Royal Society of Chemistry Environmental Chemistry Group 2013

A Review of the Global Supply of Rare Earths

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Outline

- Occurrences of rare earths
  - Geological settings
  - Main ore minerals
- Review of historical and current rare earth supply
  - Pre-1990s
  - Post Chinese dominance (1990-Present)
  - Current production and progress of exploration
- Future supply of rare earths
  - Availability of rare earths in China
  - Recycling
  - Forecast supply

Rare Earth Occurrences

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The Light and Heavy rare earth elements

LREEs

lanthanum	cerium	praseodymium	neodymium	samarium
57	58	59	60	62
La	Ce	Pr	Nd	Sm
138.91	140.12	140.91	144.24	150.36

HREEs

europium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium	lutetium	yttrium
63	64	65	66	67	68	69	70	71	39
Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97	88.906

TREO

lanthanum	cerium	praseodymium	neodymium	samarium	europium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium	lutetium	yttrium
57	58	59	60	62	63	64	65	66	67	68	69	70	71	39
La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
138.91	140.12	140.91	144.24	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97	88.906

Mainly as REE_2O_3 (except for CeO_2)

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Geological Setting

- Acidic/Alkaline igneous intrusives, carbonatites and associated hydrothermal deposits:
  - Mountain Pass (USA)
  - Mount Weld (Australia)
  - Bayan Obo (China)
  - Aràxà (Brazil)
  - Lovozersky (Russia)

- Secondary placer/beach sand deposits:
  - India Rare Earths
  - Malaysia/Australia/Thailand/USA

- Ion absorption clays:
  - Southern China
  - Tantalus RE (Madagascar)
  - Burma??

Major LREE Minerals

Ore type	TREO%	Advantages	Disadvantages
Bastnaesite	1-8%	High REO content, Previously processed economically	Typically occurs in carbonates which can increase reagent consumption during processing. Mainly contains LREEs (La & Ce)
Monazite (primary and placer deposits)	0.5-10% (0.5-2.5%)	Weathered monazite particularly high REO contents and reduced Th & U, Developed processing method	Often occurs along with U and Th minerals.
Loparite	2-3%	Developed processing method, Titanium content	Significant Th and U content in ores, Mainly contains LREEs

Major HREE Minerals

Ore type	TREO%	Advantages	Disadvantages
Ion absorption clays	<0.5%	Well established main source, easy to process, Low cost	TREO content, environmentally damaging mining techniques
Eudialyte (RE Silicates)	~0.5-1.5%	Favourably contains HREEs	Hard rock deposits requiring more processing stages, high reagent consumption, No widely established metallurgical process
Xenotime	1-2%	High yttrium content, Established process	Deposits of “pure” xenotime are quite unusual and are often small. Some deposits have significant levels of Th and U
Uranium tailings	~5%	Material already mined reducing overall mining costs	Composition variable, Y levels may be low, capacity limited by amount of tailings generated

Rare Earth Supply

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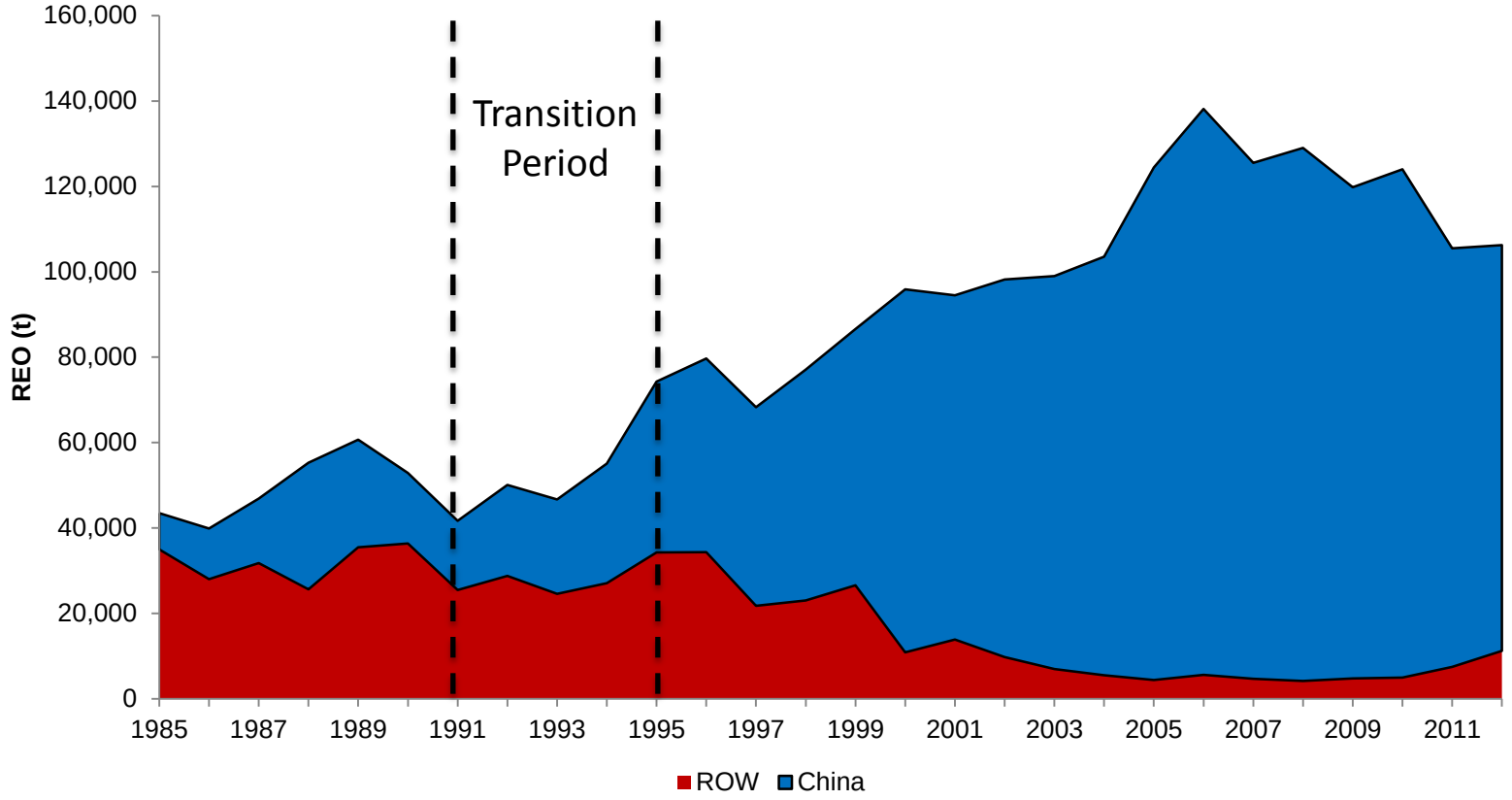
Pre 1990s – Mountain Pass, USA

- Prior to the 1990s, the Mountain Pass mine in California, USA was the largest supplier of REs to the global market



Source: MLR, MIIT, NDRC, CREIC, Company reports, Roskill estimates

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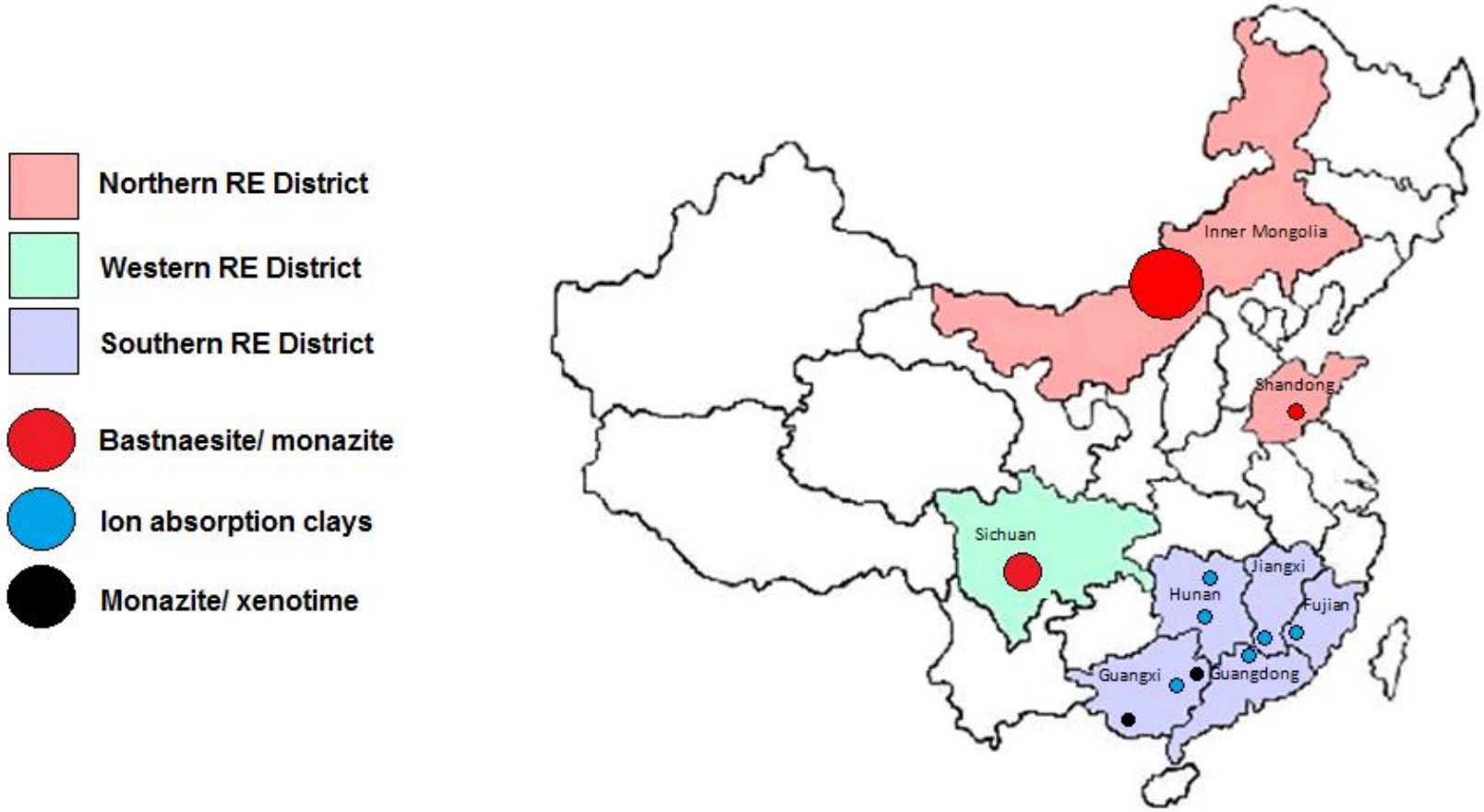
Post 1990 – Chinese dominance

- Increased production as a by-product of iron ore mining in Inner Mongolia (Baotou Steel RE)
- Numerous small scale and artisanal mining projects in southern China became an important source of HREOs
- China's dominance of the rare earths market was not a concern to the ROW until the mid-late 2000s, as rare earth export quotas tightened and there was little ROW production to fall back on
- By 2005, China accounted for 96% of global rare earth production, including 99.8% of HREO production
- Chinese dominance of REE production peaked in 2008 accounting for 97% of global production

Where are the Chinese Production Centres?



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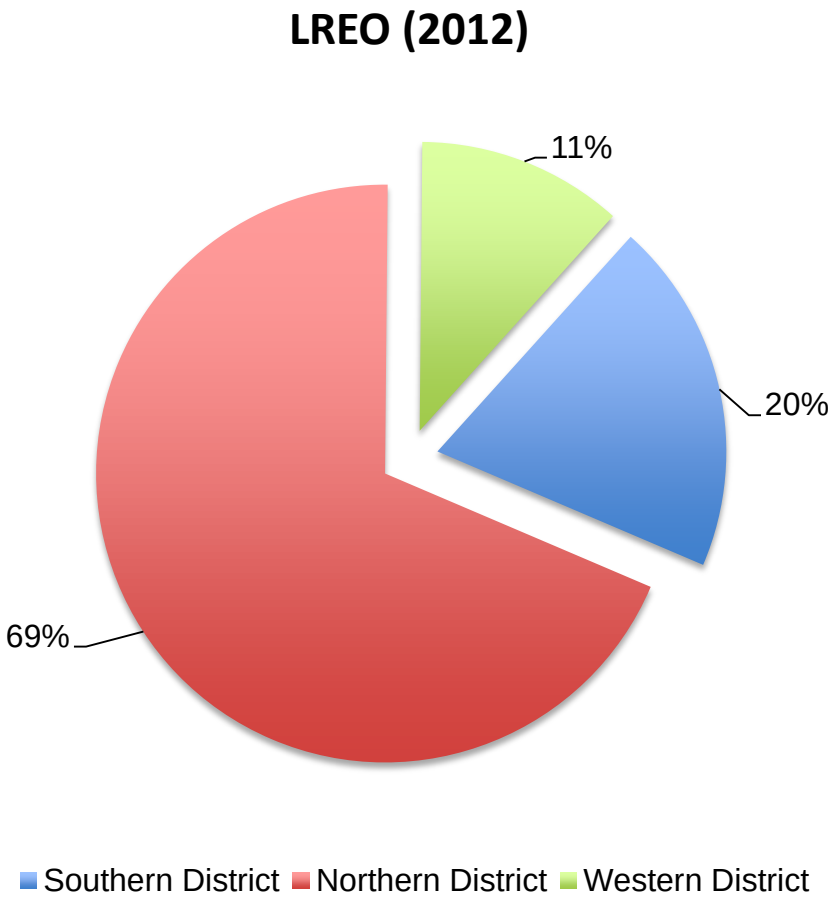

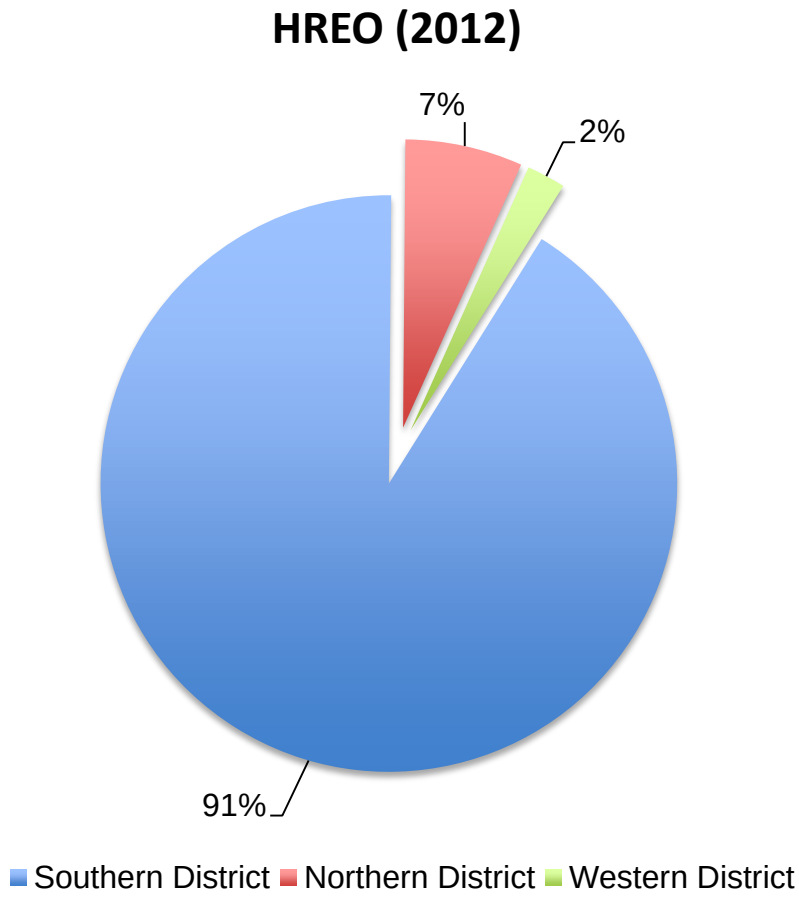

Source: Roskill estimates

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China – Northern RE District

- Comprises rare earth companies within Inner Mongolia Autonomous Region and Shandong province
- Inner Mongolia Baotou Steel Rare-Earth (Group) Hi-Tech Co. is the largest producer of REs in the northern district.
- Estimated production in 2012 equalled 62% of Chinese production
- Production quota in 2012 : 51,500tpy REO
- Production is predominantly LREEs

China – Western RE District

- Western District includes rare earth producers in Sichuan province at seven mining licences
- Sichuan Jiangxi Copper Rare Earths Co. is the largest producer from the Maoniuping mine. Other mining licences holders are:
  - Mianli Rare Earths Refining Plant,
  - Sichuan Mianning Mining Industry
  - Sichuan Mianning Yinshan RE Mining & Refining Plant
  - Diaoloushan Rare Earths Mine
  - Sichuan Hanxin Mining Development
  - Xichang Zhineng Industry
- Estimated production in 2012 totalled 10% of Chinese production
- Production quota in 2012: 24,400t REO
- Predominantly light rare earths

China – Southern RE District

- Southern district includes Jiangxi, Guangdong, Fujian, Hunan, Guangxi and Yunnan

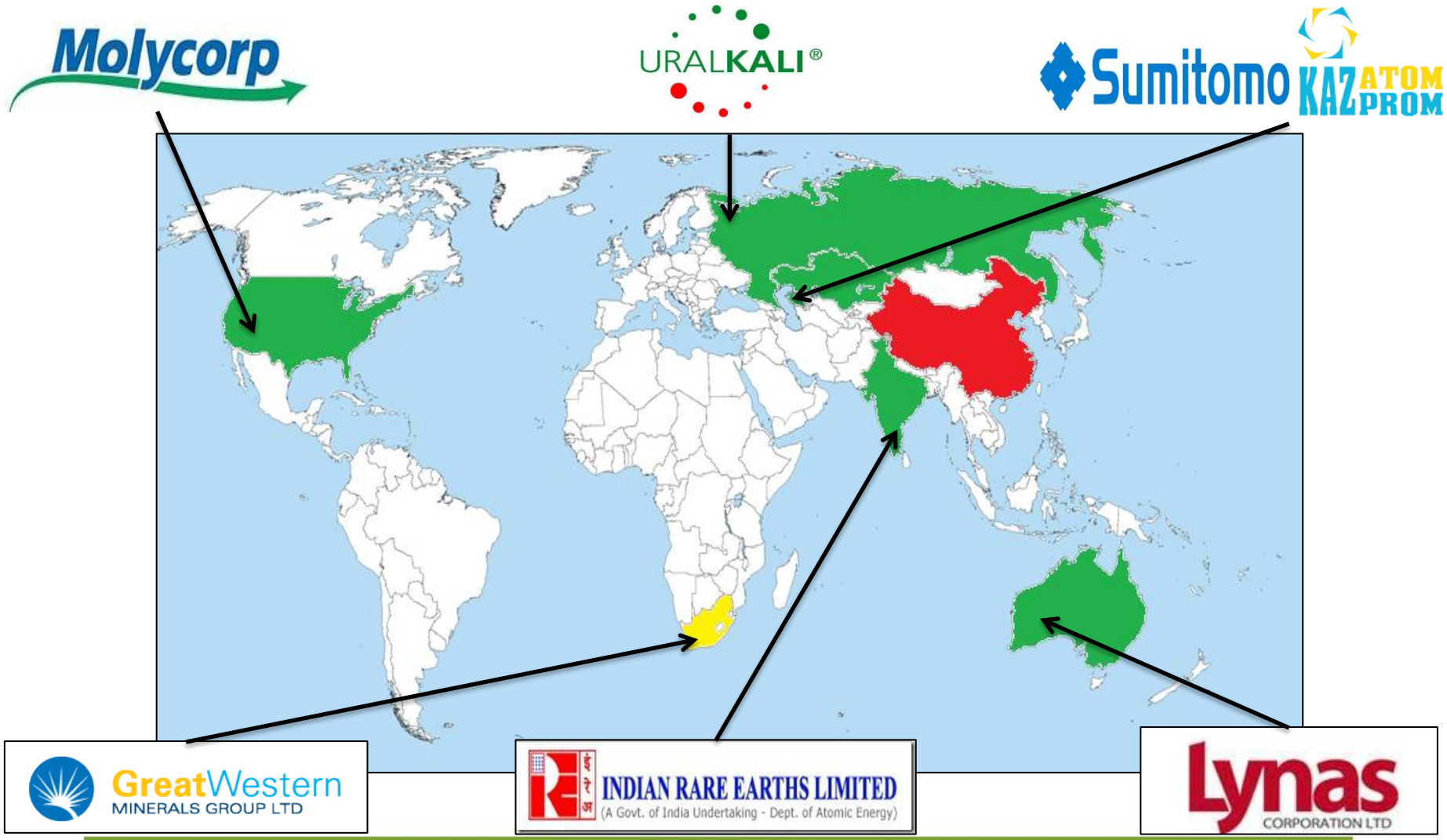
- Major producing companies:
  - China Minmetals RE (Fujian, Hunan, Guangdong)
  - Ganzhou RE Group (Jiangxi)
  - Chinalco (Guangdong, Guangxi)
  - Guangdong Rare Earth Industry Group (Guangdong)
  - China non-Ferrous Metals (Jiangxi, Guangdong)

- Estimated production in 2012 totalled 27% of Chinese production

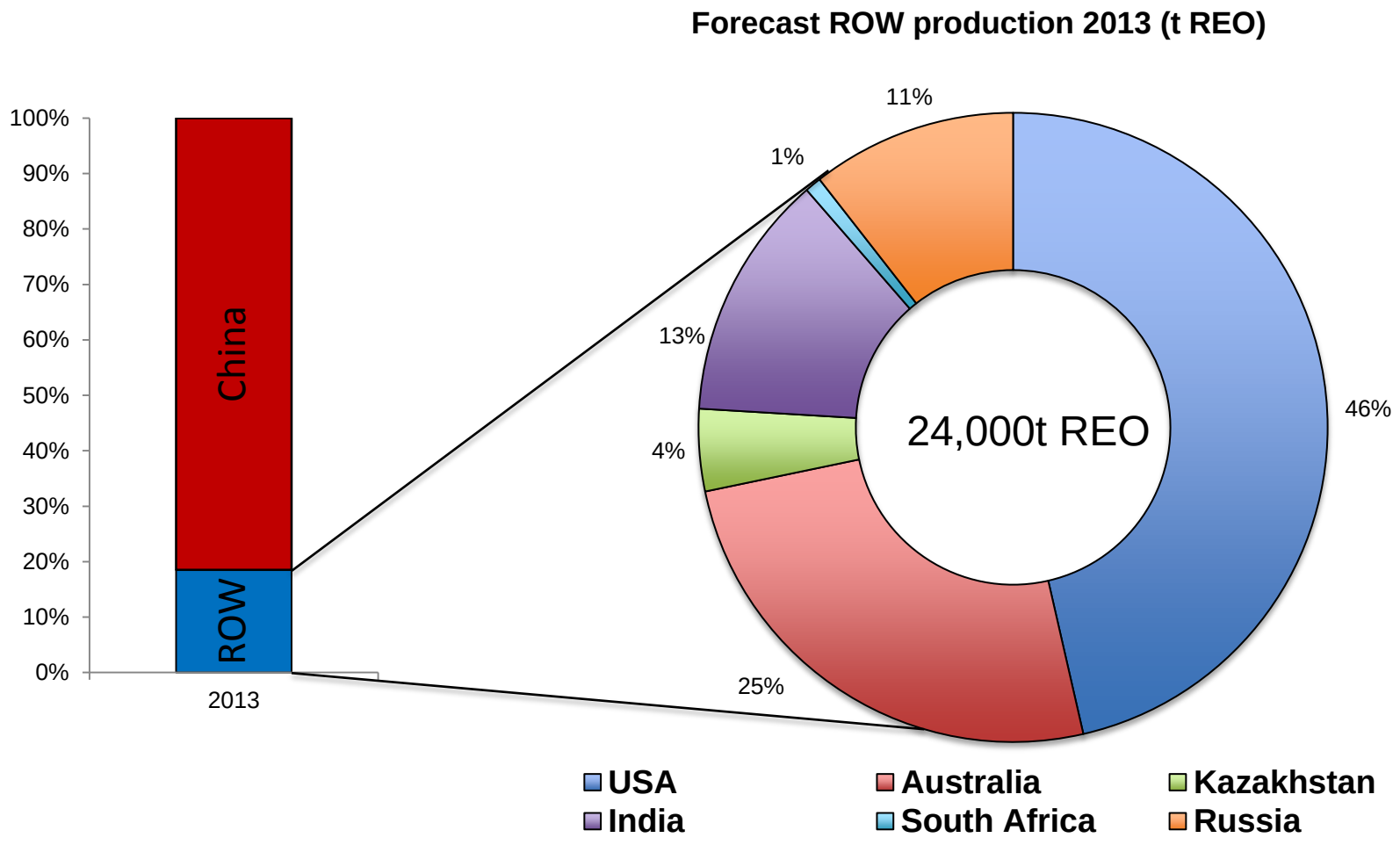
- Production quota in 2012: 17,900t REO

- Source of >90% of global HREE production in 2012

Mine Production outside China in 2013



Production outside China



Source: Roskill estimates

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Production outside China

- To date, successful companies have been those which are affiliated with chemical companies:
  - Molycorp (Silmet, Neo Material Technology)
  - Lynas Corp. (Solvay/Rhodia)
  - SARECO (Sumitomo)
  - Great Western (Ganzhou Qiandong RE Group)
  - Alkane (Shin-Etsu)

- Hydrometallurgy is complex, especially to produce high purity separated rare earth oxides, carbonates, chlorides, etc…

On-going exploration

- There were >200 projects exploring for rare earths outside of China at the end of 2012
- Majority of exploration projects are located in Canada, although projects are being explored in Angola, Argentina, Ireland, USA, Australia, etc...
- Market demand could potentially sustain 6-8 new rare earth producers by 2018, mainly HREE exploration projects
- A lack of debt and equity finance and falling RE prices in 2012 has driven some exploration companies to focus on by-product production of REs or abandon RE exploration completely

Rare earth metallurgy

Mining

- Open pit
- Underground
- In-situ

Milling

- Crushing & grinding
- Mixing

Physical separation

- DMS (loparite, monazite)
- Magnetic/electrostatic separation (Fe/Ti impurities)
- Flotation (bastnaesite, monazite)

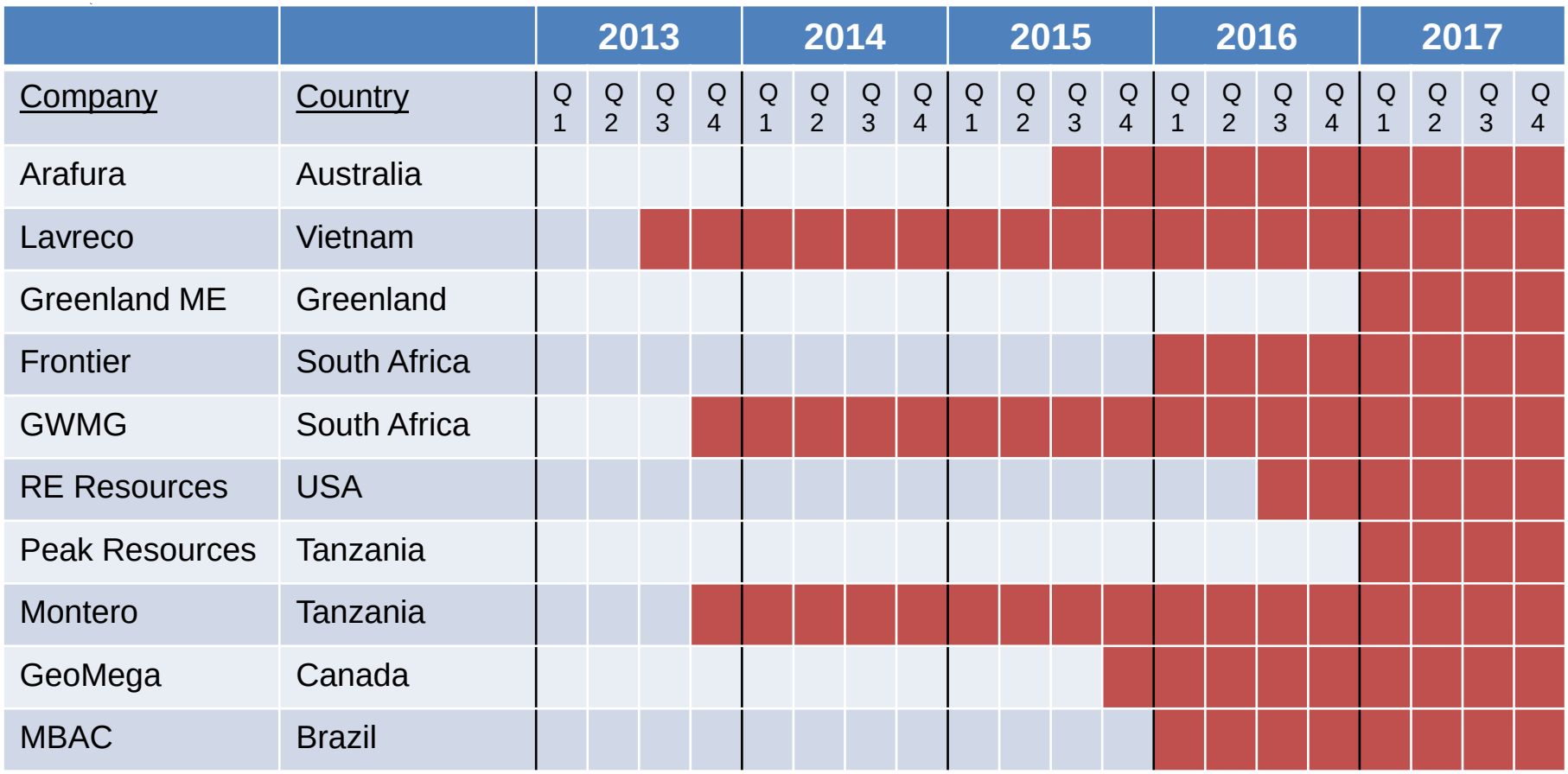
Cracking and Precipitation

- Acid digestion
- Alkaline cracking (monazite)
- Heating
- Precipitation (Na_2SO_4, $CaCO_3$, Oxalic acid)

RE Separation

- Solvent extraction
- Ion absorption

LREE Development Projects



Company	Country	2013				2014				2015				2016				2017			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Arafura	Australia																				
Lavreco	Vietnam																				
Greenland ME	Greenland																				
Frontier	South Africa																				
GWMG	South Africa																				
RE Resources	USA																				
Peak Resources	Tanzania																				
Montero	Tanzania																				
GeoMega	Canada																				
MBAC	Brazil																				

Source: Roskill estimates, Company reports

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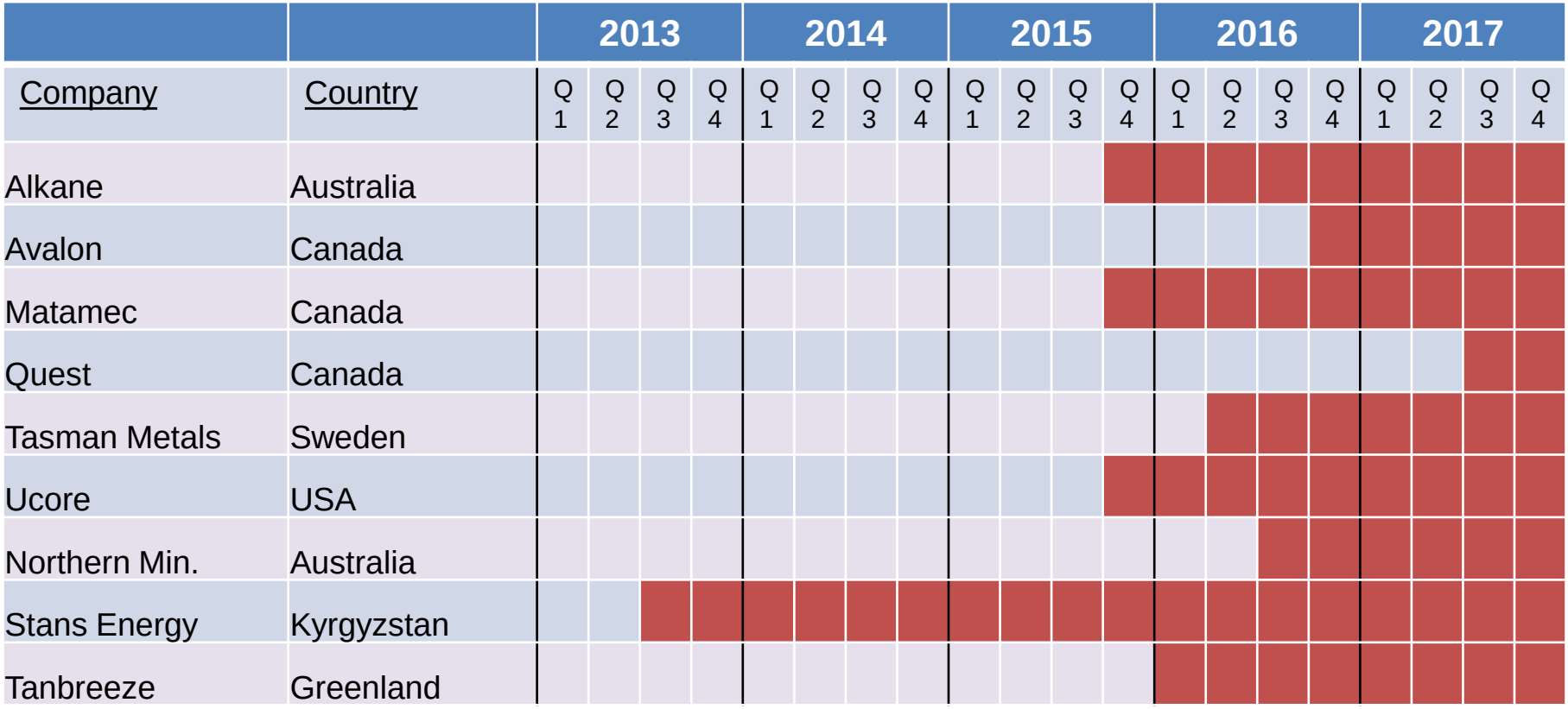
HREE Development Projects



Company	Country	2013				2014				2015				2016				2017			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Alkane	Australia																				
Avalon	Canada																				
Matamec	Canada																				
Quest	Canada																				
Tasman Metals	Sweden																				
Ucore	USA																				
Northern Min.	Australia																				
Stans Energy	Kyrgyzstan																				
Tanbreeze	Greenland																				

Source: Roskill estimates, Company reports

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Future Supply of Rare Earths

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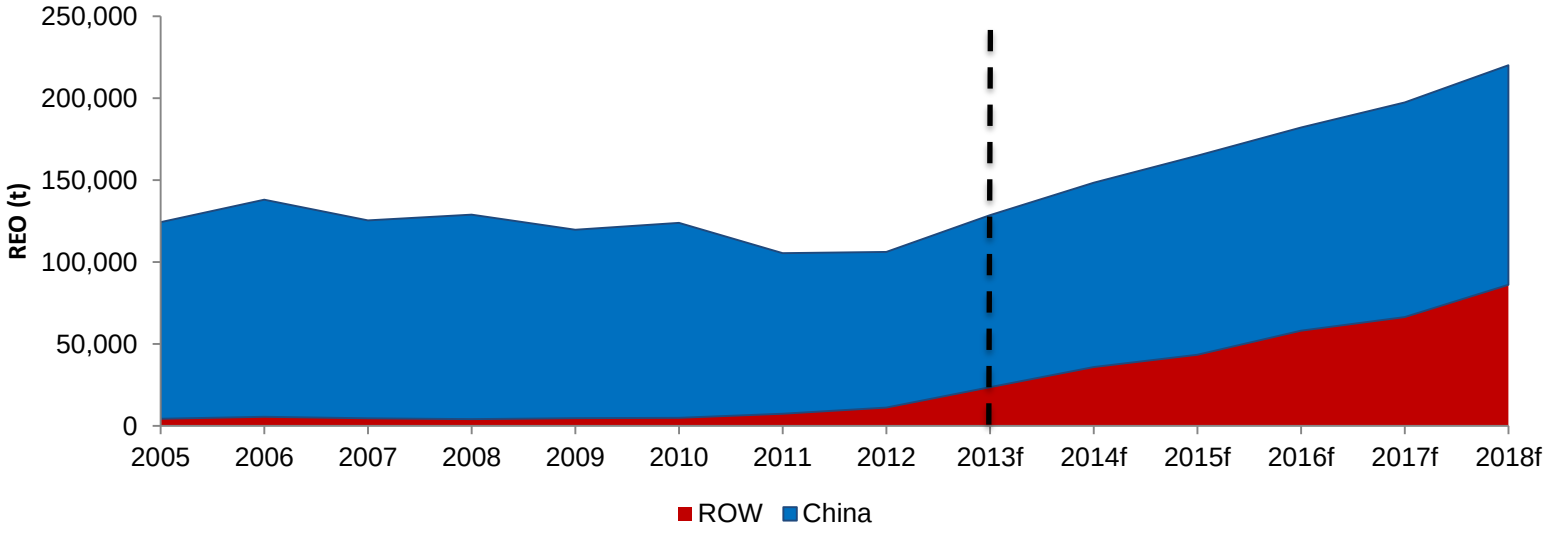
Where will future supply come from?

- Primary production from mines
  - China
  - ROW

- Recycling or Urban Mining
  - Phosphors - Umicore/Rhodia
  - Magnets - Hitachi, Mitsubishi and Showa-Denko
  - Polishing powders - Asahi Glass

Where will future supply come from?

- China will account for an estimated 74% of global RE production in 2015
- Chinese dominance is set to fall to 61% by 2018, but supply from the ROW will have a much larger impact on LREEs than on HREEs



Source: Roskill estimates

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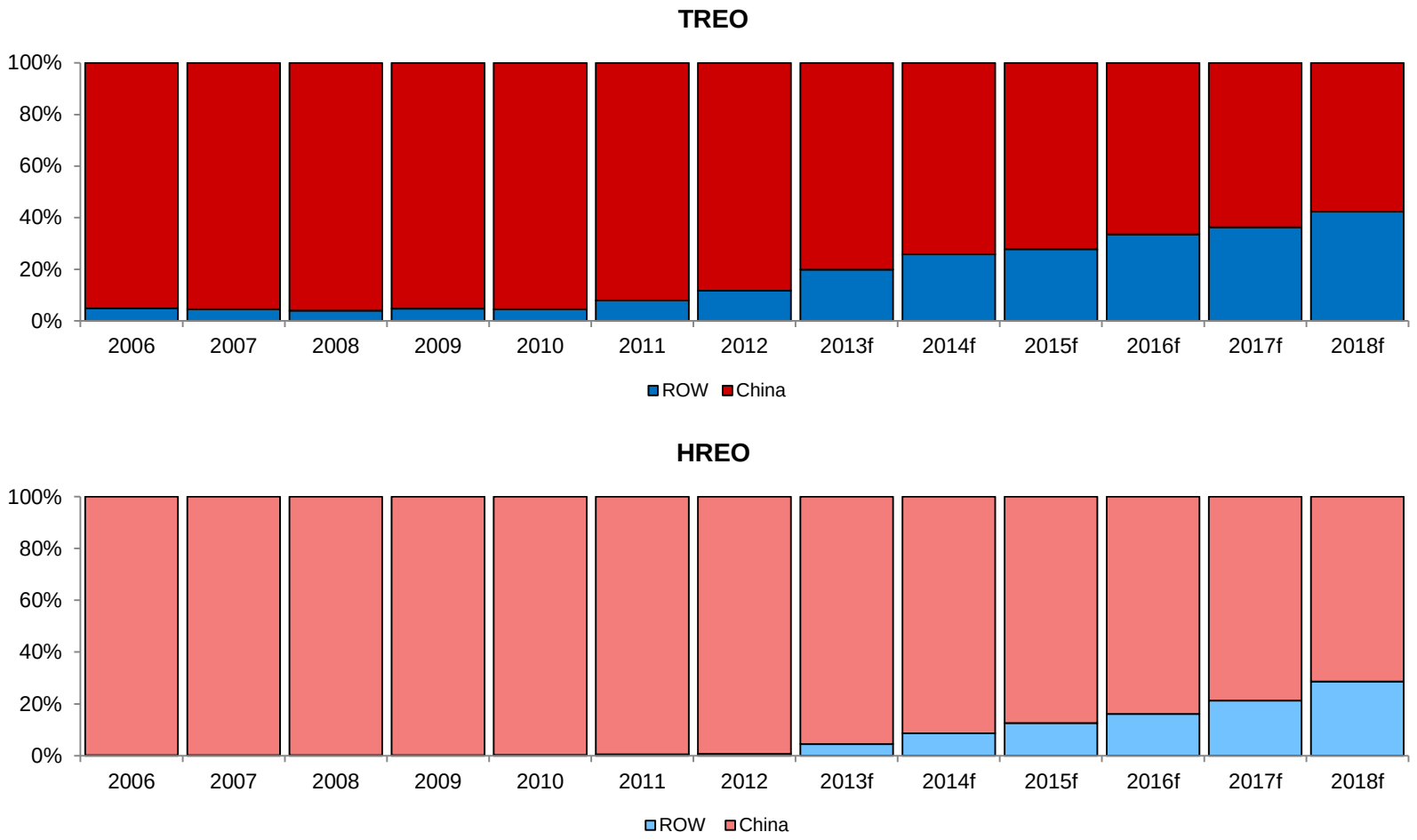
Where will future supply come from?



Source: Roskill estimates

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Will RE availability in China affect supply?

- Some deposits in Ganzhou, Jiangxi province may have a limited mine life of 15-20 years
- REE content of ores at Baotou expected to decline as pit migrates west

BUT

- Since mid-2011, the 2008 ban on new mining licences was partially lifted to allow new mines in Fujian, Hunan and Guangxi
- Reserves of ion adsorption clays in Guangxi total 6.7Mt, a further ~3.2Mt have been identified in Fujian and reserves of 0.6Mt REO of ion absorption clays in Jiangxi were reported at the end of 2012
- Baotou estimated to contain reserves of 28.8Mt REO, enough to maintain production of 50,000tpy REO (production quota) for over 500 years

EXPLORATION

- China Minmetals is setting up a joint venture in the far west of Yunnan province to develop rare earth resources
- Next stop Burma? Just over the border from deposits in Yunnan, and Minmetals are being directed to review and develop overseas resources

Recycling

Phosphors	Rhodia's plant at La Rochelle has a capacity to process 1,000tpy phosphor powder, not necessarily all RE phosphors. REs form a minor portion of output and the process is not yet economically attractive.
Magnets	Currently no commercial recycling of 'old' scrap, although processes are being developed to process RE magnets from hard disk drives. Recycling of 'new' scrap produced during magnet manufacturing has been undertaken for some years now.
Polishing Powders	Powders are collected and reused internally at the majority of plants outside China. The availability of RE polishing powders in China has reduced installation of recycling circuits. Glass technology has also led to a decline in demand

Where will future supply come from?

- China will remain the dominant supplier of REs until beyond 2018
- Strong growth in ROW supply is expected, predominantly from the ramp up and expansion of projects in the USA and Australia, but also from new projects entering production
- Recycling is not expected to be a major source of rare earth until a scheme to collect RE magnets and phosphors over a large catchment area is implemented

Rare Earth Criticality

Element or Element Group	Symbol	Relative Supply Risk Index	Leading Producer	Top Reserve Holder
Rare Earth Elements	REE	9.5	China	China
Tungsten	W	9.5	China	China
Antimony	Sb	9.0	China	China
Bismuth	Bi	9.0	China	China
Molybdenum	Mb	8.6	China	China
Strontium	Sr	8.6	China	China
Mercury	Hg	8.6	China	Mexico
Barium	Ba	8.1	China	China
Carbon (graphite)	C	8.1	China	China
Beryllium	Be	8.1	USA	Unknown
Germanium	Ge	8.1	China	Unknown
Niobium	Nb	7.6	Brazil	Brazil

Is this criticality ranking warranted?

Source: BGS Risk List 2012

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For more information on Roskill Consulting Group and the full range of Roskill reports, including Rare Earths & Yttrium: Market Outlook to 2015, and Lithium: Market Outlook to 2017, please go to our website

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Or contact David Merriman

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