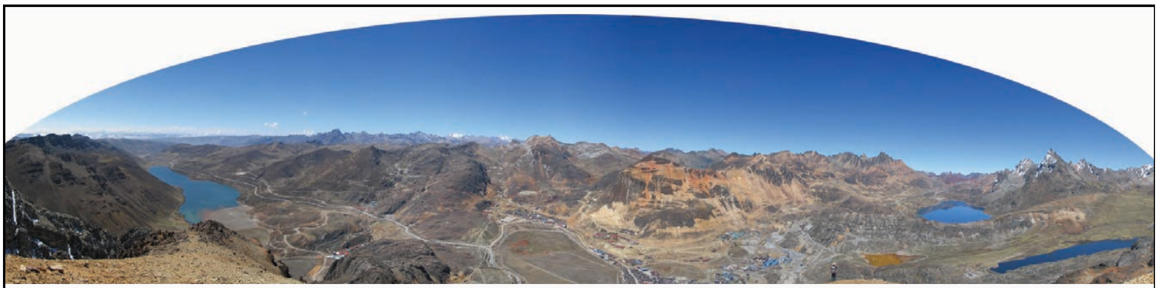

Mineral resources in a low carbon future

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The Geological Society
Bryan Lovell Meeting,
London, January 2019

Mineral Resources and Geofluids
Department of Earth Sciences

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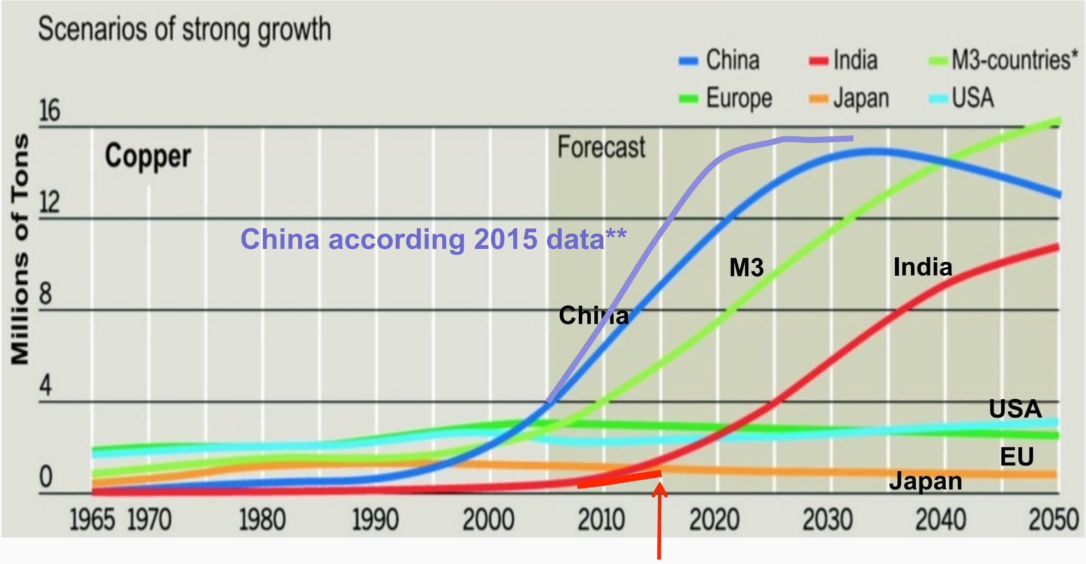
Market Growth 2004-2015

(Sykes et al., 2016 in Jowitt and Mudd 2018, SEG Keystone)

Commodity	2004-15 market growth (%)	Commodity	2004-15 market growth	Commodity	2004-15 market growth
Lithium	**388**	**Barite (Ba)**	**169**	**Cadmium**	**53**
Germanium	**355**	Uranium	156	Ilmenite (Ti)	51
Gallium	**327**	Copper	155	Tin	50
Mercury	**320**	**Thorium**	**146**	Aluminium	44
Tungsten	**298**	**Chromium**	**144**	*World (GDP)*	*41*
Rutile (Ti)	295	**Silicon**	**118**	**Vanadium**	**24**
China (GDP)	294	**Tellurium**	**116**	**PGE**	**19**
Silver	271	**Manganese**	**105**	Nickel	12
Gold	221	Zinc	105	*USA (GDP)*	*10*
Beryllium	**215**	**REE**	**93**	**Cobalt**	**−5**
Bismuth	**214**	**Tantalum**	**74**	Molybdenum	−18
Antimony	**211**	**Niobium**	**72**	**Arsenic**	**−30**
Lead	190	**Magnesium**	**62**	**Borate (Bo)**	**−57**
Rhenium	**171**	**Indium**	**57**	**Strontium**	**−57**

Now China (stronger growth than forecasted in 2005)
Tomorrow India, M3 countries



India according 2015 data***

(NZZ, Nov. 2006, mod.)

M3: Brazil, Indonesia, Korea, Mexico, Nigeria, Philippines, Russia, South Africa, Thailand, Turkey

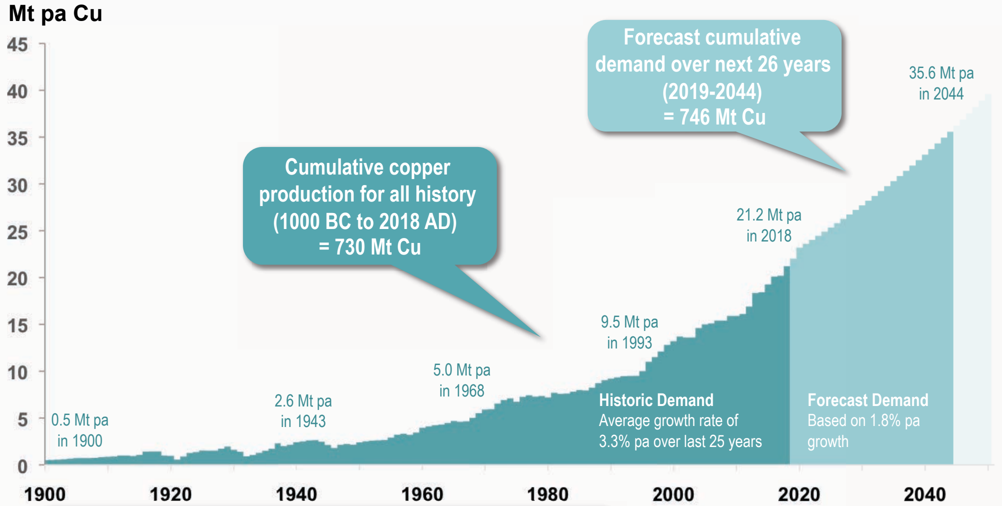
** China 2015: 11.45 Mt. Yang et al. (2017) China's Copper Demand Forecasting Based on System Dynamics Model (table 4).

*** India 2015: 0.55 Mt (Hindalco Industries, 2015)

Recycling is good but not enough

World's demand for metals doubles every 20-30 years

Primary copper production for World: 1900-2050



Over the next 26 years the world is going to mine more copper than what has been mined in all history

Schodde, 2018 (IMARC Conference, OCt. 2018)

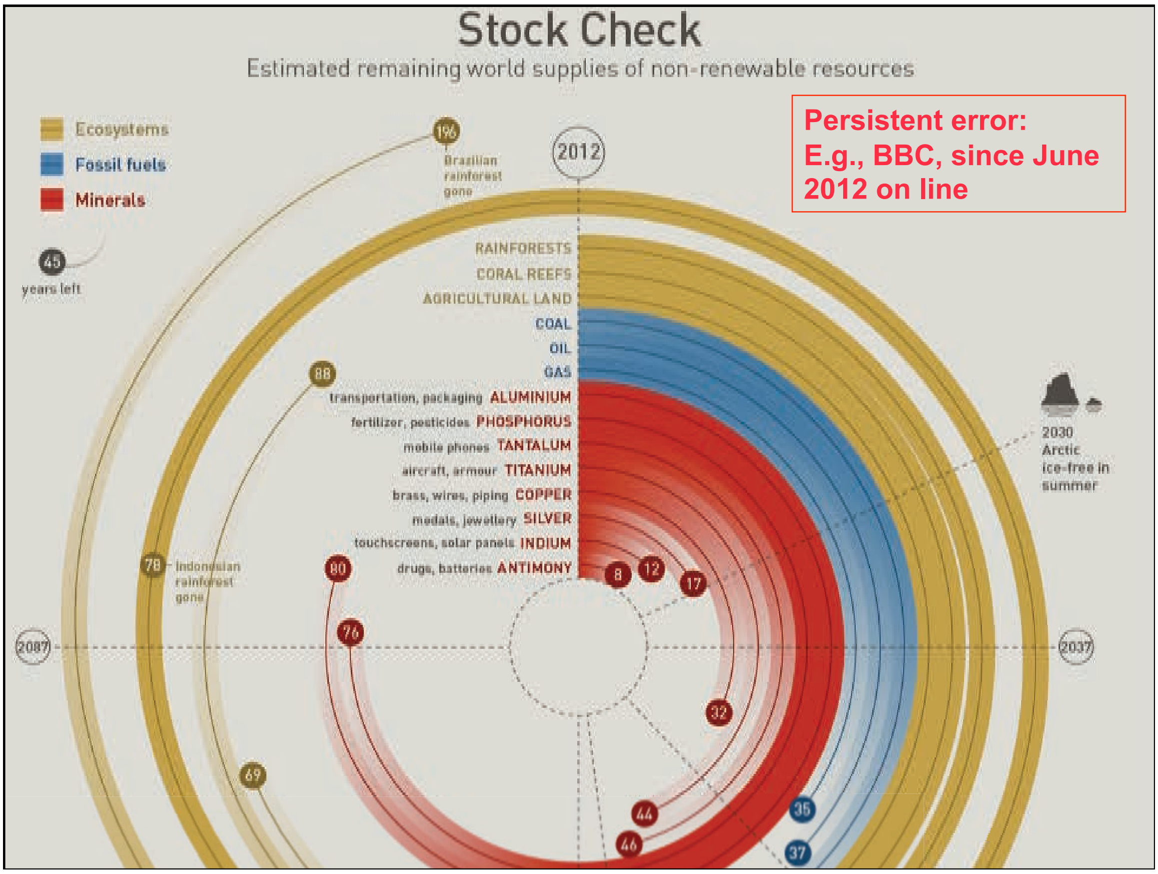
Sources: Historical data from USGS and
Office of the Chief Economist Sept 2018

Impact on cumulative demand by 2050, under the 2°C scenario (Fraction of cumulative demand if the 2013 production levels are sustained to 2050. World Bank, 2017, The Growing Role of Minerals and Metals for a Low Carbon Future) ***Impact of the scenario of 100% e-vehicles*** *(As increase of production over 2015 levels (UBS, 2017, Lab Electric Car Teardown – Disruption Ahead?)*		**Approximate market value of 2013 production in US$ Millions** (Sykes et al., 2016, Applied Earth Science)
Copper	**3 %**	**131.010**
Copper (100% e-vehicles)	***22 %***	
Nickel	**3 %**	**37.395**
Nickel (100% e-vehicles)	***105 %***	
Neodymium	**18 %**	**6.647**
Cobalt	**2%**	**3.294**
Cobalt (100% e-vehicles)	**1928 %**	
Lithium	**1480 %**	**929**
Lithium (100% e-vehicles)	***2898 %***	
Indium	**148 %**	**477**
Germanium	**"significant"**	**241**
Niobium	**"significant"**	**178**
Gallium	**"significant"**	**143**

- Emerging energy and mobility technologies create a strong demand for raw materials, and for **some critical raw materials this demand will dramatically exceed current production in the next 10-15 years. Limited access to these materials might negatively impact the transition**, thus reducing the competitiveness of European actors downstream.

Karen Hanghøj, (2019, abstract of this meeting)

- **How limited?**
- **Two levels of discussion:**
    - **For how long do we have metals? Answer: no risk of exhaustion in a foreseeable future**
    - **However, certain risks of temporary supply shortages**



Persistent error:
E.g., BBC, since June 2012 on line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omepage: www.elsevier.com/locate/re

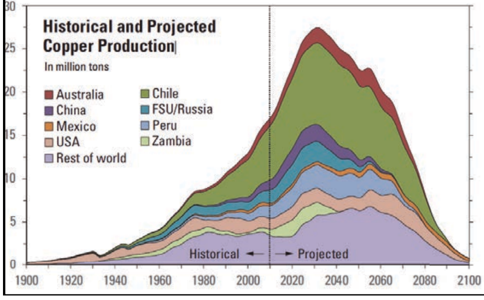
"The extractable ores of the world's geologically scarcest mineral resources (e.g. antimony, molybdenum and zinc) may be exhausted within several decades to a century, if their extraction continues to increase" (Henckens, et al., 2016)

Also in high impact journals

Mineral resources: Geological scarcity, market price tren
generations

M.L.C.M. Henckens [a,*], E.C. van Ierland [b], P.P.J. Driessen [a], E. Worrell [a] (2016)

Very scarce (EGR exhausted before 2050)		Scarce (EGR exhaustion time < 100 years after 2050)		Moderately scarce (EGR exhaustion time between 100 and 1000 years after 2050)	
Antimony	-10	Gold	10	Arsenic	400
		Molybdenum	50	Bismuth	200
		Rhenium	80	Boron	200
		Zinc	50	Cadmium	500
				Chromium	200
				Copper	100
				Iron	300
				Lead	300
				Nickel	300
				Silver	200
				Tin	200
				Tungsten	300



Mohr et al. in Kerr, Science (2014)

- **Most alerts are just wrong and essentially derived from a confusion between resources and reserves**

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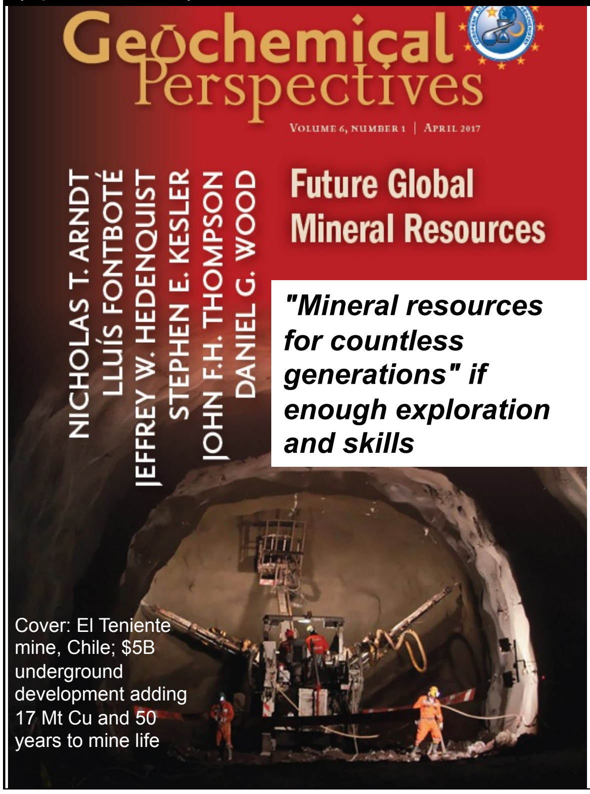
http://www.geochemicalperspectives.org/
(open access)



"Mineral resources for countless generations" if enough exploration and skills

Cover: El Teniente mine, Chile; $5B underground development adding 17 Mt Cu and 50 years to mine life

NICHOLAS T. ARNDT was awarded a Ph.D. from the University of Toronto Canada, in 1975. Following a year with an Australian mineral exploration company, he occupied academic positions in the United States, Canada, Australia and Germany before moving to France, and is now an emeritus professor at the University Grenoble Alpes. His research interests include petrology and geochemistry of mafic and ultramafic rocks, the early-Earth environment and magmatic ore deposits.

LLUÍS FONTBOTÉ is full professor at Geneva University, Switzerland, where he leads a research group active worldwide. He has mainly worked on epithermal polymetallic deposits linked to porphyry systems, iron oxide copper gold, and MVT deposits, and he has also published, together with his students, on VHMS and orogenic gold deposits, mainly in the Andes, as well as on acid mining drainage. He has worked in exploration for several commodities.

JEFFREY W. HEDENQUIST was educated in the USA and New Zealand, and has 24 years experience with three national institutes in the USA, New Zealand and Japan. He has conducted research on lunar studies, geothermal energy, volcanic discharges, and the formation of epithermal gold and porphyry copper deposits. Since 1999, Jeff has been an independent geologist working with the mineral exploration industry in over 35 countries worldwide, based in Canada.

STEPHEN E. KESLER was educated in the United States and has taught economic geology for 50 years, principally at the University of Toronto and University of Michigan, where he is currently emeritus professor. He has been directly involved in regional and deposit-focused exploration projects, and in production geology from large operations to campesino mines. He is the author of several books, including Mineral Resources, Economics and the Environment.

JOHN F.H. THOMPSON was educated in the UK and Canada. He has 35 years of global experience in mineral exploration, mining and research. Currently, he is the Wold Professor of Environmental Balance for Human Sustainability at Cornell University, and runs a consulting business from Vancouver BC directed at exploration, mining and sustainability. He is a director of public and private companies and not-for-profit organizations, and has been a member of the World Economic Forum Agenda Council on the Future of Mining and Metals. He Chairs the IUGS Resources for Future Generations 2018 conference.

DAN G. WOOD was educated in Australia, and worked in mineral exploration for 24 years with BHP and 18 years with Newcrest Mining. He led Newcrest's exploration team, judged by Metals Economics Group of Canada as the world's most successful gold explorer, 1992-2005. He has received several international professional awards and in 2015 was appointed an Officer of the Order of Australia for service to the mining and resource industry through his contribution as a geologist, academic and in executive roles; he led discovery teams that defined over $100B of mineral wealth around the world, most now being mined.

The authors are all Fellows of the Society of Economic Geology, a non-profit society of 7000+ members from research, academia and industry in over 100 countries that is committed to advancing the science and discovery of mineral resources through research and publication, and by supporting its 2000 student members. Four of the authors are past presidents of this society.

Arndt. Fontboté, Hedenquist, Kesler, Thompson, Wood (2017)

Reserve life time depends mainly on investment and type of commodity, NOT on geology

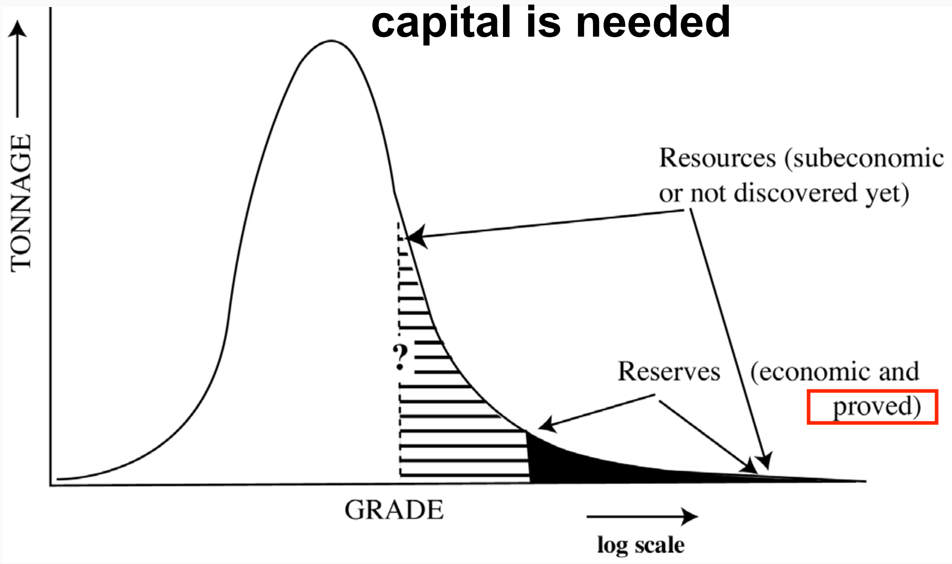
1981 higher figures: result of increased (partly subsidized) exploration after 1973 oil shock

	1969	1981	1994	2001	2011	2017
Cu	51	**72**	33*	27*	38*	40*
Zn	16	**40**	20	21	21	17
Au			21	19	19	17
Fe	238	**191**	152*	140*	61*	71*

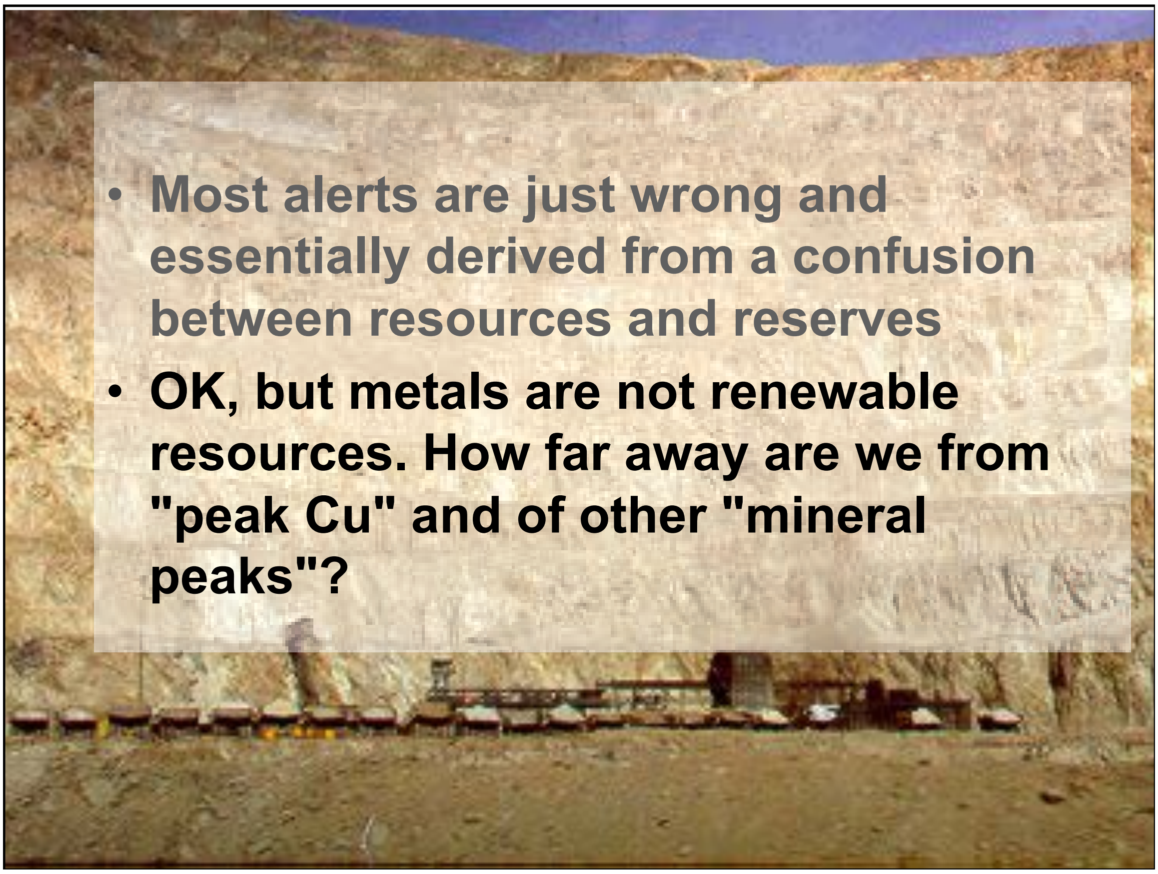
USGS

*Reserves 1994.	Cu: 310 Mt	Fe: 150.000 Mt
*Reserves 2001.	Cu: 340 Mt	Fe: 140.000 Mt
*Reserves 2011.	Cu: 690 Mt	Fe: 170.000 Mt
*Reserves 2017.	Cu: 790 Mt	Fe: 170.000 Mt

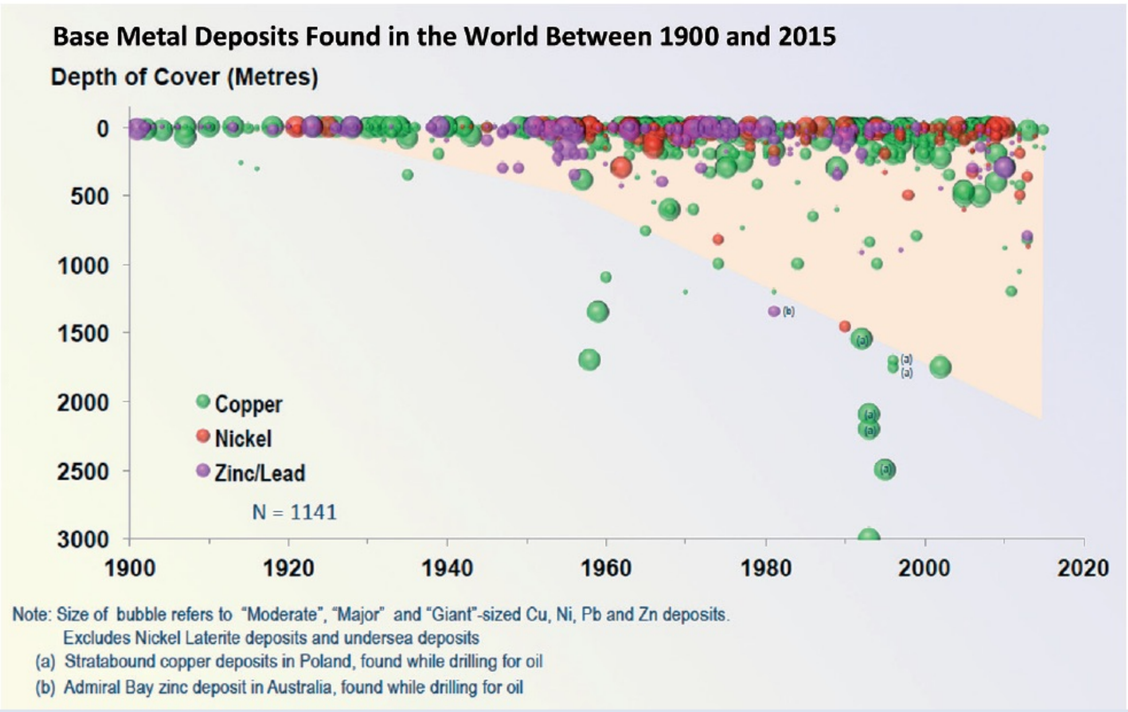
To transform resources into reserves: capital is needed



- **To invest in defining reserves at a (very) long term is not a good business model**
- **The result is that companies tend to define only the reserves required to justify the investment to develop a mine**
  - **For large deposits (typically Cu) ~ 30-50 years**
  - **For intermediate-size deposits (typically Zn-Pb-Ag, Au) ~ 15-20 years**



- Most alerts are just wrong and essentially derived from a confusion between resources and reserves
- **OK, but metals are not renewable resources. How far away are we from "peak Cu" and of other "mineral peaks"?**

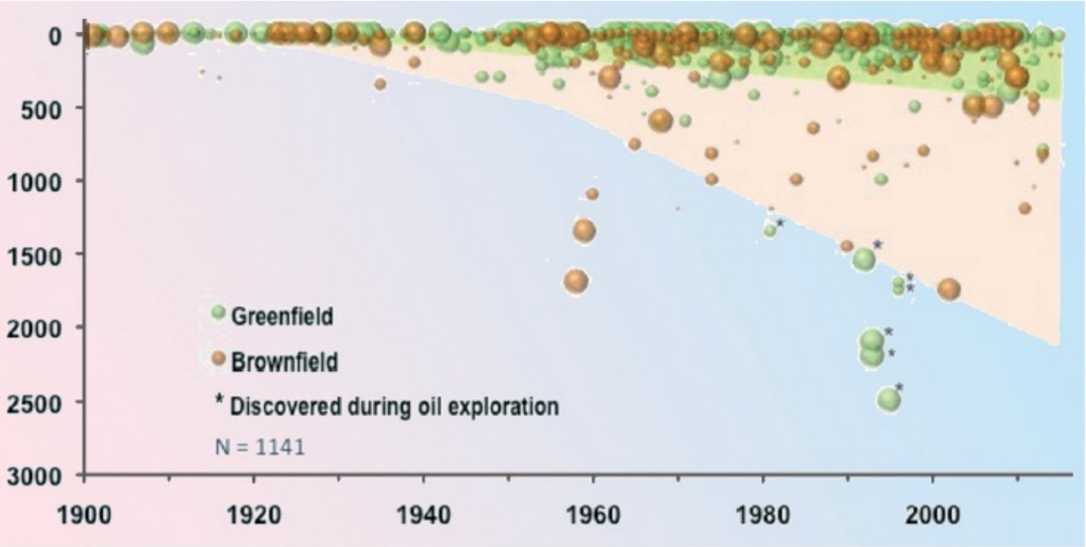


Base Metal Deposits Found in the World Between 1900 and 2015

Note: Size of bubble refers to "Moderate", "Major" and "Giant"-sized Cu, Ni, Pb and Zn deposits.
Excludes Nickel Laterite deposits and undersea deposits
(a) Stratabound copper deposits in Poland, found while drilling for oil
(b) Admiral Bay zinc deposit in Australia, found while drilling for oil

R. Schodde in Arndt. Fontboté, Hedenquist, Kesler, Thompson, Wood (GP, 2017, Fig. 1.8)

Most deep discoveries: brown field or during oil exploration



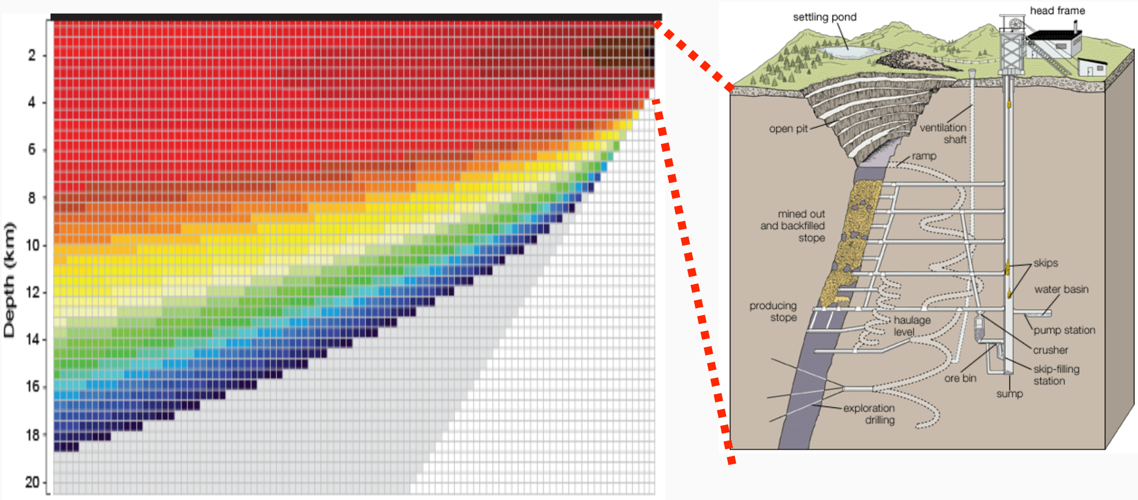
gure 3.11 Depth to top of brownfield and greenfield discoveries of moderate to giant size base metal deposits, 1900-2015 (modified from Schodde, 2014a); the deep (>1 km) greenfield discoveries were made during exploration for oil (R. Schodde, personal communication, August 2016).

Arndt. Fontboté, Hedenquist, Kesler, Thompson, Wood (GP, 2017, Fig.3.11)

The "tectonic diffusion" model

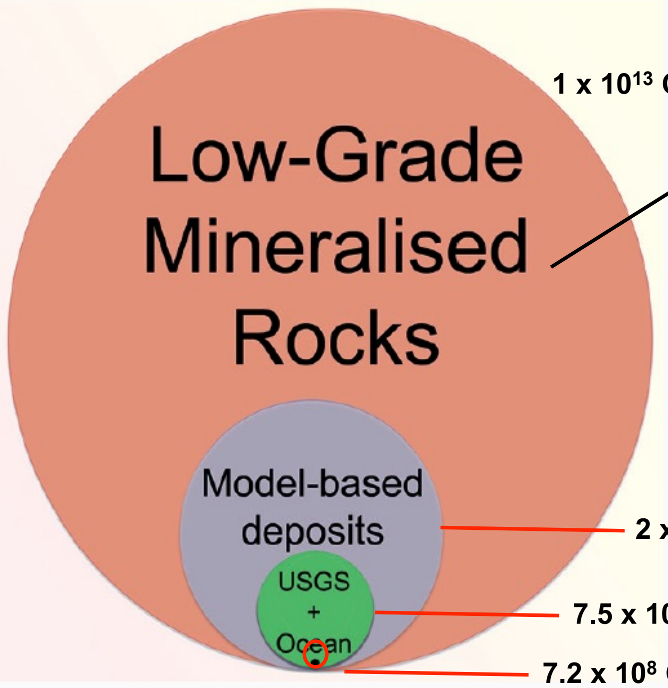
(Kesler, Wilkinson, Univ. Michigan, 2005, 2009 , 2010)

If 50% of resource above 3 km are found and mined
PRESENT PRODUCTION RATE can be maintained for
~1000 years for Au
~2500 years for Cu
(only magnitude order, same ore deposit types, similar grades and metallurgical processes: potential to improve!)



- And beyond?
- How about mining really low grades (e.g., 200- 2000 ppm Cu)?

Aitik porphyry deposit, head grade of 0.25-0.30% Cu



1 x 10^{13} Cu

Minable if Cu becomes scarce and prices go up
(implications on environmental impact and energy consumption!)

2 x 10^{11} Cu

(Cu resources with with grades as today)

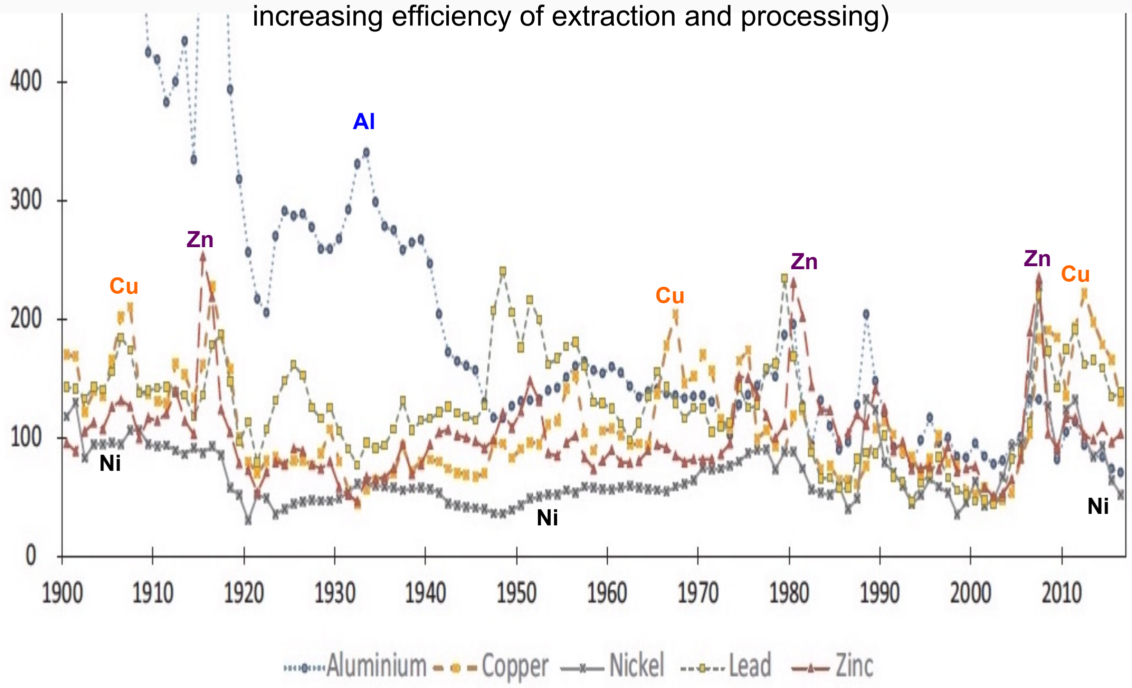
7.5 x 10^{9} Cu

7.2 x 10^{8} Cu USGS "reserves"

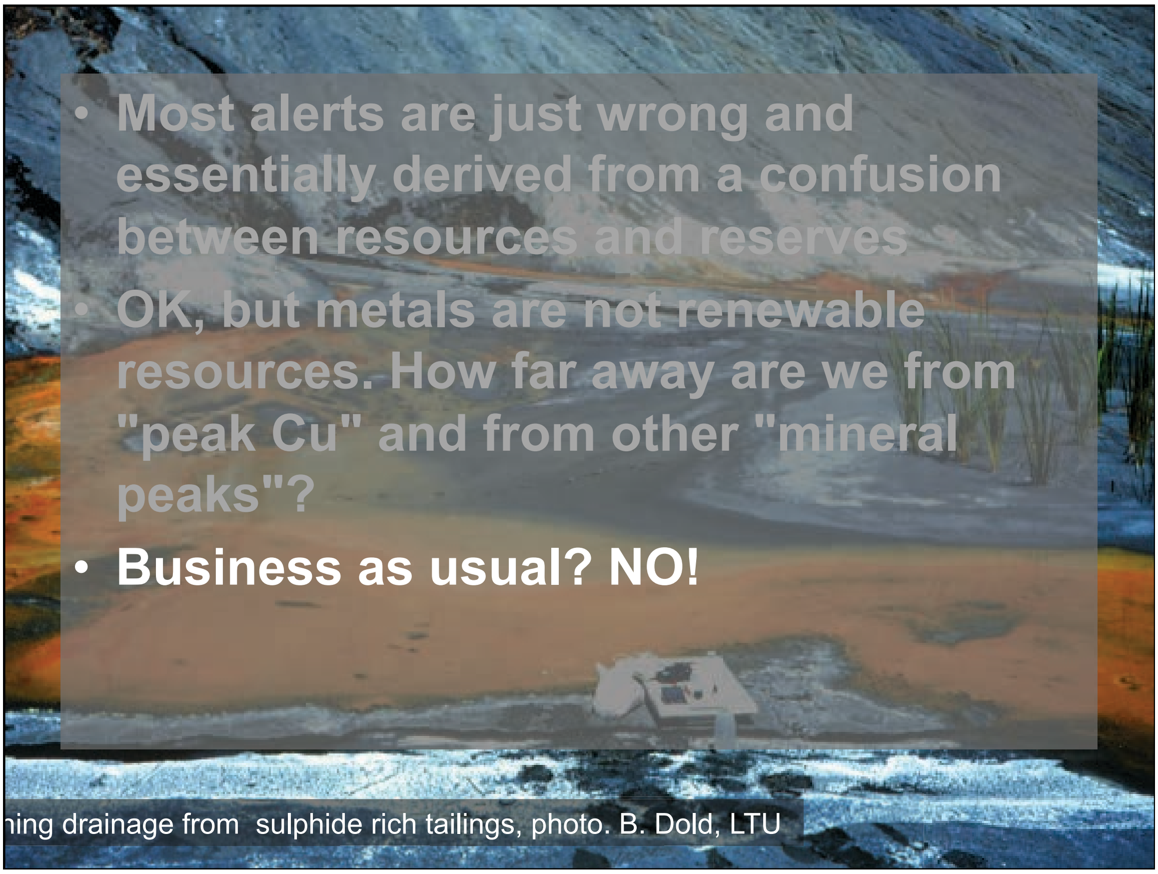
Arndt. Fontboté, Hedenquist, Kesler, Thompson, Wood (GP, 2017, Fig.3.11)

So far, in the long term, prices have not increased

lower grades mined not due to increasing prices but to increasing efficiency of extraction and processing)



Tilton et al. (2018 Resources Policy)
(in 2016 US$ 100 =Average of 2000 - 2009 prices).



- Most alerts are just wrong and essentially derived from a confusion between resources and reserves
- OK, but metals are not renewable resources. How far away are we from "peak Cu" and from other "mineral peaks"?
- **Business as usual? NO!**

ing drainage from sulphide rich tailings, photo. B. Dold, LTU

Multiple challenges

- New needs
- Exploration effort
  - Land access: Environmental impact, social license to operate, NYMBY
  - Economics:
    - Cyclic nature of prices on a long term business
    - Certain "green" materials: Niche markets, vertical integration, lack of transparence, byproducts, substitution potential and technology changes => high risk investment
  - Increasingly under cover and deeper: excellent geoscience skills needed: science, technology, education, training

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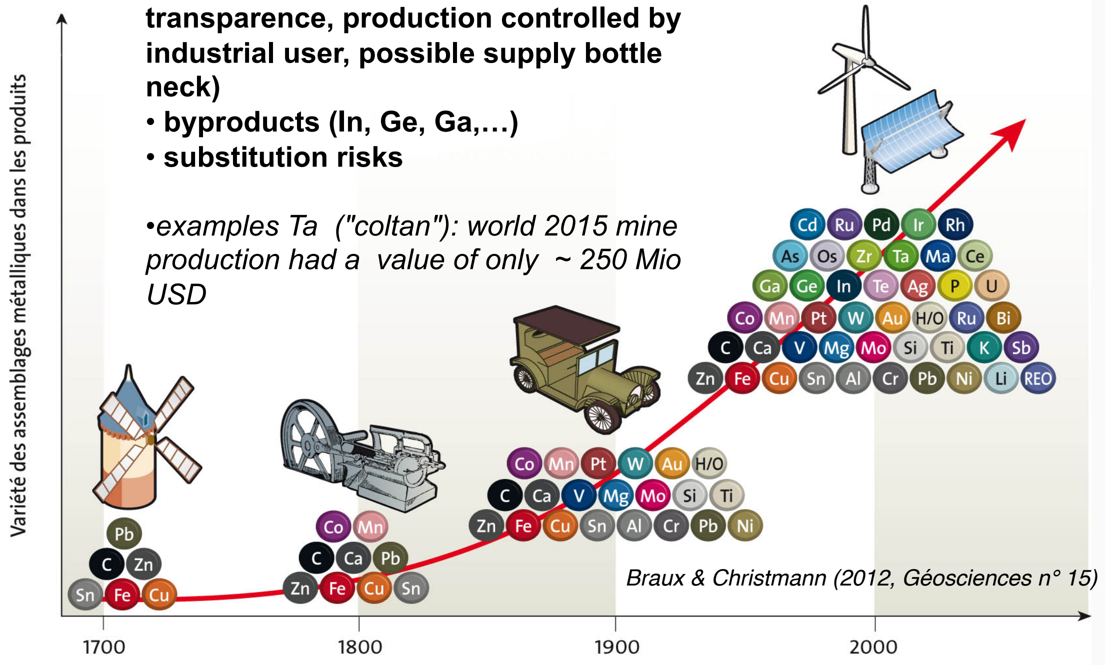
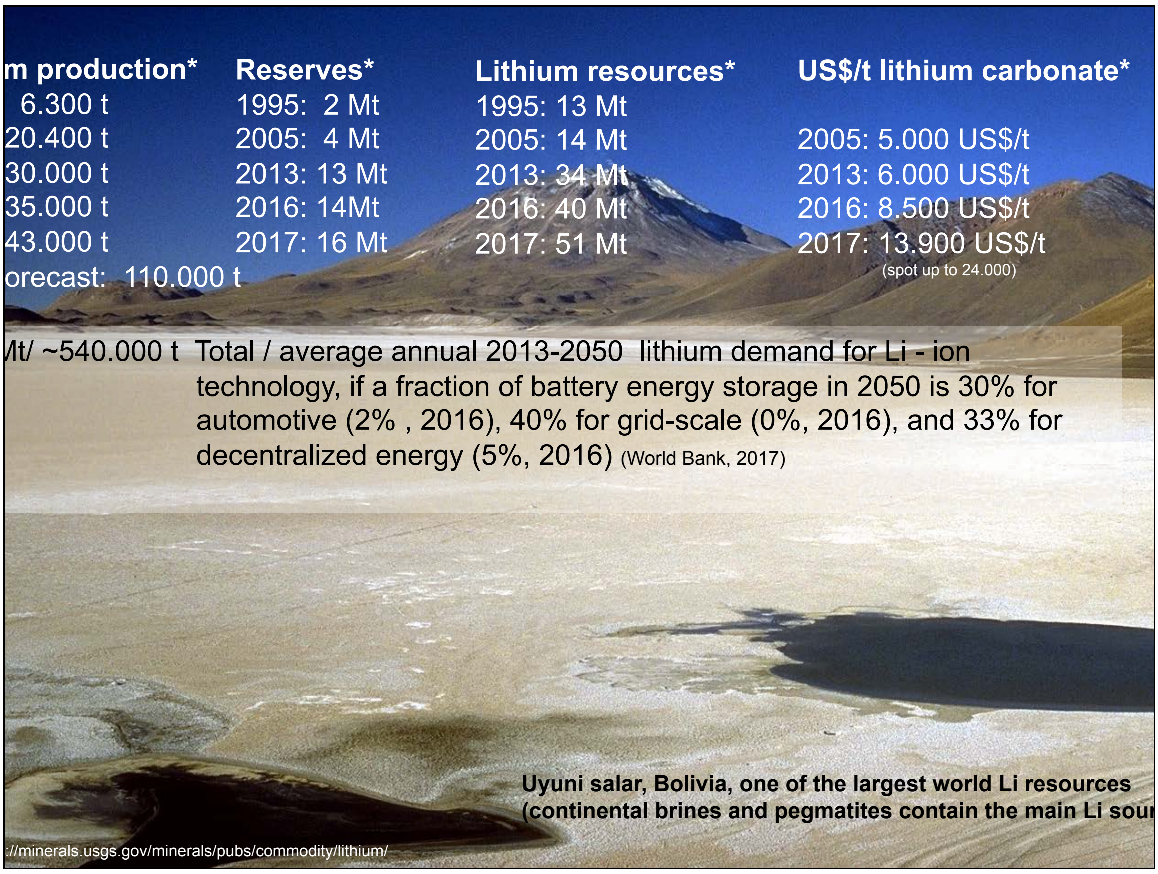
•New needs: Increasing element diversity

- **some are essential but *niche markets** (=> extreme price volatility, no price transparence, production controlled by industrial user, possible supply bottle neck)**
- **byproducts (In, Ge, Ga,…)**
- **substitution risks**

•examples Ta ("coltan"): world 2015 mine production had a value of only ~ 250 Mio USD



Braux & Christmann (2012, Géosciences n° 15)



m production*	Reserves*	Lithium resources*	US$/t lithium carbonate*
6.300 t	1995: 2 Mt	1995: 13 Mt	
20.400 t	2005: 4 Mt	2005: 14 Mt	2005: 5.000 US$/t
30.000 t	2013: 13 Mt	2013: 34 Mt	2013: 6.000 US$/t
35.000 t	2016: 14Mt	2016: 40 Mt	2016: 8.500 US$/t
43.000 t	2017: 16 Mt	2017: 51 Mt	2017: 13.900 US$/t (spot up to 24.000)
orecast: 110.000 t			

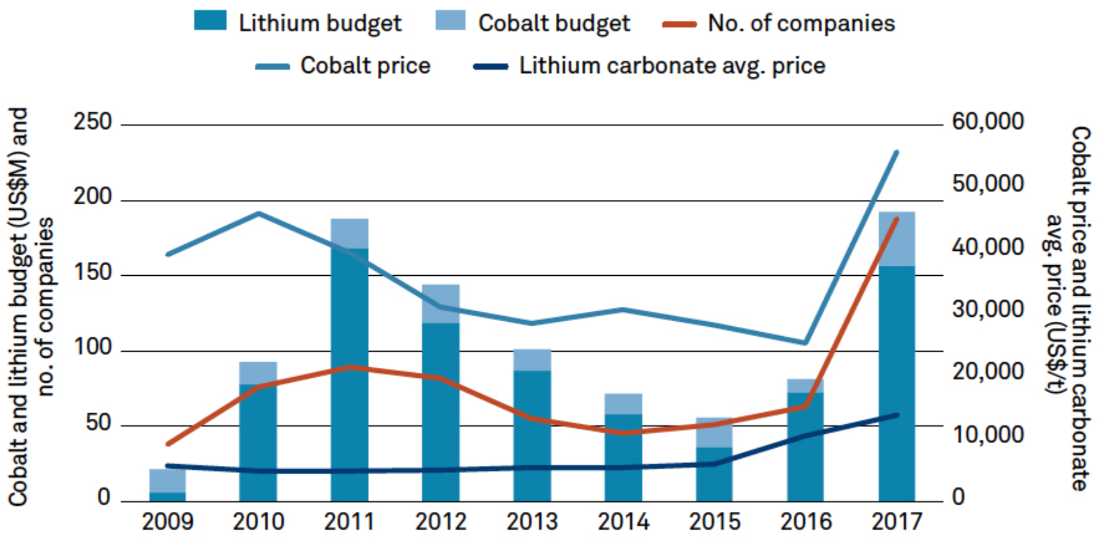
Mt/ ~540.000 t Total / average annual 2013-2050 lithium demand for Li - ion technology, if a fraction of battery energy storage in 2050 is 30% for automotive (2% , 2016), 40% for grid-scale (0%, 2016), and 33% for decentralized energy (5%, 2016) (World Bank, 2017)

Uyuni salar, Bolivia, one of the largest world Li resources (continental brines and pegmatites contain the main Li sour

://minerals.usgs.gov/minerals/pubs/commodity/lithium/

Battery metals exploration surges
- Lithium: 136 companies budgeting US$157 million in 2017, (2 x 2016 budget).
- Cobalt: 52 companies spending US$36 million in 2017 (4x 2016 budget)

Cobalt and lithium exploration budgets, 2009-2017



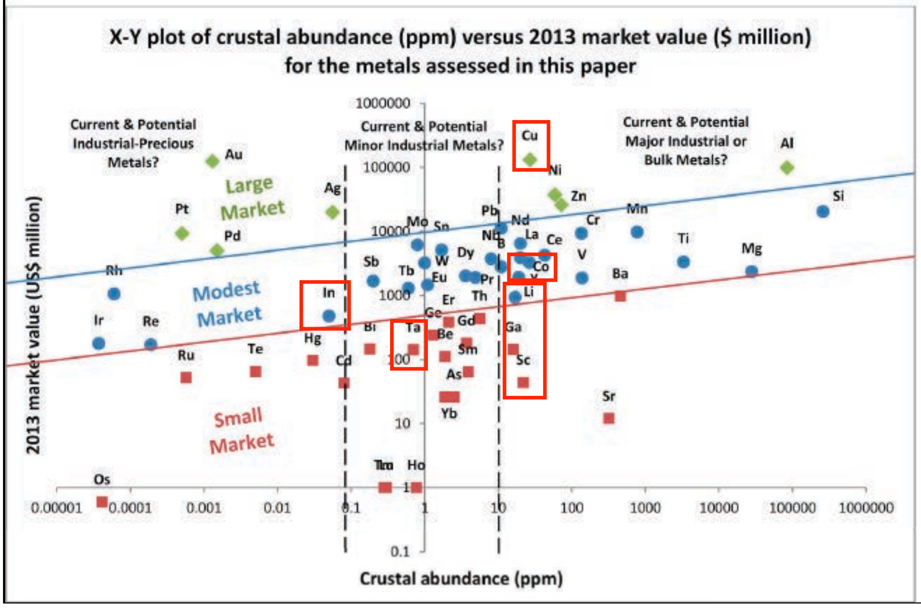
Data as of Jan. 30, 2018.
Source: S&P Global Market Intelligence

Byproducts

Copper	Zinc	Tin	Nickel	Platinum	Aluminium	Iron	Lead
Cobalt	Indium	*Niobium*	*Cobalt*	Palladium	Gallium	*REE*	*Antimony*
Molybdenum	Germanium	*Tantalum*	*PGM*	Rhodium		*Niobium*	Bismuth
PGM	Cadmium	Indium	Scandium	Ruthenium		Vanadium	Thallium
Rhenium				Osmium			
Tellurium				Iridium			
Selenium							
Arsenic							

Graedel et al., 2014

Market size


X-Y plot of crustal abundance (ppm) versus 2013 market value ($ million) for the metals assessed in this paper

Sykes et al., 2016

Environmental Impact - Social License - NIMBY - Land Access

Aborted VMS Tambogrande, project, Peru, 2001

Clashes corporate giants

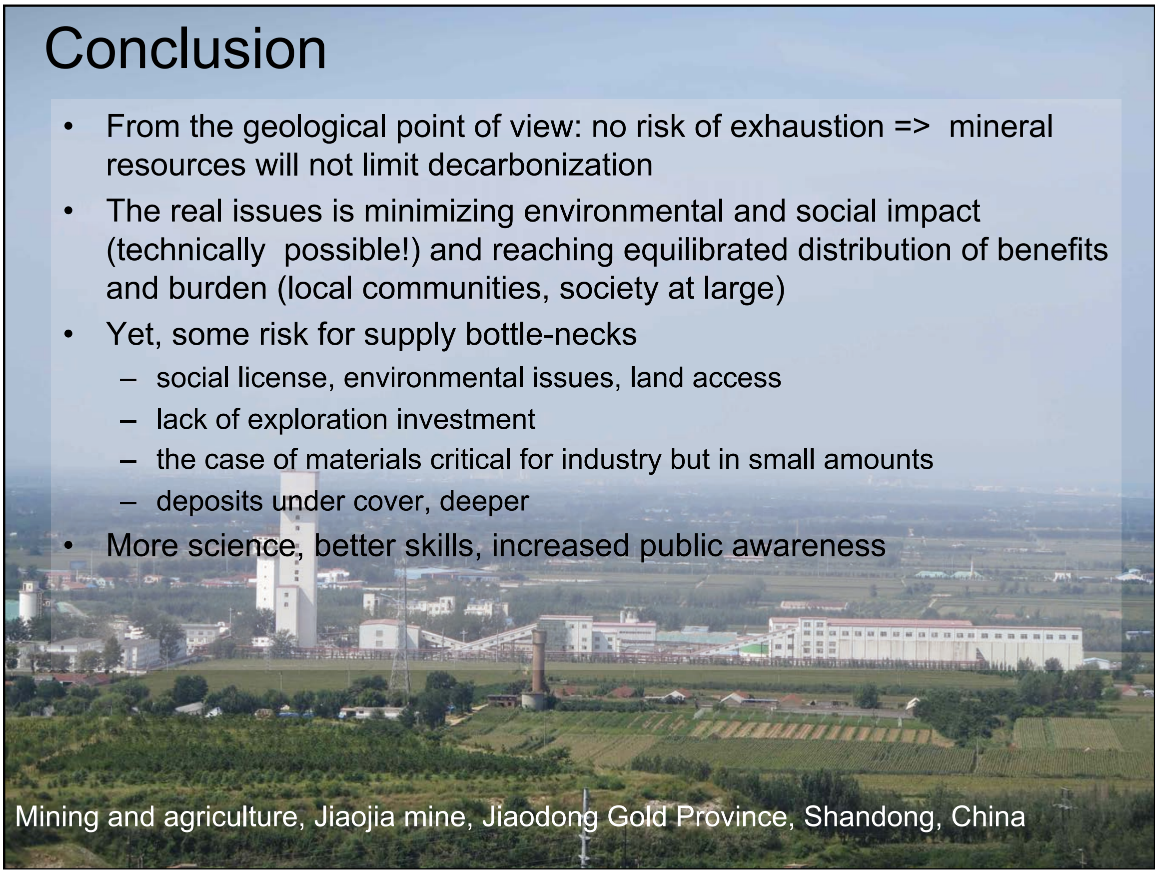
Complex issue

- good mining and exploration practices (historical record is not good!)
- transparency
- trust
- sharing benefit and burden, mining also in Europe!
- increasing public awareness that our society depends on metal supply
- public engagement of local communities and of society at large

Deeper, under cover, cleaner: Science, technology, skills

- **Mineral exploration, mining, geometallurgy: reduce costs, better efficiency, higher success rate, reduced environmental and social impact**
- **Smaller footprint in exploration, less invasive, more predictive**
- **Less waste, better use of by-products, improve mineral ore dressing efficiency**
- **New "geo-models" (mineral deposits and belts)**
- **Creation and transfer of technical know-how (geophysics, mineralogy, drilling, data integration)**
- **Basic (incl. field!) geological skills**

Mining in Europe: Opened in 2009, Las Cruces Mine, 15 km of Seville, Spain



Conclusion

- From the geological point of view: no risk of exhaustion => mineral resources will not limit decarbonization
- The real issues is minimizing environmental and social impact (technically possible!) and reaching equilibrated distribution of benefits and burden (local communities, society at large)
- Yet, some risk for supply bottle-necks
  - social license, environmental issues, land access
  - lack of exploration investment
  - the case of materials critical for industry but in small amounts
  - deposits under cover, deeper
- More science, better skills, increased public awareness

Mining and agriculture, Jiaojia mine, Jiaodong Gold Province, Shandong, China