# Rare Metals Essential for Next Generation Vehicles: Current and Future Problems

Institute of Industrial Science,
The University of Tokyo

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'Rare Metals Essential for Next Generation Vehicles: Current and Future Problems',
Toru H. Okabe:
International Electric Vehicle Technology Conference (EVTeC), EVTeC 2023 Plenary Session, "Toward Carbon Neutral Transportation by Electrification", (2023 年5 月22 日(月)～24 日(水), 会場: パシフィコ横浜ノース(神奈川県横浜市)), EVTeC2023 Plenary Session, 2023年5月22日(月) 10:10～10:50 (40分間), [横浜] (2023.5.22).
[Plenary Talk]
(リアル講演会＋ネット配信のハイブリッド講演会)

Why do we have to recycle rare metals?

What will be the bottlenecks of
rare metal supply?

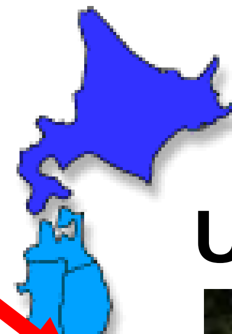
# Dr. Toru H. Okabe’s footmark

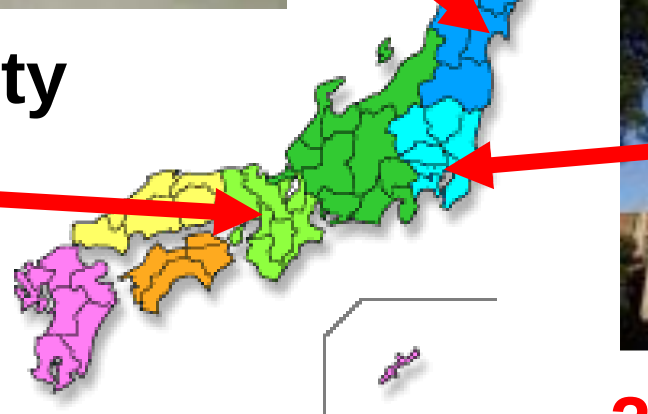
**MIT, Boston**

**1993～1995**

**Tohoku University**

**1995～2000**





**Kyoto University**

**1984～1993**

**University of Tokyo**

**2001～**

1984～1993 Kyoto Univ. (Student)

B: Ti

M: Ti

D: Nb, Ta, (Ti, Y, …)

1993～1995 MIT (Postdoc)

Ta, (Al, …)

35 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)

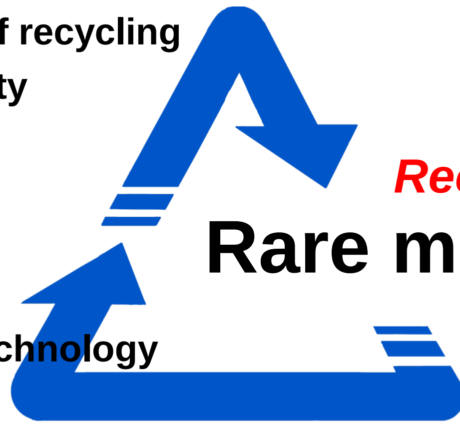
Currently: Ti, Sc, V, PGMs (Pt, Rh, Ru, Ir, …)

Nb, Ta, REMs (Nd, Dy, …), W, Re…


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.

持続可能な開発目標（SDGs）〔2015年9月25日国連持続可能な開発サミットで採択　2016年1月1日発効〕

# Background and Keywords for Materials Research for Development of Highly Sustainable Society




**Materials engineering for establishing an advanced sustainable society / Development of new integrated academic field for resource, environment, and recycling / Inducing the paradigm shift of global vision related to resources and environment.**

**Fig. 1**
**Aiming to establish an advanced recycling society through various approaches, the pivotal items necessary to realize a materials recycling society (rare metals and precious metals are shown as representatives) are listed. In the future, recycling and environmental technologies for rare metals and precious metals will be key for a highly sustainable society.**

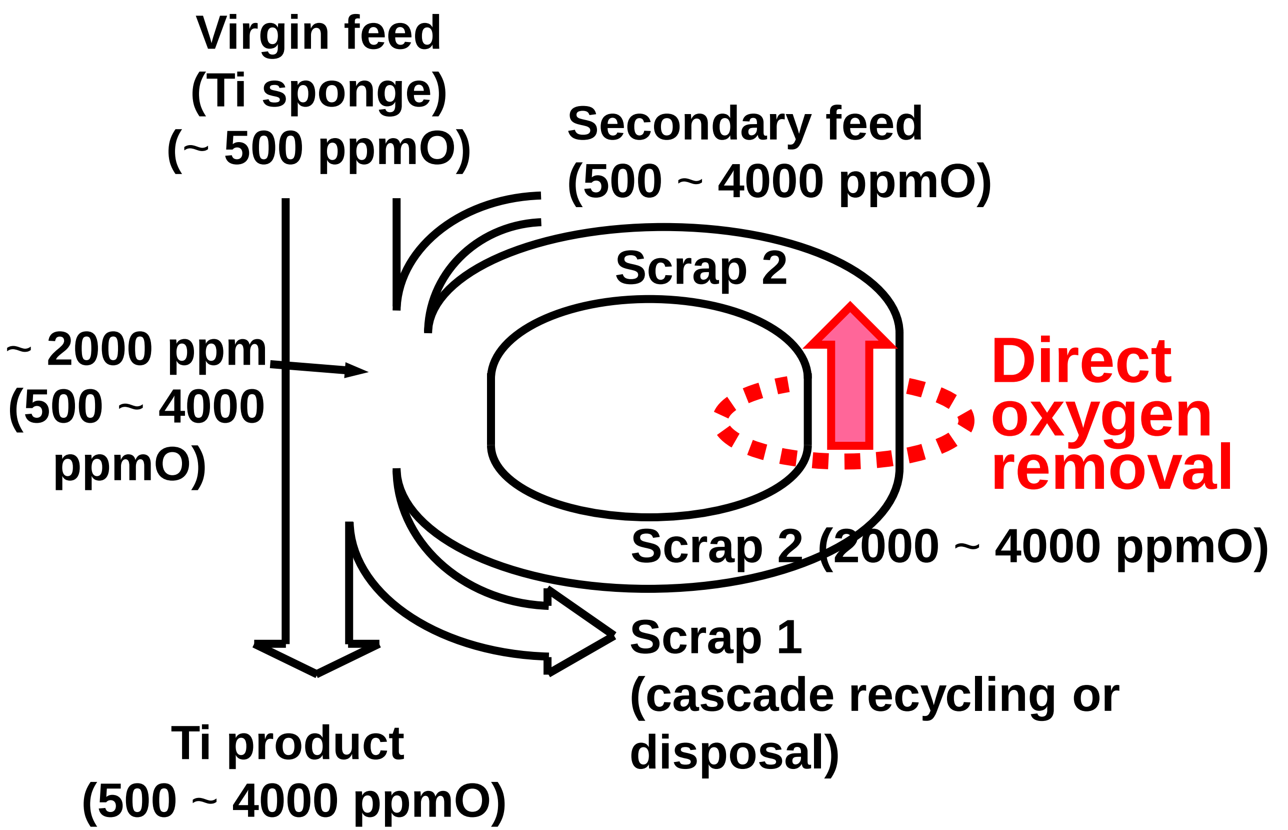

**Fig. 1**

Aiming to establish an advanced recycling society through various approaches, the pivotal items necessary to realize a materials recycling society (rare metals and precious metals are shown as representatives) are listed. In the future, recycling and environmental technologies for rare metals and precious metals will be key for a highly sustainable society.

# Development of new up-grade recycling process of titanium

## Environmentally sound technology for producing high-purity Ti directly from Ti scraps

# Up-grade recycling of titanium




**A deoxidation method, that reduces the oxygen concentration of Ti to the level of 500 mass ppm O, decreases the cascade use of Ti scrap for Fe–Ti alloy.**

**In the future, recycling of Ti scrap will be an essential technology.**

Fig. Material flow of Ti and its alloys with respect to the oxygen concentration [16-Tani1].


[16-Tani1] Taninouchi Y, Hamanaka Y, and Okabe TH (2016) Electrochemical Deoxidation of Titanium and Its Alloy Using Molten Magnesium Chloride. Metall. Mater. Trans. B 47(6): 3394–3404. doi: 10.1007/s11663-016-0792-9

# 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)**

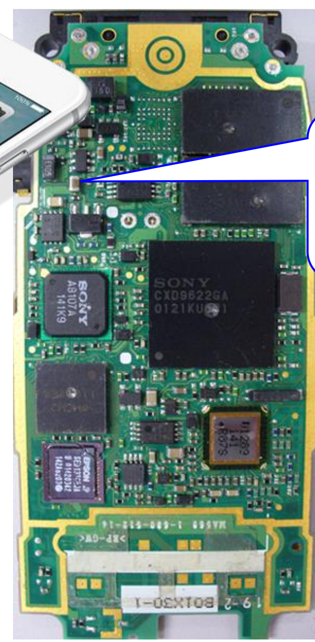
**http://www.okabe.iis.u-tokyo.ac.jp/**

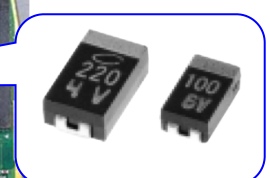
# Rare Metals

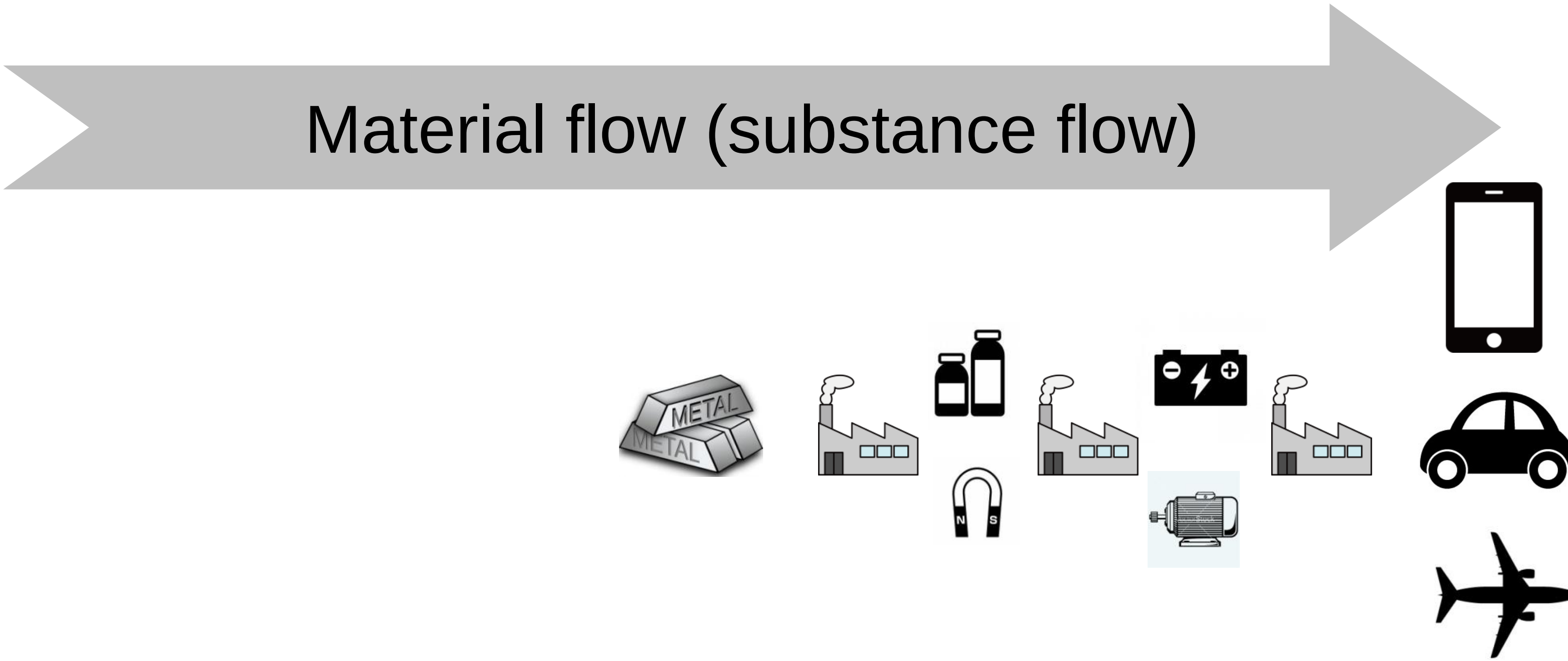


## PGMs, REMs, Ga, Ta…

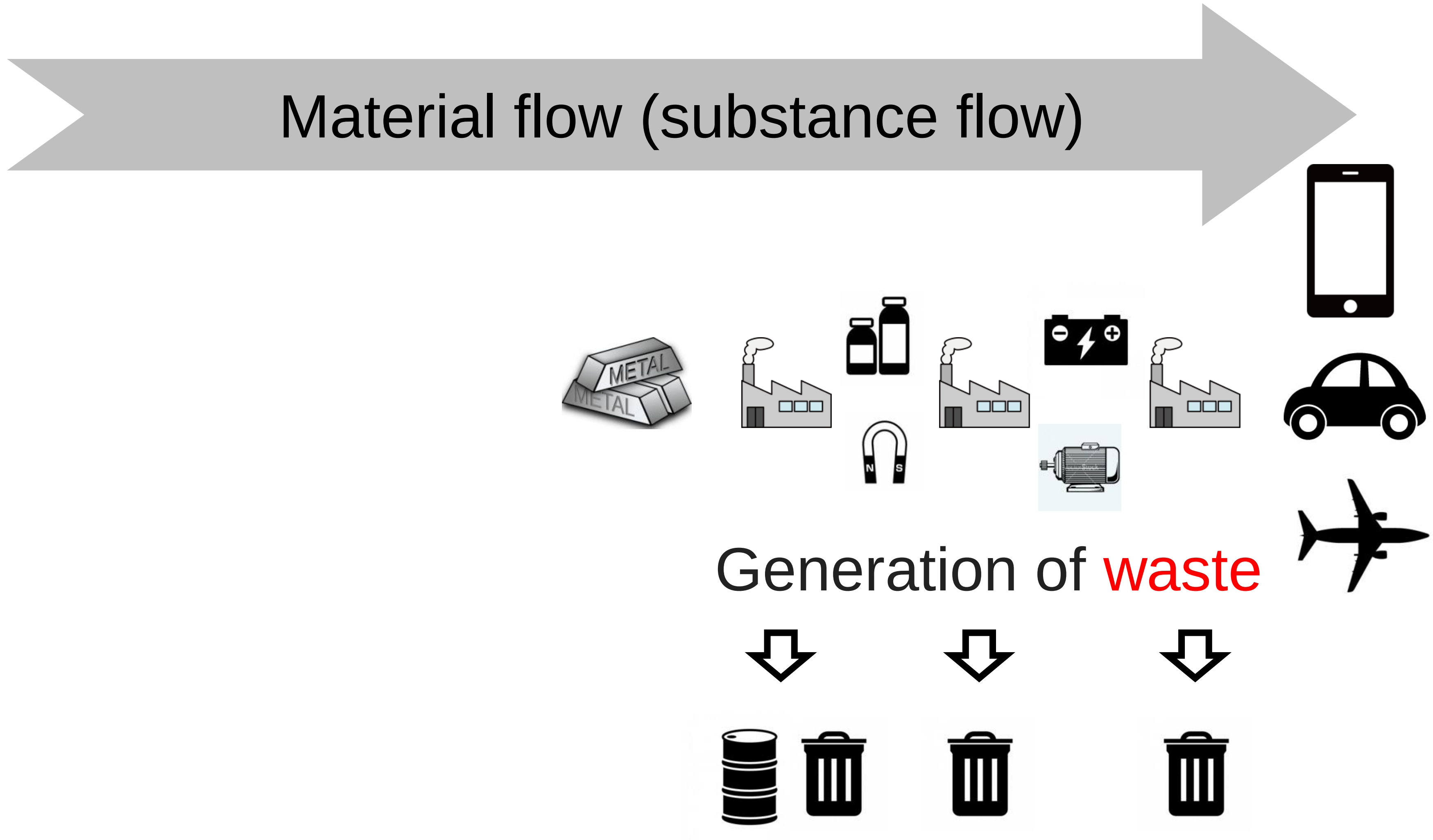


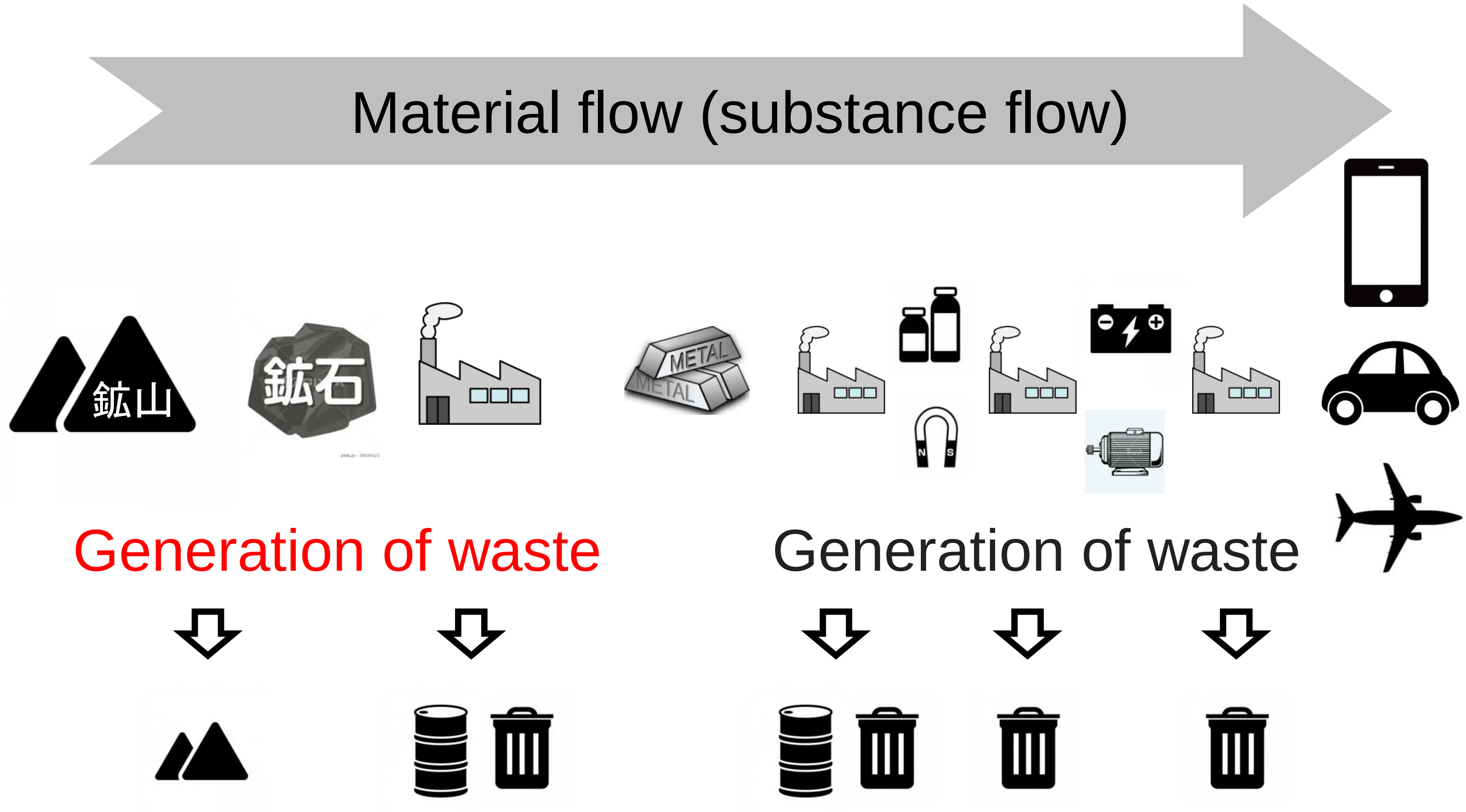


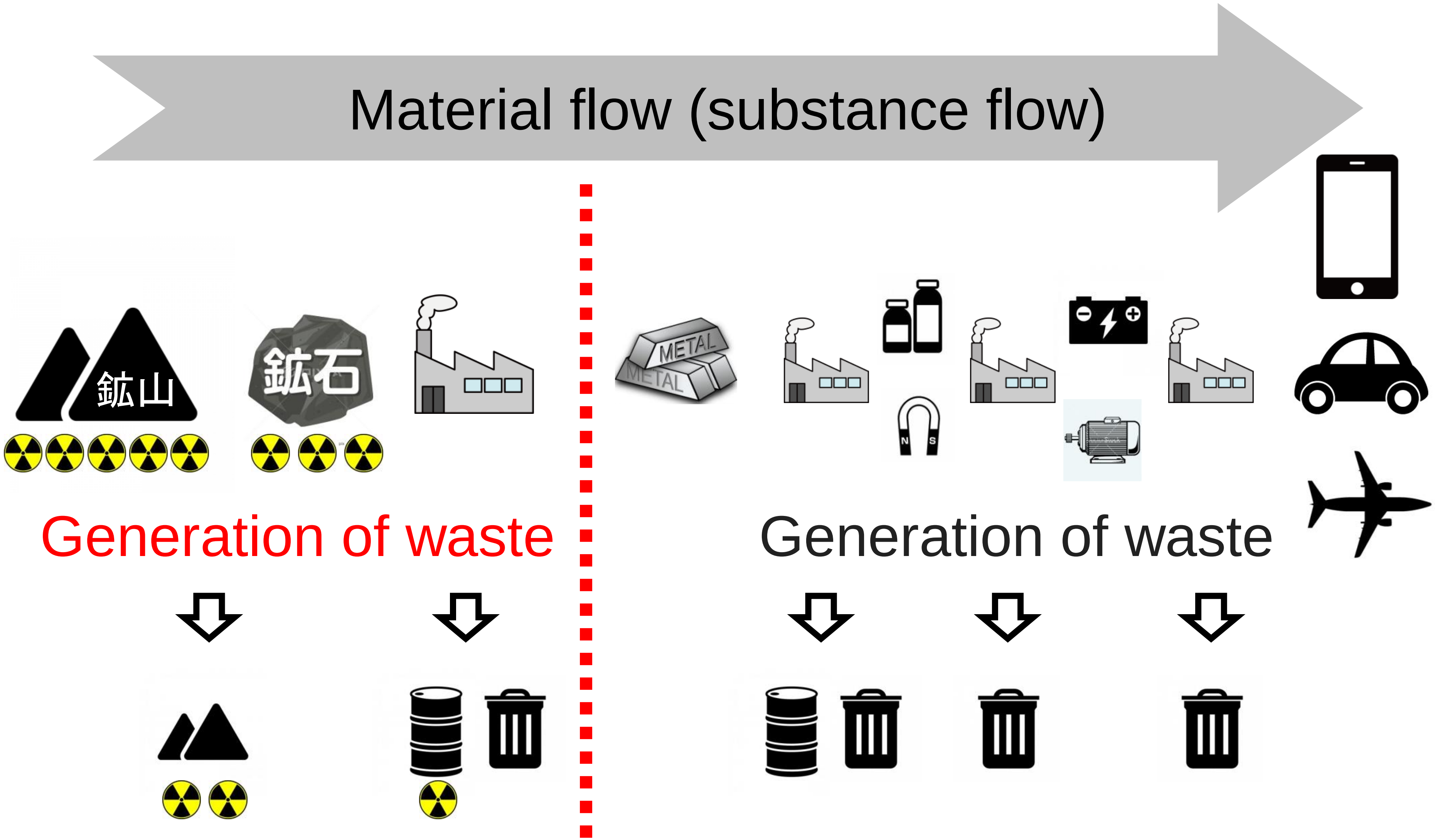

People in developed countries import rare metals from overseas, and produce high-performance or high-tech products. They believe that it contributes to the environment…




People also know that wastes are generated when making things.



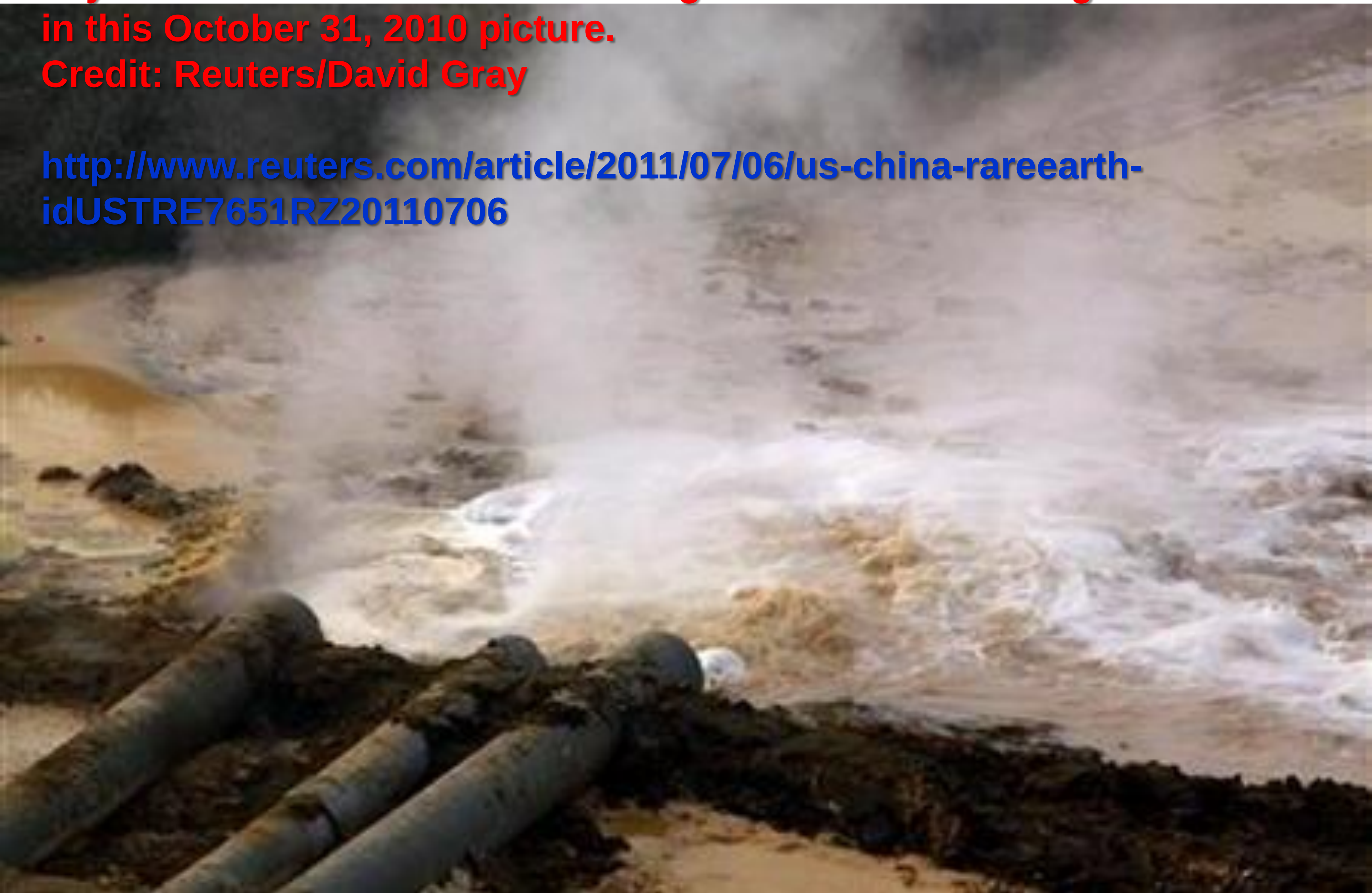

Some people can imagine that an enormous amount of waste is generated in mining and smelting




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**

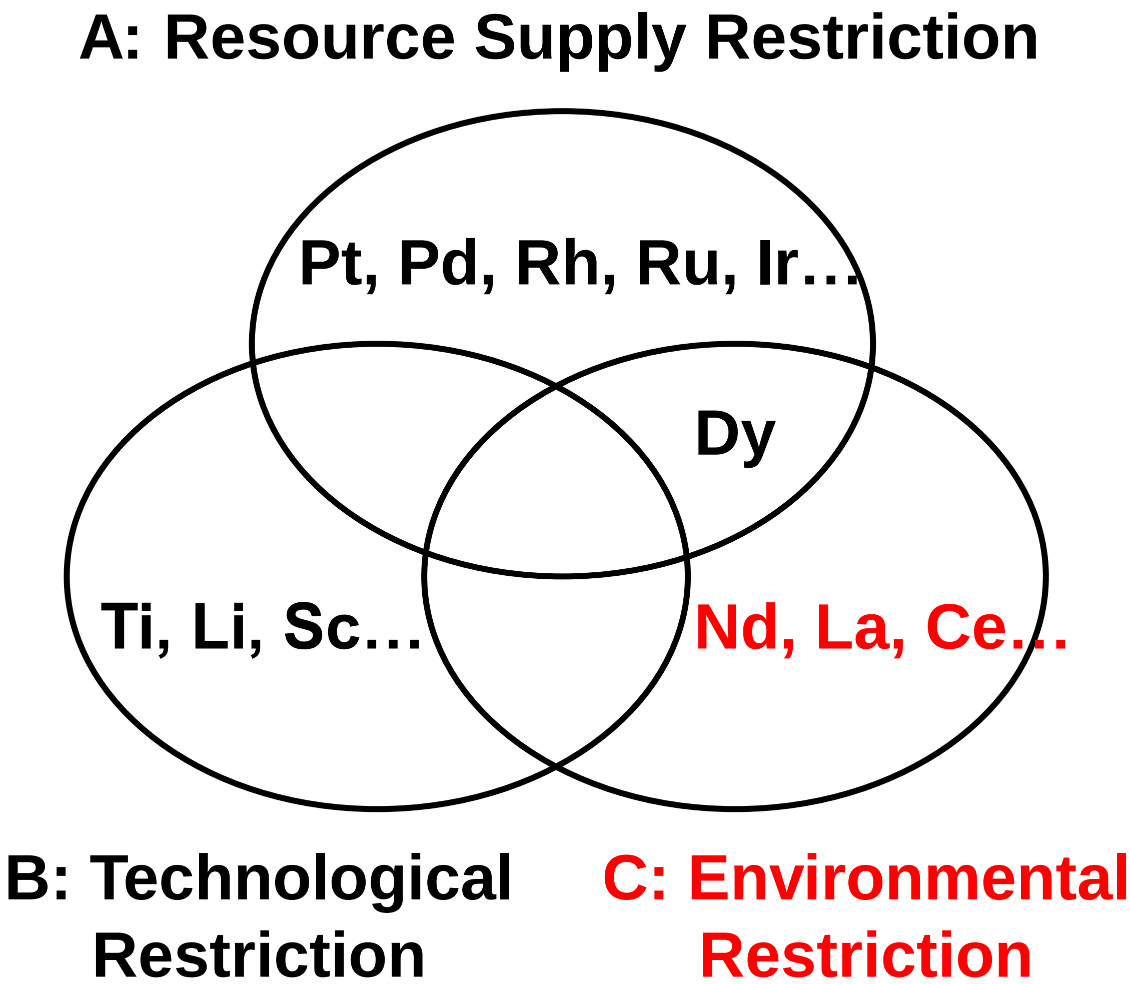


**Regarding the production and supply of rare metals,**
**the main three items to consider bottlenecks are as follows:**

**A: Resource Supply Restriction**

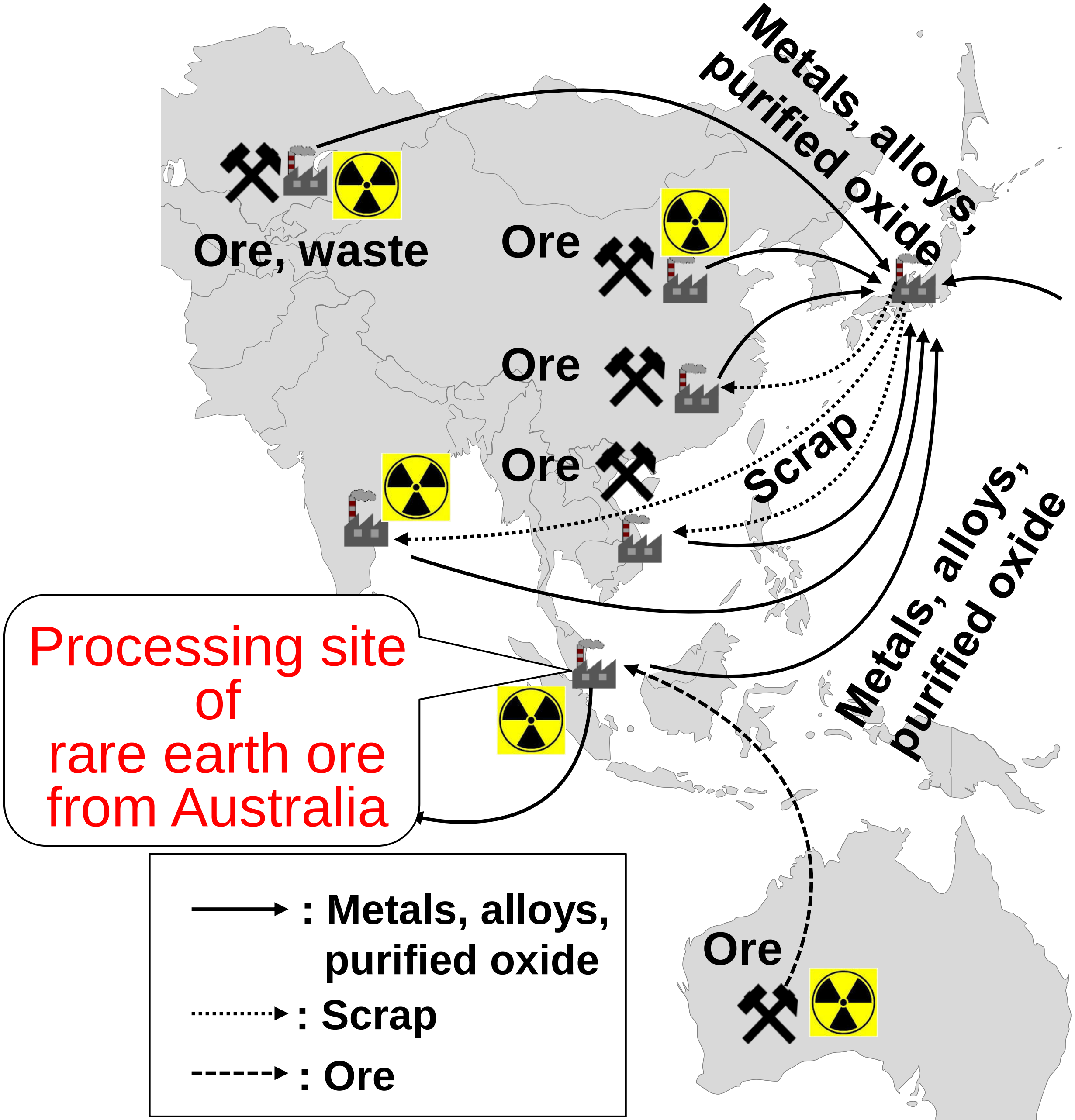
**B: Technology Restriction**

**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.**



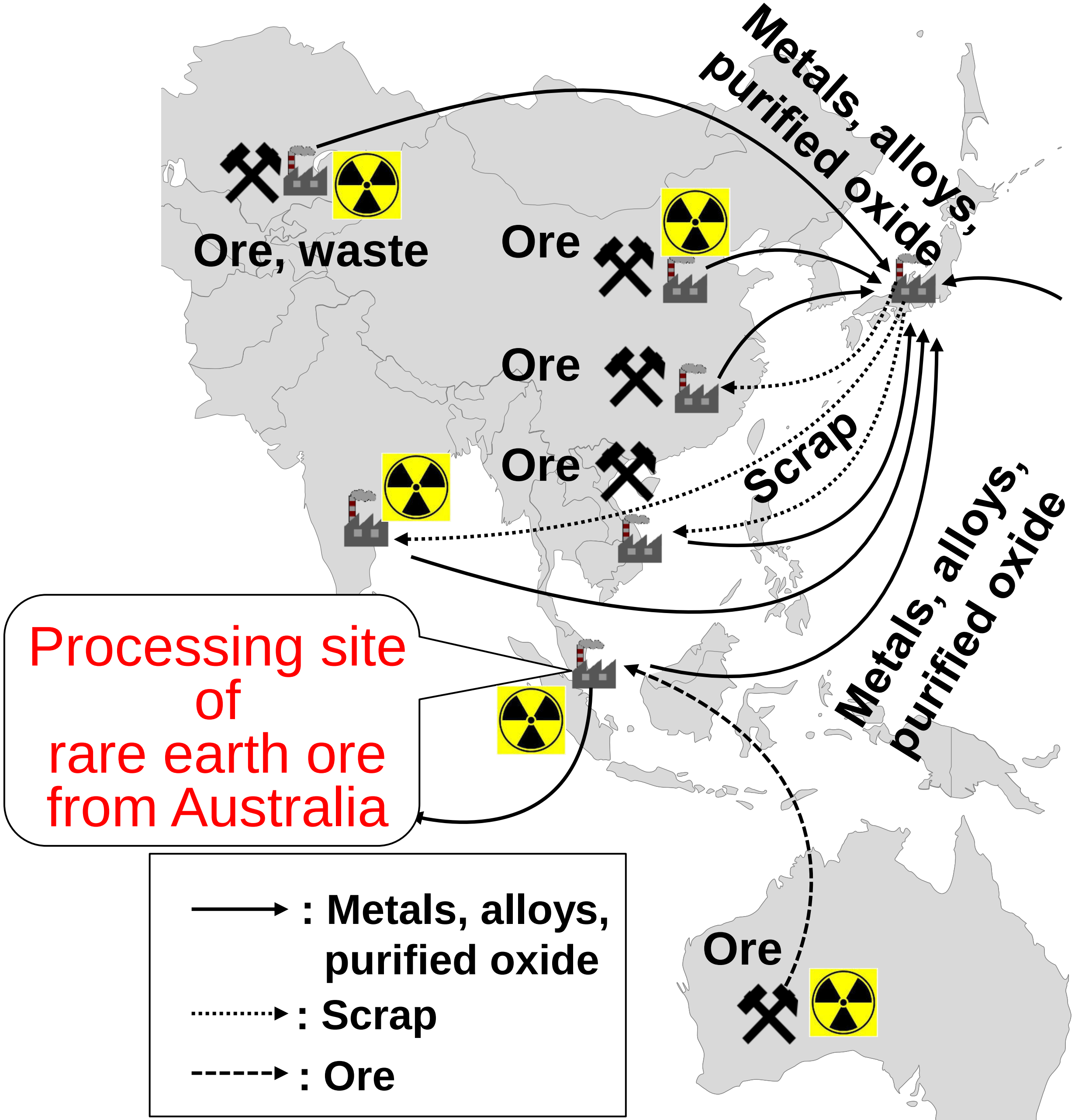

**Supply problems for rare metals depending on the ubiquity of the country of supply and region.**

**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.**

Why do we have to recycle rare metals?

What will be the bottlenecks of rare metal supply?




**Material flow of rare earth metals and alloys in the world.**

**Japan imports only purified materials.**

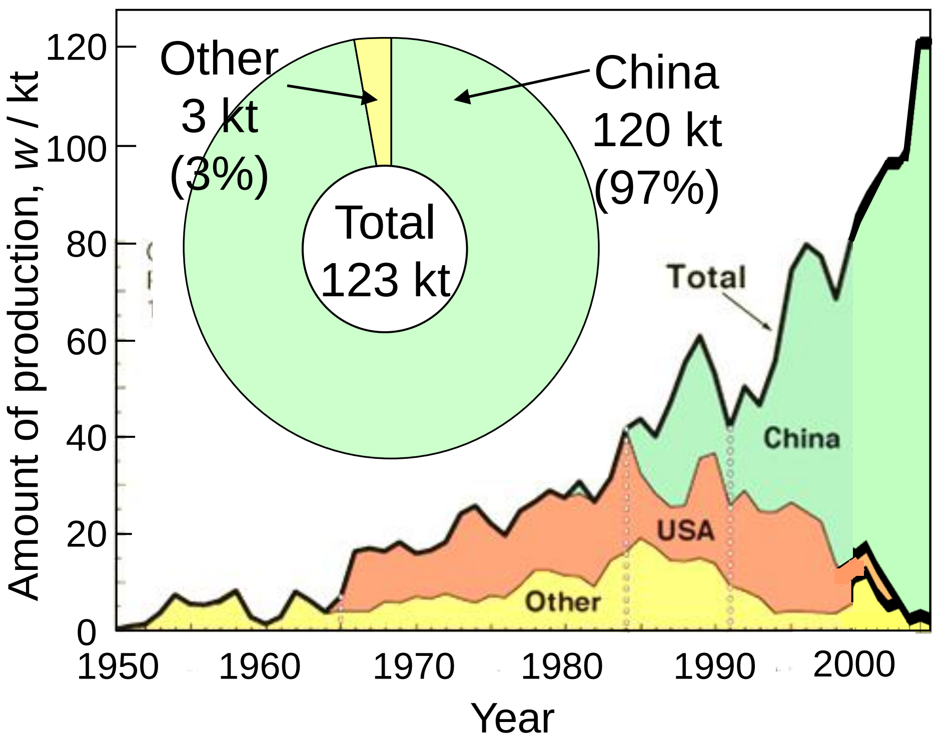
**Practically, we can not import ore which contains radio active elements (NORM).**

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

China has extremely high quality mineral resource and cheep labor.

Worlds' 97 % supply is dominated by China.

# Problems in supply of REE




Dy: ∼$ 50 /kg Dy metal
Nd: < $ 10 /kg Nd metal

Dy: ∼$ 400 /kg Dy metal
(max.> **$3500 / kgDy !**)
Nd: ∼$ 150 /kg Nd metal
(max. **$450 / kgNd !**)

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

# Grade of Nd & Dy in the ore.

| Ore | | Ion cray | Bastnaesite | | Monazite |
|---|---|---|---|---|---|
| Mining Site | | Longnan (China) | Bayan Obo (China) | Mt. Pass (USA) | Mt. Weld (Australia) |
| REO grade in Ore (wt%) | | 0.05～0.2 | 6.00 | 8.90 | 11.20 |
| Grade in REO (wt%) | Nd | 3.00 | 18.50 | 12.00 | 15.00 |
| | Dy | 6.70 | 0.10 | trace | 0.20 |
| Grade in Ore (wt%) | Nd | 0.0015～0.006 | 1.11 | 1.068 | 1.68 |
| | Dy | 0.00335～0.0134 | 0.006 | trace | 0.0224 |

Dy grade in ore is very low, but
very easy to extract directly from ion clay...

(石原舜三, 村上浩康:レアアース資源を供給する鉱床タイプ, 地質ニュース624号, 10 - 24. (2006))
(USGS Mineral Commodity Summaries (2010))

**Table 4** Unit mass of rare earth used for industrial products (rough estimate).

| Product | Unit mass of RE (kg RE / Unit) |
|---|---|
| Hybrid vehicle (HV) | 0.25~1.25[a] |
| Electric vehicle (EV) | 1.3~ |
| Power steering | 0.09 |
| Air conditioner | 0.12 |
| Hard disk drive | 0.01 |
| Mobile phone | 0.0005 |
| MRI[b] | 1500 |

**1.3 kg RE magnet / EV**

**a: In the case of hybrid vehicles (HV) unit mass of RE varies with output power of motors.**
**Small HVs use about 0.25 kg/unit RE and large ones about 1.25 kg/unit.**

**b: Magnetic Resonance Imaging (MRI) units.**

When producing high performance **motors for HEV or EV,**
about 1.3 kg of Rare earth magnet (Nd-Fe-B) is necessary.


**1.3 kg of Rare Earth magnet contains**
- 21（～26）% of Neodymium (Nd)
- 10（ ～5）% of Dysprosium (Dy)
- (Rest: Boron)

→ Magnet with high thermal stability requires large amount of Dy.

Ore grade of Nd is about 1% (Bastnaesite)
Ore grade of Dy is about 0.01%-0.003% (Ion cray)

When producing high perfomance motors:
about 0.27 kg of Nd (31 kg of Bastnaesite ore)
**about 0.17 kg of Dy (1 to 4 tons of Ion cray)**
are required.
For producing one motor, large amount of ore is required, and environment problems are induced when mining and refining.

Far larger mass of ore compared to the mass is automobile is consumed when producing high performance automobile.

# Key points:

- Production of Nd–Fe–B magnet for industrial motors will drastically increase in the future.
- Large amount of magnet scrap will be discarded.
- Resource of Dy (from ion cray) is scarce and limited (now available only from China).
- **Production of Nd from mineral ore induces environmental pollution.**
- Minerals for heavy REE, such as Dy, are unevenly distributed in the world.

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)**

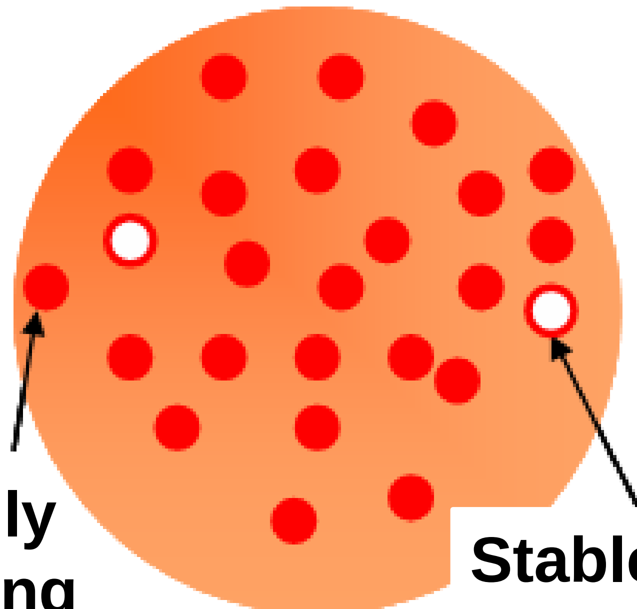
**Radioactive elements generated by cosmic rays (Cosmogenic NORM)**

**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**



Naturally occurring radioactive elements

Stable elements generated after elemental decay

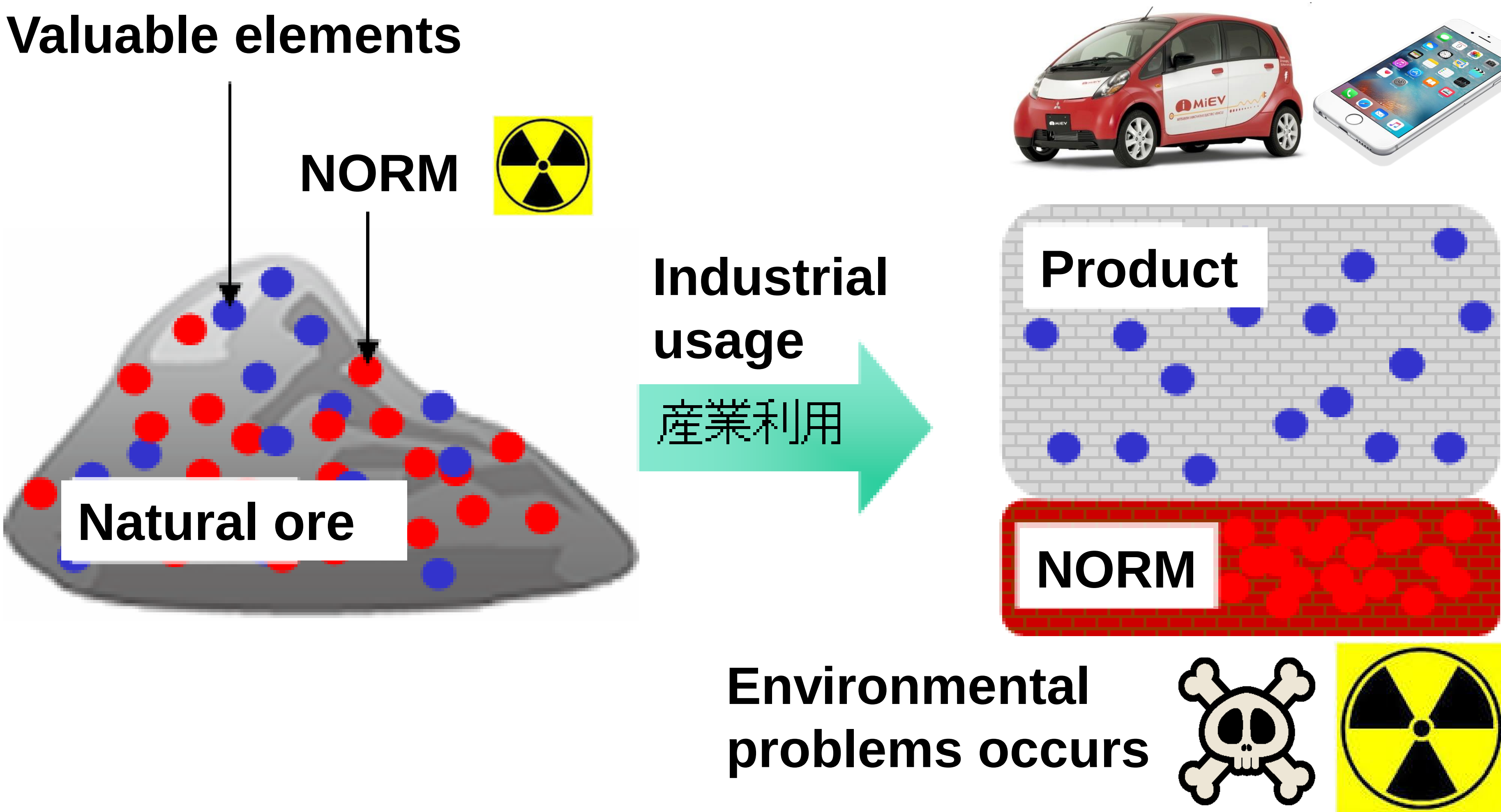
**4.6 B years**

**Earth now**

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

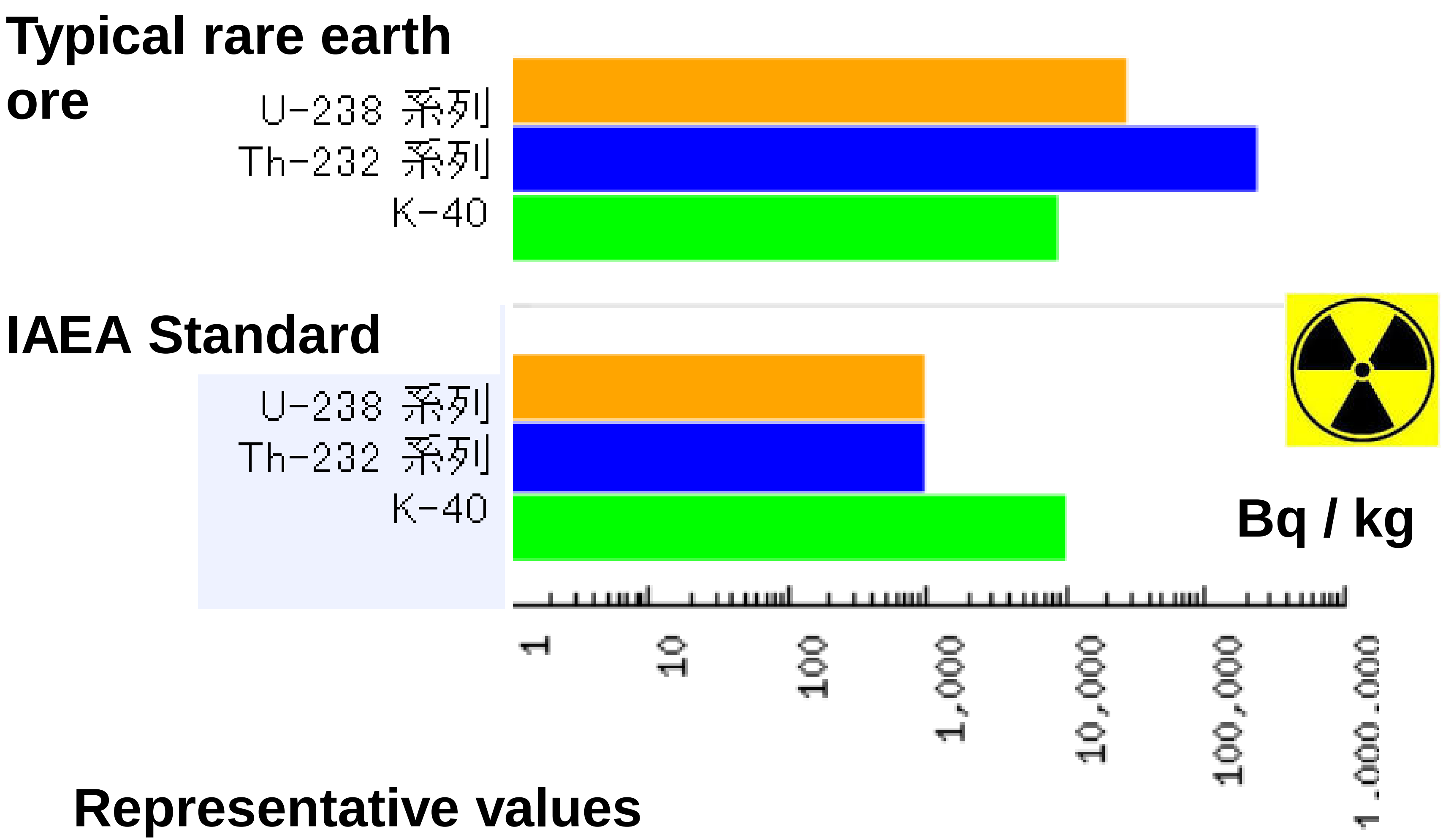
http://www.nirs.go.jp/db/anzendb/NORMDB/1_NORM.php
放射線医学総合研究所のホームページより

# 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

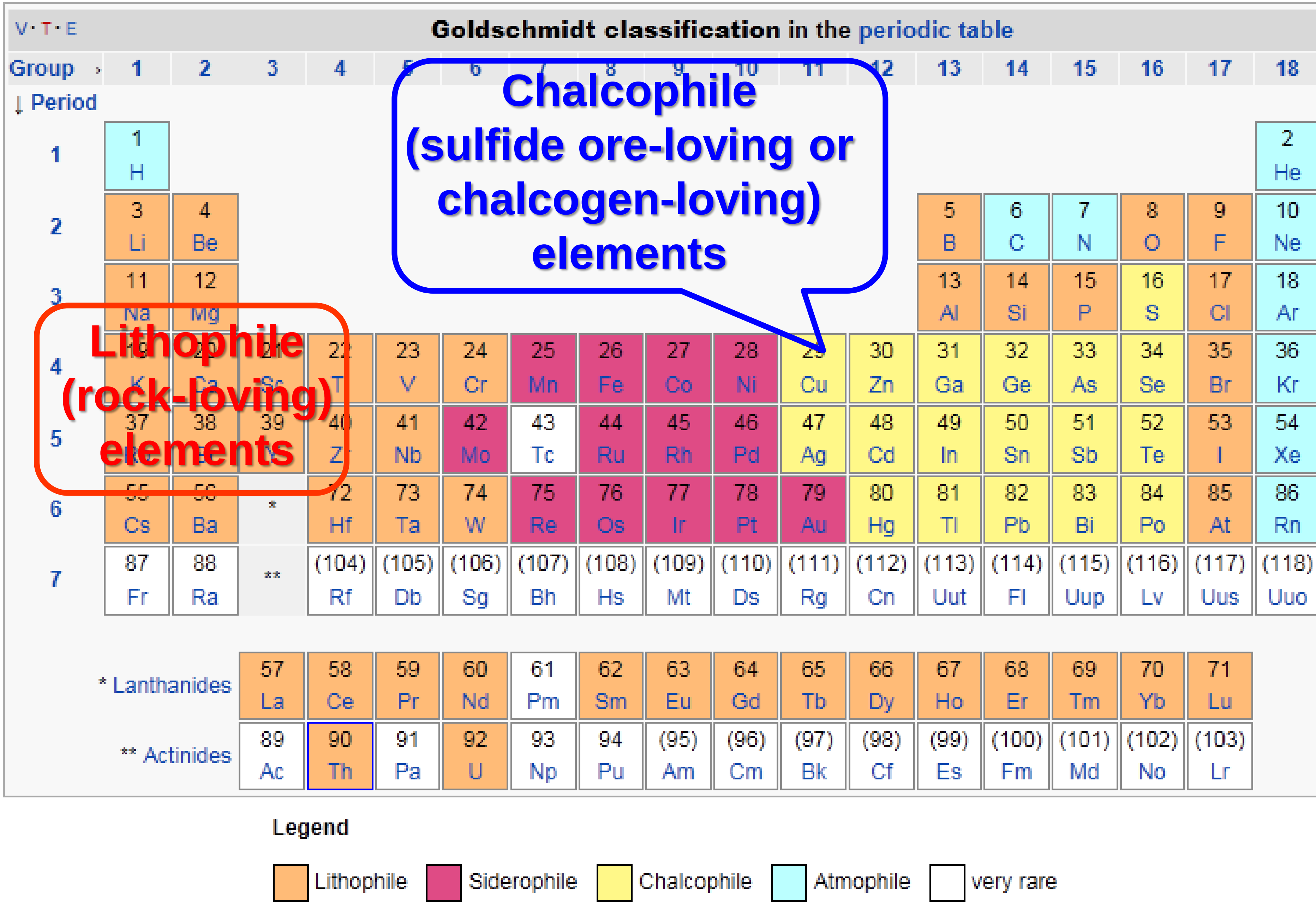
**Lithophile elements (rock-loving)**

**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)

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

親銅元素

## Atmophile elements (gas-loving)

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

親気元素

H, C, N, noble gases

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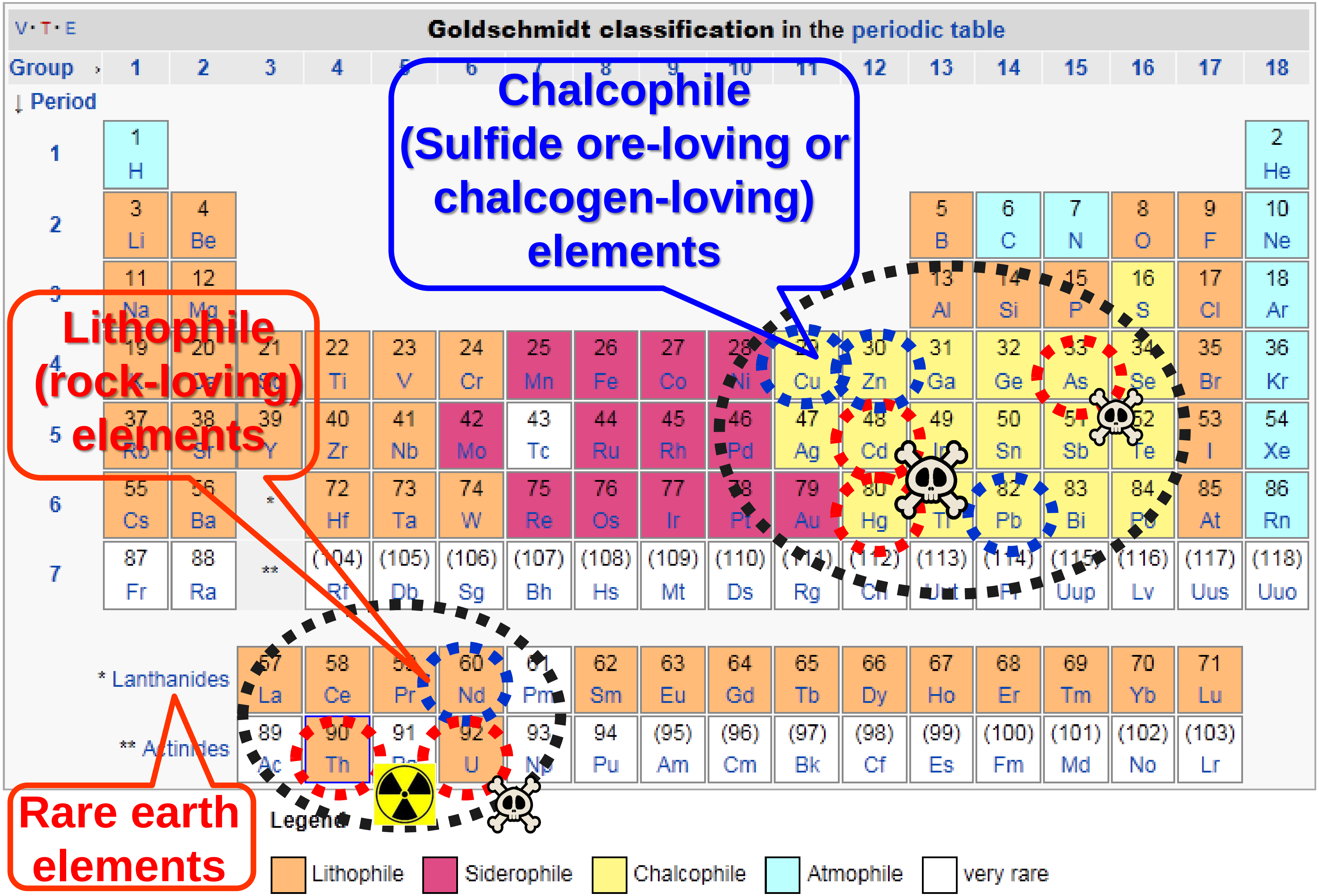
## Biophile elements (bio-loving)

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

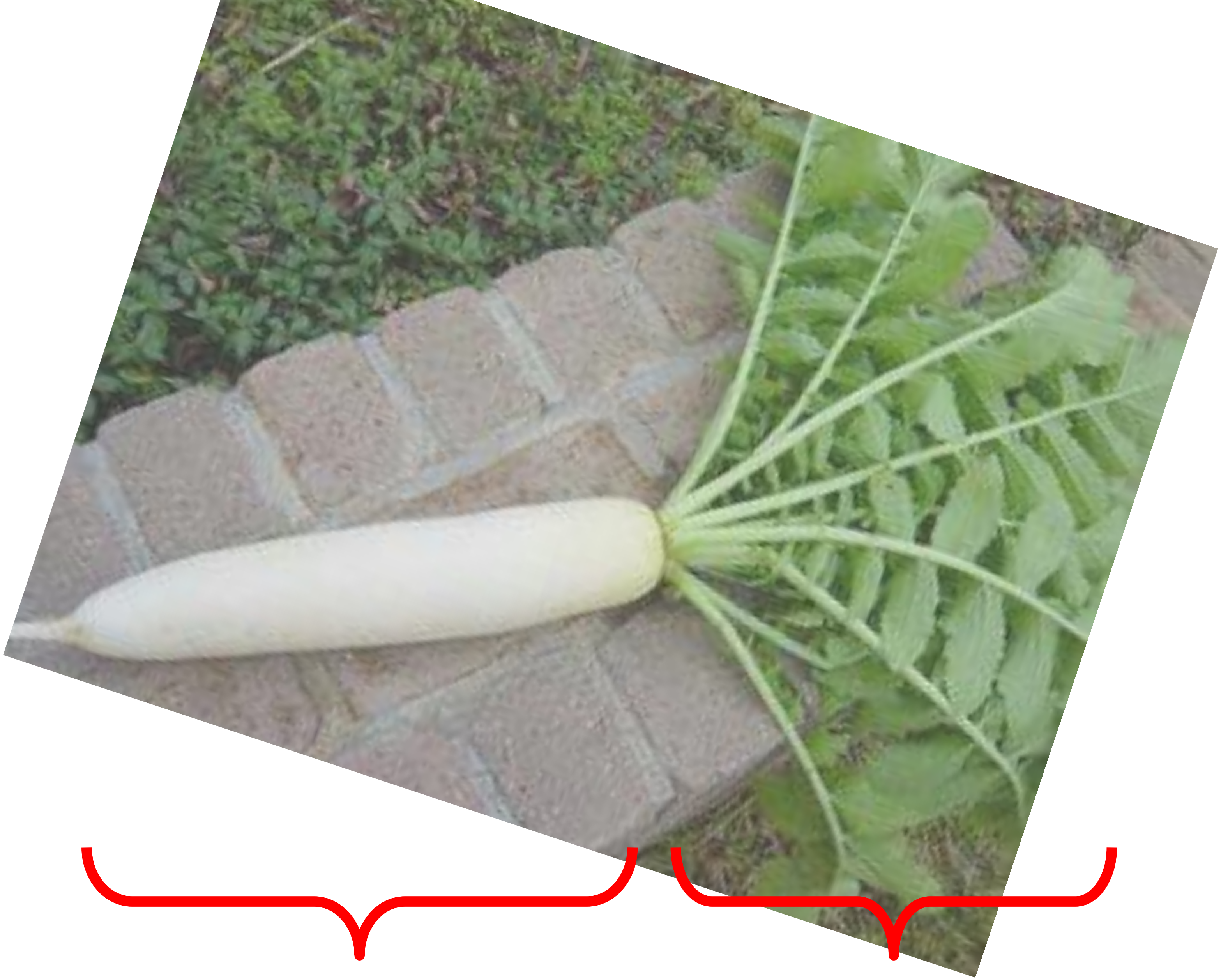
Gold (Au) ←by-product of copper (Cu)

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)

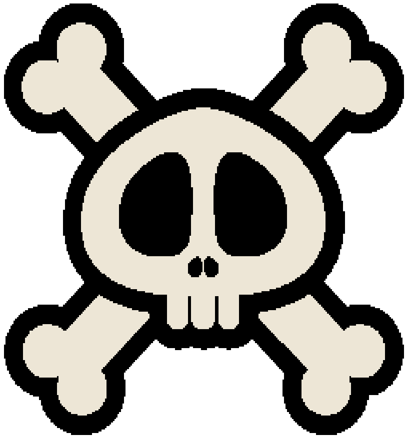
Rhodium (Rh) ←by-product of platinum (Pt)
Ruthenium (Ru) ←by-product of platinum (Pt)
Iridium (Ir) ←by-product of platinum (Pt)



**Root of radish** **Leaf of radish**

# Relationship between main products and by-products.

## Bad stories….



# Harmful by-products

Arsenic (As) ←by-product of copper (Cu) or
Mercury (Hg) zinc (Zn) or lead (Pb)
Cadmium (Cd)

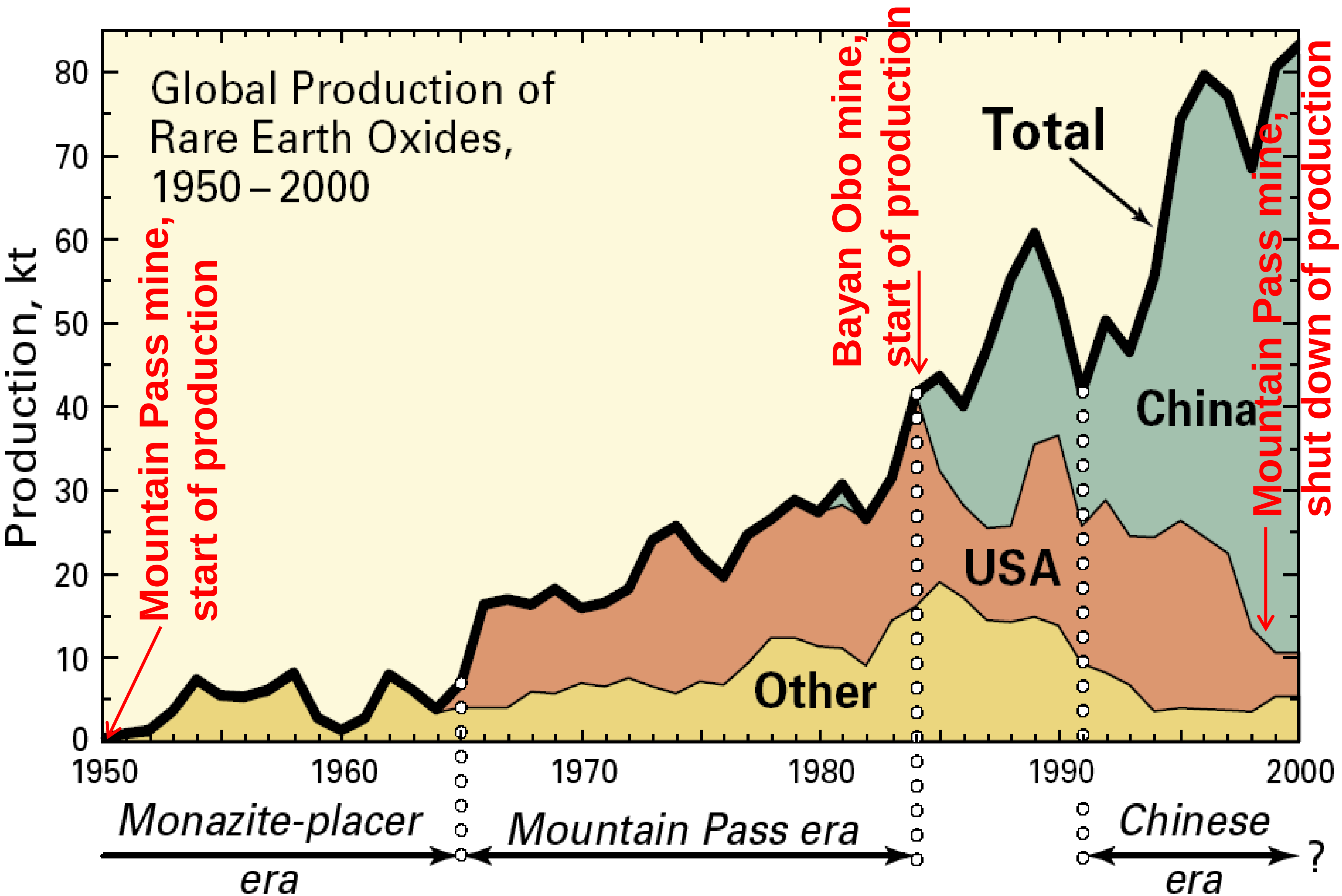
Uranium (U) ←by-product of rare earth
Thorium (Th) metals (REMs)

**When producing metals from natural ore, harmful/toxic materials are also generated.**

**Majority of the harmful/toxic materials are treated at mining/smelting site.**

**Most of the people do not realize the real situation of waste treatment.**

# Transaction of rare earth ore production




G.B. Haxel, J.B. Hedrick, and G.J. Orrs, *USGS Fact Sheet,* 087-02, (2002).

Courtesy of Prof. Osamu Takeda / Tohoku University

# Supply of REE

- Worlds' 97 % supply is dominated by China.

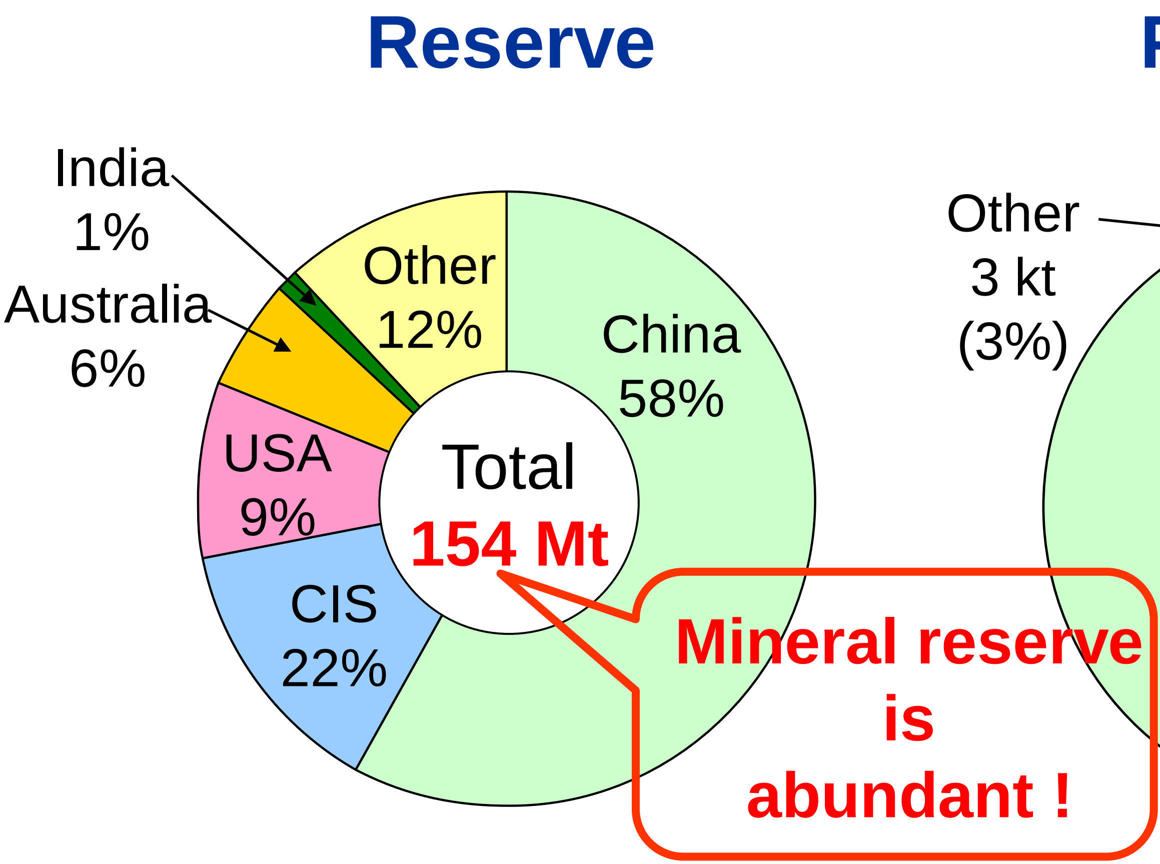



Fig. REE reserves in 2005.
(http://homepage3.nifty.com/bs3/Magnet/)

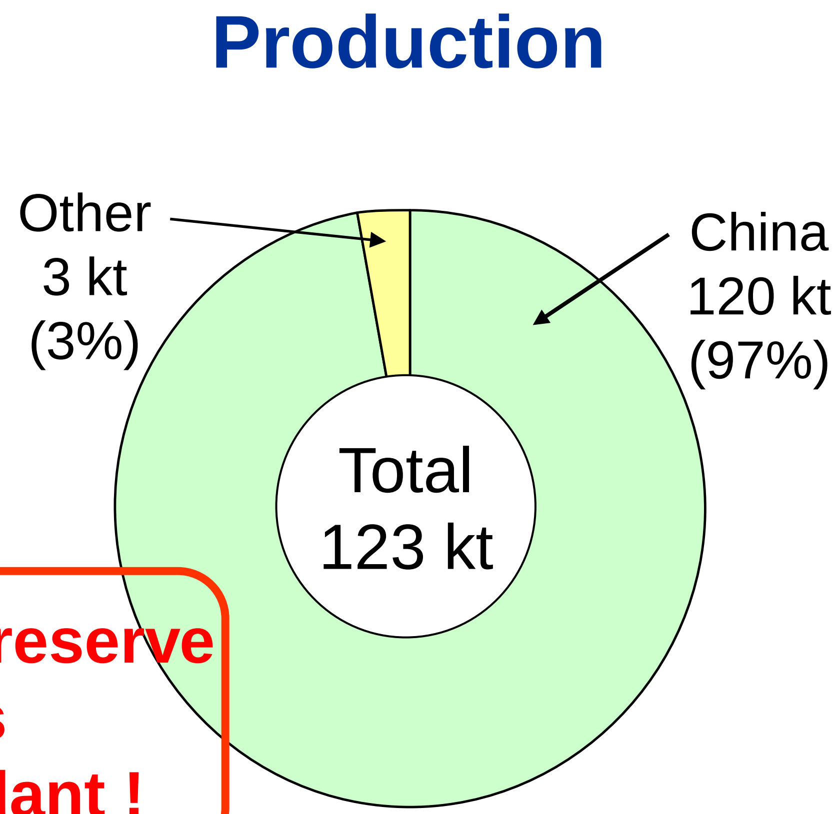



Fig. World share in supply of REE in 2006.
(USGS Mineral Commodity Summaries (2007))

# Harmful by-products

Arsenic (As) ←by-product of copper (Cu) or zinc (Zn) or lead (Pb)
Mercury (Hg)
Cadmium (Cd)

Uranium (U) ←by-product of rare earth metals (REMs)
Thorium (Th)

# Open-pit Bayan Obo Mine

露天掘りの白雲鄂博鉱山


Open-pit Bayan Obo Mine
露天掘りの白雲鄂博鉱山

# Open-pit Bayan Obo Mine

# 露天掘りの白雲鄂博鉱山


Open-pit Bayan Obo Mine
露天掘りの白雲鄂博鉱山

# Open-pit Bayan Obo Mine
# 露天掘りの白雲鄂博鉱山

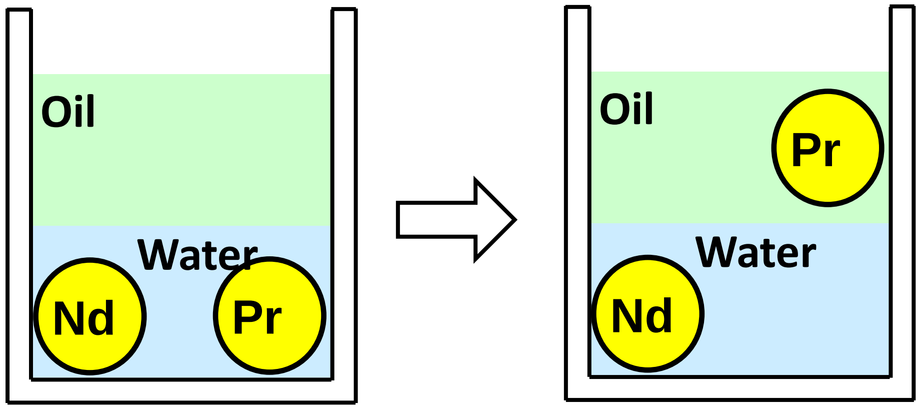
# Huge tailing dumping site / 白雲鄂博鉱山 尾鉱処分場

# Solvent extraction (SX) plant / 溶媒抽出工場

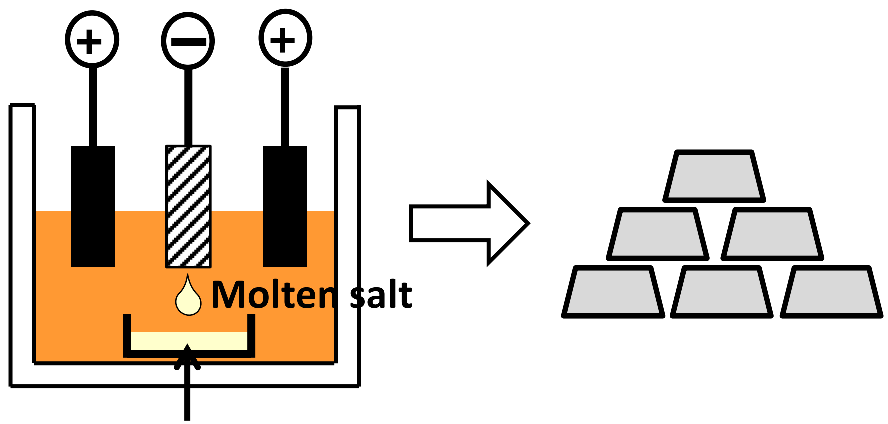
湿式製錬
→溶媒抽出

Hydrometallurgy
→Solvent Extraction

# Separation / purification of rare earth




# Metal production by molten salt electrolysis




Molten RE metal or alloy

RE metal/alloy ingot

東北大学大学院　工学研究科金属フロンティア工学専攻　竹田　修　博士　作成

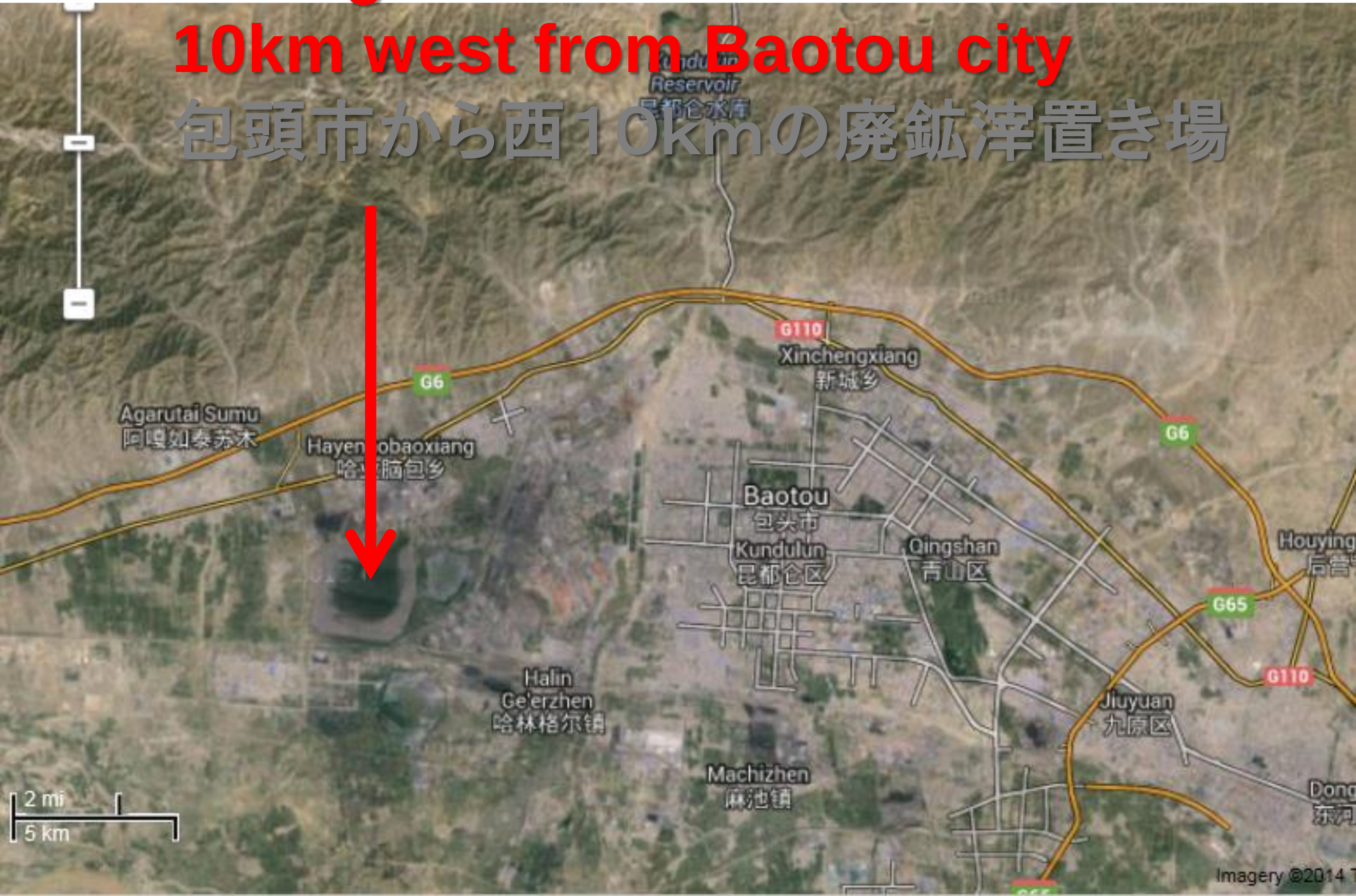
参考）足立吟也編：「希土類の機能と応用」，CMC出版(2006); 足立吟也編：「希土類の材料技術ハンドブック」，NTS (2008); JOGMEC NEWS, Vol. 27 (2011)


Exchanging anode from
molten salt electrolysis furnace /
溶融塩電解炉
のアノードの
交換作業
This process generates HF gas
because it utilizes fluoride monten salt
Photo by Toru H. Okabe 2014.7, Baotou

# Molten salt electrolysis plant / 溶融塩電解工場

Photo by Toru H. Okabe 2014.7, Baotou

# Tailing dam
# 10km west from Baotou city
# 包頭市から西10kmの廃鉱滓置き場




Tailing dam / 廃鉱滓処分場

http://blogs.unimelb.edu.au/sciencecommunication/2013/09/08/whats-all-this-commotion-about-rare-earth-elements/

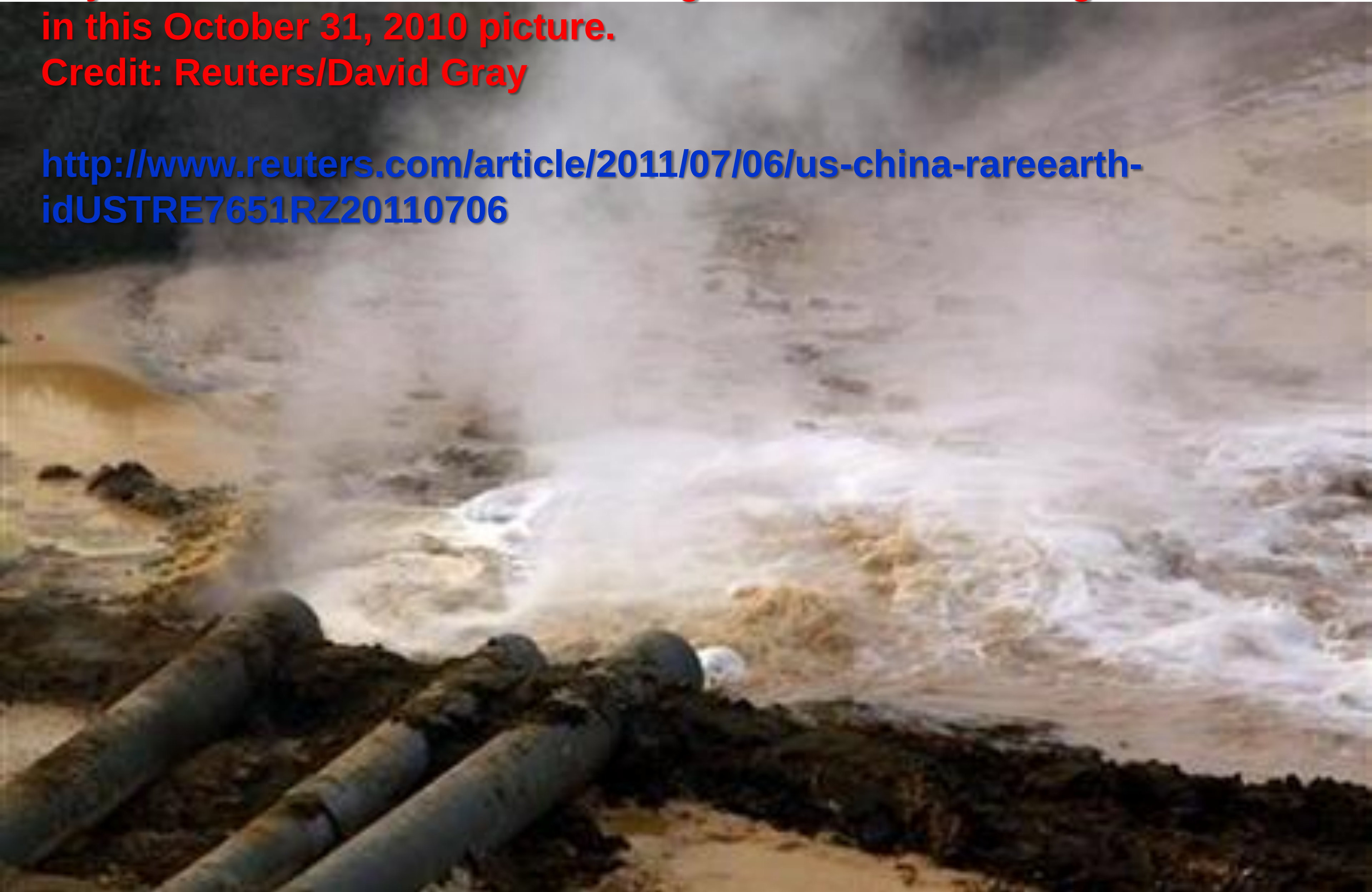
http://www.rootforce.org/2013/05/01/clean-and-green-rare-earth-elements-and-technology/

# When googling “Baotou Tailing Dam” various images can be obtained

http://www.reuters.com/article/2010/11/21/us-climate-emissions-idUSTRE6AK1OU20101121

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



# Mountain Pass Mine (USA)

**Re-stating mining operation?!**

**Mountain Pass Rare Earth Mine had been the largest mine in the past.**

**This mine also has NORM problems!**

# Mining methods of rare earth

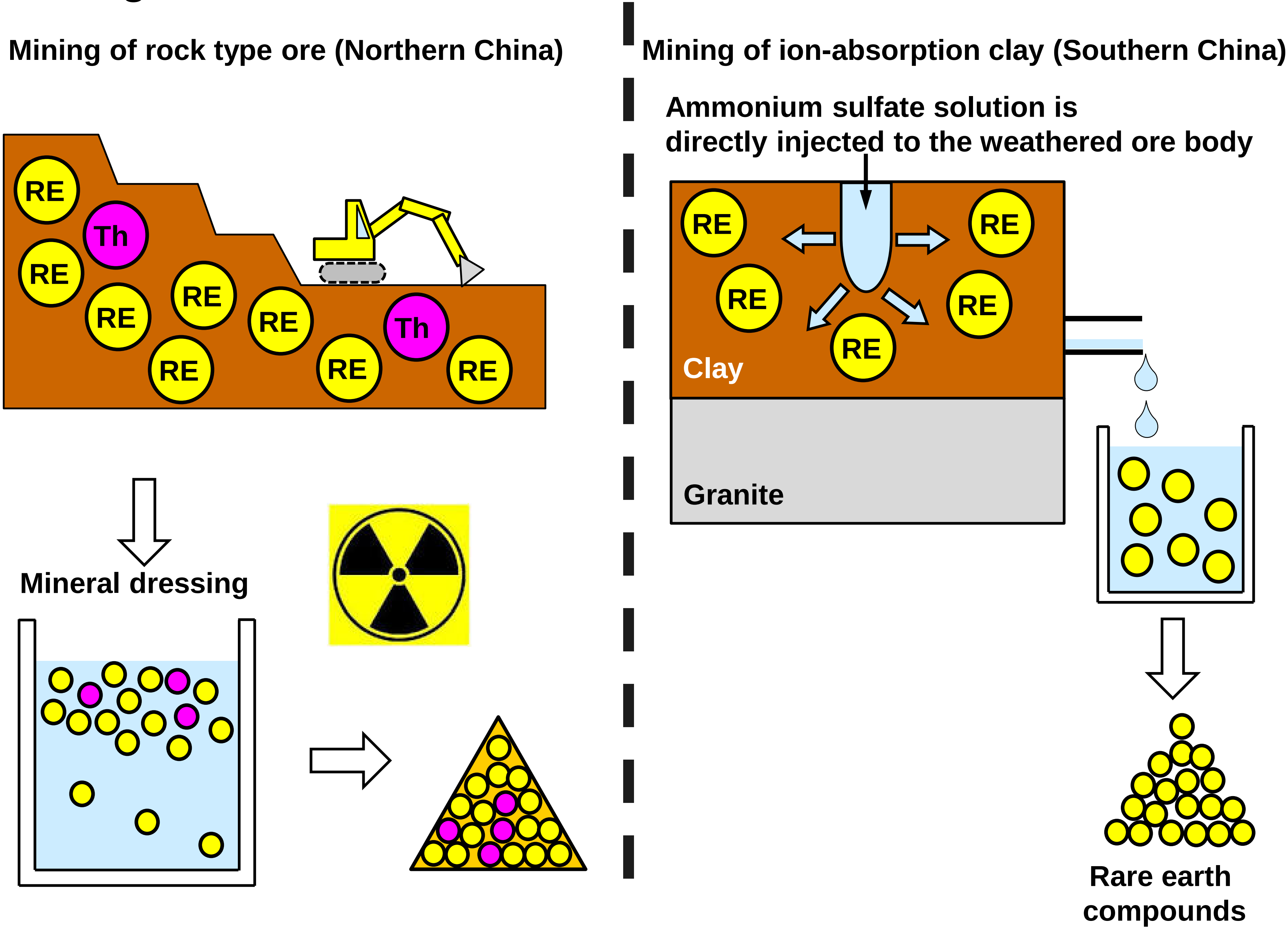


**Table 2**
Overview of rare earth elements (REE) market (2013) (Unit: REO t)[9]. Supply source of REE is expanded, but supply source of Dy is still limited in China.

| | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy |
|---|---|---|---|---|---|---|---|---|---|
| China (north & south) | 28492 | 40622 | 6352 | 19374 | 2762 | 389 | 1946 | 250 | 1247 |
| Australia Lynas | 255 | 467 | 53 | 185 | 23 | 4 | 8 | 1 | 1 |
| USA Molycorp | 1328 | 1964 | 174 | 480 | 32 | 4 | 7 | 1 | 1 |
| Russia Lovozerskiy | 521 | 1081 | 101 | 265 | 20 | 3 | 4 | - | - |

**Industrial Rare Metals, Annual Review 2014, Arumu Publ. Co.**

# Bottlenecks in rare metal supply

Institute of Industrial Science,
The University of Tokyo

Toru H. Okabe

'Bottlenecks in rare metal supply',
Toru H. Okabe:
9th Japan-U.S. Bilateral Meeting on Rare Metals,
March 10-11, 2022, (JST)
(Organizer: CMI (Critical Materials Institute) & NEDO),
(講演: Japan-U.S. Bilateral Meeting on Rare Metals, 3月 10日 (木曜日),
Session 2: Critial MaerialsSupply Chains, 午前10:00～午後12:00),
[東京][依頼講演]

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

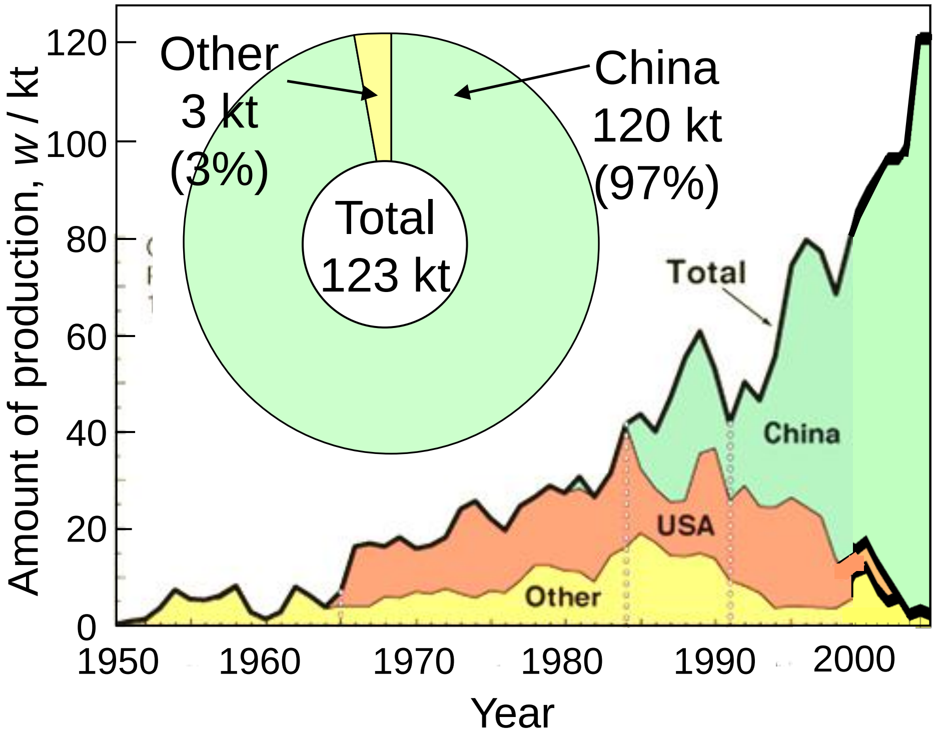
Rare Metals

# Environmentally sound technology for producing and recycling less-common metals

China has extremely high quality mineral resource and cheep labor.

Worlds' 97 % supply is dominated by China.

# Problems in supply of REE




Dy: ~$ 50 /kg Dy metal

Nd: < $ 10 /kg Nd metal

Dy: ~$ 400 /kg Dy metal

(max.> **$3500 / kgDy !**)

Nd: ~$ 150 /kg Nd metal

(max. **$450 / kgNd !**)

Change in amount of production of REE, and share in supply of REE in 2006.

(USGS Mineral Commodity Summaries (2007))

# 近年は、米国や豪州の希土類鉱石の生産量は増大している。しかし、重希土の生産は、今も、中国が独占している。

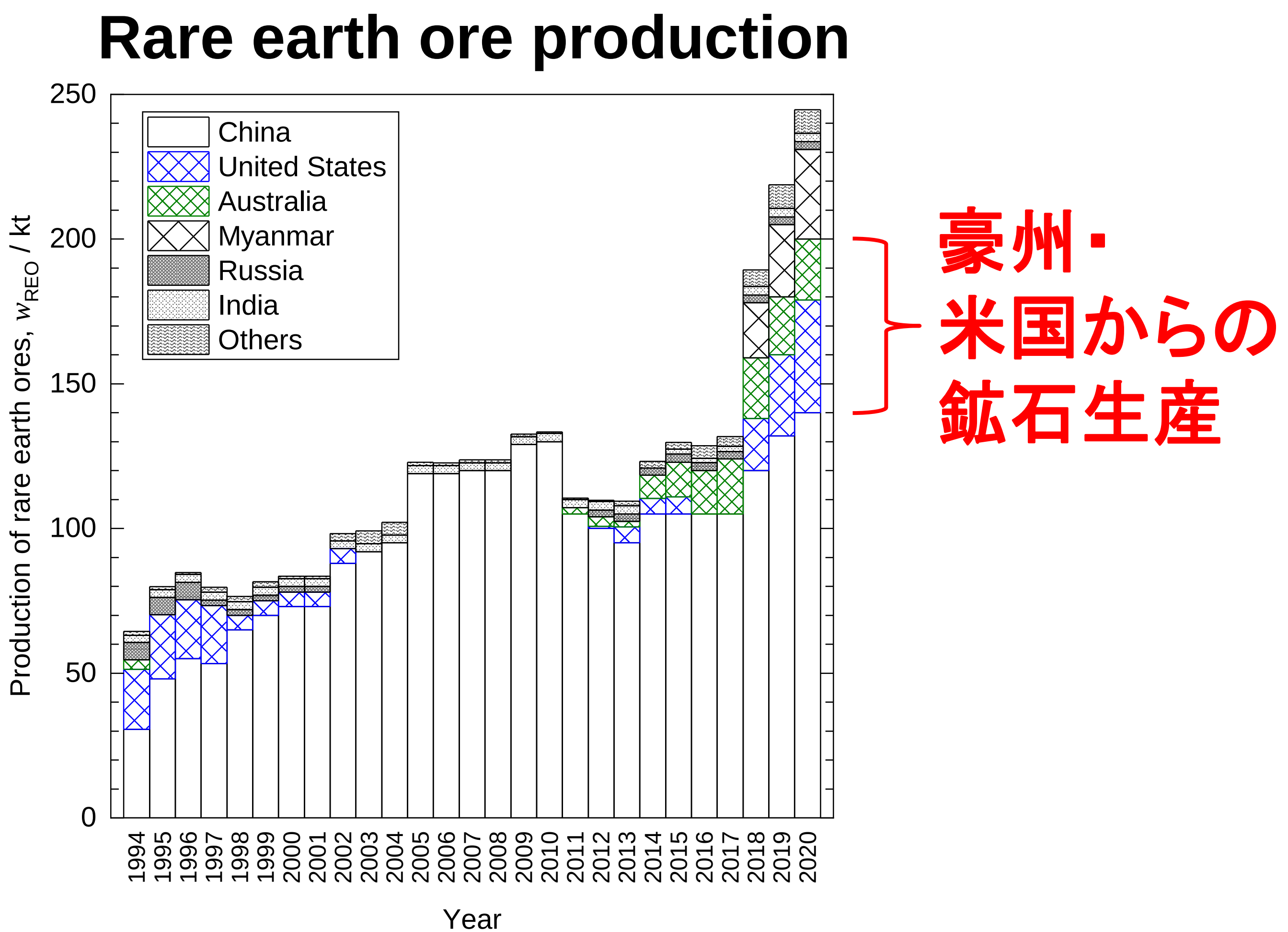
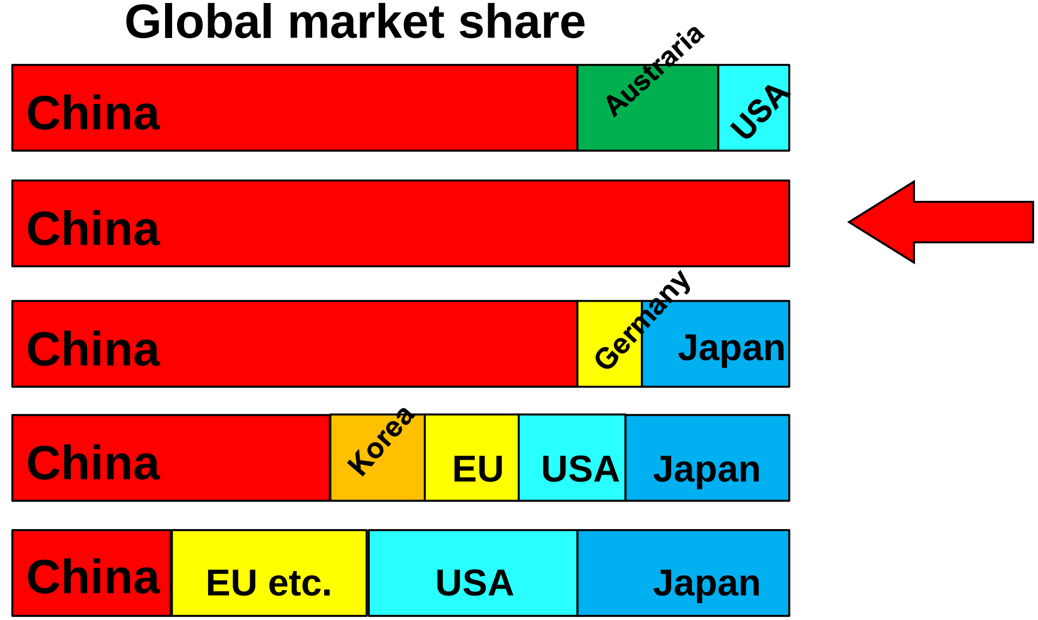



**Fig. Annual production of rare earth ores. [USGS]**

# Bottlenecks in supply chain in EV (with respect to REMs)

Mining & feed supply
↓
Smelting & refining
↓
Alloy and magnet production
↓
Motor production
↓
EV production

Global market share




**Serious bottlenecks in REMs supply chain is monopoly on smelting and refining plants by China.**

# Grade of Nd & Dy in the ore.

| Ore | | Ion cray | Bastnaesite | | Monazite |
|---|---|---|---|---|---|
| Mining Site | | Longnan (China) | Bayan Obo (China) | Mt. Pass (USA) | Mt. Weld (Australia) |
| REO grade in Ore (wt%) | | 0.05～0.2 | 6.00 | 8.90 | 11.20 |
| Grade in REO (wt%) | Nd | 3.00 | 18.50 | 12.00 | 15.00 |
| | Dy | 6.70 | 0.10 | trace | 0.20 |
| Grade in Ore (wt%) | Nd | 0.0015～0.006 | 1.11 | 1.068 | 1.68 |
| | Dy | 0.00335～0.0134 | 0.006 | trace | 0.0224 |

Dy grade in ore is very low, but
very easy to extract directly from ion clay...

(石原舜三，村上浩康：レアアース資源を供給する鉱床タイプ，地質ニュース624号，10 - 24. (2006))
(USGS Mineral Commodity Summaries (2010))

**Table 4** Unit mass of rare earth used for industrial products (rough estimate).

| Product | Unit mass of RE (kg RE / Unit) |
|---|---|
| Hybrid vehicle (HV) | 0.25~1.25[a] |
| Electric vehicle (EV) | 1.3~ |
| Power steering | 0.09 |
| Air conditioner | 0.12 |
| Hard disk drive | 0.01 |
| Mobile phone | 0.0005 |
| MRI[b] | 1500 |

**1.3 kg RE magnet / EV**

**a: In the case of hybrid vehicles (HV) unit mass of RE varies with output power of motors.**
**Small HVs use about 0.25 kg/unit RE and large ones about 1.25 kg/unit.**
**b: Magnetic Resonance Imaging (MRI) units.**

When producing high performance **motors for HEV or EV,**
about 1.3 kg of Rare earth magnet (Nd-Fe-B) is necessary.


**1.3 kg of Rare Earth magnet contains**

21（～26）% of Neodymium (Nd)
10（ ～5）% of Dysprosium (Dy)
(Rest: Boron)

→ Magnet with high thermal stability requires large amount of Dy.

Ore grade of Nd is about 1% (Bastnaesite)
Ore grade of Dy is about 0.01%-0.003% (Ion cray)

When producing high perfomance motors:
about 0.27 kg of Nd (31 kg of Bastnaesite ore)

**about 0.17 kg of Dy (1 to 4 tons of Ion cray)**

are required.
For producing one motor, large amount of ore is required, and environment problems are induced when mining and refining.

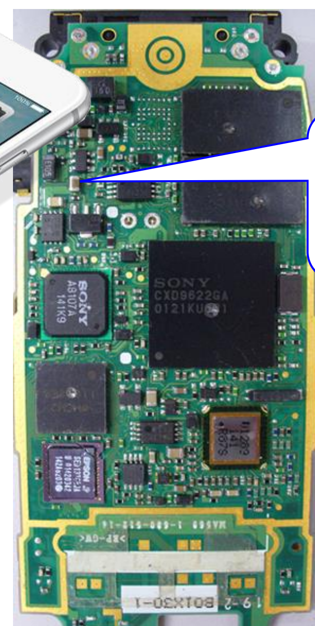
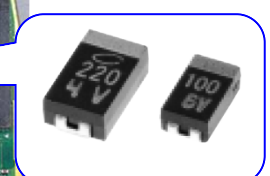
Far larger mass of ore compared to the mass is automobile is consumed when producing high performance automobile.

# Rare Metals

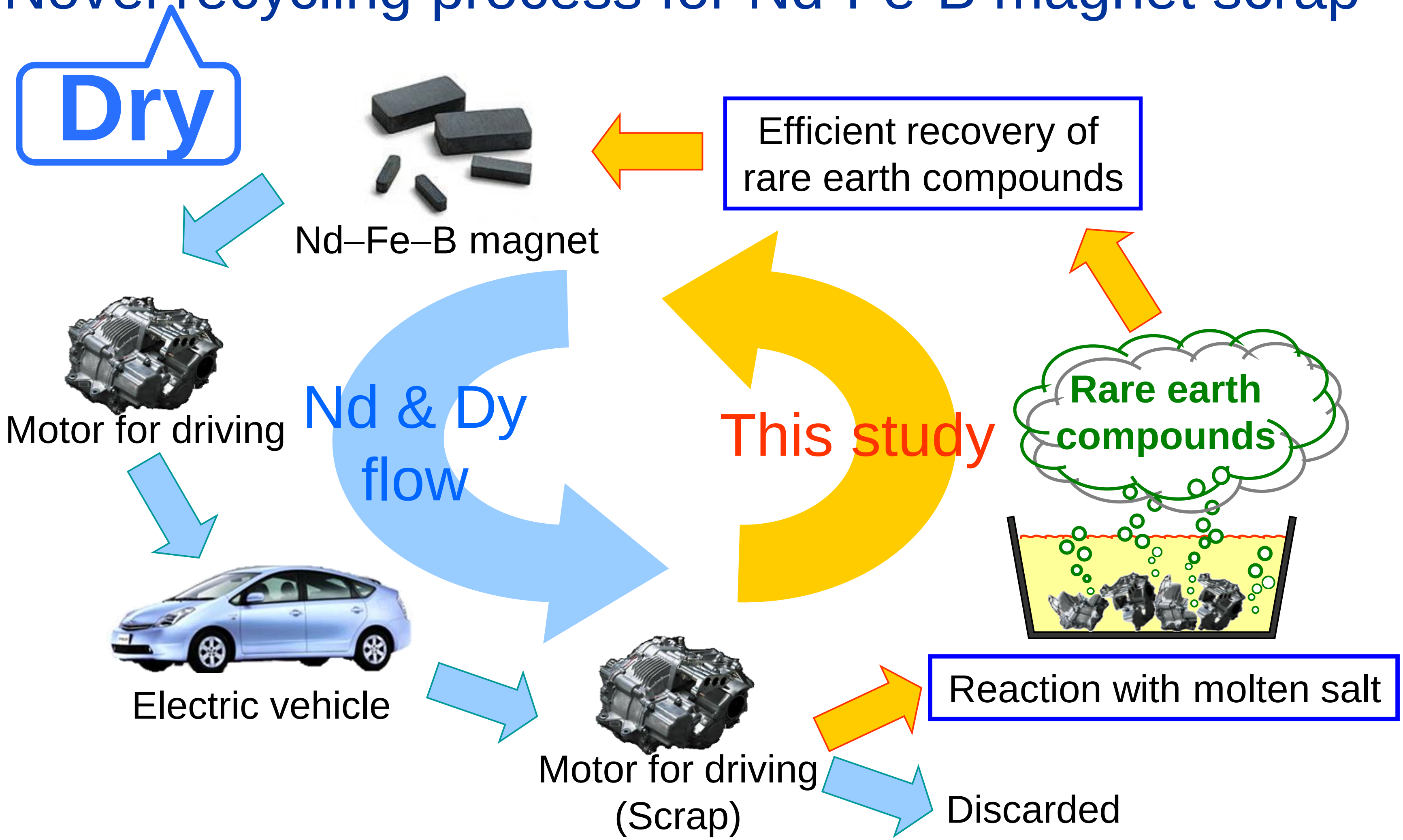


# PGMs, REMs, Ga, Ta…




# Novel recycling process for Nd-Fe-B magnet scrap




Development of effective recovery process
by utilizing molten salt as a rare earth extracting agent

# Okabe's dream:

Development of efficient and environmentally sound recycling processes:

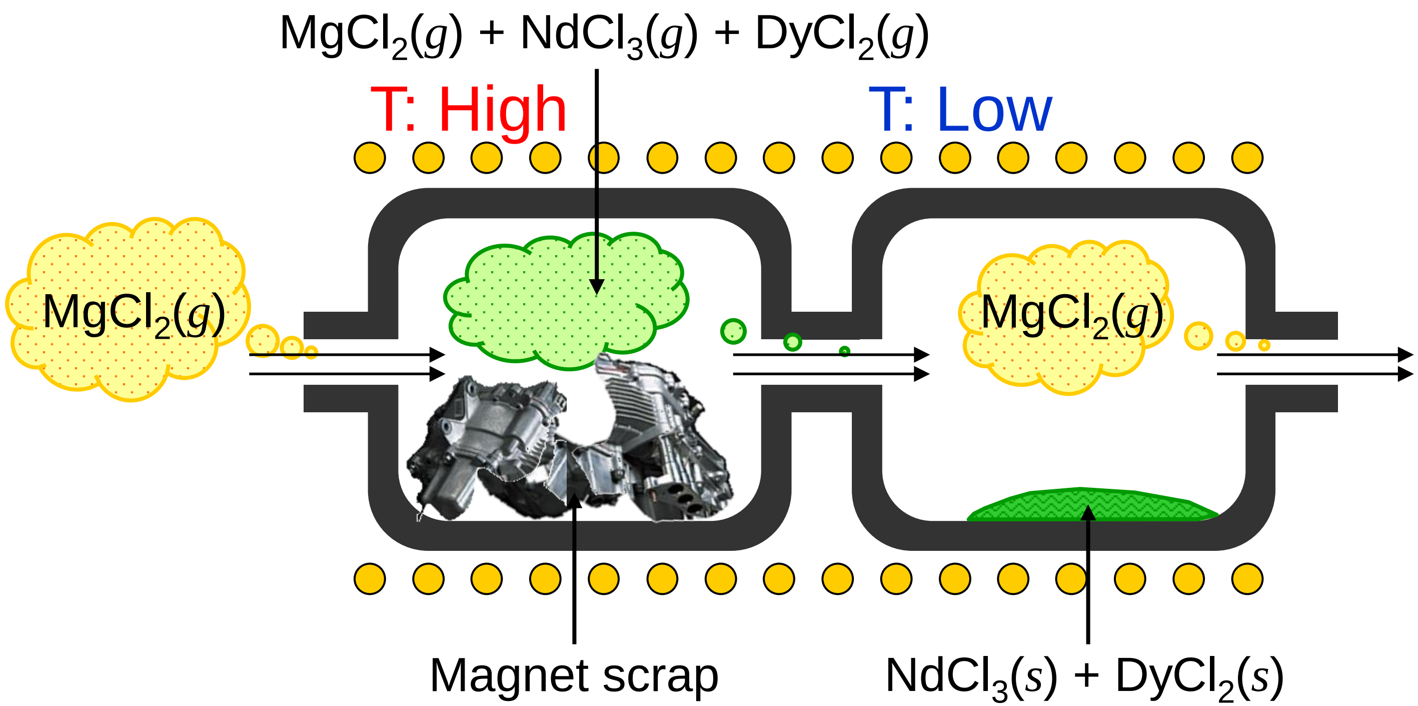



Fig. Schematic illustration of novel recycling process for magnet scrap.

# 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 and economy-based analyses of the material flow of rare

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

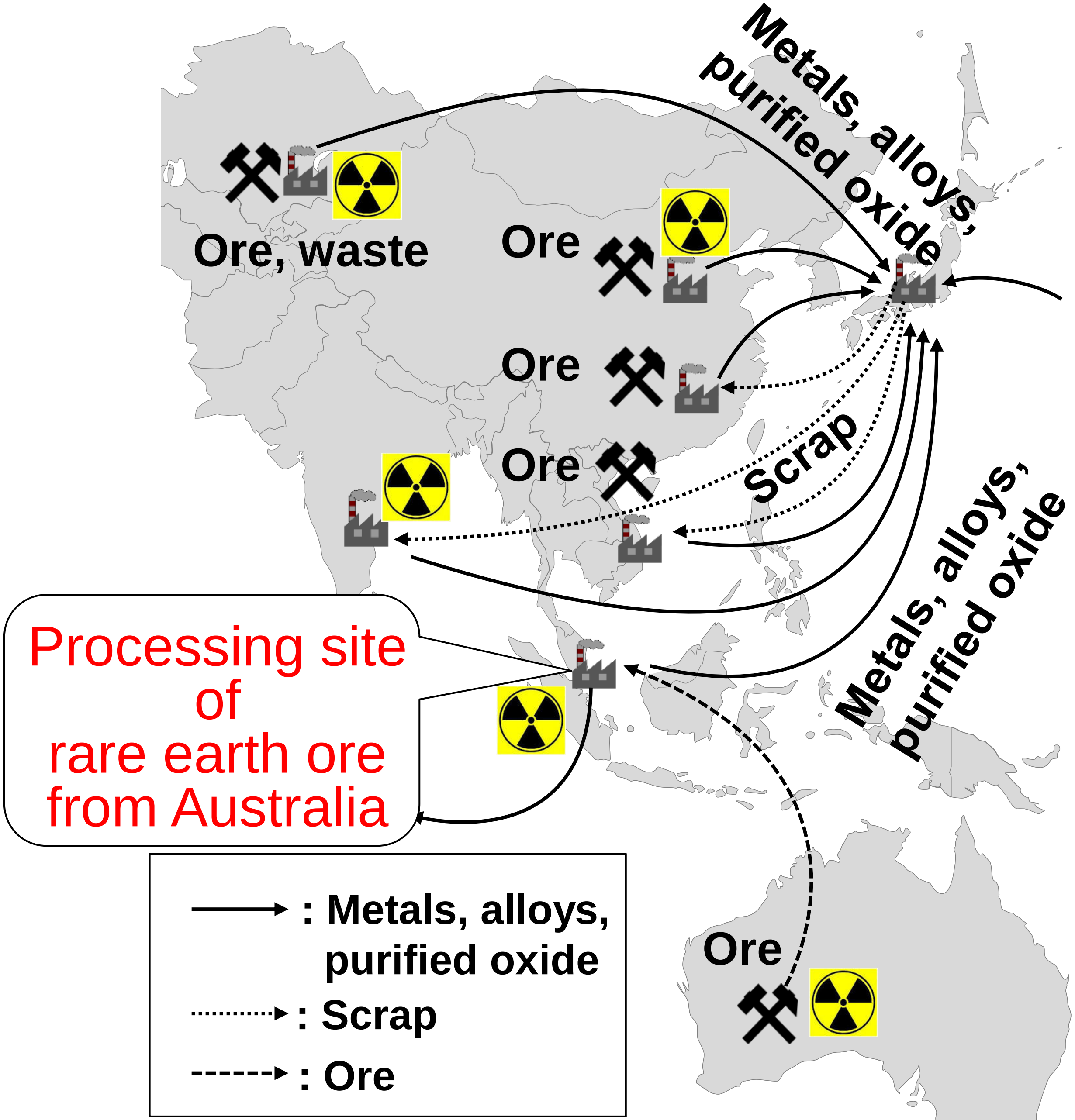
# Development of new recovery process of rare metals from scraps

Rare Metals

# Environmentally sound technology for producing and recycling less-common metals

## Comparison of costs for producing metal and alloys of rare earth metals

| | Japan | US | China | Australia |
|---|---|---|---|---|
| Feed cost | × high | × high | ◎ very low | ○ low |
| Energy cost | × high | ○low | ? low | ○ low |
| Environmental cost | × very high | × high | ◎ very low | × high |
| Employment cost | × high | × high | × low | × high |




**Material flow of rare earth metals and alloys in the world.**

**Japan imports only purified materials.**

**Practically, we can not import ore which contains radio active elements (NORM).**

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

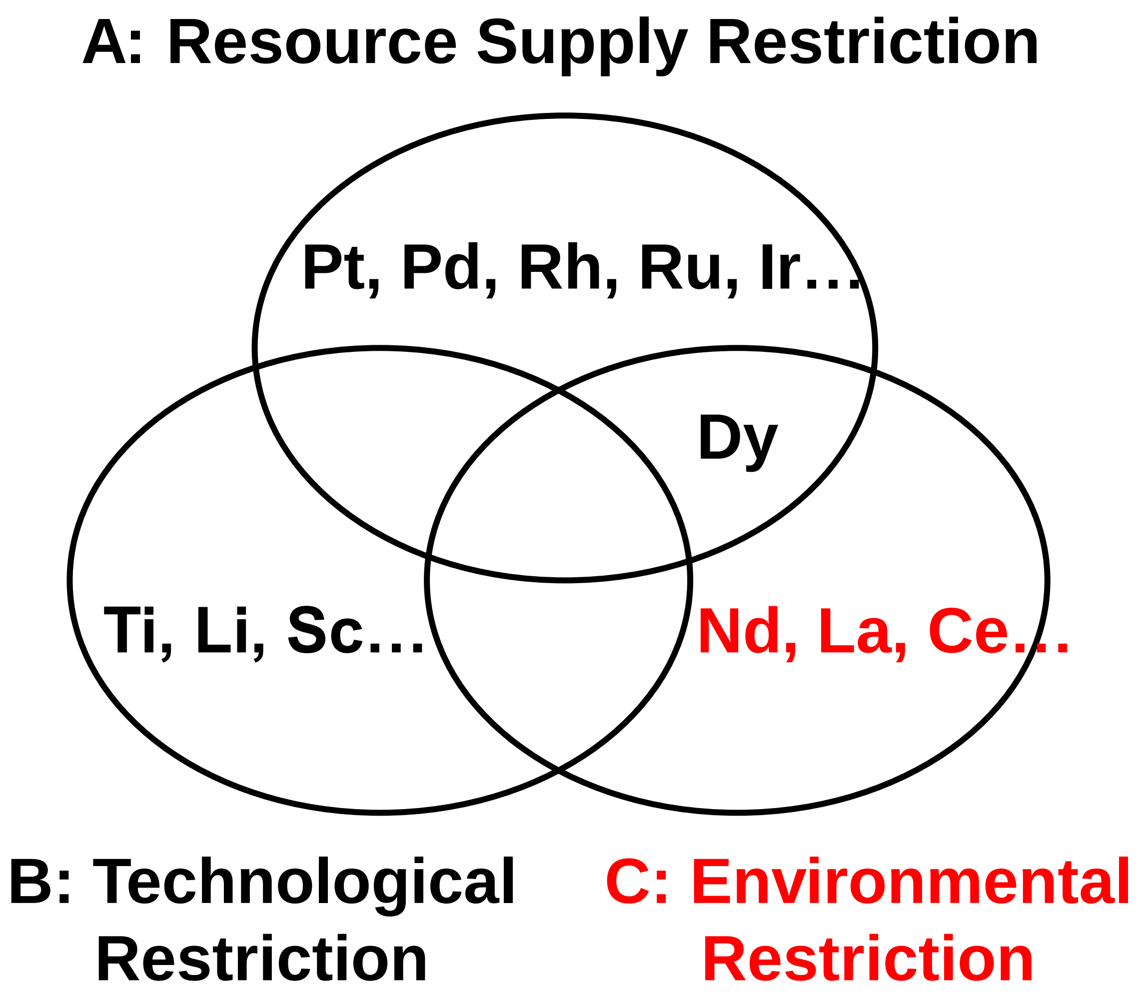



**Fig. Key factors that determine rare metal supply.**
**Environmental and technological restrictions are the major practical constraints, not the resource supply restriction, especially for rare earth metals.**

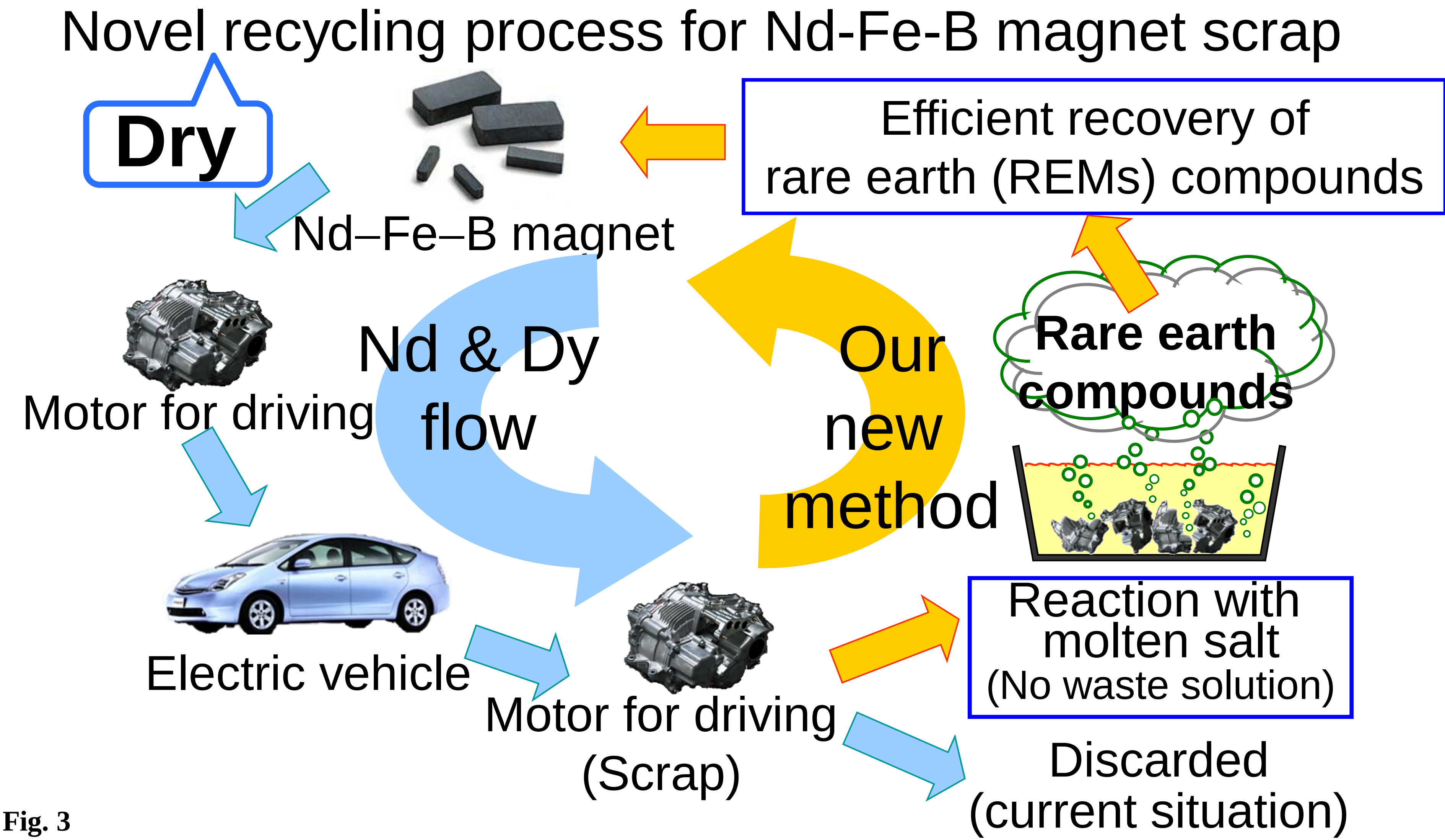



**Fig. 3**

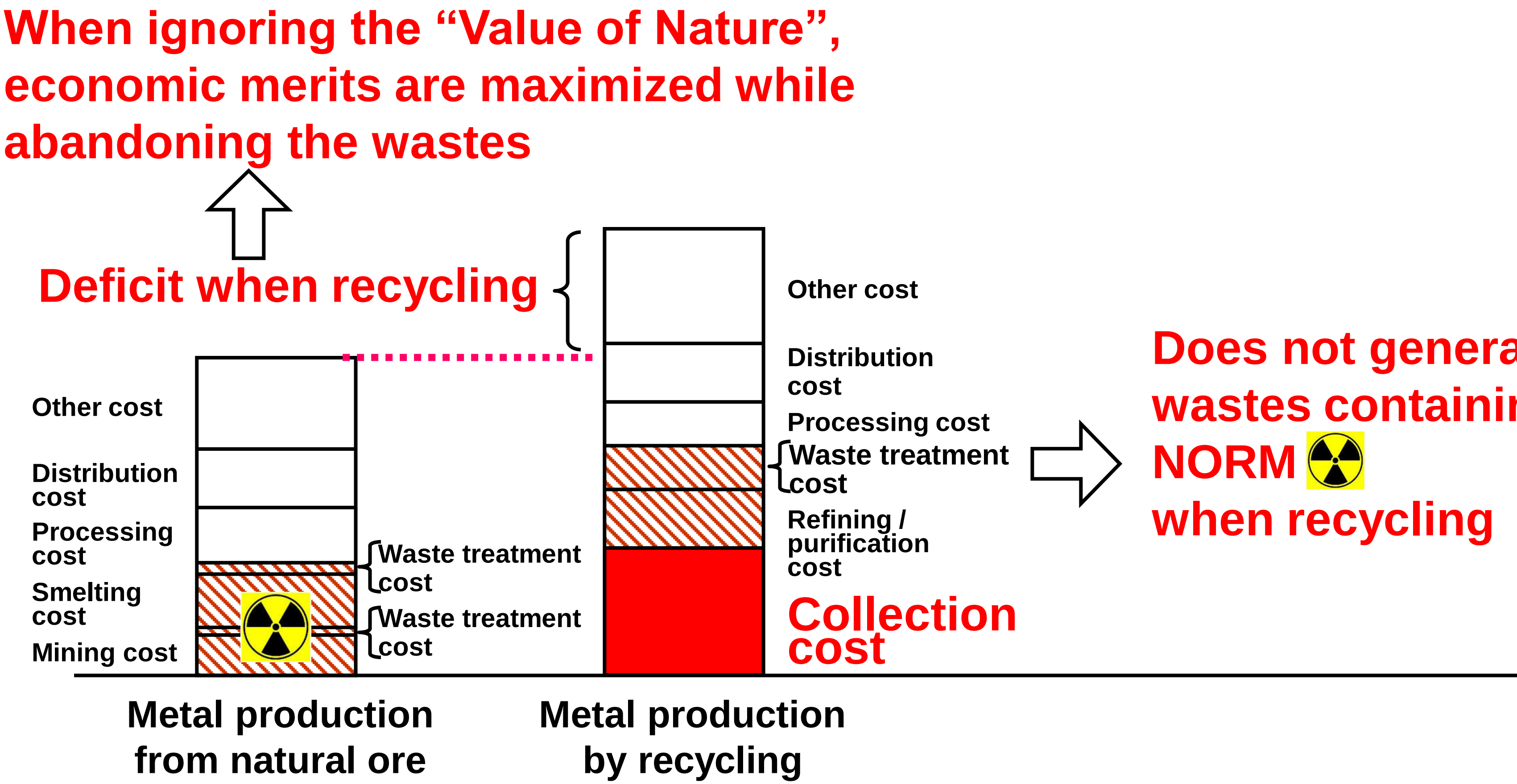
**A representative scheme for the development of an effective recovery process by utilizing molten salt as a rare-earth extracting agent. A novel environmentally sound recycling process for Nd–Fe–B magnet scrap, which does not generate any waste aqueous solution, is currently under development.** (T. H. Okabe, S. Shirayama: International patent PCT/JP2009/056079 (2009.3.26), US Patent No. 8323592 (2012.7.19), Chinese Patent No. ZL200980119301.3 (2013.7.10), German Patent No. 60329388.3 (2009.9.23), British Patent No.1512475 (2009.9.23), Japanese Patent No. 5424352 (2013.12.6), Y. Miyamoto, T. Okamoto, T. H. Okabe: Japanese Patent No. 5709164, International patent PCT/JP2012/056032 (2012.3.8), etc.) **This**

**When considering the bottlenecks of supply of rare metals (including REMs), many people put heavy weight on the resource constraints of rare metal supply.**

**However, in practice, environmental and technological constraints are the major bottlenecks, rather than any problem with shortage of resources.**

# Value of nature

(a) Nominal value of rare metals based on
the current economic principles



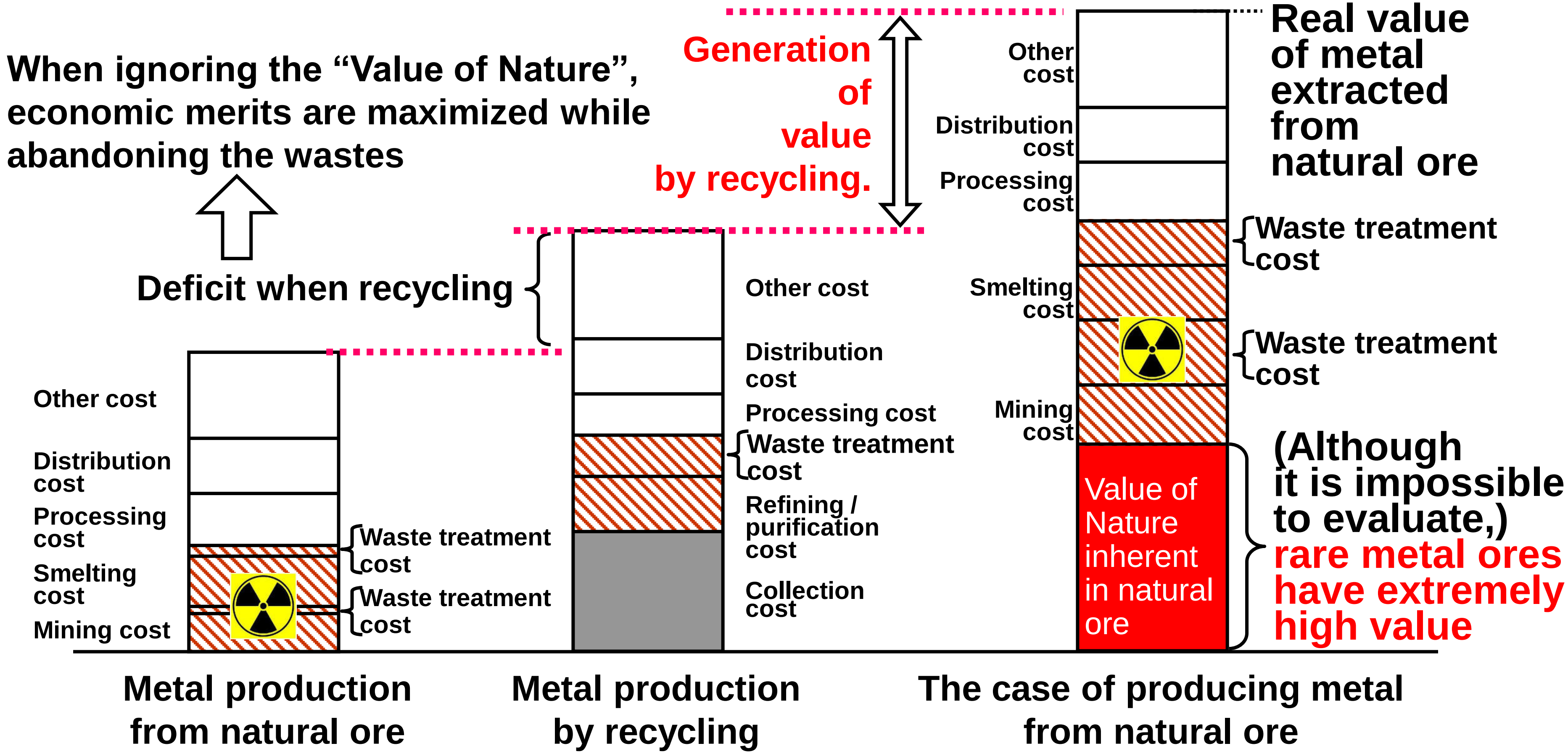

※ Hatched parts in the figure are often carried out in mining countries or regions.

**Fig. 9 The concept for evaluating the value of metals. In the current societal system, the value of nature is not considered. Recycling prevents consumption of natural resources and suppresses loss of the value of nature.**

# Value of nature

(a) Nominal value of rare metals based on the current economic principles

(b) Real value of rare metals counting the value of nature.




※ Hatched parts in the figure are often carried out in mining countries or regions.

When considering the value of nature, waste treatment cost also increases

**Fig. 9 The concept for evaluating the value of metals. In the current societal system, the value of nature is not considered. Recycling prevents consumption of natural resources and suppresses loss of the value of nature.**

**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.**

# Development of new recovery process of rare metals from scraps

Rare Metals

# Environmentally sound technology for producing and recycling less-common metals

**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.**

# Development of new recovery process of rare metals from scraps

Rare Metals

# Environmentally sound technology for producing and recycling less-common metals

# Innovation Changes
# Rare Metal to be recycled efficiently

(Carnegie Museum of Art, Pittsburgh, Pennsylvania, cover page of JOM, Nov. 2000)

# Environmentally sound metal production / recycling technology has to be developed

MINERAL PROCESSING AND EXTRACTIVE METALLURGY, 2017
VOL. 126, NOS. 1–2, 22–32
http://dx.doi.org/10.1080/03719553.2016.1268855

IOM3 The Institute of Materials, Minerals and Mining
AusIMM THE MINERALS INSTITUTE
Taylor & Francis
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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**
Received 8 September 2016
Accepted 23 November 2016

**KEYWORDS**
Rare metals; REMs; bottleneck; 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.**

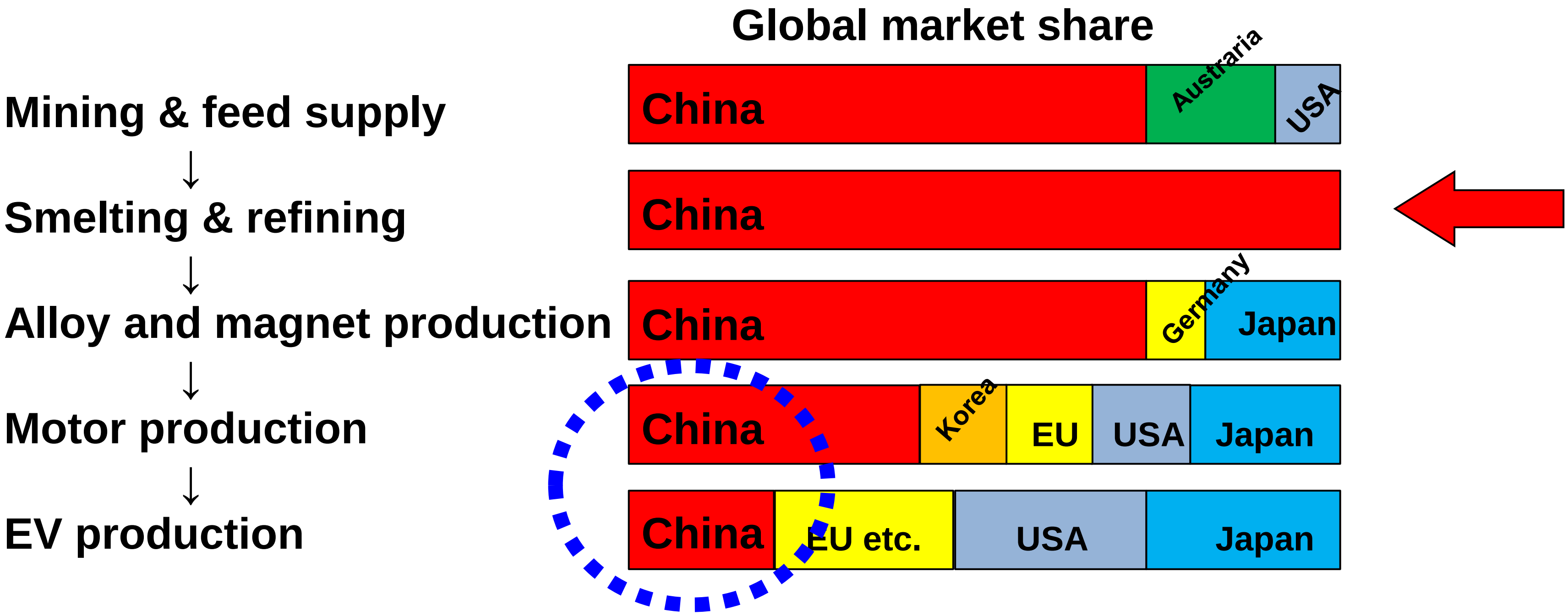
## 1. Introduction

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

# Bottlenecks in supply chain in EV (with respect to REMs)




China's presence is growing further.

**Serious** bottlenecks **in REMs supply chain is monopoly on smelting and refining plants by China.**

**In the future, downstream market will also be dominated.**

# Rare Metals Essential for Next Generation Vehicles: Current and Future Problems


**Institute of Industrial Science, The University of Tokyo**

**Toru H. Okabe**



**'Rare Metals Essential for Next Generation Vehicles: Current and Future Problems',**

**Toru H. Okabe:**

**International Electric Vehicle Technology Conference (EVTeC), EVTeC 2023 Plenary Session, "Toward Carbon Neutral Transportation by Electrification", (2023 年5 月22 日(月)～24 日(水), 会場: パシフィコ横浜ノース(神奈川県横浜市)), EVTeC2023 Plenary Session, 2023年5月22日(月) 10:10～10:50 (40分間), [横浜] (2023.5.22).**

**[Plenary Talk]**

**(リアル講演会＋ネット配信のハイブリッド講演会)**

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