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SCIENTIFIC AND STRATEGIC ENVIRONMENTAL CONSULTING

A sustainable approach to material (mineral) recycling
Genetic, thermodynamic, environmental and economic issues

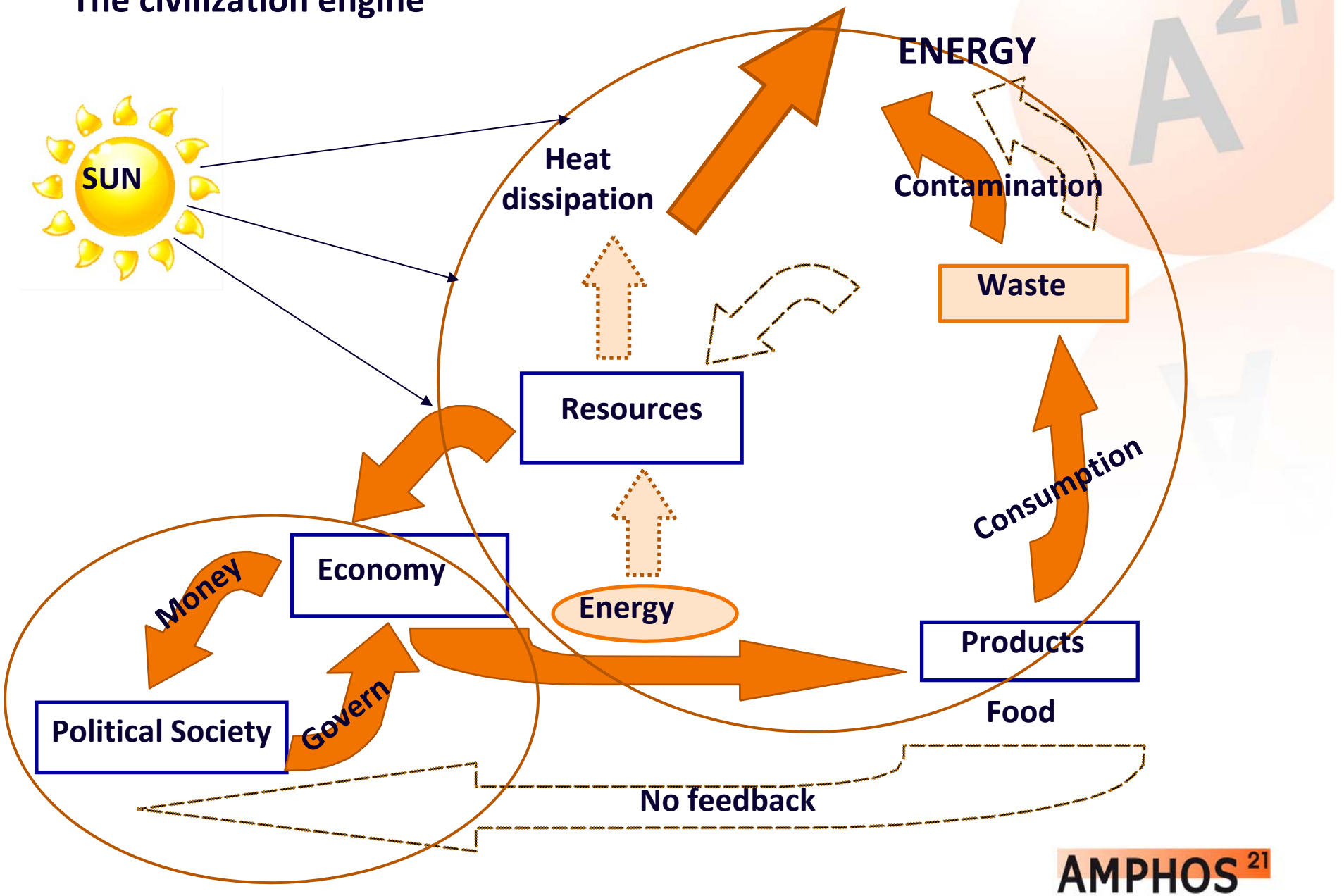
Jordi Bruno (with contributions by Manolo Prieto and David Arcos)

1994-2014 20 YEARS FLOWING

Lay out

- What are we talking about?
- Environmental issues related to mining
- The limits of recycling

The civilization engine



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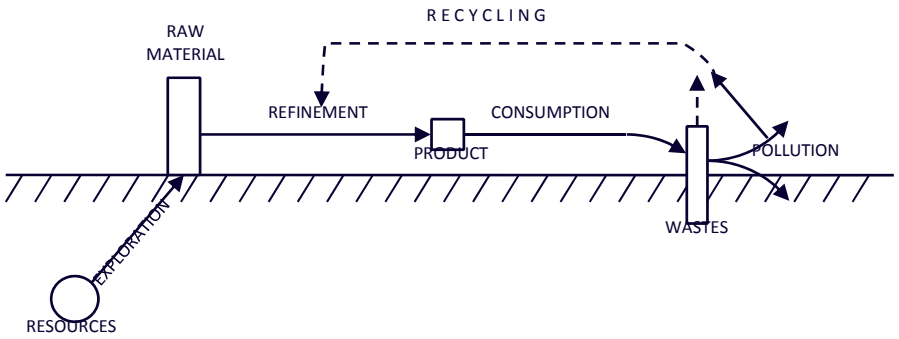
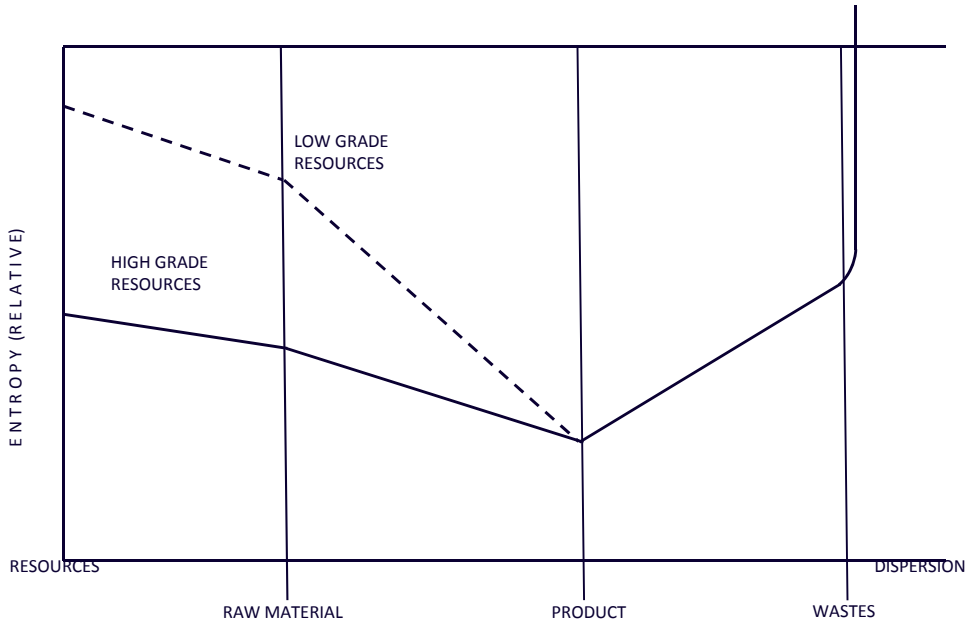
Stumm and Morgan, 1981





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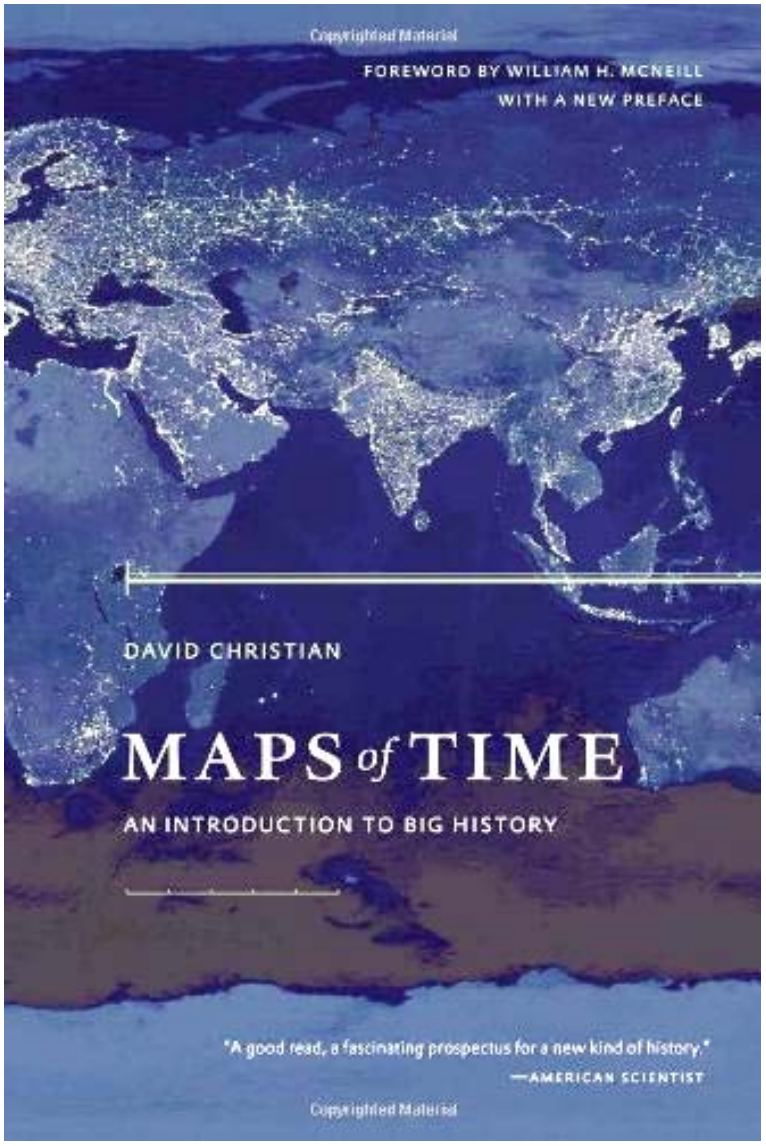
Minerals and the Big History

Big History is a framework for all knowledge. From the Big Bang to the modern day — and to what may lie ahead

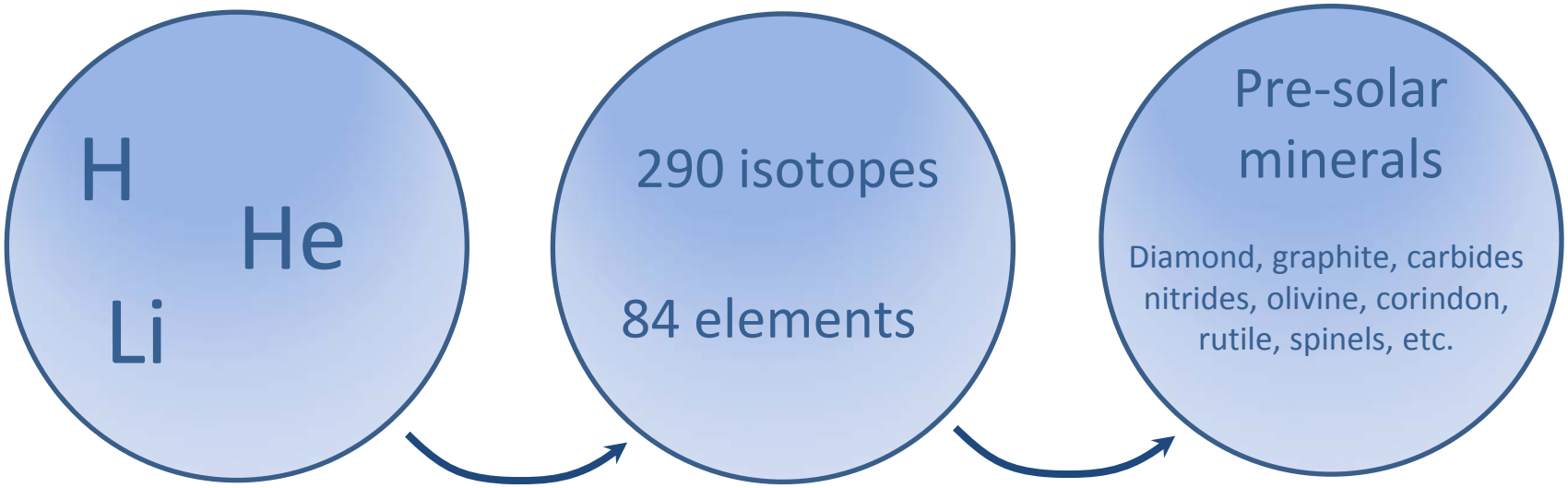
Mineralogy is the 4th dimension of the stardust and the development of human life



M. Prieto, 2014

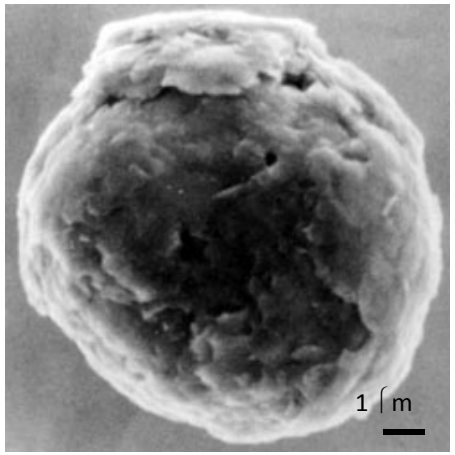
The first minerals

M. Prieto, 2014



IX-ray image of a supernova
Blue (Si and S)
Green (Mg)
Orange (O)

http://chandra.harvard.edu



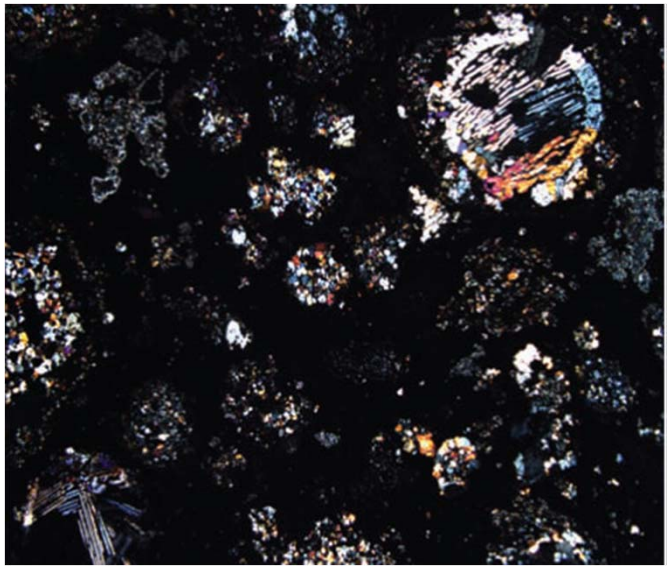
H 12

Pre-nebular graphite

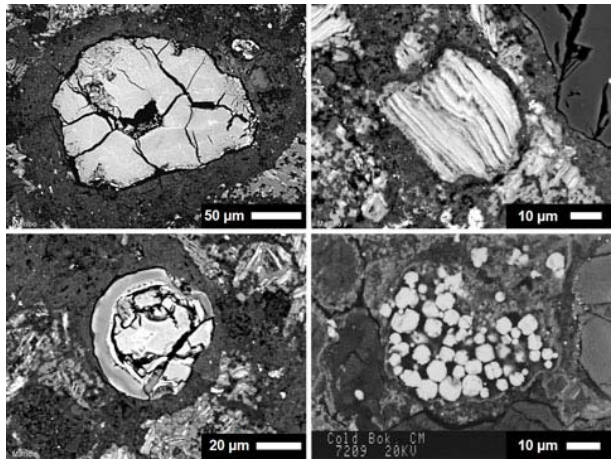
http://news.wustl.edu/news/

Condritic minerals

Hazen et al. (2008) Mineral Evolution. Am. Mineral. 93, 1693-1720.



Microphotography of a a chondrite. Olivine is the most abundant birefractory mineral.



http://www.uni-muenster.de/Planetology

Condriles	Olivino (rico en Mg)	$(Mg,Fe)_2SiO_4$
	Piroxeno (rico en Mg)	$(Mg,Fe)SiO_3$
	Kamacita (metal)	⟨ -(Fe,Ni)
	Taenita (metal)	®(Fe,Ni)
	Troilita (sulfuro)	FeS
	….	
Inclusions rich in Al and Ca	Corindón	Al_2O_3
	Espinela	$MgAl_2O_4$
	Perovskita	$CaTiO_3$
	Hibonita	$CaAl_{12}O_{19}$
	Anortita	$CaAl_2Si_2O_8$
	Ca-piroxenos (diópsido)	$CaMgSi_2O_6$
	….	
Matrix silicates	Olivino	$(Mg,Fe)_2SiO_4$
	Piroxeno	$(Mg,Fe)SiO_3$
	Augita	$Ca(Mg,Fe,Al)(Si,Al)_2O_6$
	Anortita	$CaAl_2Si_2O_8$
	….	
Matrix Opaques	Grafito	C
	Kamacita (metal)	⟨ -(Fe,Ni)
	Taenita (metal)	®(Fe,Ni)
	Troilita (sulfuro)	FeS
	….	

H_2O

Chlorite, serpentine, talc, etc.

< 950ºC and stirred H 60

Albite, feldespatoids, micas, piroxenes, anfíboles

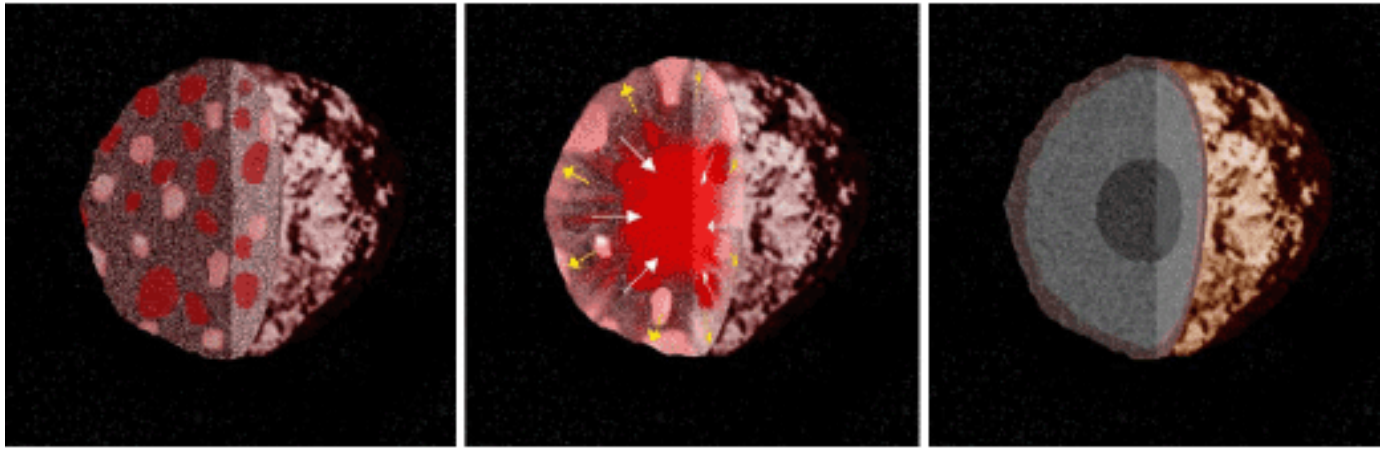
Majorite, coesite, estisovite, silicate-spinel, etc.

M. Prieto, 2014

Acondrites y planetesimals

Partial fusion (> 950ºC)

http://www.psrd.hawaii.edu



Acondritic meteorite

http://www.meteorlab.com

Metallic meteorite

H 250

New minerals

Quartz, K-feldspar, titanite, zircon, metalic sulphides..

M. Prieto, 2014

Los diez estadios de la evolución mineral en la Tierra

ERA/Stage	Age (Ga)	Number
Prenebular minerals	*> 4.6*	*12*
Planetary accrecion era		
1. Primary condrític minerals	*> 4.56*	*60*
2. Acondrites and planetesimales	*> 4.56 – 4.55*	*250*
Era of the mantle and crust reworking		
3. Igneous rock evolution	*4.55 – 4.0*	*350 – 500*
4.Granite and pegmatites building	*4.0 – 3.5*	*1000*
5. Plate tectonics	*> 3.0*	*1500*
Era of biomineralization		
6. Anoxic biologic world	*3.9 – 2.5*	*1500*
7. The big oxidation	*2.5 – 1.9*	*> 4000*
8. The bored oceans	*1.9 – 1.0*	*> 4000*
9. Glaciations	*1.0 – 0.542*	*> 4000*
10. The phanerozoic era	*0.542 - Present*	*4400 +*

R. M. Hazen & J.M. Ferry (2010) Mineral Evolution. Elements 6, 9-12.

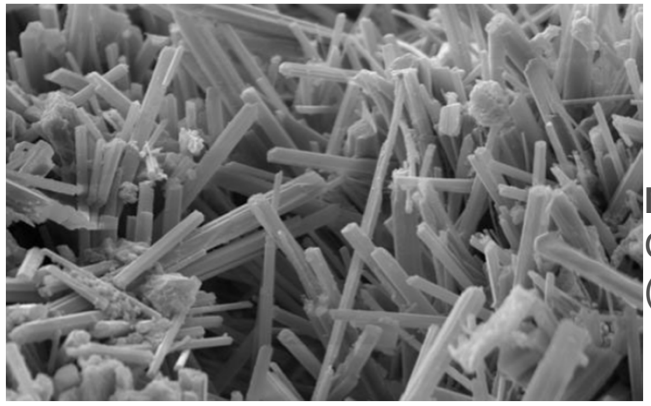
M. Prieto, 2014

Big history and the mineral concept

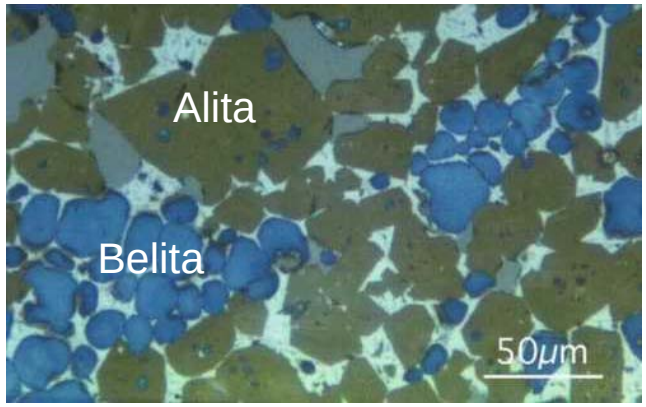
Anthropogenic

Incrustaciones de estruvita: $MgNH_4PO_4 \cdot 6H_2O$

Incrustaciones de calcita: $CaCO_3$



Minerales del cemento:
Cristales de etringita
$(CaO)_3(Al_2O_3)(CaSO_4)_3 \cdot 32\ H_2O$

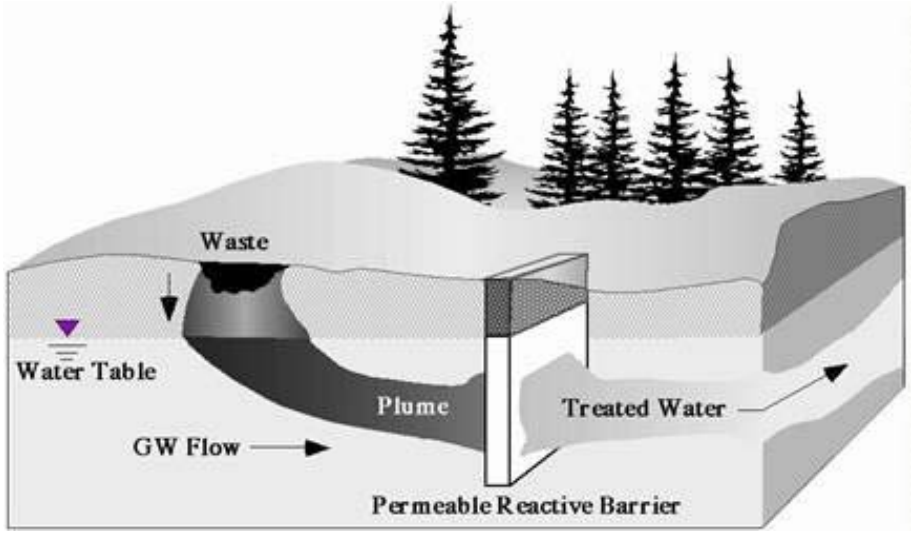


Minerales del cemento:
Alita: $3CaO \cdot SiO_2$
Belita: $2CaO \cdot SiO_2$
C3A: $3CaO \cdot Al_2O_3$
C4AF: $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$
C3A3S: $3CaO \cdot 3Al_2O_3 \cdot SO_3$
etc.

M. Prieto, 2014

Waste dumps: Mineral reactors?

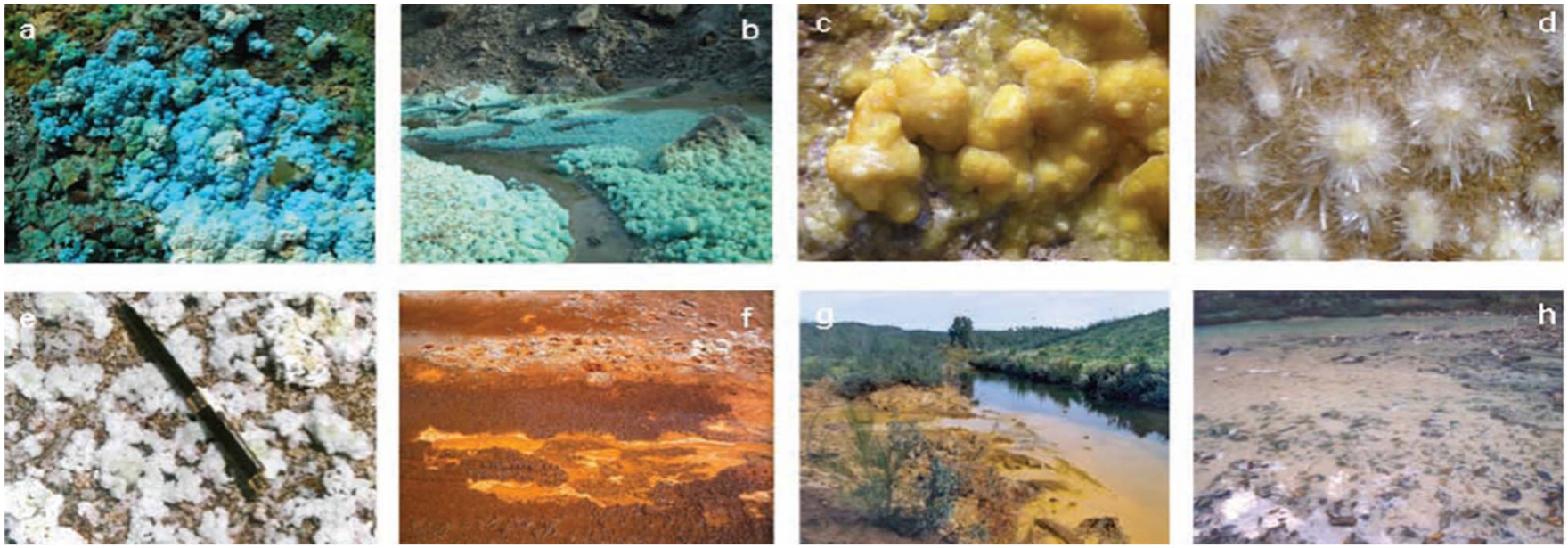
Cement and concrete dumps



Anthropogenic effects

Sánchez-España (2008) Acid Mine Drainage in the Iberian Pyrite Belt. Macla 10, 34-43.

New phases are build as waste streams react with the environment

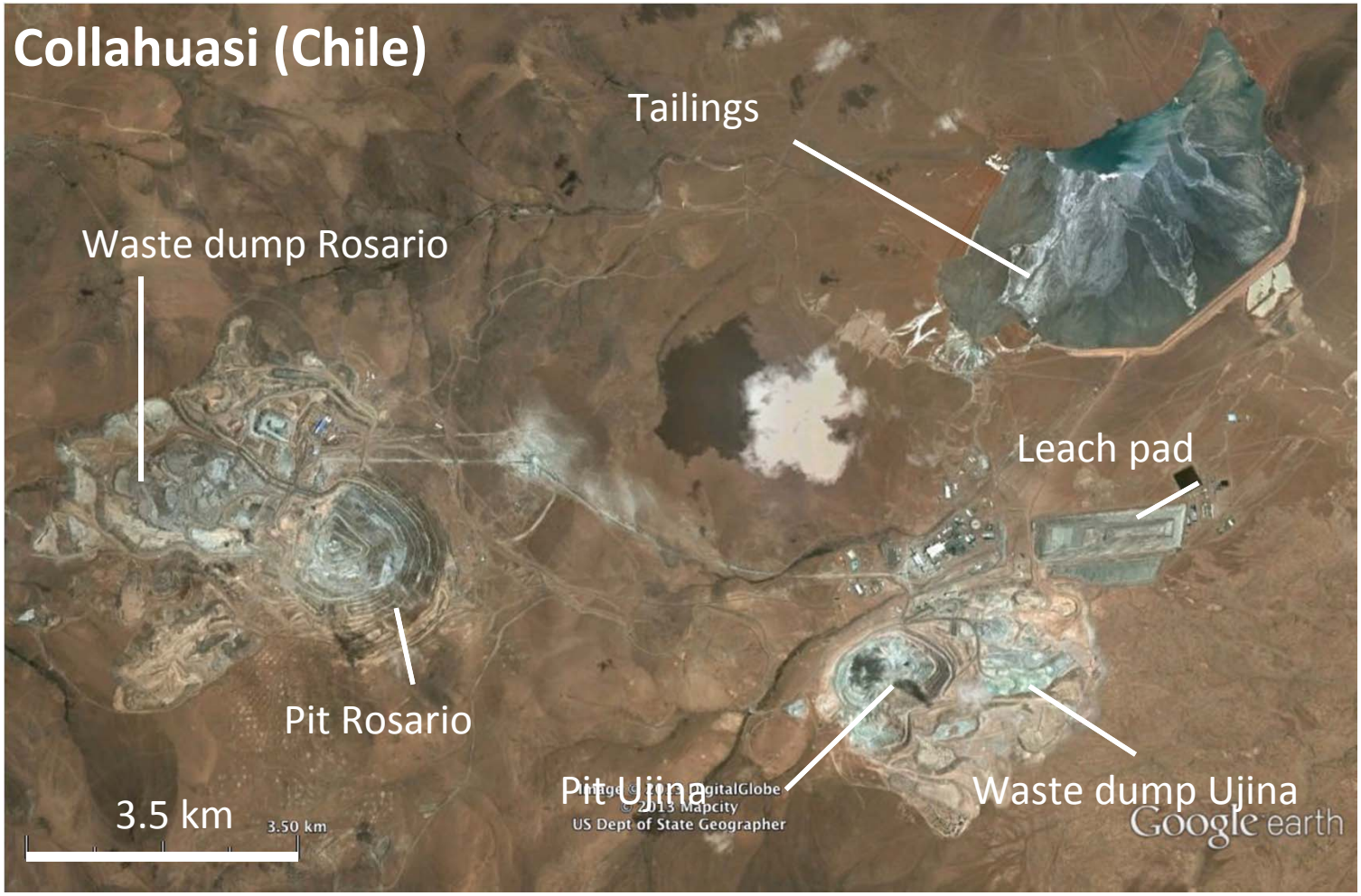


Mineral precipitation as a result of the interaction of mine drainage.

M. Prieto, 2014

Introduction

- Mining operations involve the extraction and removal of large quantities of material



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Open pit mining

Waste dumps

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Drainage of tailings

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Tailings dranaige

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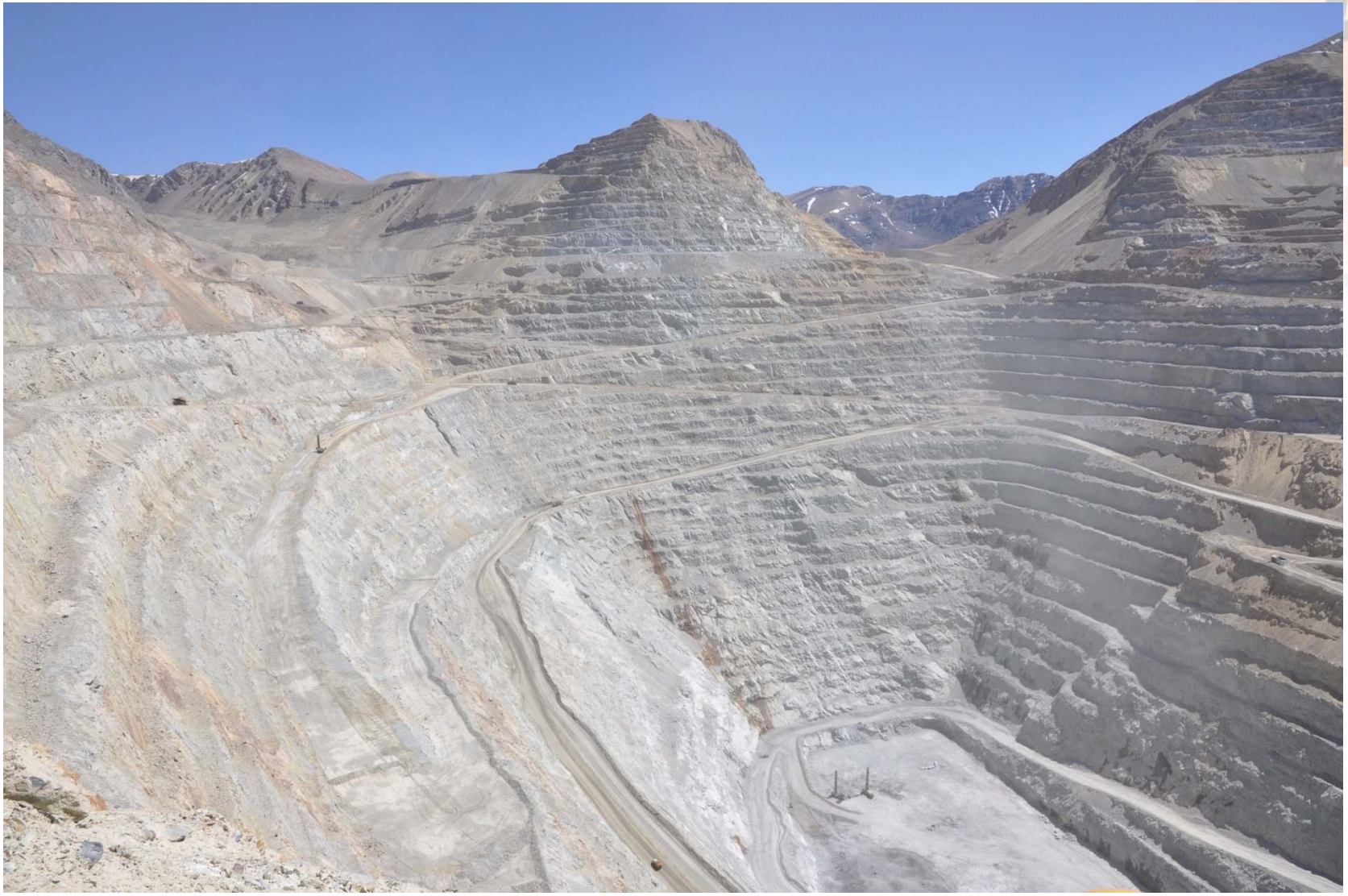
Pit dranaige

Pit dranaige



Acid drainage generation (ADG)

$$FeS_2 + 3{,}75\ O_2 + 3{,}5\ H_2O \longrightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+$$

- When sulphides meet water and oxygen….

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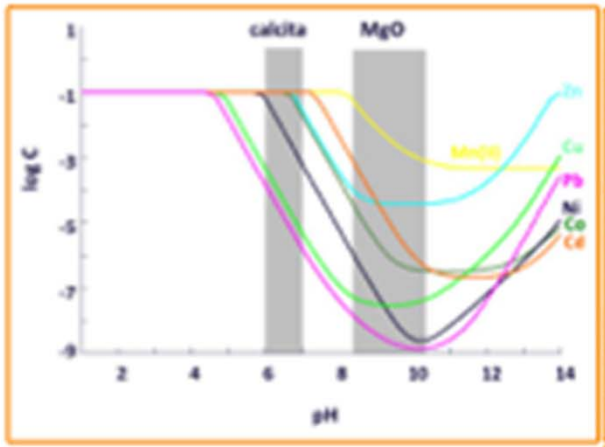
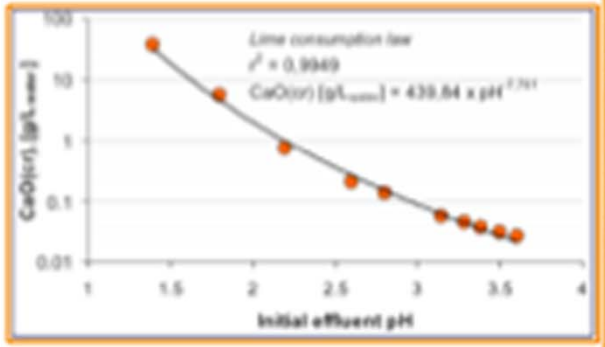
PREDICCIÓN Y MODELAMIENTO DE EFLUENTES Y SU TRATAMIENTO

- Estimación de efluentes: calidad y cantidad
- Diseño y dimensionamiento de estrategias de tratamiento (pasivo, activo)





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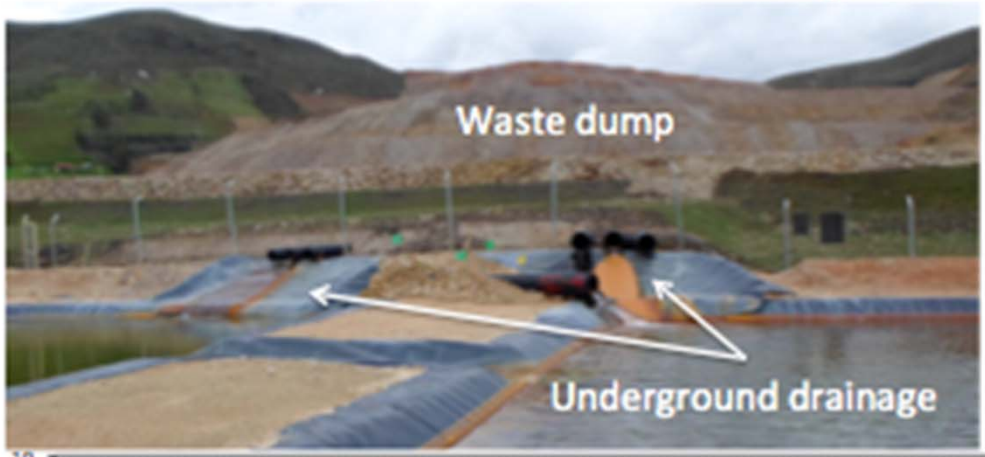
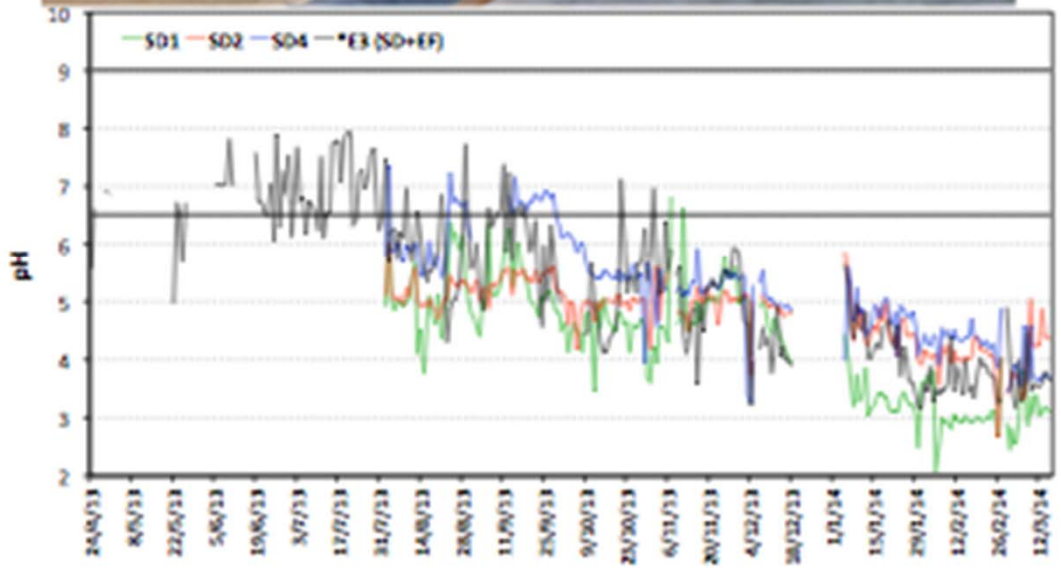
- Drainage waters have large metal content

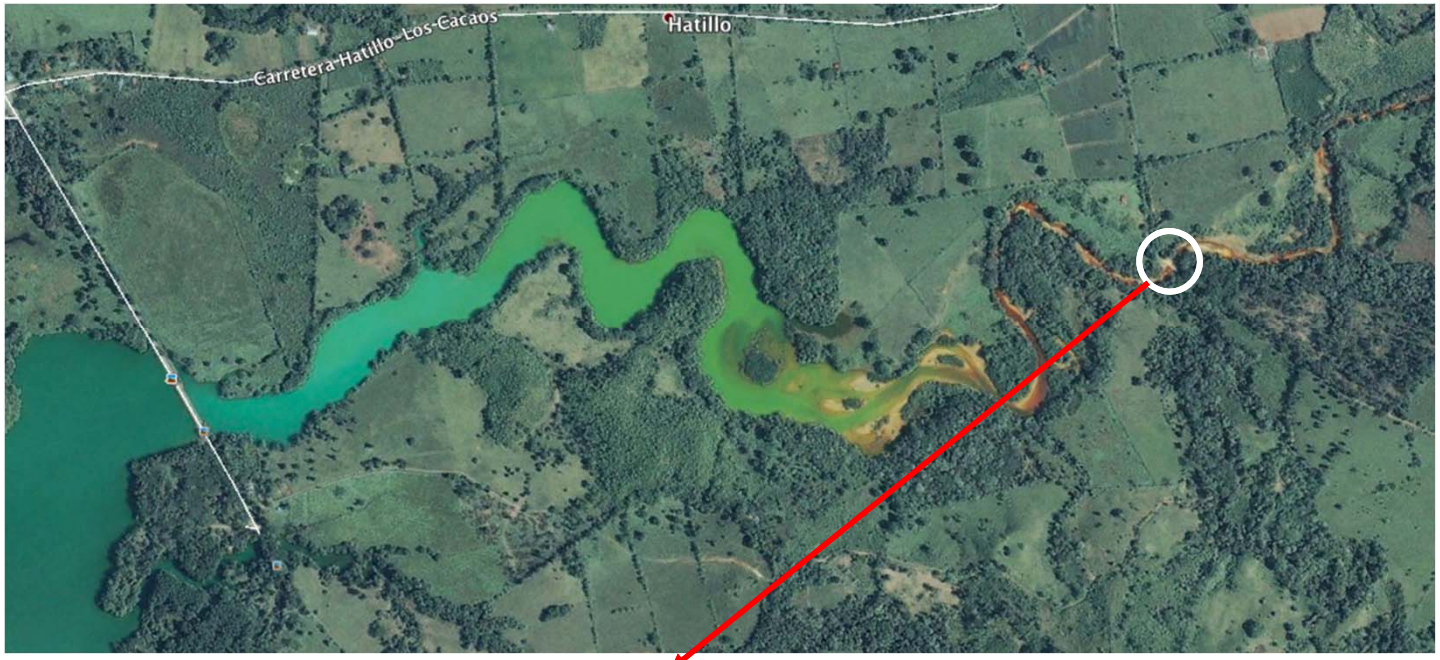
Acid Mine Drainage and Metal Leaching





	Drinking water (mg/l)	Drainage (mg/l)
pH	6.5	3.1
Al	0.2	73.9
As	0.01	0.41
Cd	0.003	0.06
Cu	2	4.9
Fe	2	71.3
Ni	0.07	0.11
Pb	0.01	0.5
Sulphate	500	741
Zn	3	11.8

Acid Mine Drainage and Metal Leaching



	Drinking water (mg/l)	Drainage (mg/l)
pH	6.5	2.45
Al	0.2	160
As	0.01	1.46
Cd	0.003	0.51
Cu	2	0.37
Fe	2	4.7
Ni	0.07	540
Pb	0.01	0.13
Sulphate	500	0.061
Zn	3	2800

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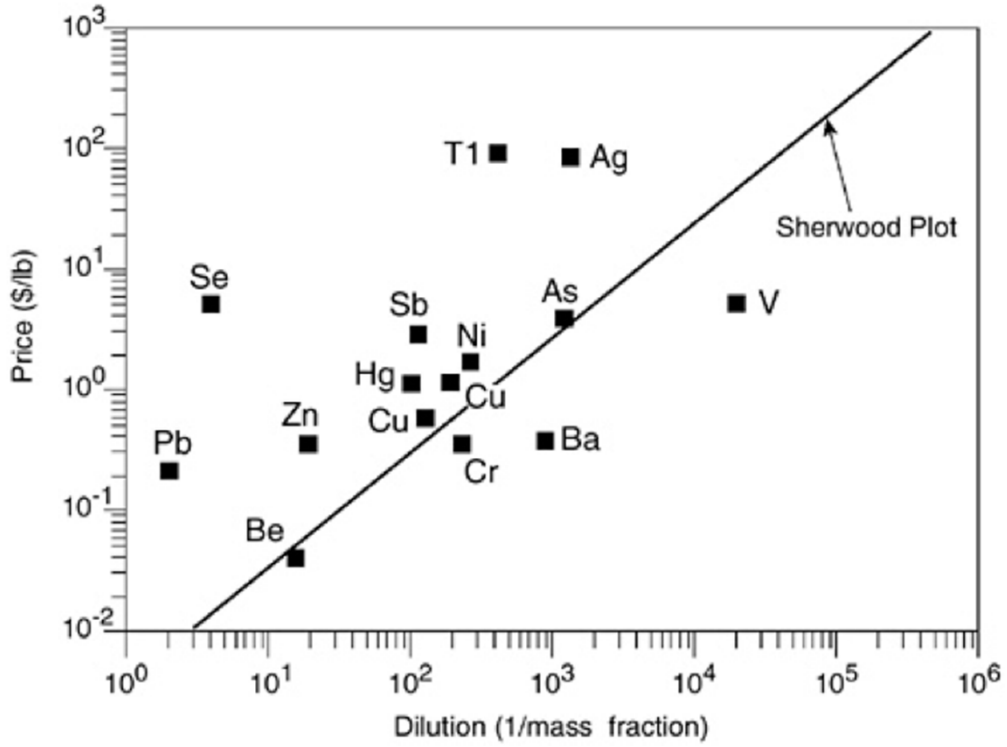
The limits of recycling

- In 1994, Allen and Behmanesh (*The Greening of Industrial Ecosystems*, National Academy Press) proposed the use of Sherwood plot to indicate the recycling potential of material waste streams.

- The Sherwood plot is named after Thomas K. Sherwood a chemical engineer than in 1959 published a diagram that indicated a close relationship between the price of material and its dilution (inverse of concentration) in the feed stream.



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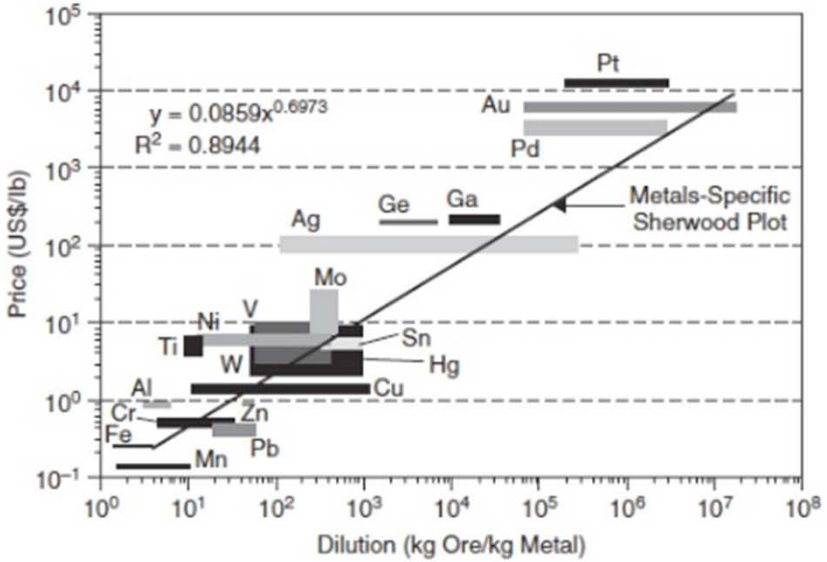
Wastes as Sources of Critical Materials: The Metals-Specific Sherwood Plot



Metal prices (2004) as a function of dilution (1/concentration) of metals in commercial ores. This Sherwood plot illustrates the concept that the more dilute a material is in its native ore, the more expensive it will be to purify into a commodity material.

David Allen. Adapted from Johnson et al. *Environ. Sci. Technol.* 2007, 41, 1759-1765)

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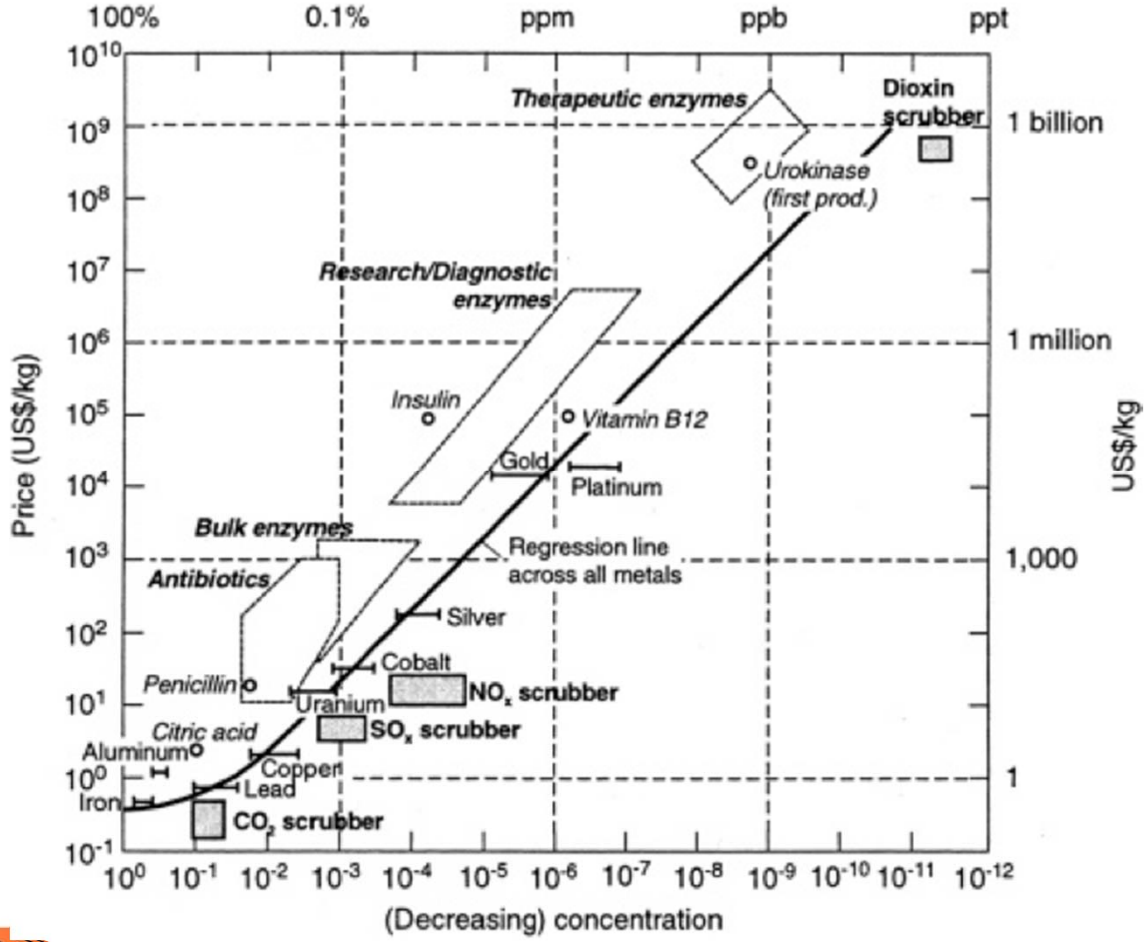
The limits of recycling

- Grübler extended the Sherwood plot to a wide variety of metals and biological materials (T*echnology and Global Change*, Cambridge University Press, 1998)



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The limits of recycling

- In 2007, Dahmus and Gotowski (ES&T, 41, 7543-7550) expanded the model to products by applying Information Theory to the increased complexities of material mixing in the manufactured goods and the subsequent separation processes

- They defined H as a measure of material mixing, defined as the average number of binary operations required to obtain any material from the mixture

- This is equivalent to the thermodynamic work of separation from and ideal solution!

The limits of recycling

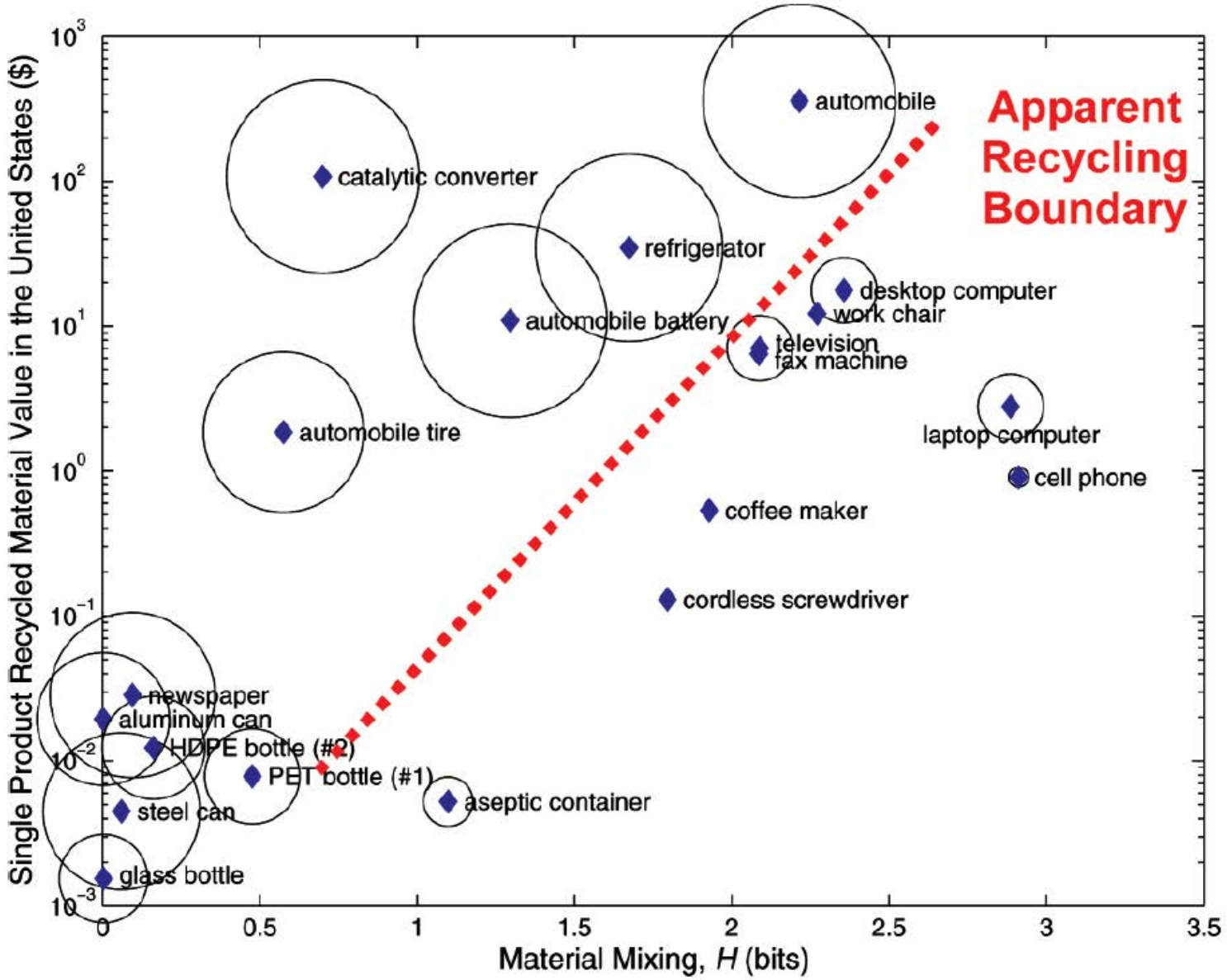
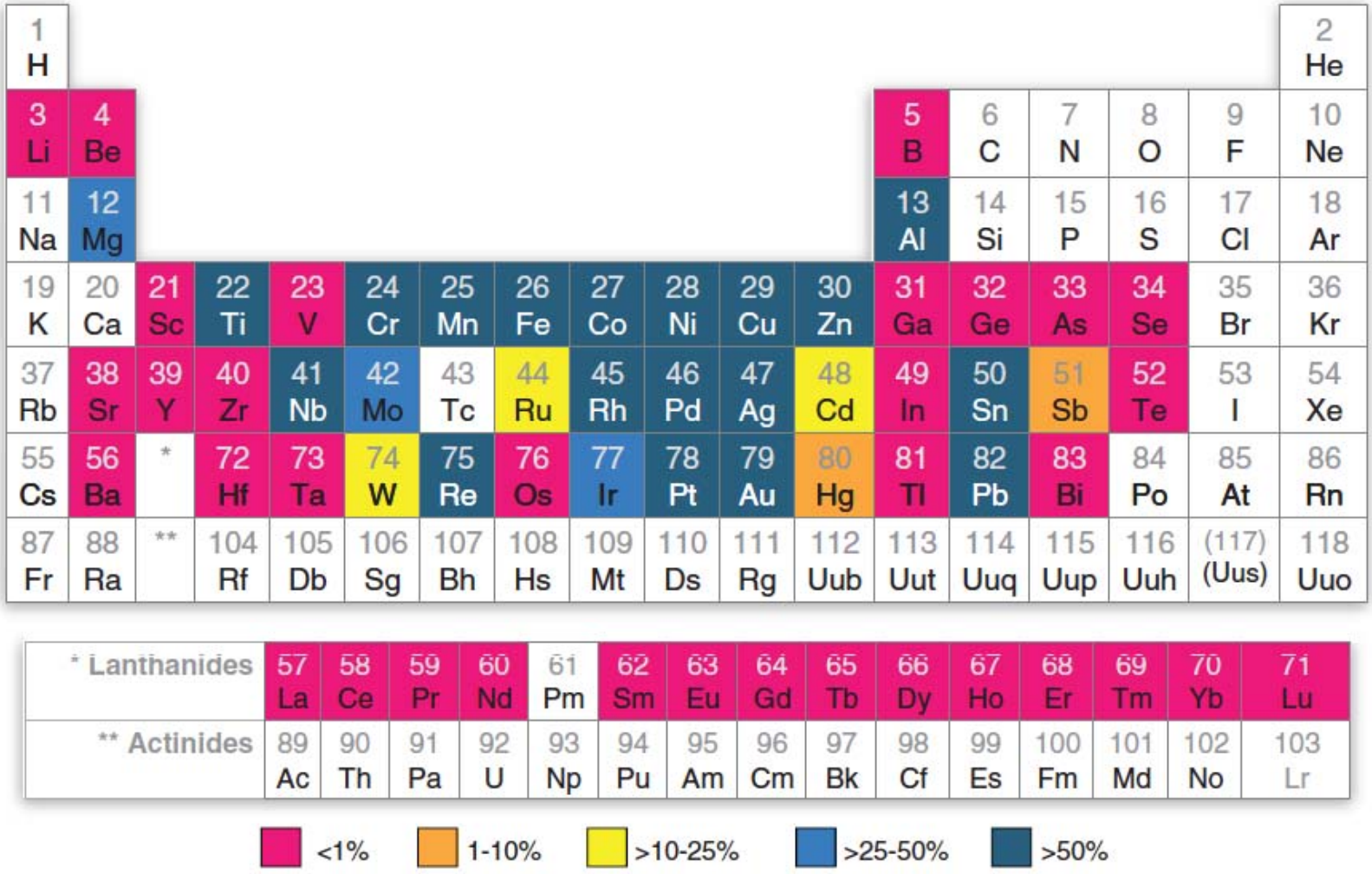


FIGURE 4. A plot of single product recycled material values ($\sum m_i k_i$), material mixing (H), and recycling rates (indicated by the area of the circles) for 20 products in the U.S. The "apparent recycling boundary" is shown.

Challenges in metal recycling



Global estimates of end-of-life recycling. Reck and Graedel, Science 2012

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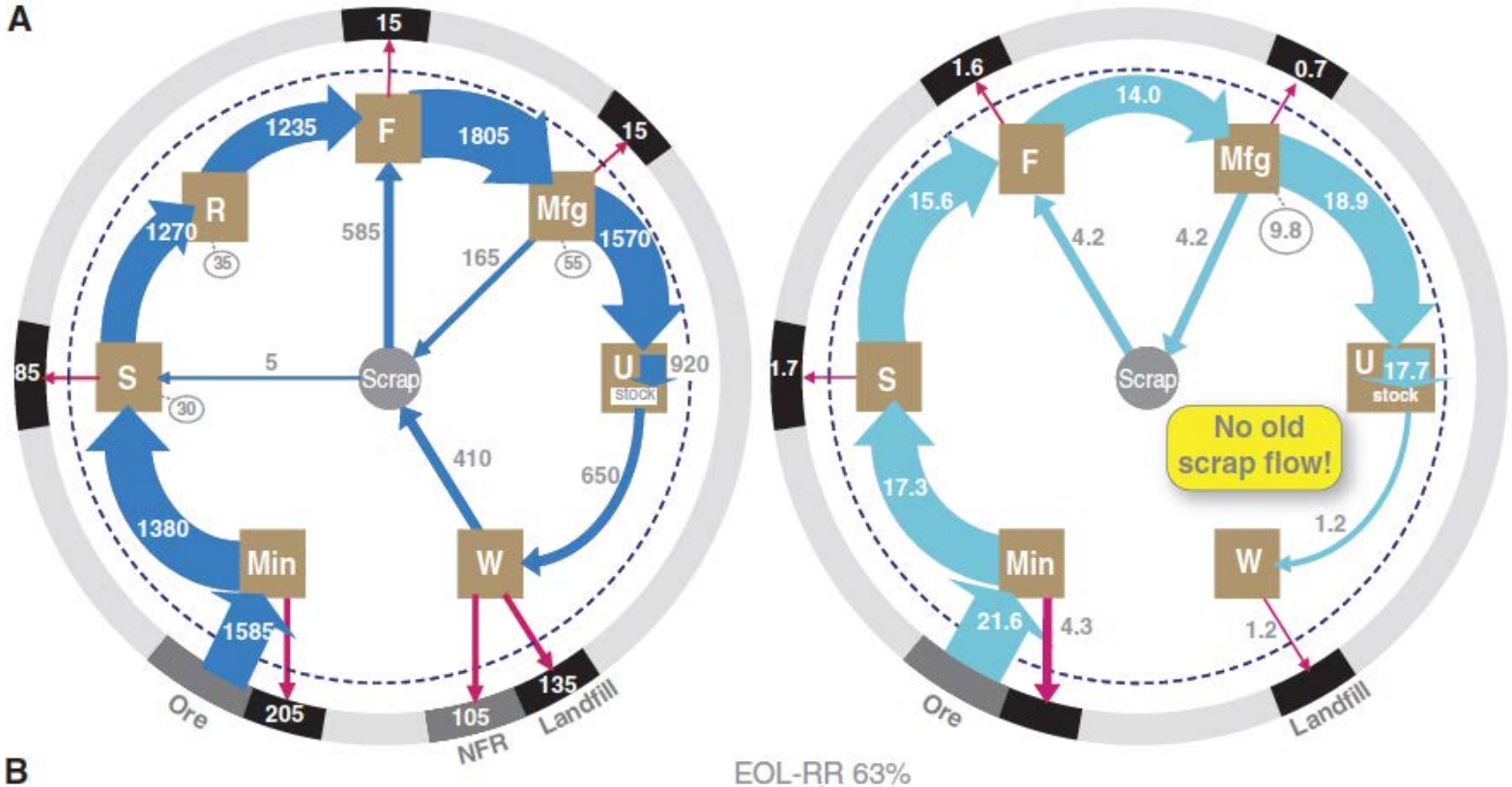
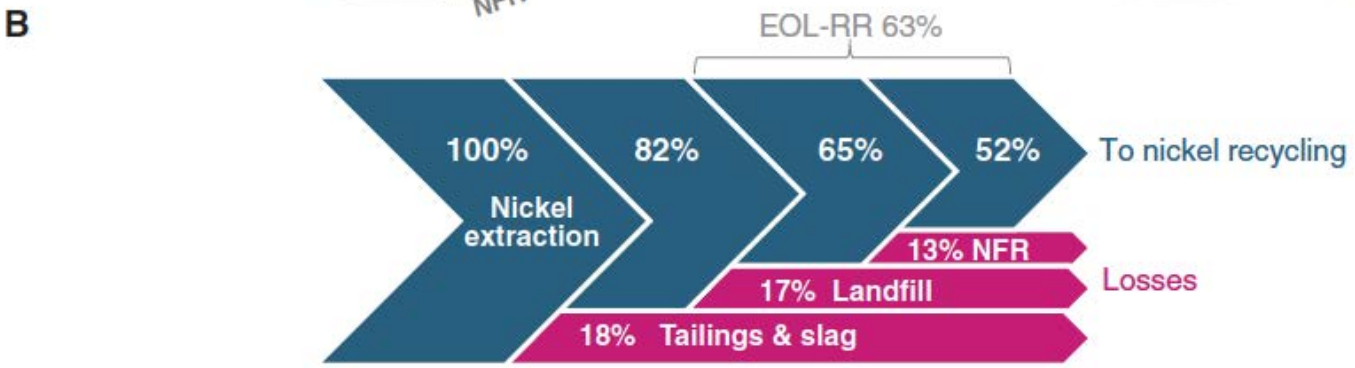
Differences in metal cycles





Reck and Graedel, Science 337, 690-697 (2012)

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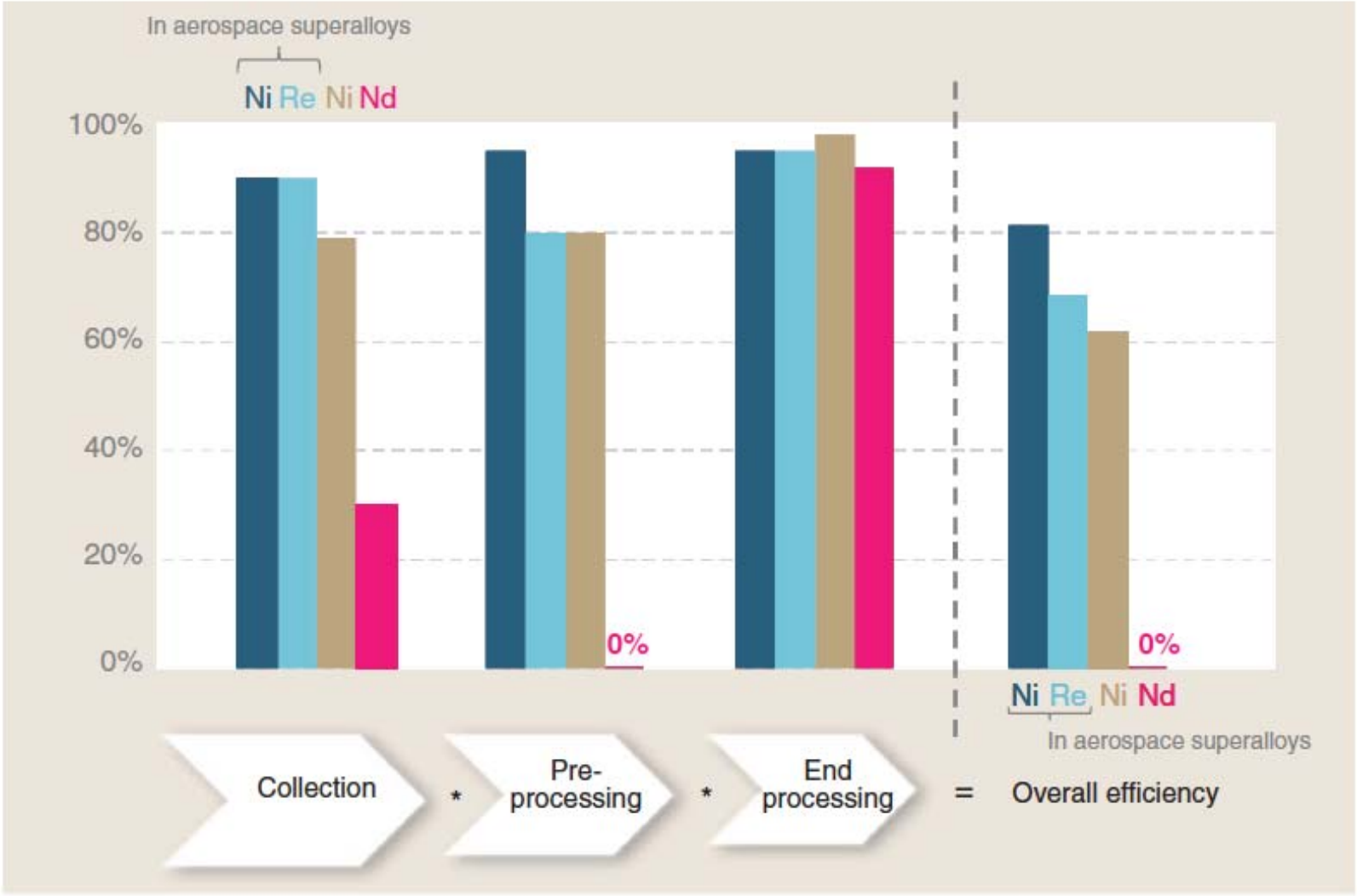
Challenges of recycling



Reck and Graedel, Science 337, 690-697 (2012)

Conclusions

- There is an ongoing production of “new minerals”, secondary resources to be explored.
- These are the result of the interaction of man made materials and fluids with the materials in the critical zone.
- Primary mining is a waste of resources, including water, energy and espace
- Secondary mining and recycling is a viable and complementary route, provided the thermodynamic limitations are well understood.
- It is then very important to understand what is feasible in terms of secondary mining and recycling to avoid economic and social fustration.

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