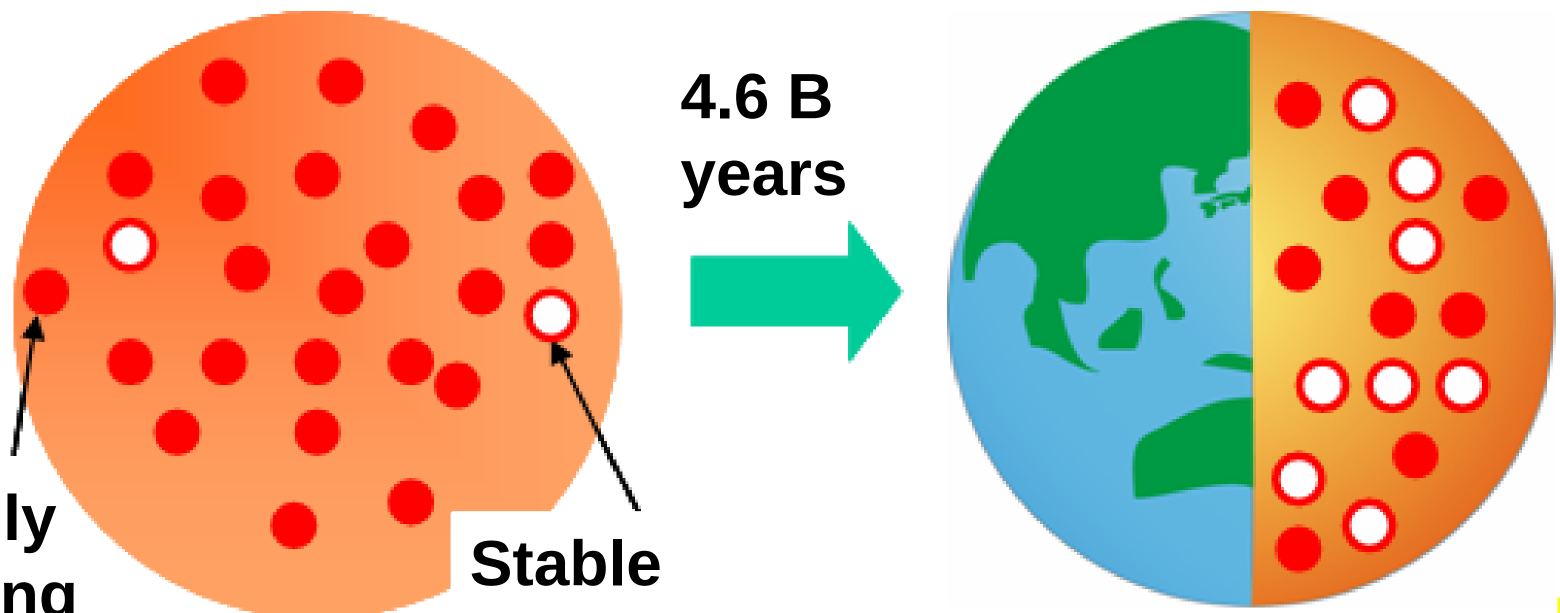
Radioactive elements generated by cosmic rays (Cosmogenic NORM)

H-3
Be-7
Na-22
C-14
Cl-36

http://www.nirs.go.jp/db/anzendb/NORMDB/1_NORM.php
放射線医学総合研究所のホームページより

Long-life radioactive elements, such as uranium (U) and thorium (Th) still exist even after 4.5 billion years of earth's history.

Earth just after born **Earth now**



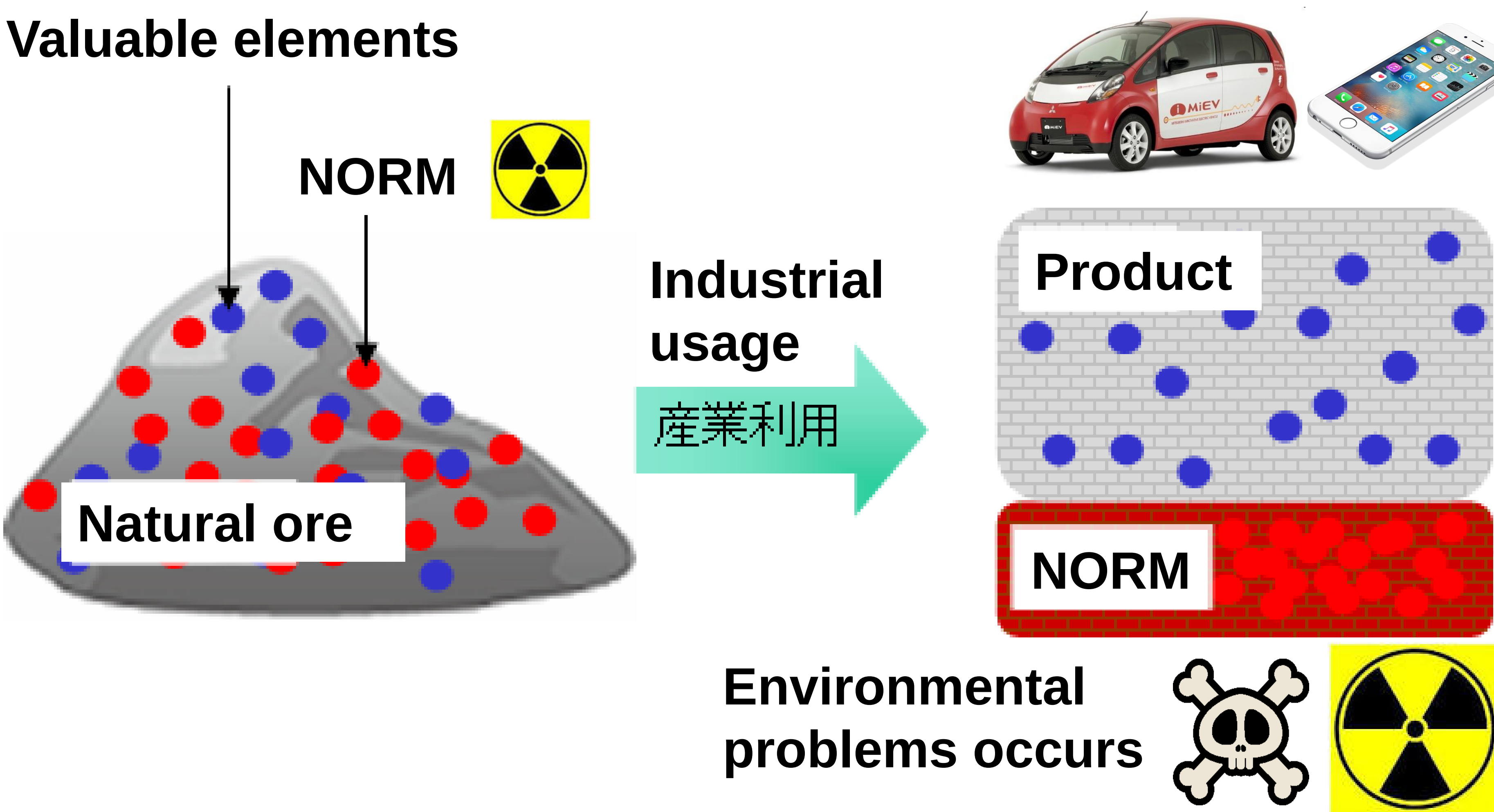
Naturally occurring radioactive elements

Stable elements generated after elemental decay

Still now, naturally occurring radioactive elements exists, and contained in natural minerals

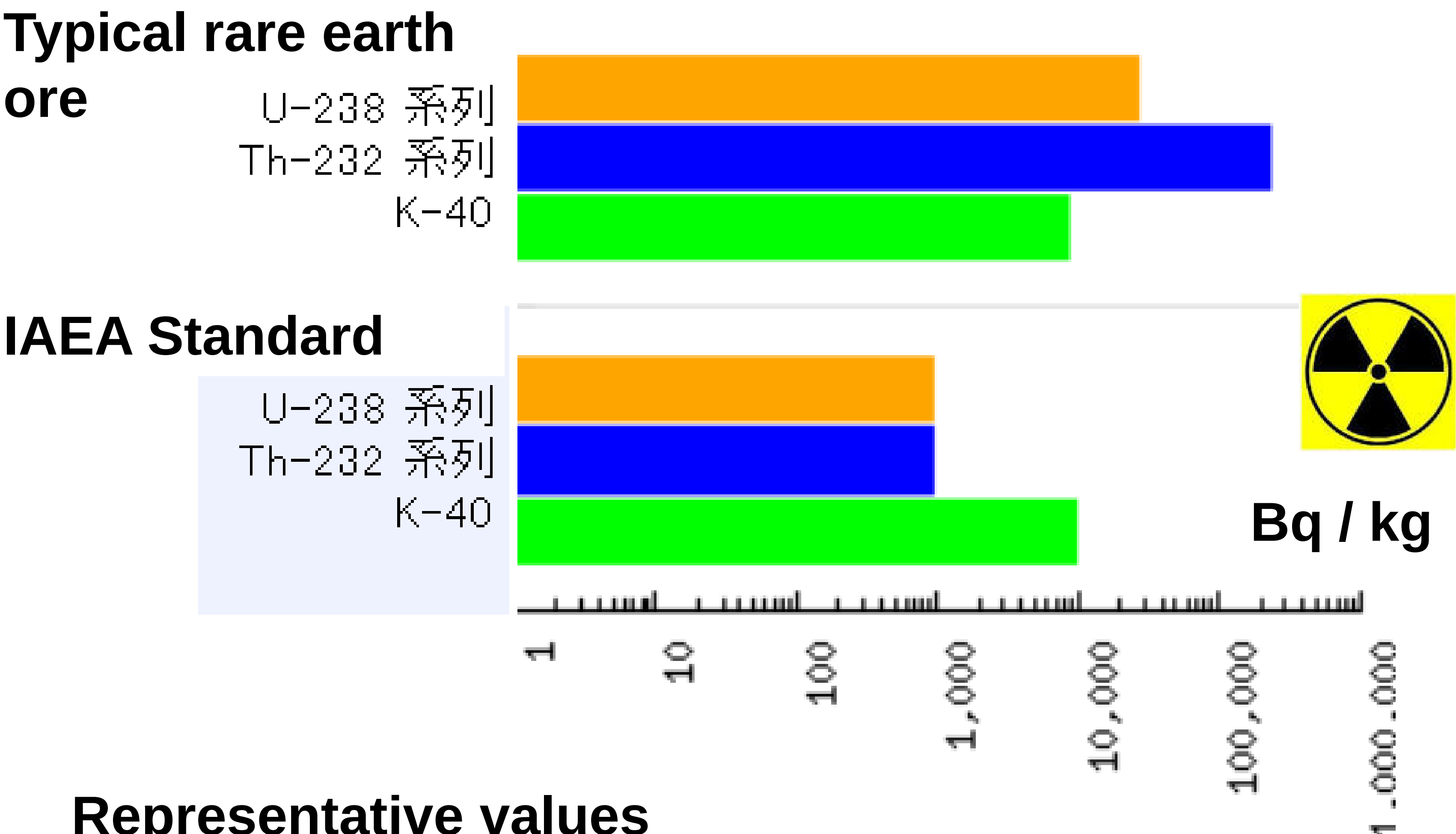
http://www.nirs.go.jp/db/anzendb/NORMDB/1_NORM.php
放射線医学総合研究所のホームページより

In some cases, wastes containing NORM ☢ is produced when extracting useful elements from natural ore.



http://www.nirs.go.jp/db/anzendb/NORMDB/1_NORM.php
放射線医学総合研究所のホームページより

Radio activity of rare earth ore



Representative values
(Values largely differs depending on types of ores)

http://www.nirs.go.jp/db/anzendb/NORMDB/1_NORM.php
放射線医学総合研究所のホームページより

Before starting the talk on the real problems, following topics has to be introduced…

1. NORM (Naturally Occurring Radioactive Materials)

2. Goldschmidt's classification of elements

3. Relationship between main products and by-products.

Goldschmidt's classification of elements

Lithophile elements (rock-loving)

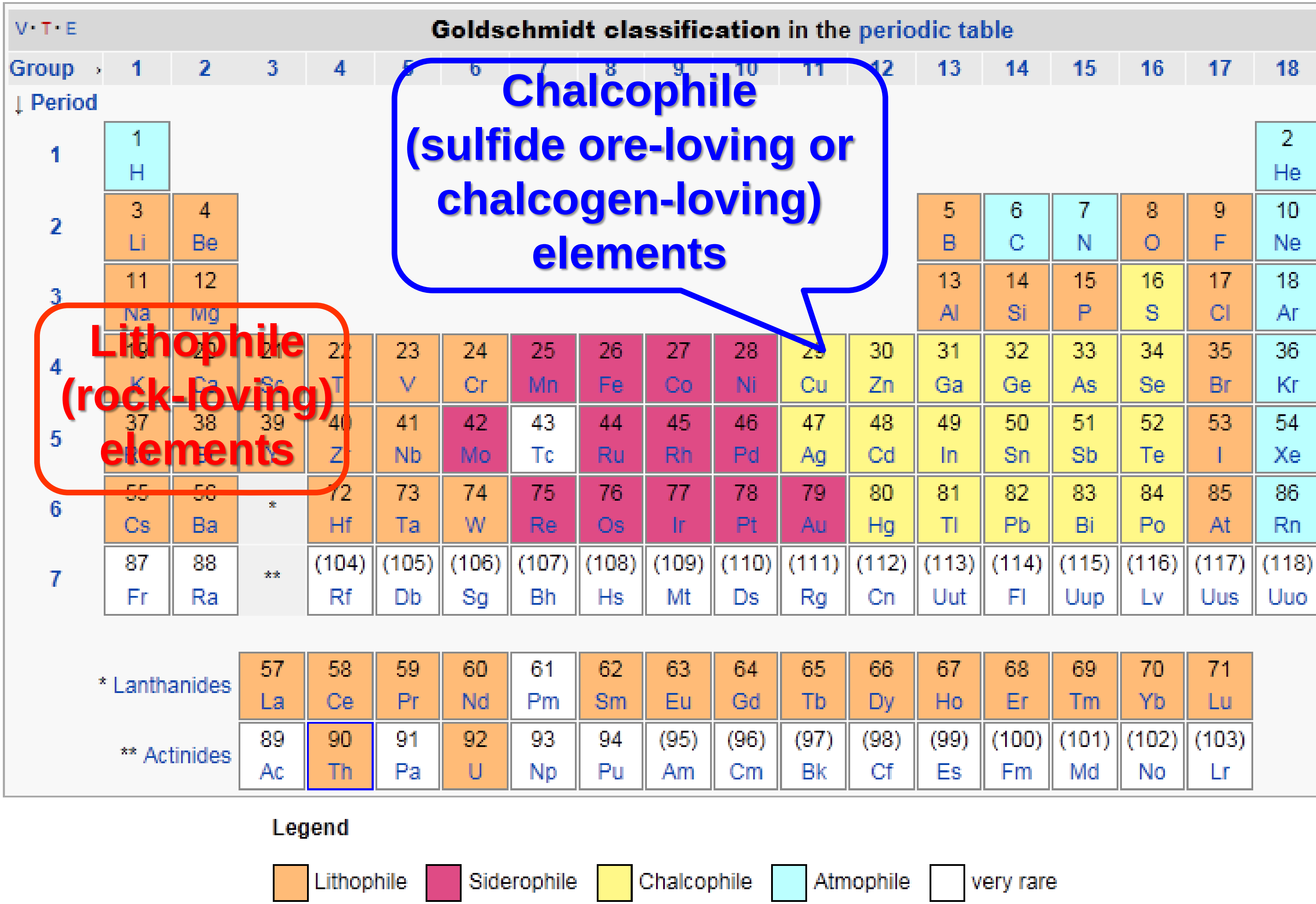
Siderophile elements (iron-loving)

Chalcophile elements (sulfide ore-loving or chalcogen-loving)

Atmophile elements (gas-loving)

or volatile (the element, or a compound in which it occurs, is liquid or gaseous at ambient surface conditions).

Biophile elements (bio-loving)



http://en.wikipedia.org/wiki/Goldschmidt_classification

Lithophile elements (rock-loving) 親石元素

Al, At, B, Ba, Be, Br, Ca, Cl, Cr, Cs, F, I, Hf, K, Li, Mg, Na, Nb, O, P, Rb, Sc, Si, Sr, Ta, Th, Ti, U, V, Y, Zr, W, Lanthanides

Rare earth elements

Siderophile elements (iron-loving) 親鉄元素

Au, Co, Fe, Ir, Mn, Mo, Ni, Os, Pd, Pt, Re, Rh, Ru

Chalcophile elements (sulfide ore-loving or chalcogen-loving) 親銅元素

Ag, As, Bi, Cd, Cu, Ga, Ge, Hg, In, Pb, Po, S, Sb, Se, Sn, Te, Tl, Zn

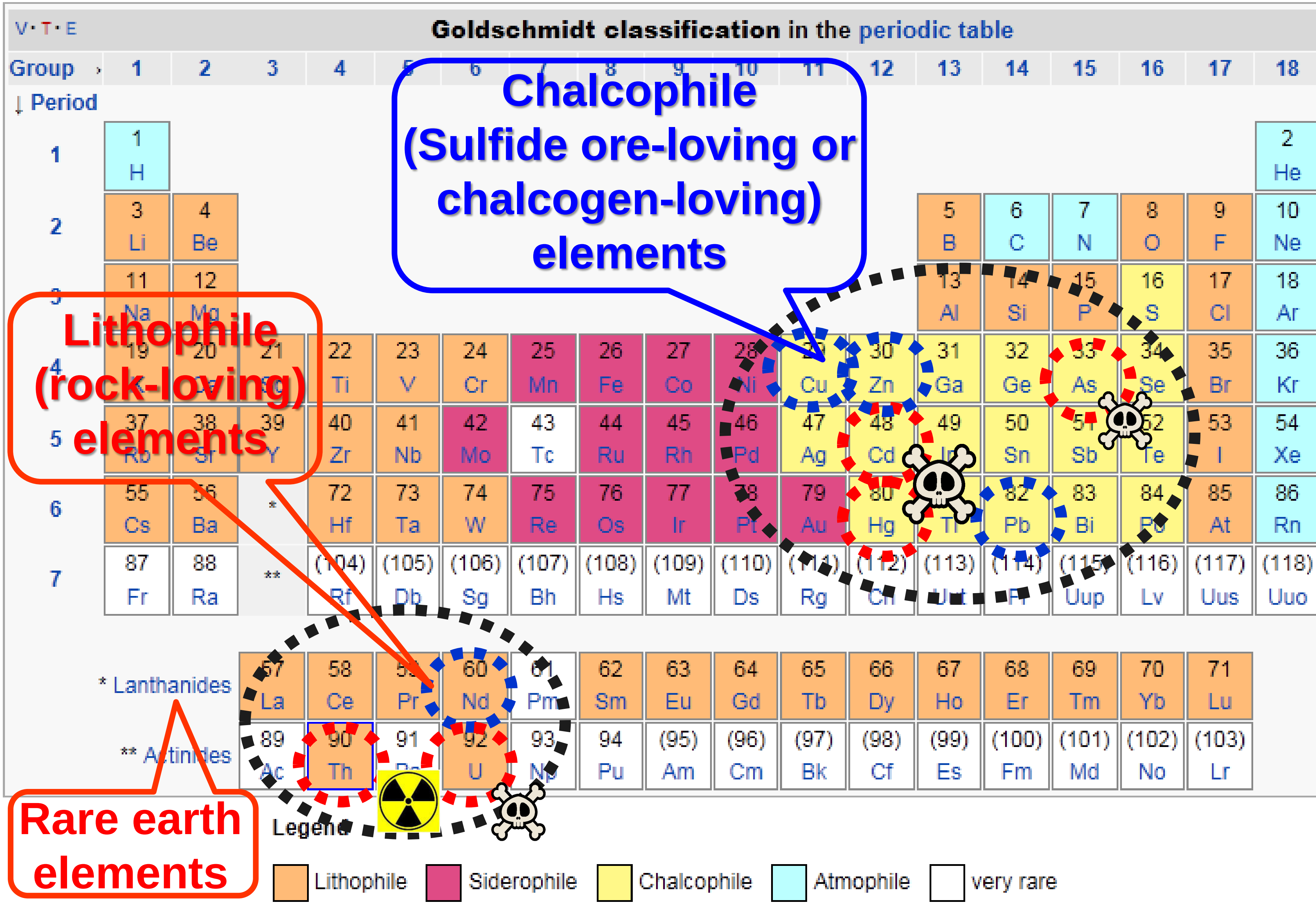
Atmophile elements (gas-loving) 親気元素

or volatile (the element, or a compound in which it occurs, is liquid or gaseous at ambient surface conditions).

H, C, N, noble gases

Biophile elements (bio-loving) 親生元素

C, H, O, N, S, P, Ca, K, Mg, B, Na, Mn, Zn, Fe



http://en.wikipedia.org/wiki/Goldschmidt_classification

<u>Oxide ores</u> such as rare earth metals (REMs), niobium (Nb), titanium (Ti) ores, generally, contains uranium (U) and thorium (Th).

→ Lithophile (rock-loving) elements.

<u>Sulfide ores</u> such as copper (Cu), lead (Pb), and zinc (Zn) ores, contains arsenic (As), cadminium (Cd), and mercury (Hg).

→ Chalcophile (Sulfide ore-loving or chalcogen-loving) elements

Before starting the talk on the real problems, following topics has to be introduced…

1. NORM (Naturally Occurring Radioactive Materials)

2. Goldschmidt's classification of elements

3. Relationship between main products and by-products.

Relationship between
main products and by-products.

Relationship between
root of radish and leaf of radish

Good stories….

Important by-products

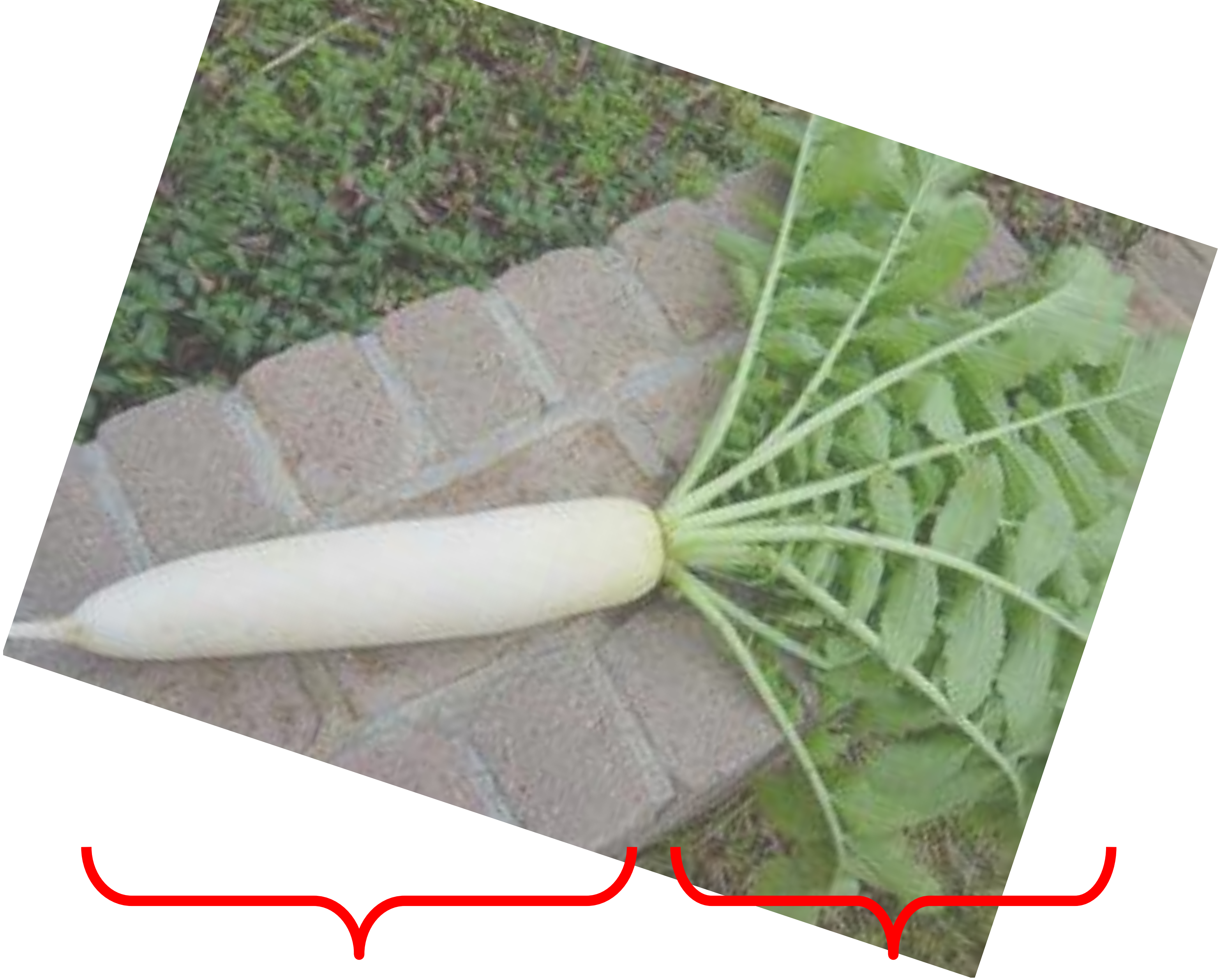
Gold (Au) ←by-product of copper (Cu)

Silver (Ag) ←by-product of copper (Cu)

Important by-products

Indium (In) ←by-product of zinc (Zn)
Gallium (Ga) ←by-product of aluminum (Al)
Scandium (Sc) ←by-product of uranium (U) and tungsten (W)

Rhodium (Rh) ←by-product of platinum (Pt)
Ruthenium (Ru) ←by-product of platinum (Pt)
Iridium (Ir) ←by-product of platinum (Pt)



Root of radish **Leaf of radish**