



# A global overview of the geology and economics of lithium production

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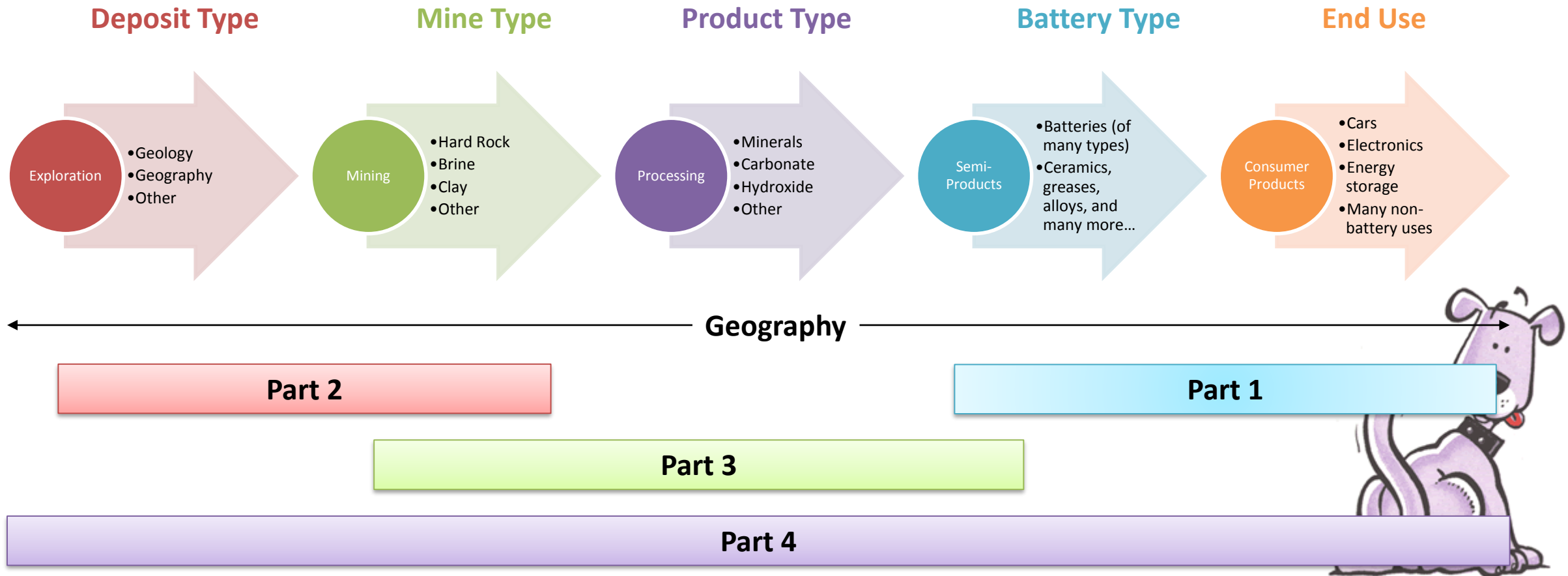
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# Linking geology and economics in the lithium industry

## MINE-TO-MARKET



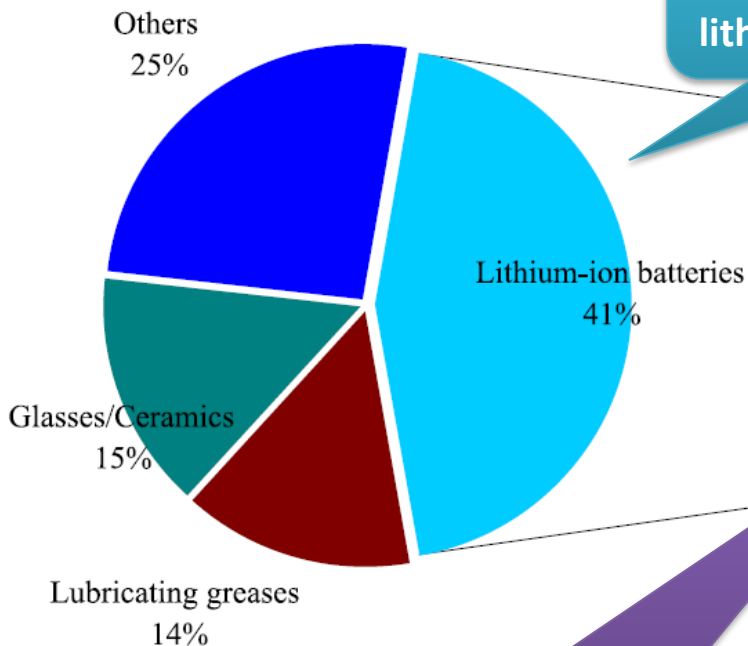


A global overview of the geology and economics of lithium production

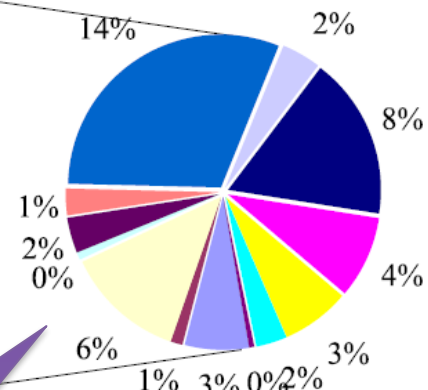
# A BRIEF INTRODUCTION ON EVOLVING LITHIUM DEMAND

# Lithium demand is in flux: switching to batteries

China (2015)



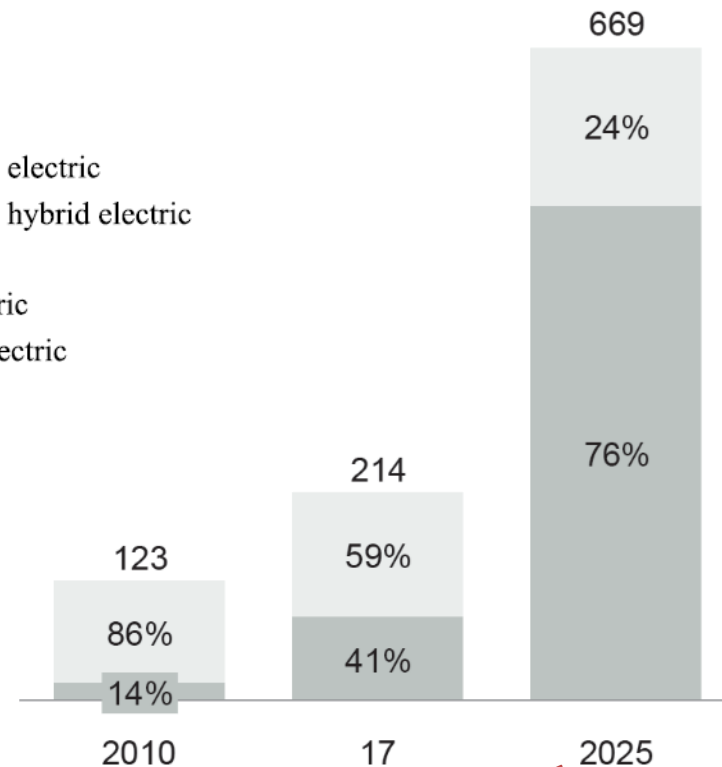
Lithium-ion batteries account for 41% of lithium demand currently



Consumer applications account for most lithium-ion battery consumption (68%)

Demand for lithium-ion batteries has transformed the lithium market in less than a decade

- Passenger vehicles - Battery electric
- Passenger vehicles - Plug-in hybrid electric
- Buses - Battery electric
- Buses - Plug-in hybrid electric
- Special vehicles - Battery electric
- Electric bicycles
- Mobile phones - Smart
- Mobile phone - Non-smart
- Laptop computers
- Tablet computers
- Power banks
- Energy storage systems
- Others



Lithium-ion batteries are forecast to dominate the lithium market over the next decade

# Lithium-ion battery consumption is in flux as well – switching to automotive from consumer applications

Application	LCE Content
Mobile Phone	~3g
Laptop	~30g
Power Tool	~35g
HEV (3kWh)	~1.6kg
PHEV (15kWh)	~12kg
BEV (25kWh)	~20kg
Tesla (85kWh)	~50kg

Growth in EVs from 2010 to 2025 split by hybrid and pure electric

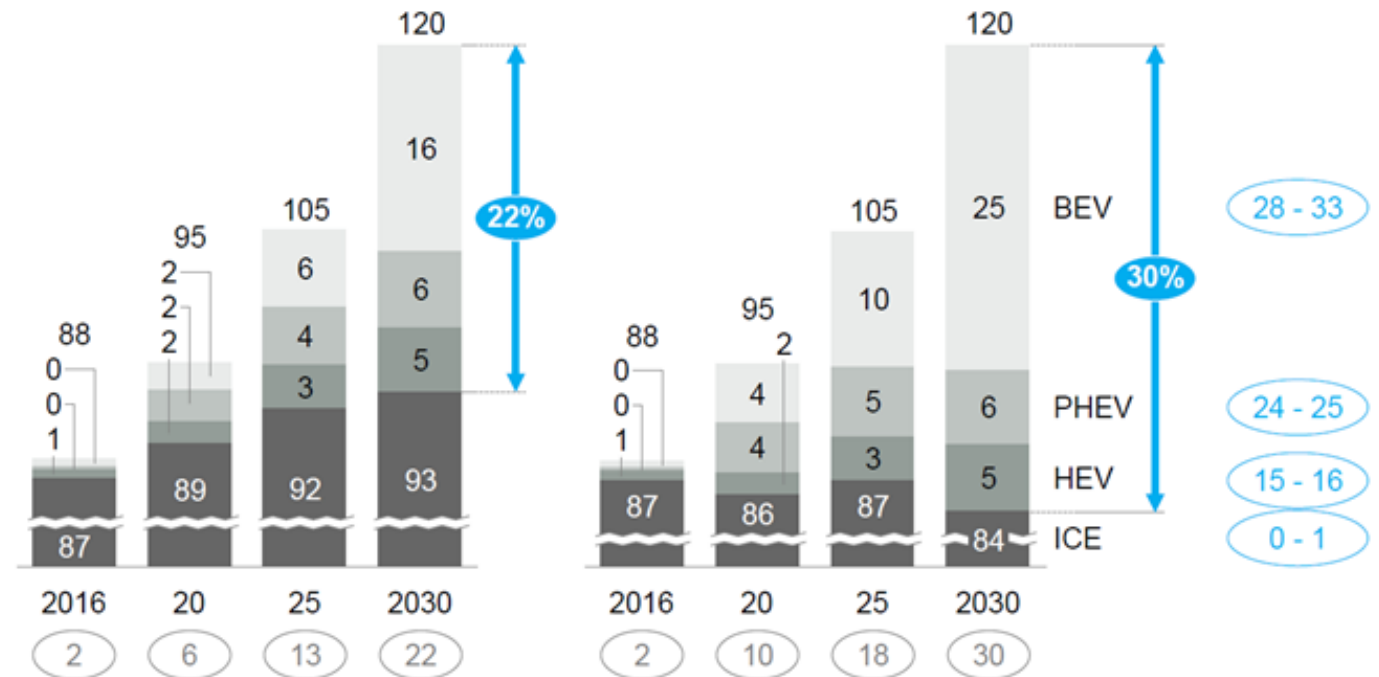
Global light vehicle production  
Million vehicles produced per year

(X) Share of EVs combined Percent

Base

Aggressive

CAGR<sup>1</sup> 2016 - 30 Percent



# However, there are many different types of lithium-ion battery with different performance characteristics

## Battery technologies by chemistry with pros and cons

### Key performance metrics of cathode chemistries

#### Cathode level metrics

Material	Description	Key performance metrics				
		Safety	Cost USD/kWh	Energy density kWh/kg	Cycle life Times	Ni content Kg/kWh
LCO (LiCoO <sub>2</sub> )	Mostly applied to consumer electronics. Limited application for xEVs (e.g., Tesla)	Low	Low	0.58	1,500 - 2,000	0
NMC1 (LiNi <sub>x</sub> Co <sub>x</sub> Mn <sub>x</sub> O <sub>2</sub> )	Applied mainly in consumer electronics but increasing application for xEVs	Mid	Mid	0.60	2,000 - 3,000	0.69 (51 wt%)
LMO (LiMn <sub>2</sub> O <sub>4</sub> )	Relatively mature technology. Applied in xEVs by Japanese OEMs (e.g., LEAF, iMiEV, Volt)	High	High	0.41	1,500 - 3,000	0
LFP (LiFePO <sub>4</sub> )	Relatively new technology applied in xEVs and ESS. Driven by A123 and Chinese manufacturers (e.g., BYD, STL)	Very high	High	0.53	5,000-10,000	0
NCA (LiNi <sub>0.8</sub> Co <sub>0.15</sub> Al <sub>0.05</sub> O <sub>2</sub> )	Applied mostly in consumer electronics (often blended with other chemistries) and e-vehicles (e.g., Tesla)	Mid	Mid	0.72	NA	0.68 (49 wt%)

1 For 811 configuration

2 By weight

Strong Moderate Weak

Lithium-cobalt oxide (LCO) is a good general performer and is now relatively safe, but has had issues in the past. Overall it is relatively cheap, but is vulnerable to cobalt price movements. Mainly used in consumer electronics and struggling to find application in electric vehicles (EVs). A dated technology.

Lithium-nickel-manganese-cobalt (LNMC) is a newer, higher performing range of battery chemistries giving flexibility over the price-performance trade-off. Mainly developed for the EV market but increasing cost effectiveness means they could find wider use. Popular both in China and outside.

Lithium-manganese oxide (LMO) was one of the first types of batteries developed for EVs, and as such is well established with as solid safety record. Popular outside China. However, its price-performance trade-off means that it may be a dated technology.

Lithium-iron phosphate (LFP) is the safest technology, in addition to being a relatively high performance battery. It is relatively expensive, but also has fewer intellectual property restrictions compensating for material costs. Popular in China. Increasingly popular choice for high-performance EVs, but likely to become overtaken by LNMC technologies over the longer term.

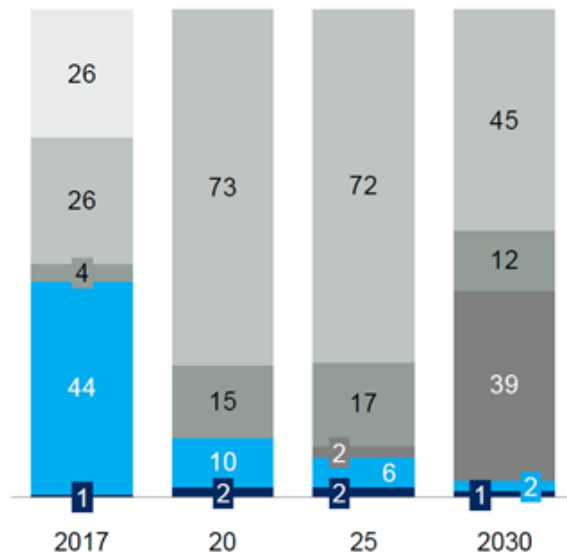
Lithium-nickel-cobalt-aluminium (LNCA) was one of the first chemistries developed with the aim of reducing cobalt consumption. Popular outside China. Solid performer and of reasonable cost so will find broad application across the first-phase of EVs – especially in high cobalt price scenarios, but over the longer term may be 'overtaken'.

# In addition, lithium-ion battery demand varies by region and is likely to evolve over time

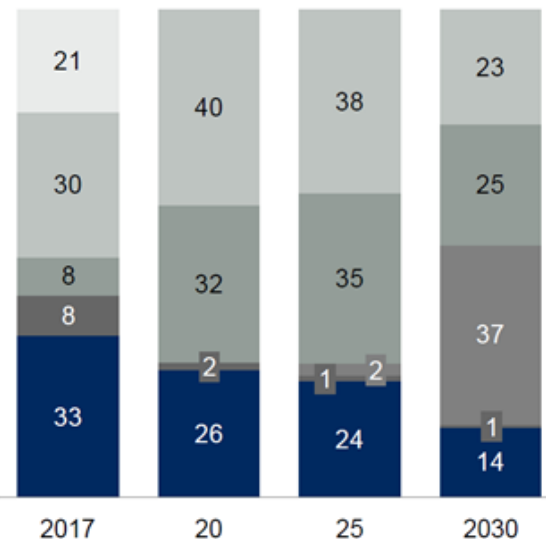
Distribution of EV by battery chemistry<sup>1</sup>

NMC 111
  NMC 622
  NMC 811
  NMC 9.5.5
  LMO
  LFP
  NCA

China  
Battery capacity demand by chemistry  
Percent



Rest of the world  
Battery capacity demand by chemistry  
Percent



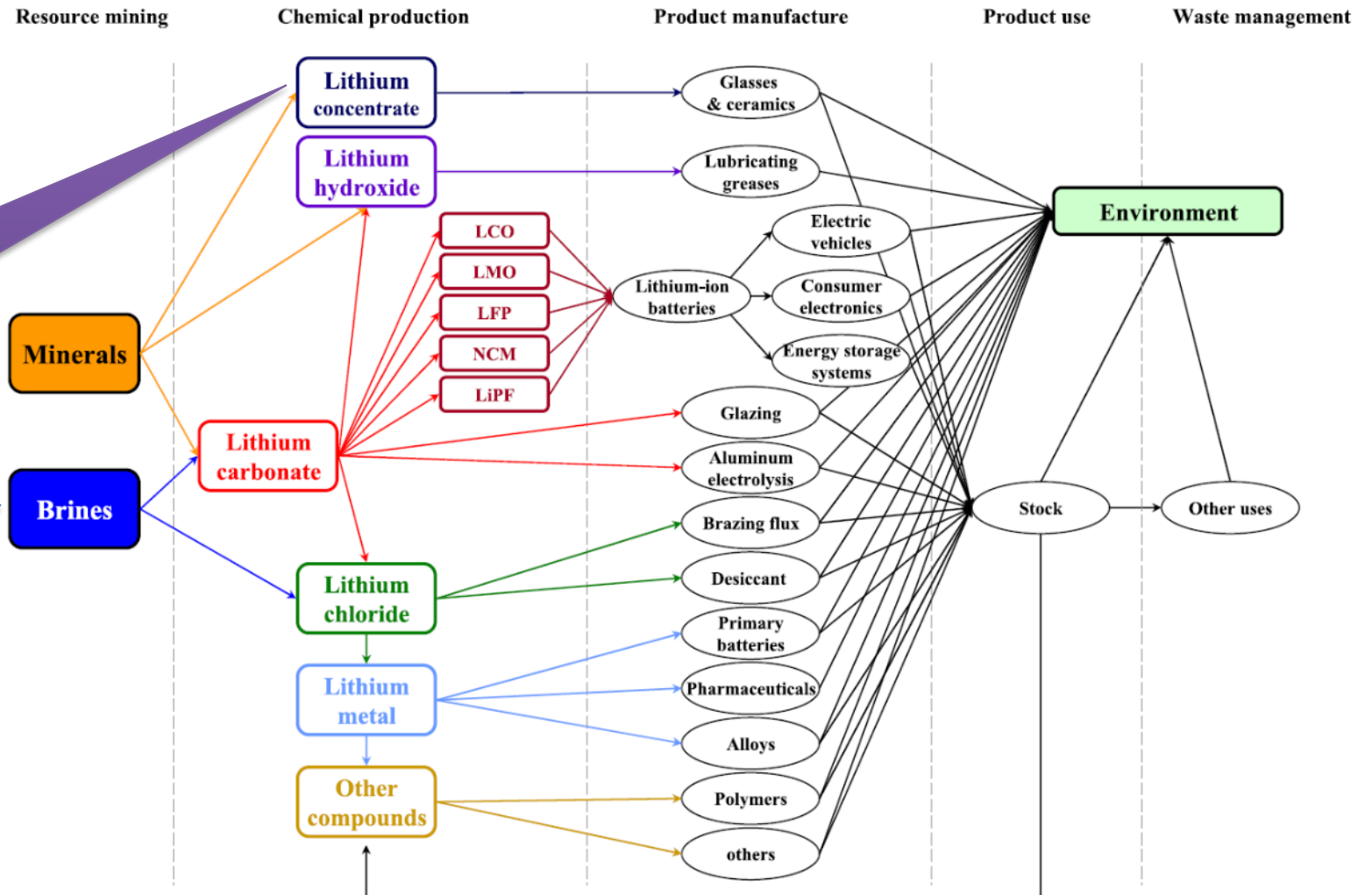
- In addition, to lithium-ion secondary (i.e. rechargeable) batteries there are several existing alternative rechargeable battery technologies;
- The most common are lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH);
- Lithium-ion batteries are generally more expensive, but have better performance;
- The current alternatives are mature technologies and in most applications lithium-ion batteries are becoming the preferred technology.
- There are several emerging battery technologies, but most also use lithium, such as lithium-air, lithium-metal, solid-state lithium and lithium-sulphur;
- However, one potential non-lithium future battery technology is sodium-ion;
- Sodium is just below lithium on the periodic table, sharing similar chemical properties, and would be similarly widely available as lithium (many rock types, salt, seawater etc.);
- Sodium-ion batteries could be cheaper than lithium-ion batteries and may also be safer.
- It should also be noted that in some applications primary (i.e. disposable) batteries can substitute for rechargeable batteries, though this is mainly consumer products and some niche uses, not EVs and associated technologies.
- Most common disposable battery technologies are based on zinc, though some minor applications use lithium technology.

# Lithium has significant supply chain complexity

Lithium minerals have the most flexibility in intermediate product (lithium chemicals) production...

...however, many of the new lithium mineral mines are currently only producing mineral concentrates, for which, uses are mainly restricted to the glasses and ceramics markets

Brines can be used to produce battery chemicals, however, the  $\text{Li}_2\text{CO}_3$  produced can be poor quality (both grade and deleterious elements), thus mineral feedstock for battery grade  $\text{LiCO}_3$  is preferred.



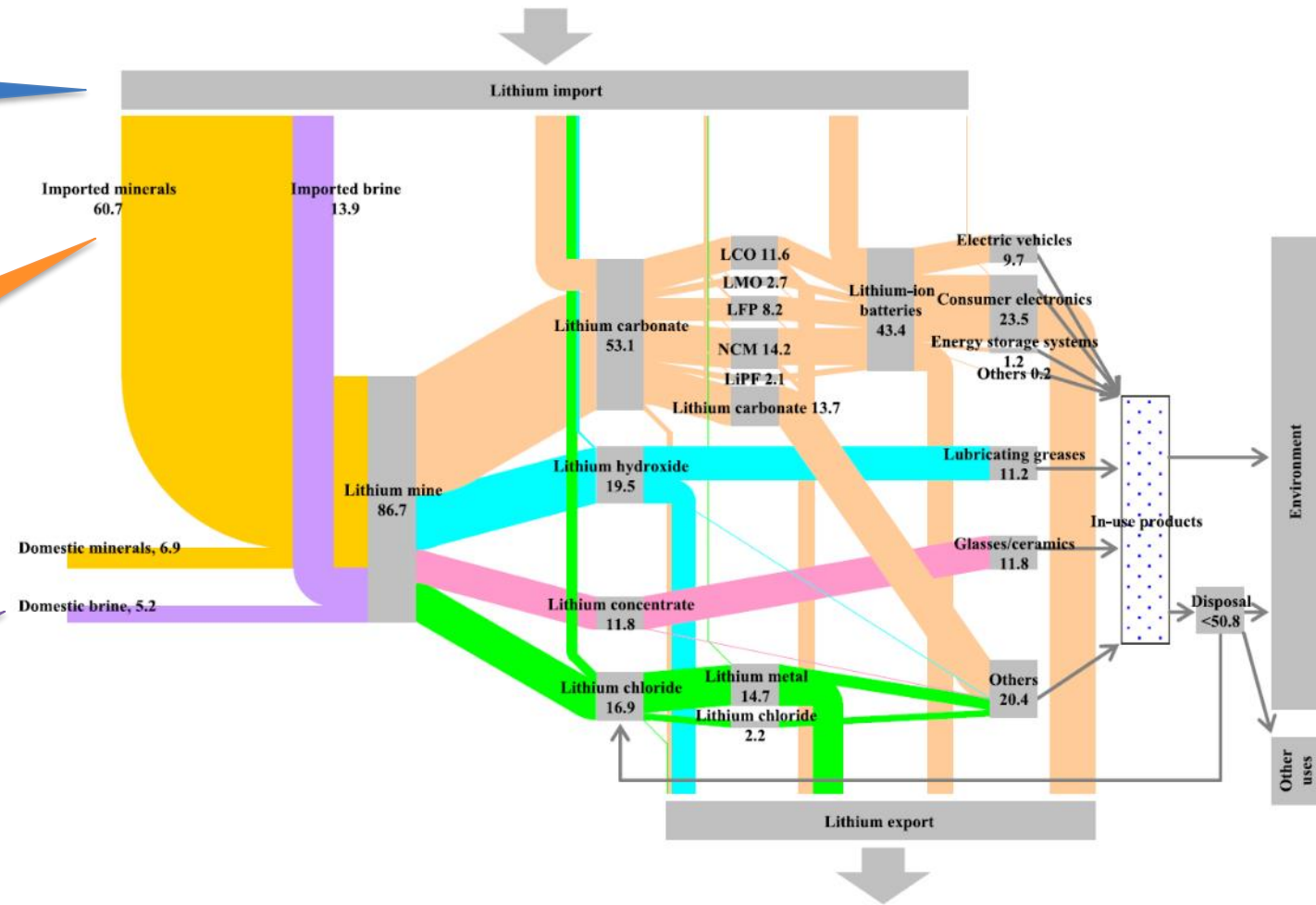


# Lithium mineral derived carbonate was previously the most popular feedstock for lithium battery production

This diagram shows the complexity of the lithium supply chain in China – the world's largest lithium raw materials consumer

...however, whilst both brines and minerals are imported the preference for using lithium minerals for producing  $\text{LiCO}_3$  and then battery chemicals is clear.

Brines are mainly used for the production of lithium chloride and lithium metal, which have general 'industrial' use.

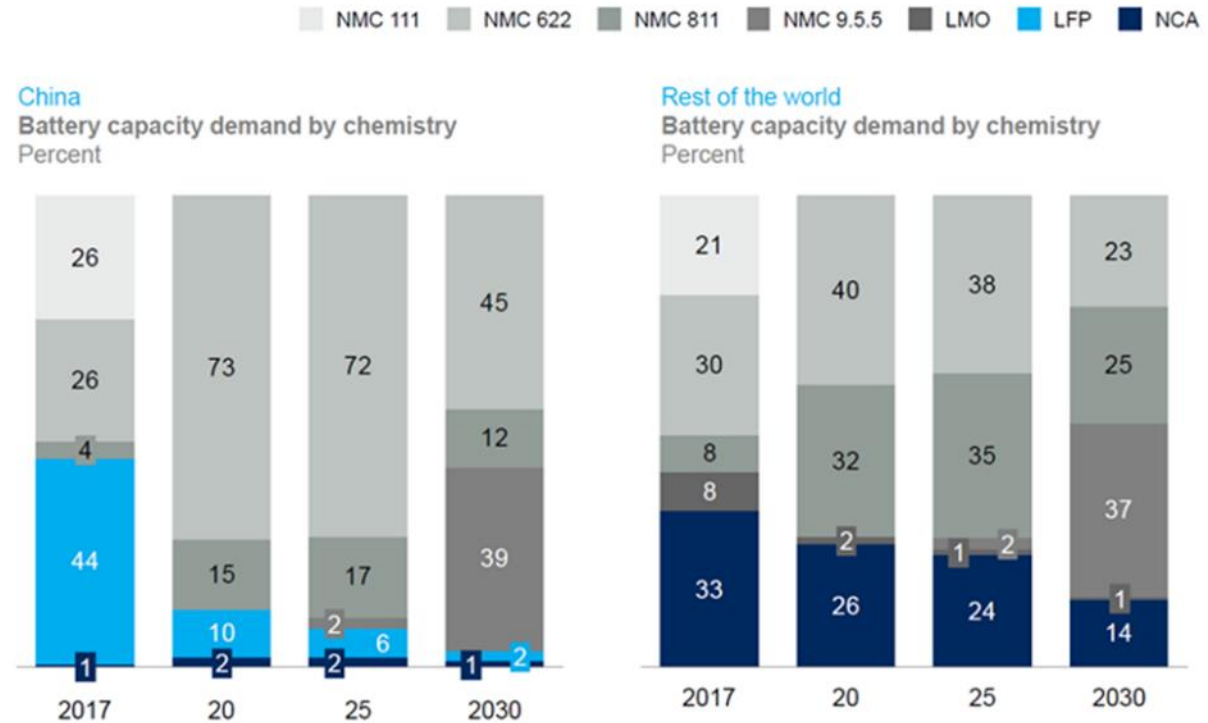



NB: units in the above diagram are tonnes of 'lithium carbonate equivalent' (LCE), where one metric tonne of LCE contains 189kg of lithium.

# Lithium hydroxide is now apparently the most popular feedstock for lithium battery production

- However, evidence from the activities of the main players in the lithium sector has shown that lithium hydroxide (LiOH) is now the most popular feedstock for lithium battery production, for example:
  - Orocobre (in partnership with Toyota & Panasonic) is building a ‘technical grade’ (>99% lithium carbonate [Li<sub>2</sub>CO<sub>3</sub>]) plant at Salar de Olaroz, which in turn will feed a battery-grade LiOH plant in Japan (Naraha);
  - Kidman Resources in a JV with SQM (Chile) is building a LiOH refinery in Western Australia that is integrated with its Earl Grey (Mt Holland) project;
- **LiOH is the preferred input for nickel-cobalt-aluminium (NCA) and nickel-manganese-cobalt (NMC) lithium-ion batteries**, whereas **Li<sub>2</sub>CO<sub>3</sub> was the preferred input for lithium-iron-phosphate (LFP) batteries** (Macquarie, 2018);
- As demonstrated in the diagram (right – and also earlier) LFP battery production, which was mainly in China, is set to fall in relative importance in comparison to NMC batteries;
- A further advantage of producing LiOH is that it by-passes the Chinese Li<sub>2</sub>CO<sub>3</sub> market (see previous slide and right) and reduces the exposure of battery producers (and users) to China;
- Although NCA batteries are also forecast to decline in relative importance, this process is forecast to be slower for LFP batteries, and also retains the advantage of being a battery technology largely produced outside of China;
- It should be noted, however, that Tianqi Lithium (China) has also built (and is expanding) a LiOH refinery in Western Australia too – Tianqi is 51% owner (with Albemarle at 49%) of the Greenbushes mines in Western Australia.

Distribution of EV by battery chemistry<sup>1</sup>



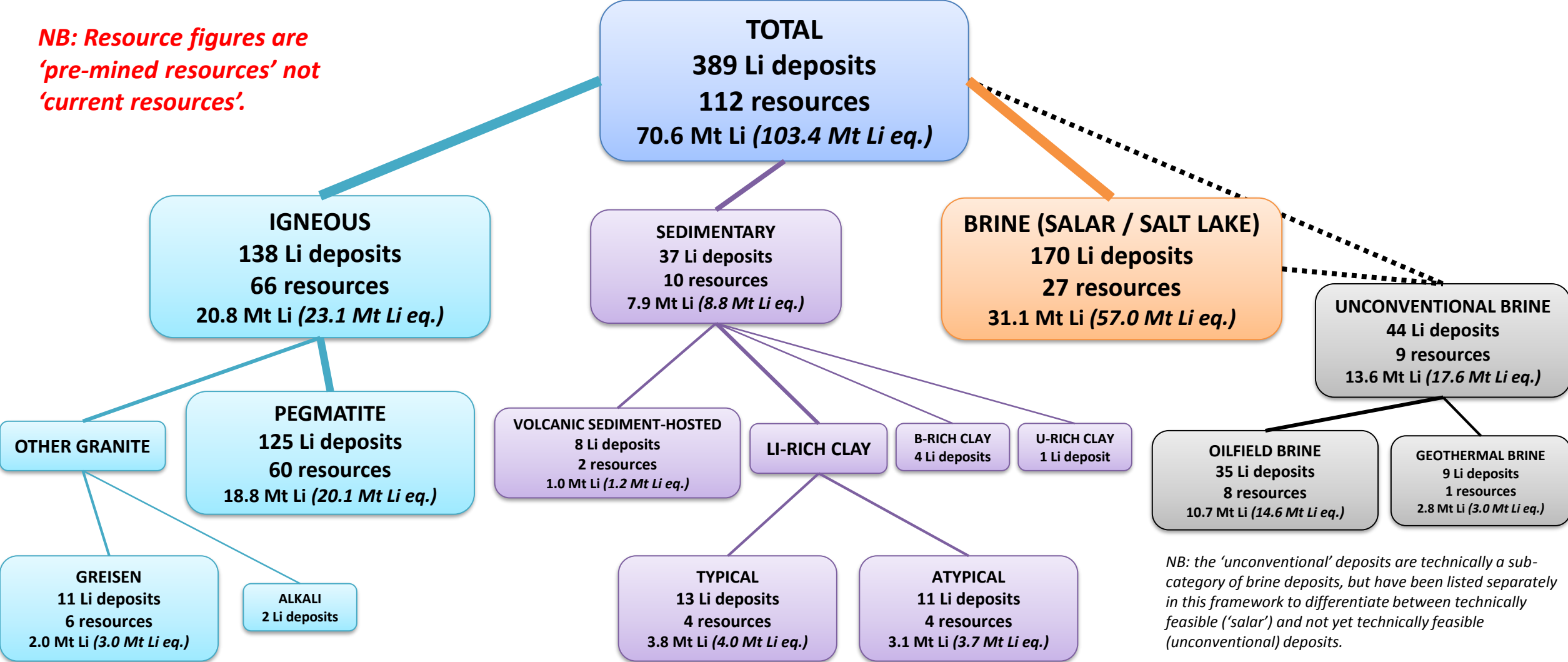


A global overview of the geology and economics of lithium production

# A BRIEF OVERVIEW OF LITHIUM DEPOSIT TYPES

# The 'MinEx' geological framework for lithium deposits

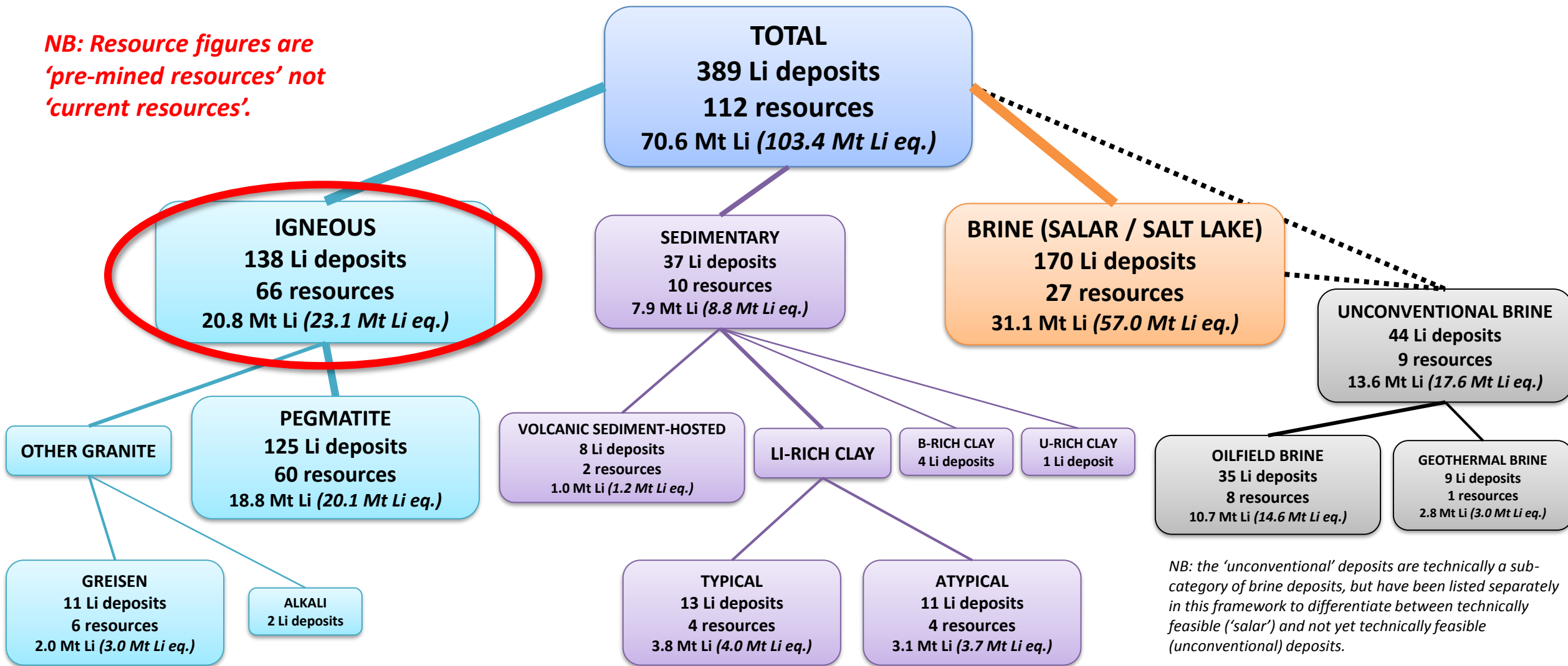
*NB: Resource figures are 'pre-mined resources' not 'current resources'.*



*NB: the 'unconventional' deposits are technically a sub-category of brine deposits, but have been listed separately in this framework to differentiate between technically feasible ('salar') and not yet technically feasible (unconventional) deposits.*

# The 'MinEx' geological framework for lithium deposits

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# Pegmatite is the dominant ‘hard rock’ lithium deposit type, though granite-type deposits are related

- For the source magma to be rich in lithium it must also undergo extreme fractional crystallisation;
- The size of the parental pluton for a lithium pegmatite is ~70-fold larger (Partington *et al.*, 1995), which may place an upper limit on the size of pegmatites;
- Parts of the parental pluton may also be sufficiently enriched in lithium or other metals to be considered an orebody (the ‘granite-related’ deposit type);
- The diagram right shows the relative enrichment of different elements in a pegmatite (at Tanco, Canada) and its parental pluton (which in this case is not considered an economic orebody, but nonetheless demonstrates the concept);
- The difference in source magmas and thus why some pegmatites are lithium rich and others are not, is poorly understood – but it may be linked to the felsic content of the magmas sourced from continental crust material;
- LCT pegmatites may be associated with aluminium-rich (S-type) granites formed by the melting of subducting metamorphosed sediments.

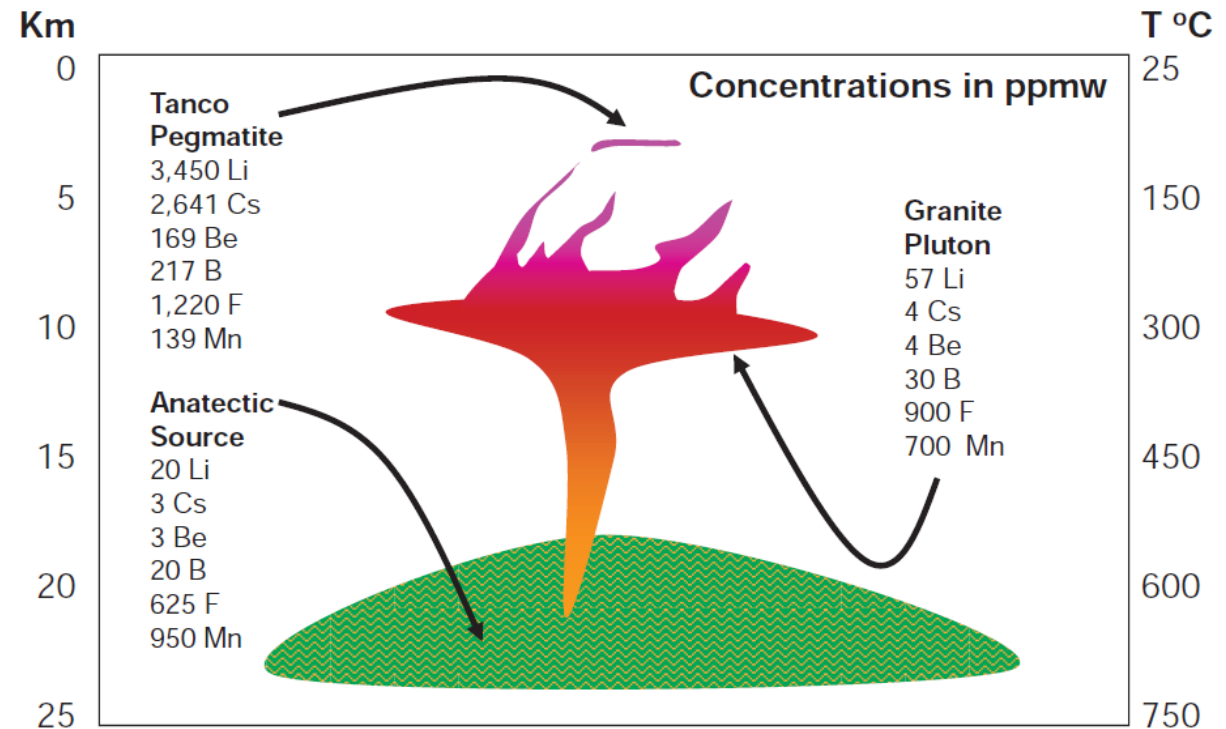


Image: Chemical fraction from source to pegmatite (London, 2016)

# Greenbushes (Western Australia) is the case example of a world-class lithium(-tantalum-tin) pegmatite

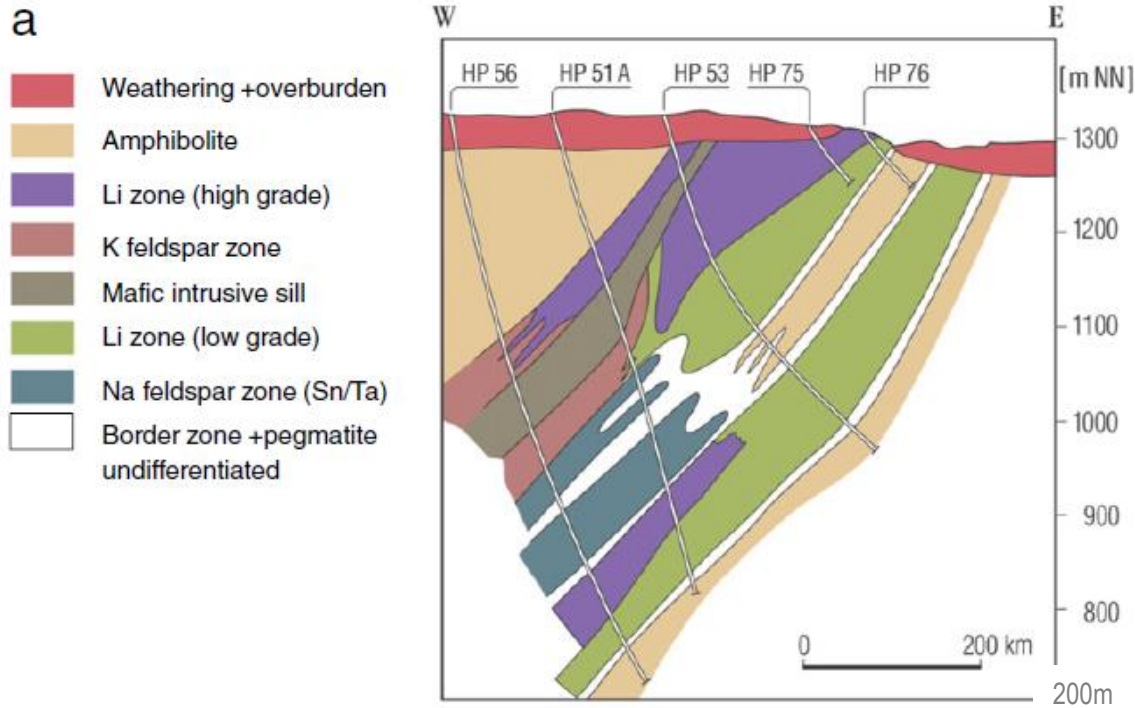


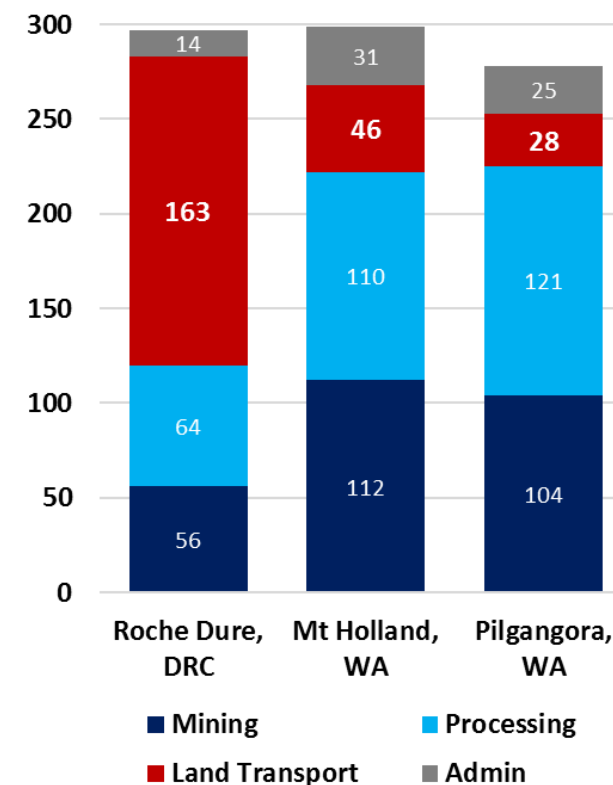
Image: Cross-section of the Greenbushes pegmatite (Dill, 2015 [corrected])

- Greenbushes is a complex of tin, tantalum, lithium and kaolin bearing pegmatites, with extensive weathered and alluvial material at surface;
- The weathered and alluvial material has been mined for tin and then tantalum since 1888, with the presence of the alluvial material critical in its discovery and exploitation (Wenman, 2006);
- Hard rock mining commenced in the 1980s and was focused on lithium, tin and tantalum;
- Currently it is mainly lithium that is mined (by a Tianqi, China and Albemarle, USA joint venture through Talison Lithium), with the other mineral rights held separately (by Global Advanced Metals) – tantalum is still mined but tin is no longer mined (though it remains economically feasible);
- The Greenbushes pegmatite is about 3km long and several hundred metres thick (see diagram);
- The extensive alluvial and weathered material suggests the original pegmatite was much larger;
- **MinEx calculates the pre-mined resource of lithium at Greenbushes to be about 131Mt @ 1.14% lithium, thus containing 1.49Mt of lithium (making it the second largest known lithium pegmatite).**

# Pegmatite mining faces several general challenges

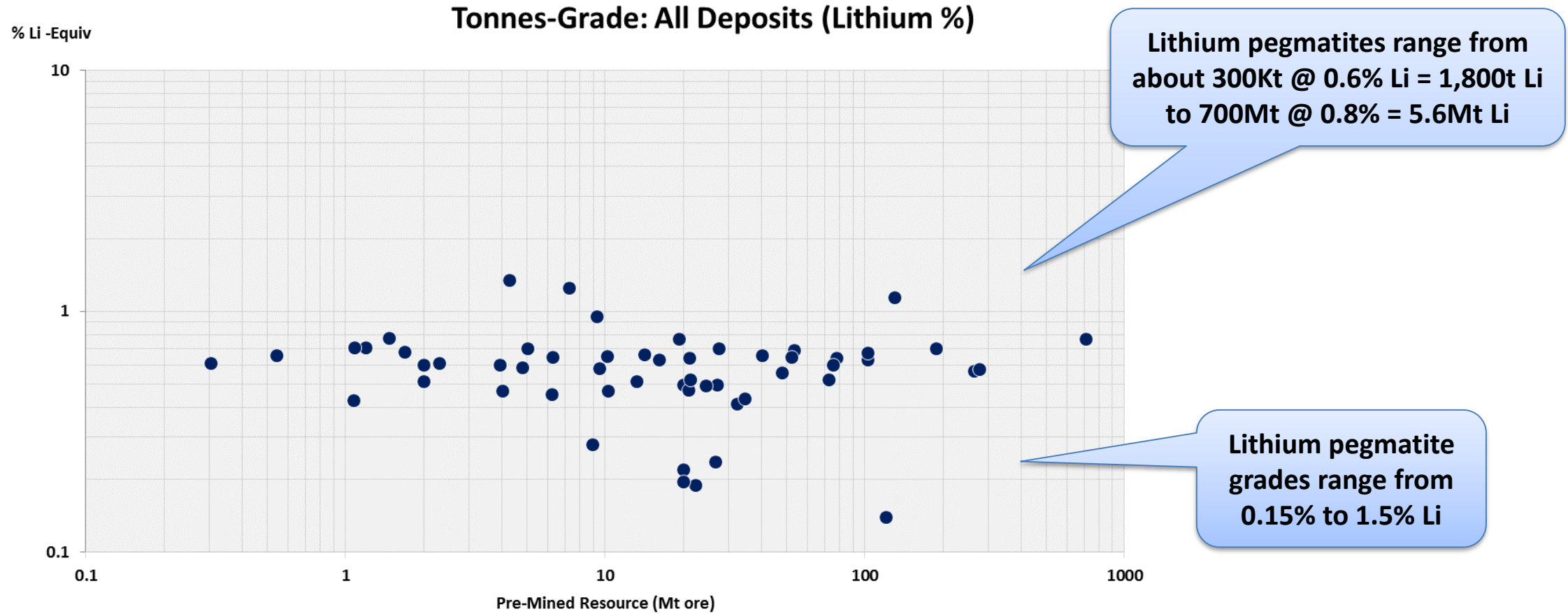
- The deposit can be complex structurally making ‘economies of scale’ difficult to capture;
- The small size of the lithium market also means operations may have to be ‘scaled to market’ in a less economic manner;
- Spodumene is the most common ore mineral, though its hardness means it can be difficult to process;
- Quality factors such as grade, purity and deleterious elements (P, F, Fe) can also significantly affect product pricing and mine economics;
- Some of the non-spodumene minerals result in even lower grade concentrates, in addition to hardness and complexity adding to processing costs – most have no ‘established’ processing route;
- A spodumene lithium concentrate is usually about 2.8% Li (6% Li<sub>2</sub>O) – this significantly increases transport costs as a share of overall operating costs, in comparison to other commodities (see diagram right);
- Details of the freight cost comparison are included below:
  - Roche Dore, DRC, 260Mt @ 0.76% Li, ~2,050km to port (Dar es Salaam)
  - Mt Holland, WA, 189Mt @ 0.7% Li, ~400km to refinery on coast (Kwinana)
  - Pilgangoora, WA, 226Mt @ 0.59% Li, ~120km to port (Port Hedland)
- **The high transport costs of the low grade lithium mineral concentrates significantly increases the incentive to integrate operations further downstream.**

Operating cost structure of three comparable lithium pegmatite deposits (US\$/t spodumene conc.)

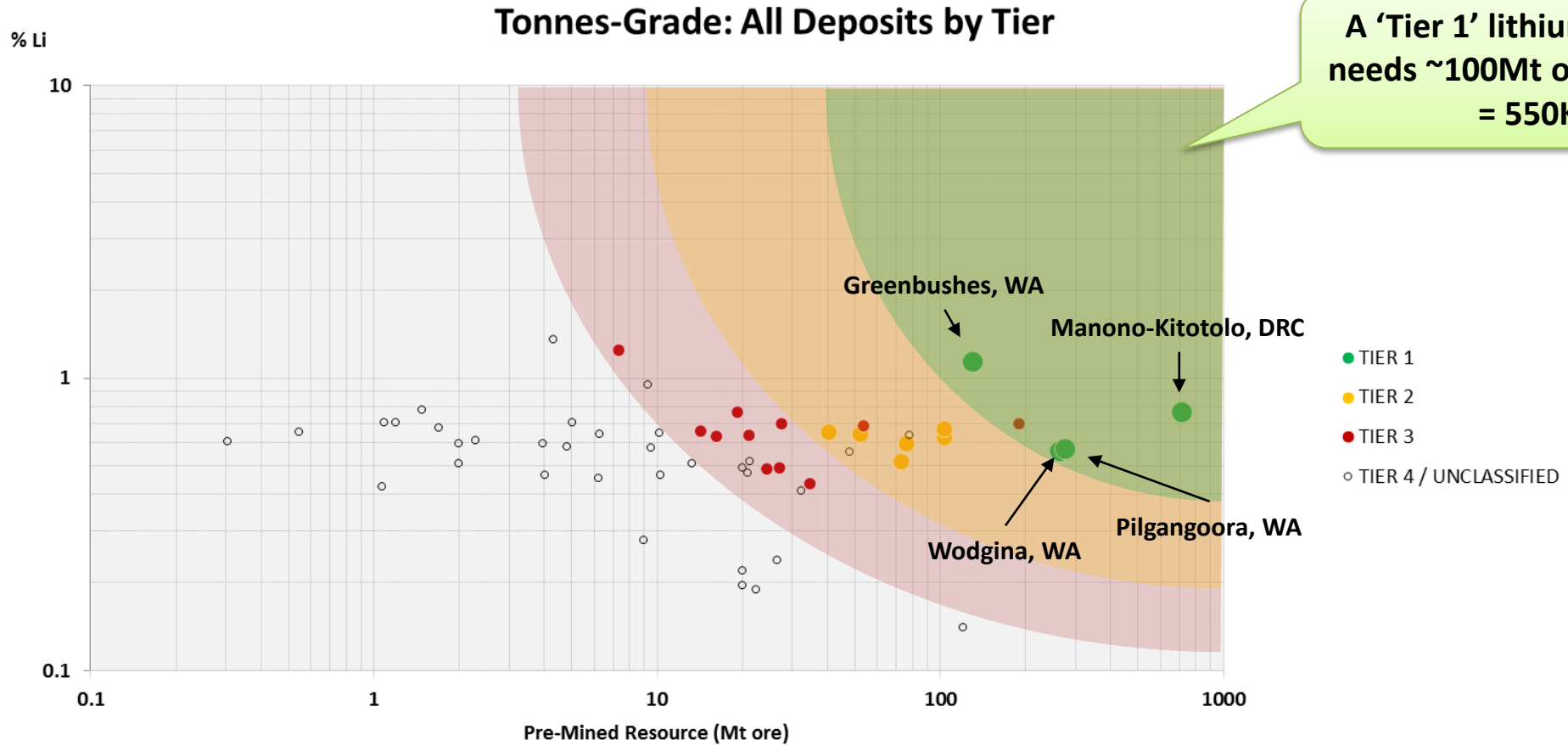




# There are 55 lithium pegmatite resources globally

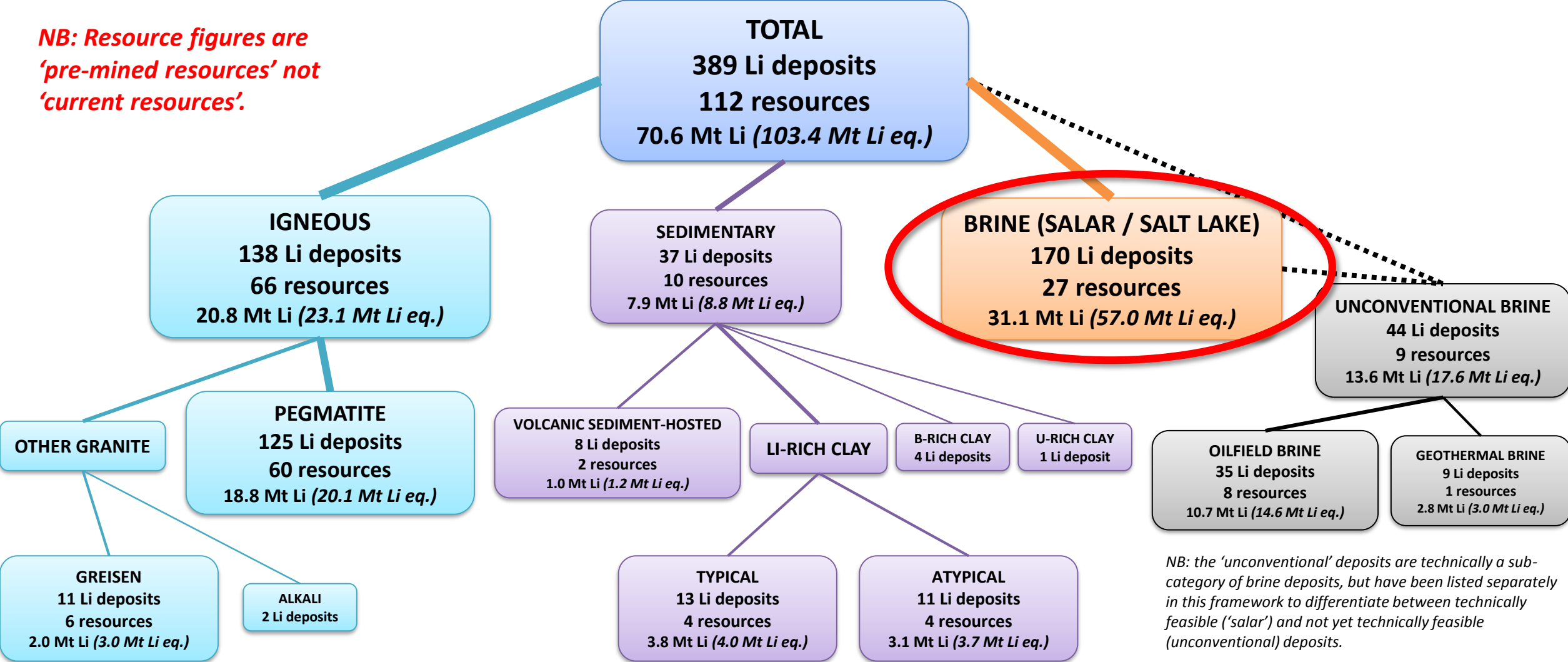


# Lithium pegmatite quality is a function of size



# The 'MinEx' geological framework for lithium deposits

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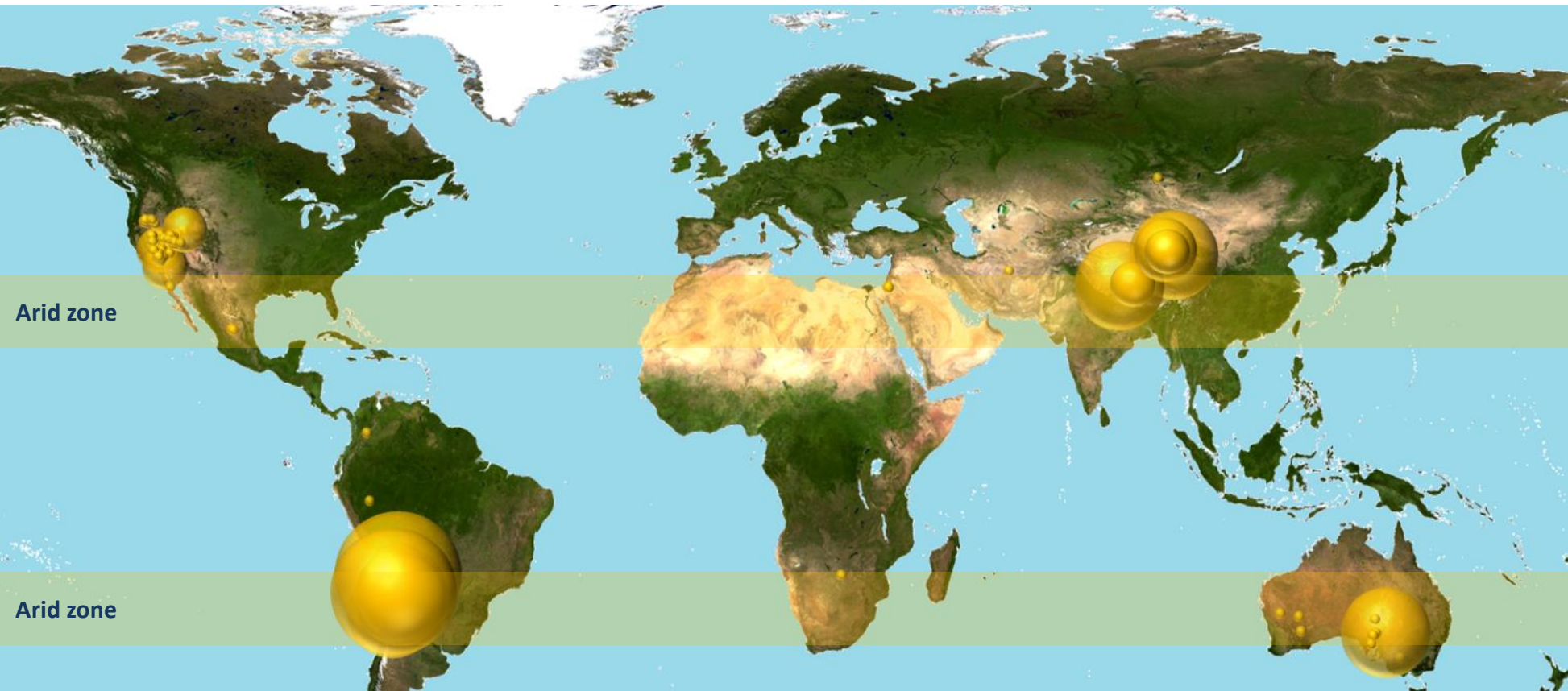
# Lithium brines in ‘salars’ (salt lakes) are the other main deposit type

- Lithium ‘salar’ deposits are salt lakes formed from groundwater, that are enriched in lithium, from which the brine can be extracted to produce lithium (and some other commodities);
- These salt lakes form in closed basins (i.e. water flows in, but not out) in arid regions which are dominated by evaporation;
- Salars are typically large in surface area (though they vary in size greatly) and very low grade (lithium in ppm), however, the ability to extract them as a brine and naturally evaporate them means they can be produced economically at these grades;
- Most of the other major lithium deposits in the MinEx Consulting lithium database are ‘salars’;
- ‘Salars’ are one of only two deposit types (the other being pegmatites) that are currently mined for lithium;
- Most of the largest lithium ‘salars’ are in the Andean Highlands (Argentina, Bolivia and Chile).

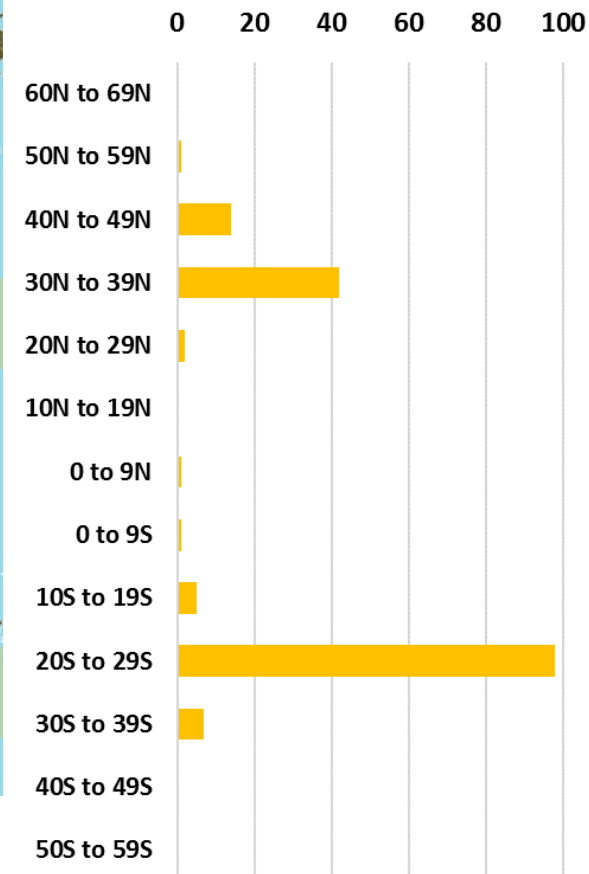


Image: Salar de Uyuni in Bolivia – the world’s largest salar and potentially the world’s largest lithium resource (though commercial mining has not yet been established on the salar). The salar is approximately 125km East-to-West. The bright white reflective crust is predominantly halite (NaCl) – common salt. The cone-shaped Cerro Tunupa volcano can be seen on the northern end of the salar.

# The requirement for arid conditions mean lithium 'salars' form primarily along the tropics in the 'arid zone'

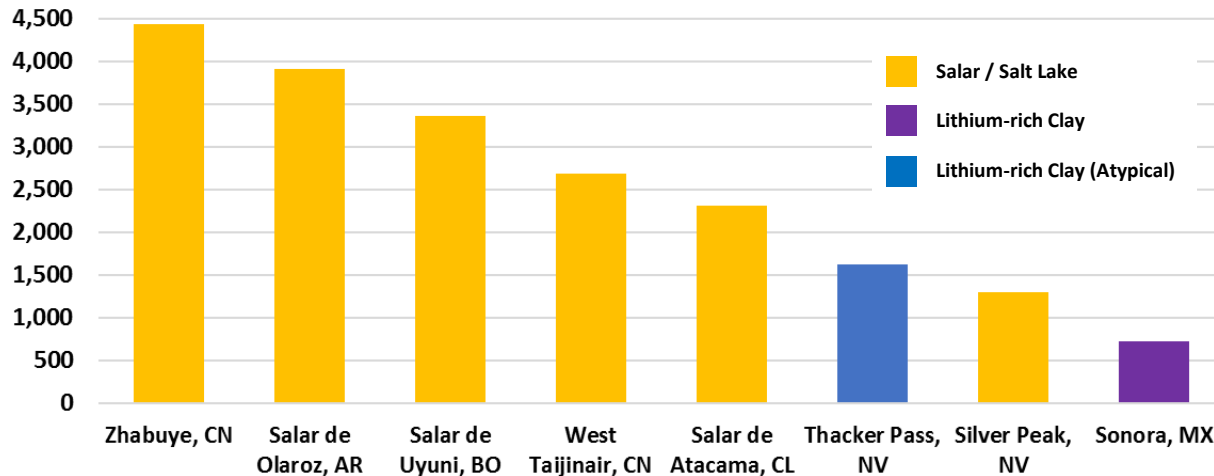


No. of lithium 'salar' deposits by latitude

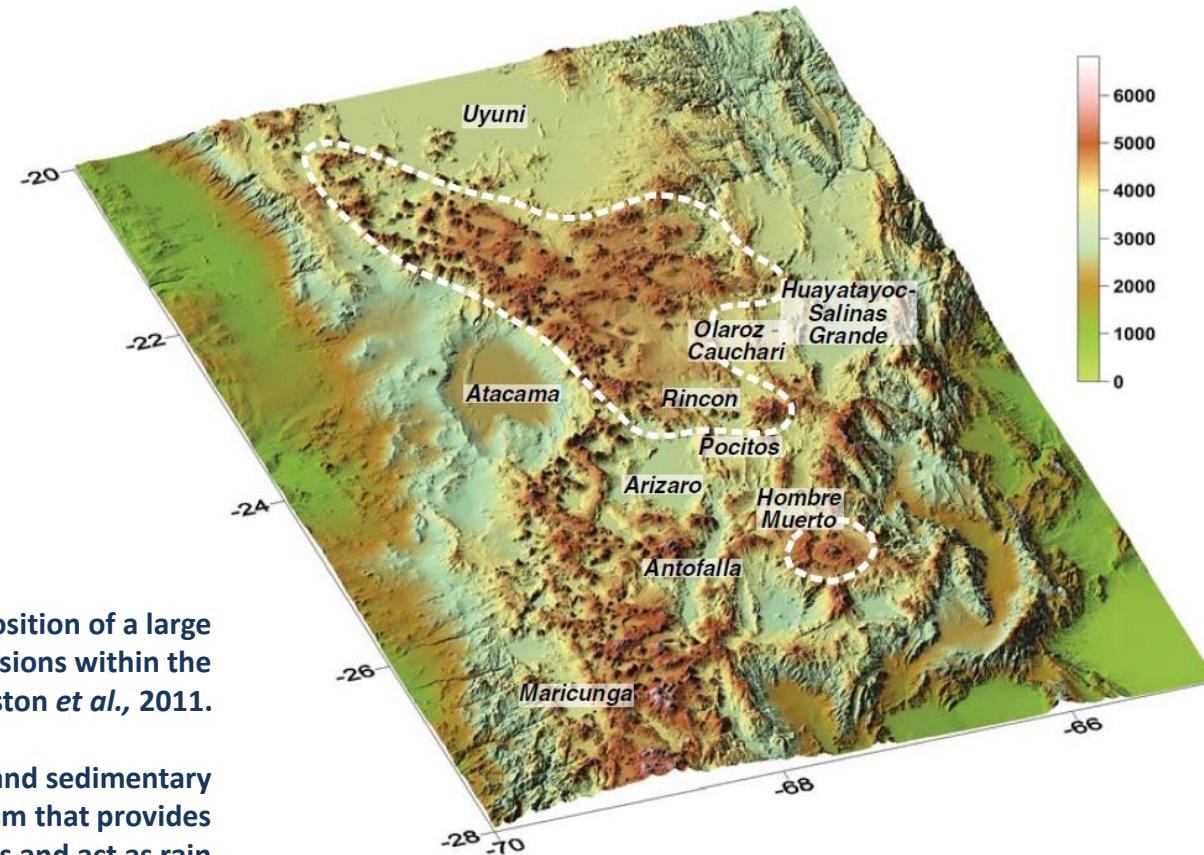


# Lithium 'salar' form at high altitude – a result of the orogenic volcanism, but also required for aridity and evaporation

Selected lithium salar and sedimentary deposits by altitude



Images (Right): Digital elevation model of the Central Andes showing the postulated position of a large sub-surface magma body (the dotted white line) and the location of major salars in depressions within the range. Source: Houston *et al.*, 2011.



Above: Approximate altitudes (derived from Google Earth) for selected key lithium salars and sedimentary deposits. The high altitude of these deposits is partly a product of the orogenic volcanism that provides the lithium. However, the orogenic ranges formed also create internal drainage basins and act as rain shadows increasing aridity. The high altitude also results in higher rates of evaporation – all of which encourage salar formation. Lithium-rich clays may form instead of salars at lower altitudes.

# Salar de Atacama (Chile) is the case example of a world-class mature lithium-brine 'salar'

- The 'Salar de Atacama' is a large lithium-brine bearing 'salar' in Chile, that it one of the world's largest producers of lithium;
- Both state company 'Sociedad Química y Minera de Chile' ('SQM') and US private company 'Albemarle' extract brine from the salar and then process the brine into lithium carbonate ( $\text{Li}_2\text{CO}_3$ ) and other chemicals in Antofagasta;
- The USGS estimates SQM's  $\text{Li}_2\text{CO}_3$  production capacity to be 48,000tpa (9,070tpa Li) and lithium hydroxide ( $\text{LiOH}\cdot\text{H}_2\text{O}$ ) production capacity to be 6,000tpa (1,750tpa Li) – though the operations are undergoing an expansion of  $\text{LiOH}\cdot\text{H}_2\text{O}$  capacity to 13,500tpa (2,255tpa Li);
- The USGS estimates Albemarle's recently expanded  $\text{Li}_2\text{CO}_3$  production capacity in Chile to be 47,000tpa (8,885tpa Li) and in with a further capacity of 4,500tpa (745tpa Li) for lithium chloride ( $\text{LiCl}$ );
- **MinEx calculates the pre-mined resource of lithium at Salar de Atacama to be about 6.1Bm<sup>3</sup> (~7.3Bt) @ 1,780mg/l (0.178%) lithium, thus containing 10.9Mt of lithium.**

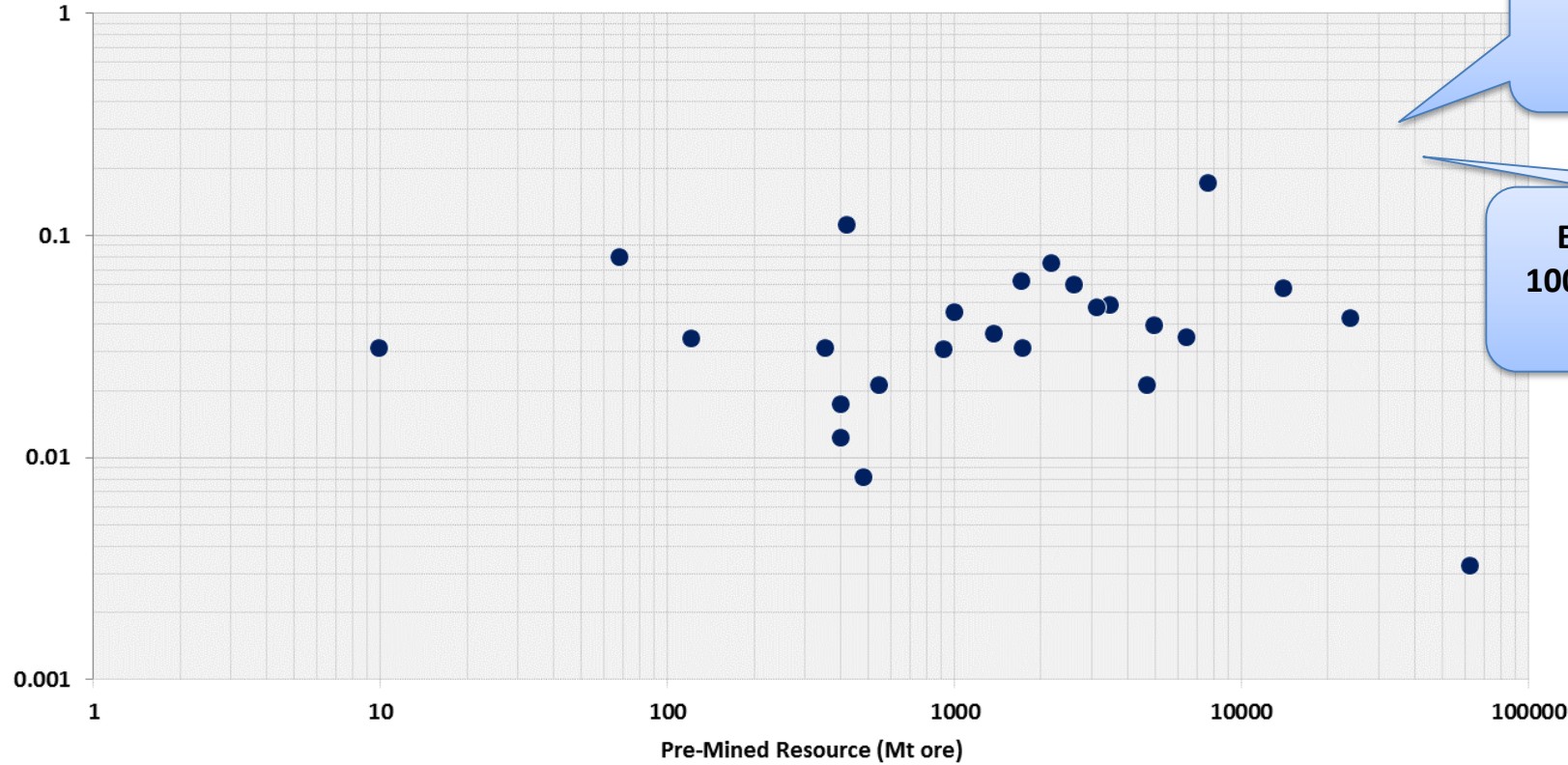


Image: Satellite image of the Salar de Atacama. The brine extraction and evaporation operations of SQM can be seen in the centre of the 'salar', with Albemarle's operations fringing the south peninsular of the 'salar'. The yellow bar represents a distance of ~10km. Source: Google Earth.

# There are 25 known lithium brine resources globally...

Tonnes-Grade: All Deposits (Lithium %)

% Li -Equiv



Lithium brines range from about 400Mt @ 0.01% Li = 40,000t Li to ~7.5Bt @ 0.15% Li = 11.3Mt Li

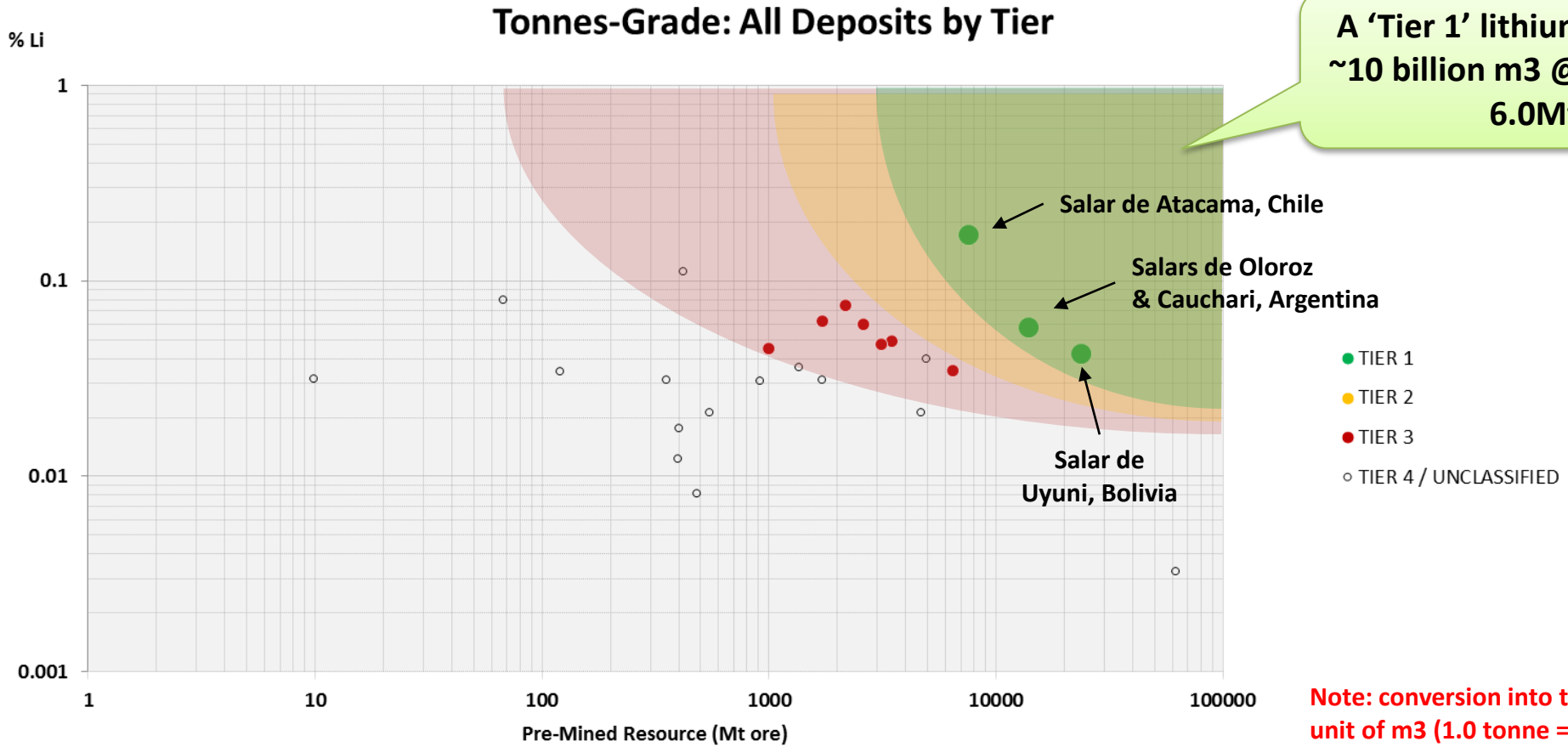
Equivalent to ~400 million m3 @ 100ppm Li = 40,000t Li to ~7.5 billion m3 @ 1,500ppm Li = 11.3Mt Li

Note: conversion into tonnes from usual unit of m3 (1.0 tonne = ~1.0m3)



# There are only a few 'Tier 1' 'salaris'

Note: conversion into percent from usual unit of ppm (1% = 10,000ppm)



A 'Tier 1' lithium salar needs ~10 billion m3 @ 600ppm Li = 6.0Mt Li

Note: conversion into tonnes from usual unit of m3 (1.0 tonne = ~1.0m3)

# Salars however also face some general challenges in extraction

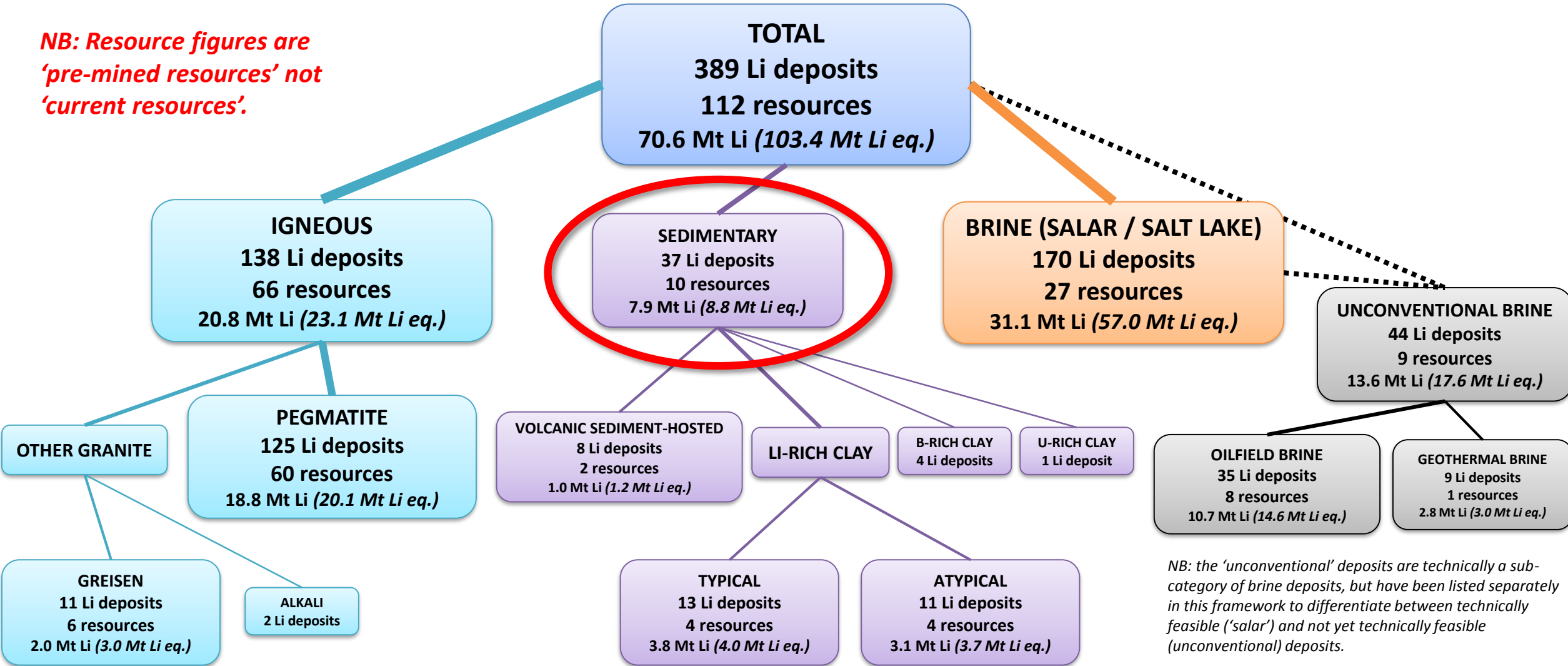
- Deleterious elements, especially magnesium, can impede recoveries;
- Deleterious elements also can affect product quality and sale prices;
- Natural evaporation of brines is time-intensive ('months') and vulnerable to bad weather (albeit rare);
- Remoteness can also be a problem;
- The hyper-aridity of many 'salar' regions means that water use is a major concern;



Image: Salar de Atacama. Source: Shutterstock.

# The 'MinEx' geological framework for lithium deposits

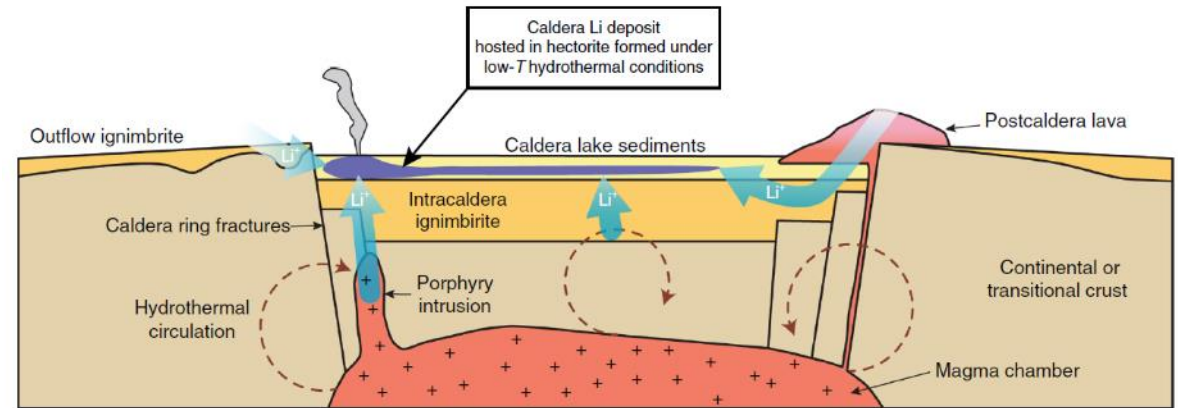
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# Sedimentary (or clay) deposits are of emergent economic importance to the lithium industry

- Sedimentary lithium, or lithium-clay, deposits are typically hosted by hydrothermally altered, volcanic-derived sediments deposited in lake beds;
- As with lithium-brine deposits the lithium is leached from rhyolitic lavas, volcanic ash and lithium-rich magmas by meteoric and hydrothermal fluids;
- There are several examples of atypical mineralisation settings and/or processes leading to the formation of deposits containing unusual lithium minerals or salts;
- One common factor is that they are often associated with unusual or even unique mineralogy;
- It is also worth noting that lithium occurs as a by-product in other 'clay' deposits, such as the borate clays of Turkey or the uranium clays in Macusani, Peru;
- Finally, a separate 'volcano-clastic' lithium deposit type has been identified at Macusani, Peru, with the lithium contained within volcanic tuffs.
- Whilst lithium-rich clays have been mined in the past, this was for the 'clays' themselves which had properties useful for drilling muds, paints and cosmetics, rather than their lithium content (for example, hectorite is named after the 'Hector' deposit in California from which such industrial clays were extracted);
- There is now more focus on extracting the lithium from lithium-clays, though there are no current operations doing this.



**Image: The most recent model for 'typical' hectorite lithium clay deposits. Lithium-enrichment primarily comes from the erupted ignimbrites and tuffs from lithium-rich rhyolitic magmas, with the volcanic sediments undergoing further enrichment during burial and diagenesis within the caldera. Hydrothermal and meteoric waters may then further enrich the deposit in lithium. Source: Benson *et al.*, 2017.**

# Thacker Pass (Kings Valley) in Nevada is the case example of a ‘typical’ hectorite lithium-clay deposit

- The Thacker Pass lithium-clay project (sometimes known as Kings Valley) is located in Nevada and owned by Canadian junior, Lithium Americas (LAC);
- The project is located within an extinct supervolcano – the McDermitt Caldera – that is associated with the Yellowstone hotspot;
- The genetic model for the deposit (see previous slide) is that of erupted volcanic sediments depositing in a caldera lake and being leached of lithium, followed by later volcanic-related uplift which drains the lake and exposes the lithium-rich sediments;
- LAC envisages a two stage operation, first producing 30,000tpa of lithium carbonate ( $\text{Li}_2\text{CO}_3$ ) or 5,670tpa of lithium, and then later doubling capacity;
- **The current resource across all of ‘Kings Valley’ is 532.7Mt @ 0.292% lithium, thus containing ~1.56Mt of lithium;**
- Although, the Thacker Pass component of the Kings Valley project has a completed prefeasibility study and defined ‘reserves’ it should be noted the extraction of lithium-clay deposits is still relatively unproven.

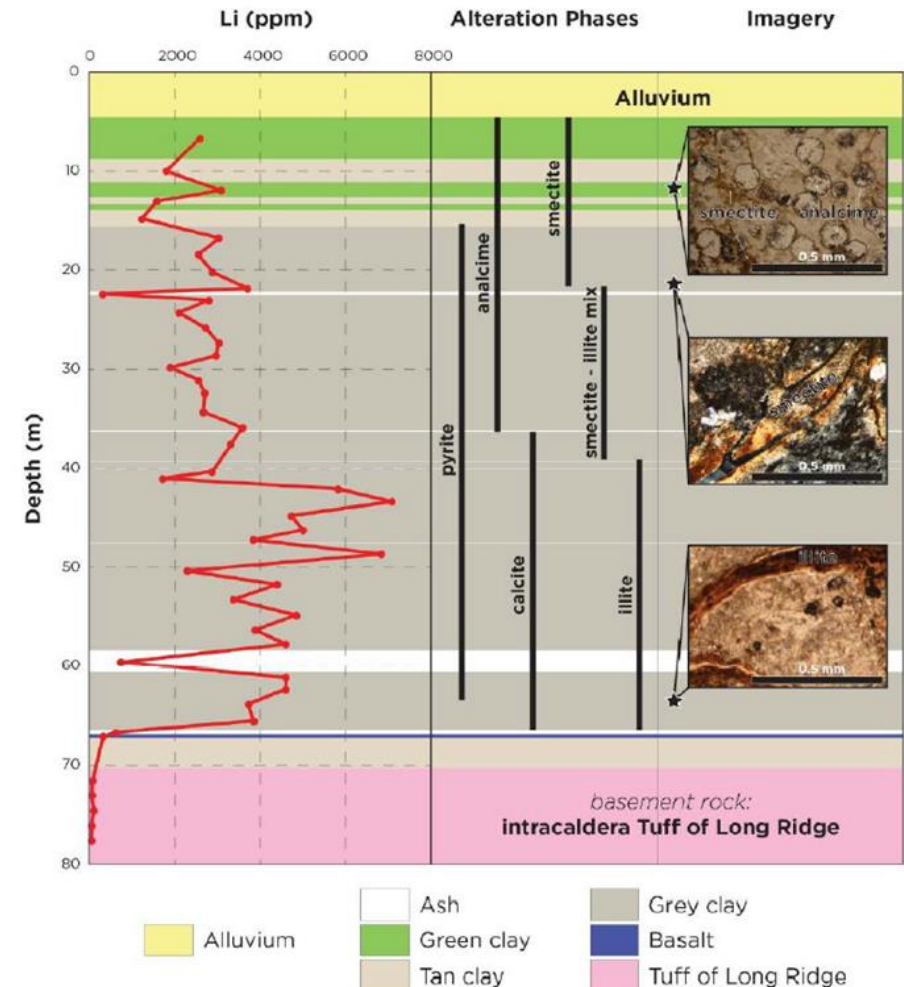


Image: Clay alteration phases with depth at the Thacker Pass project moving from relatively unaltered smectite to more altered illite, with a mixed transition zone between. In this deposit the deeper illite is more lithium-rich attributed to greater diagenesis. Source: Lithium Americas

# Jadar (Serbia) is the case example of a ‘world class’ atypical sedimentary lithium deposit

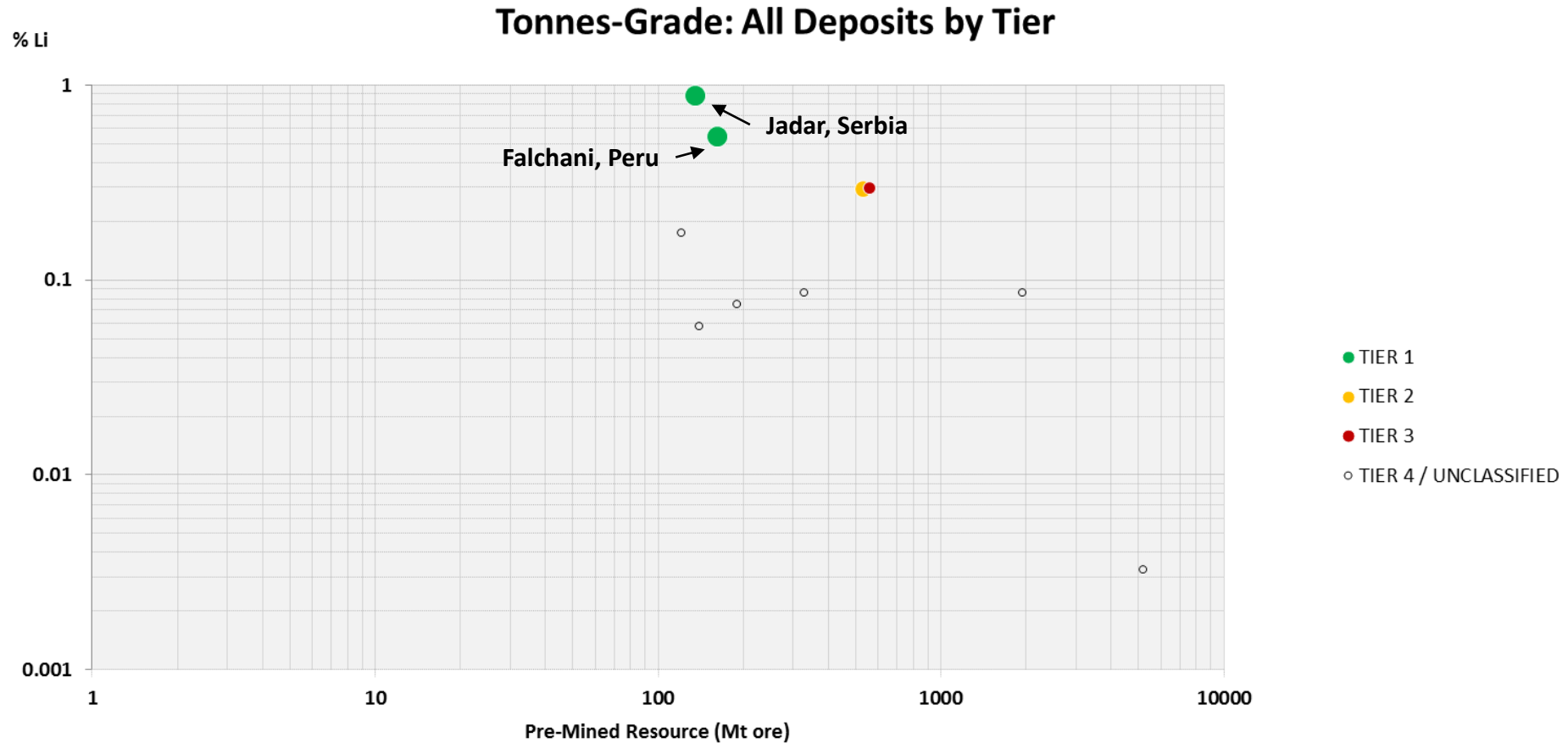
- Jadar is a lithium-boron deposit in Serbia;
- It is hosted in a sequence of oil-shales, dolomicrites and pyroclastic deposits within a lacustrine (paleo-lake) sedimentary basin;
- It is the only recorded occurrence of the mineral jadarite ( $\text{LiNaB}_3\text{SiO}_7(\text{OH})$ );
- Nonetheless, the genetics of the deposit are still the hydrothermal alteration of volcanic ash that had been deposited in an arid, closed basin;
- It appears Jadar may be a fossilised lithium salar/playa in which the lithium-rich brine has interacted with the basin sediments creating an enriched clay – something that has been noted in other lithium evaporite/brine deposits but which may have been ignored due to the presence of conventional lithium brines available for extraction;
- **The current resource at Jadar is 136Mt @ 0.887% lithium, thus containing ~1.2Mt of lithium – a noticeably higher grade than other sedimentary lithium deposits;**
- The deposit also contains abundant borate (21Mt contained, thus grading >15%) further improving project economics;
- In MinEx’s opinion it is probably the only sedimentary lithium deposit (if you exclude Zabuye from the class) with the potential to be a ‘Tier 1’ or world class lithium deposit – *should an economically viable processing route be established.*



Image: A display quality sample of Jadarite (the white mineral) embedded in host lacustrine clays.

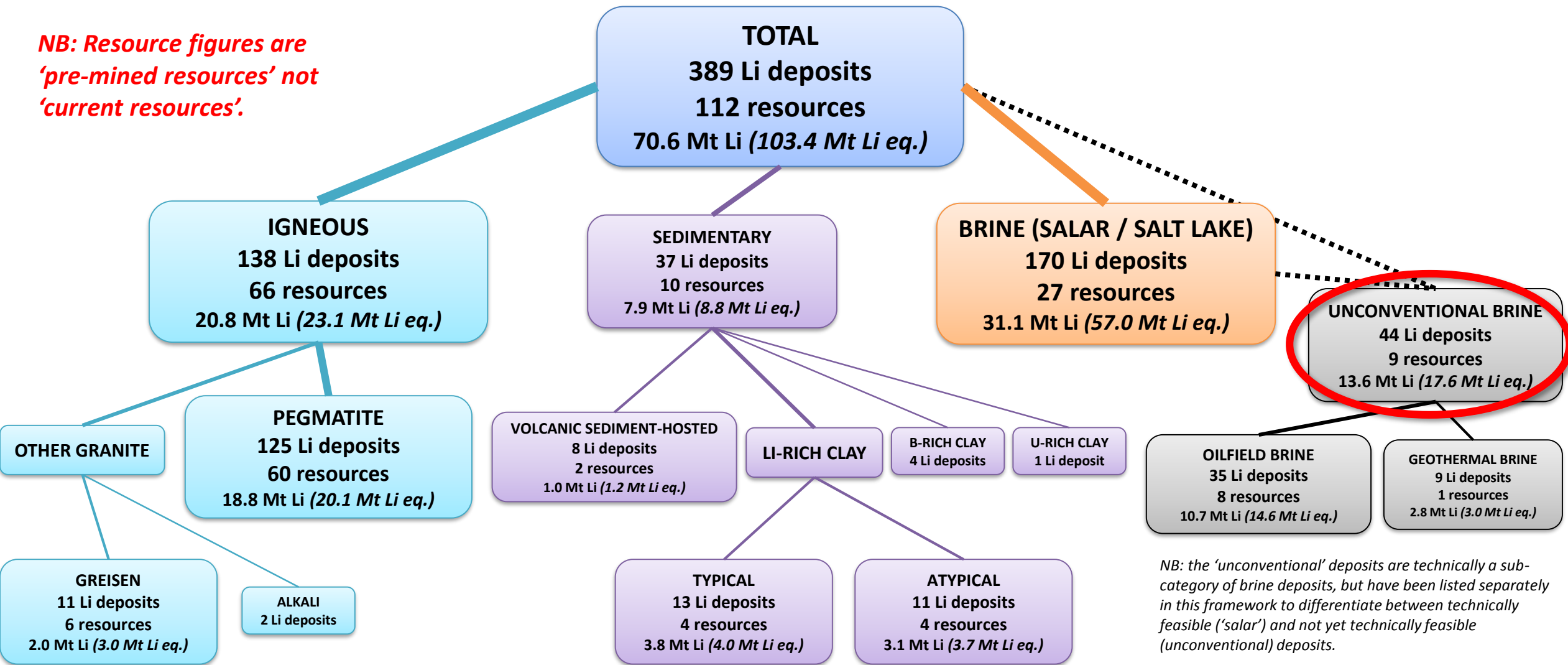
Source: [Rio Tinto](#)

# There are a few interesting (undeveloped) sedimentary deposits emerging



# The 'MinEx' geological framework for lithium deposits

*NB: Resource figures are 'pre-mined resources' not 'current resources'.*



*NB: the 'unconventional' deposits are technically a sub-category of brine deposits, but have been listed separately in this framework to differentiate between technically feasible ('salar') and not yet technically feasible (unconventional) deposits.*



# Extracting lithium (but not boric acid) from geothermal brines is not currently technologically feasible

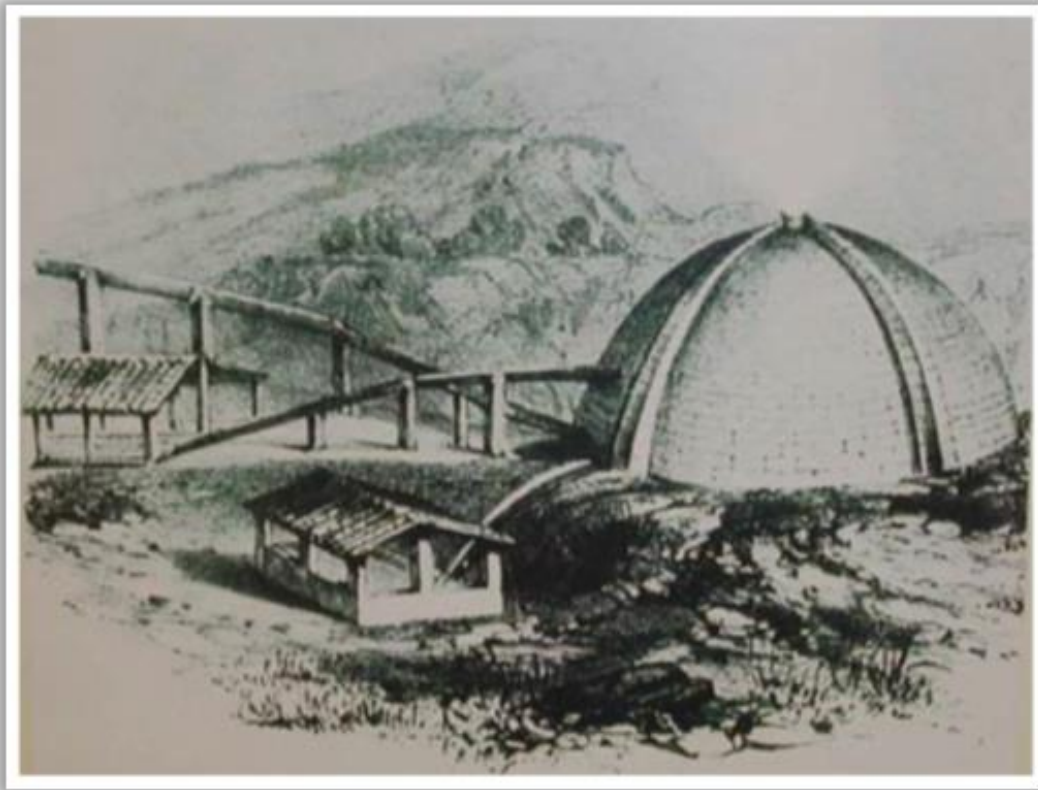


Image: Lund, 2005

- The concept has existed since at least the 1970s (e.g. Blake, 1974; Berthold & Baker Jr., 1976) – in response to the oil crises of the time;
- Presently the only advanced geothermal lithium-brine project is at the Salton Sea, California and as yet is not commercially proven;
- However, mineral extraction from geothermal brines has been proven for other minerals, such as boric acid, where it has been extracted for over 200 years in Larderello, Italy (and still is today by the [Larderello Group](#));
- The image (right) shows a ‘covered lagoon’ or “lagone coperto” – a brick structure used to extract boric acid from geothermal waters in the 19th century at Larderello;
- **However, equivalent processes for lithium have only been conducted on a small ‘test’ scale.**

# Extracting lithium (but not bromine) from oil field waste waters is not currently technologically feasible

## LITHIUM ABUNDANCES IN OILFIELD WATERS

By A. GENE COLLINS,  
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION,  
BARTLESVILLE, OK

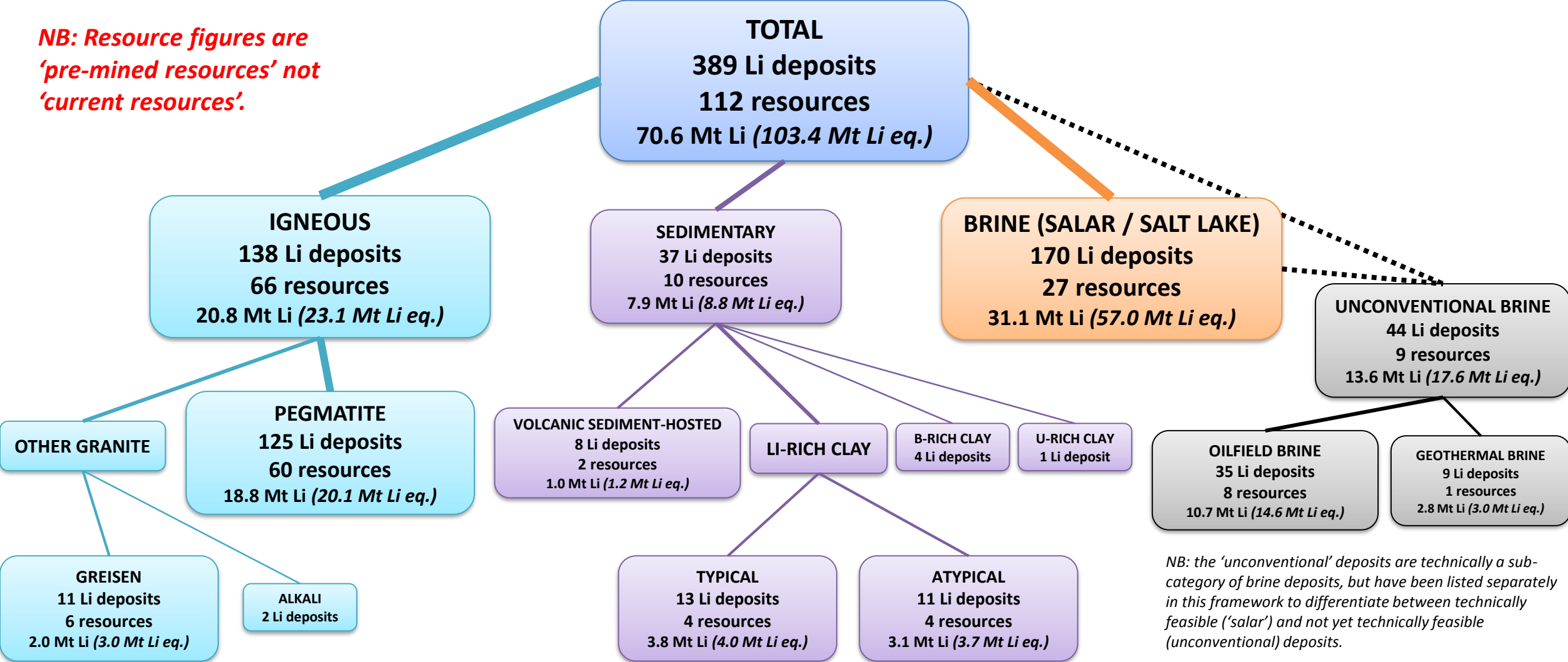


Image: Bromine brine extraction well at Lanxess' Smackover operations, Arkansas ([Standard Lithium](#))

- The concept has existed since at least the 1970s (e.g. Collins, 1976);
- Interest in lithium was in response to the oil crises of the time;
- An estimate for the Smackover oilfield in the SE USA suggested it contained 7.5 million tonnes of lithium (Collins, 1976);
- The amount of lithium contained in oil fields globally likely amounts to hundreds of millions of tonnes;
- Bromine is currently extracted by Albemarle and Lanxess (formerly Chemtura) from the Smackover Formation in Arkansas (Schnebele, 2018) and has been since 1957 (Jayroe, 2018), whilst bromine has been extracted from brines elsewhere in the US since the 1890s (Brandt *et al.*, 1997);
- These are globally significant operations within the bromine industry (Schnebele, 2018);
- Bromine is also extracted from underground brines in China, Turkmenistan and Ukraine, from surface brines in Israel and Jordan, and from seawater in India, Japan and Turkmenistan (Schnebele, 2018).

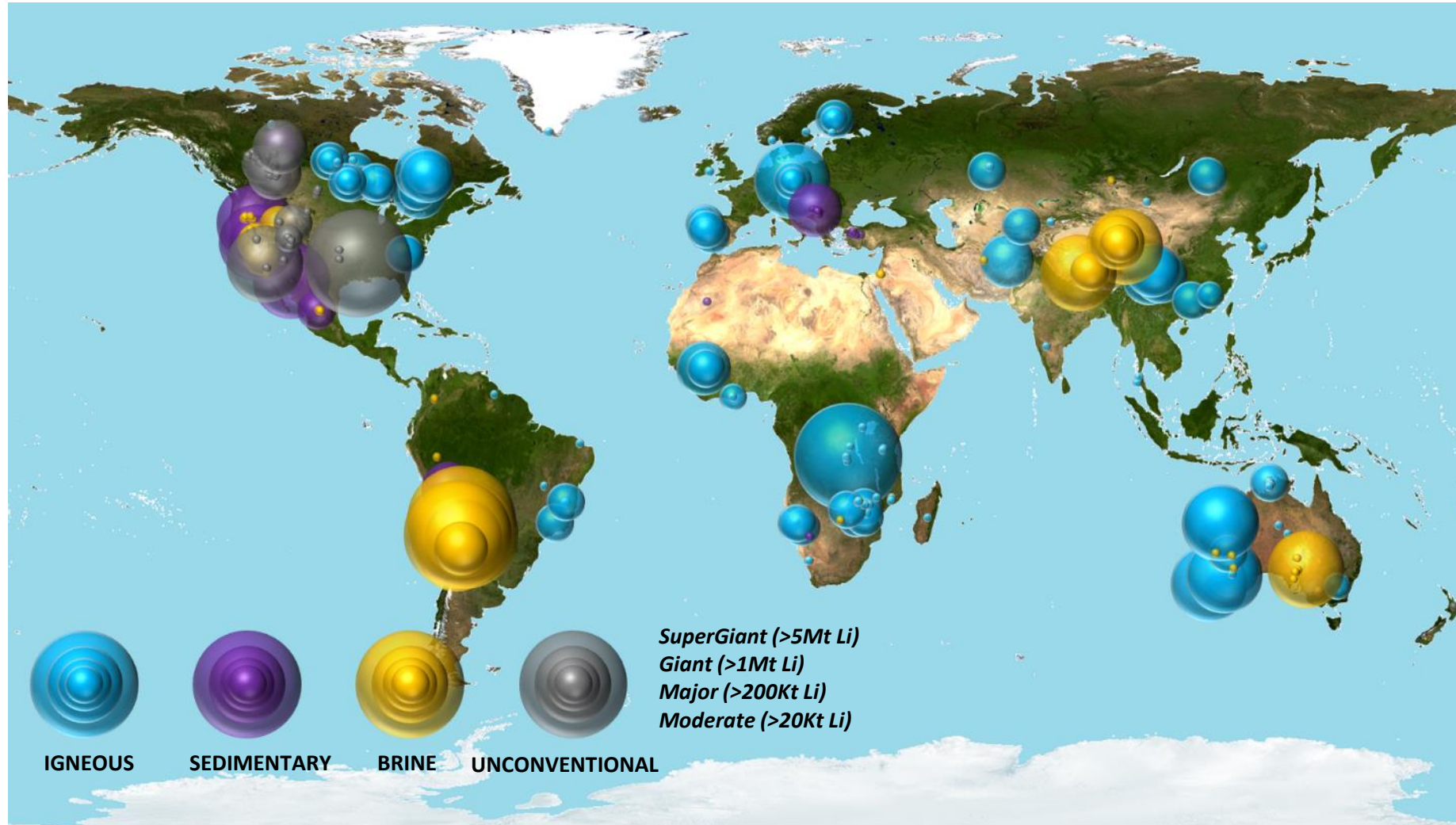
# The 'MinEx' geological framework for lithium deposits

*NB: Resource figures are 'pre-mined resources' not 'current resources'.*

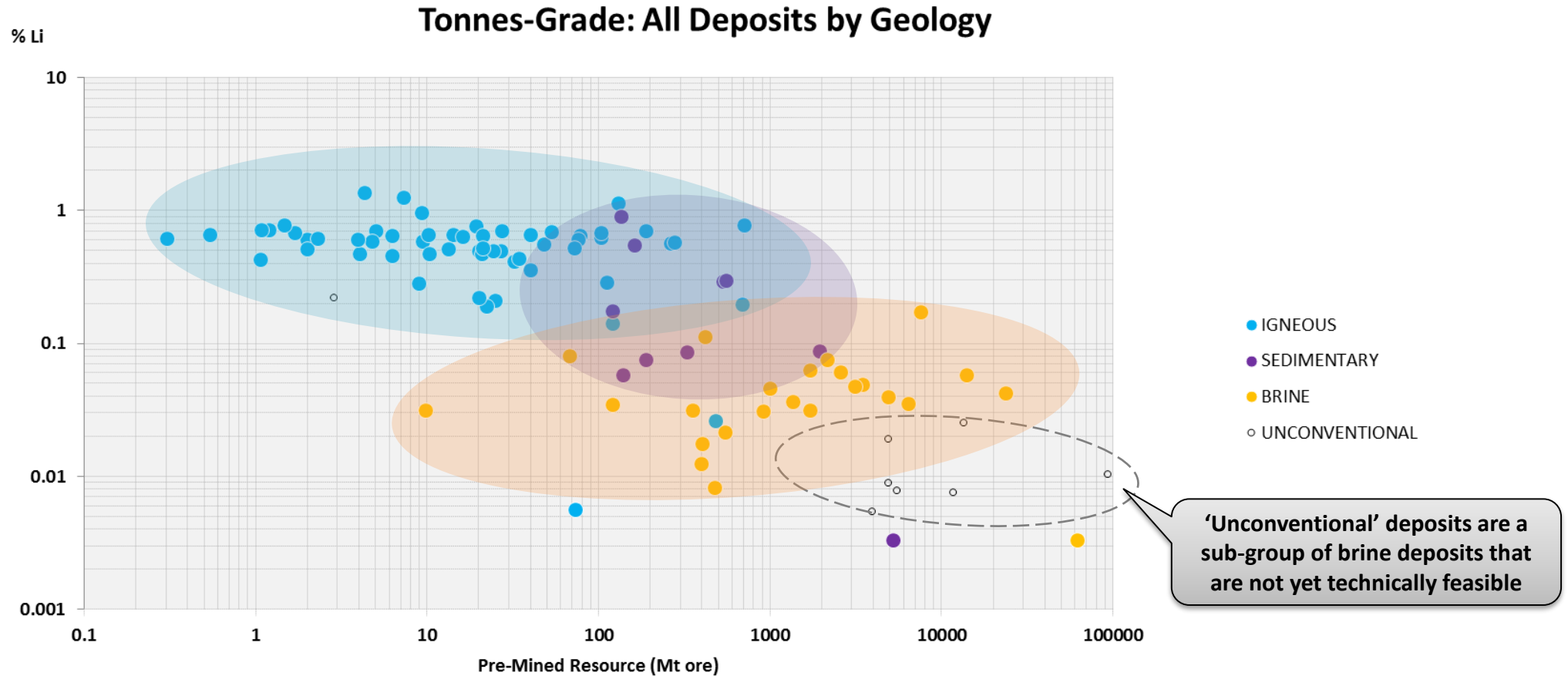


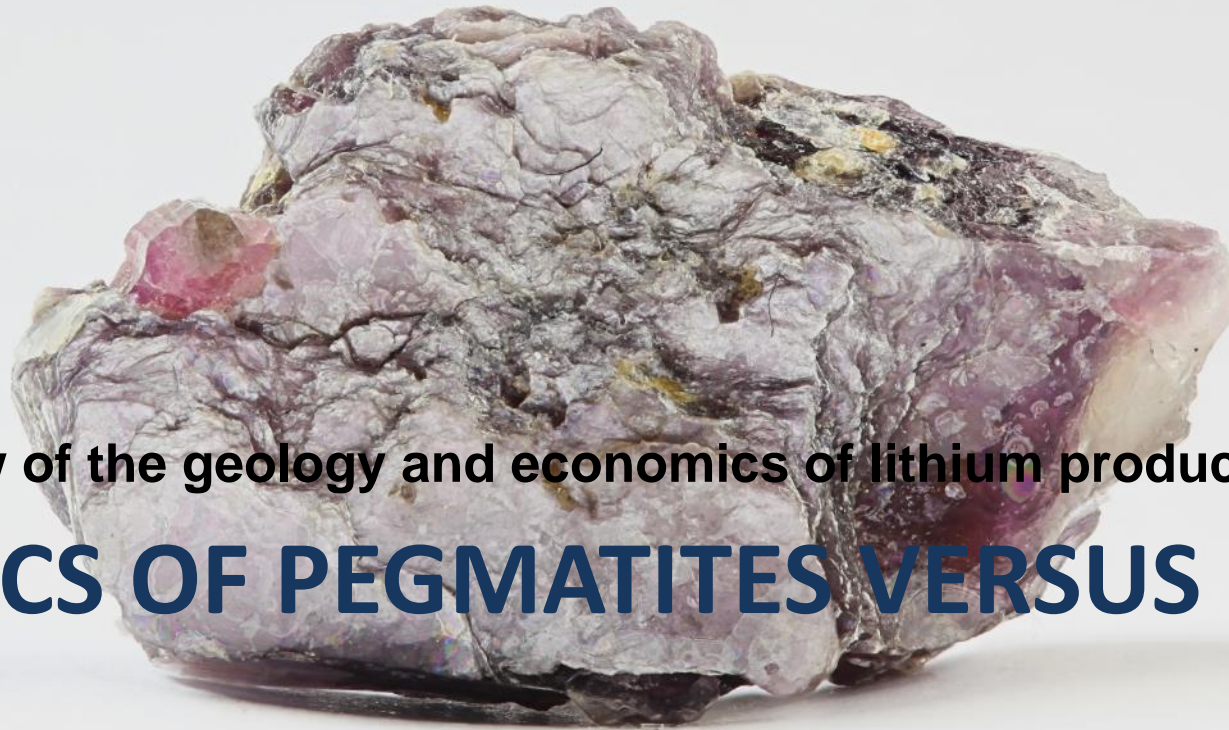
*NB: the 'unconventional' deposits are technically a sub-category of brine deposits, but have been listed separately in this framework to differentiate between technically feasible ('salar') and not yet technically feasible (unconventional) deposits.*

# The global distribution of lithium deposits (by type)



# The four main types of lithium deposit form a grade-size distribution



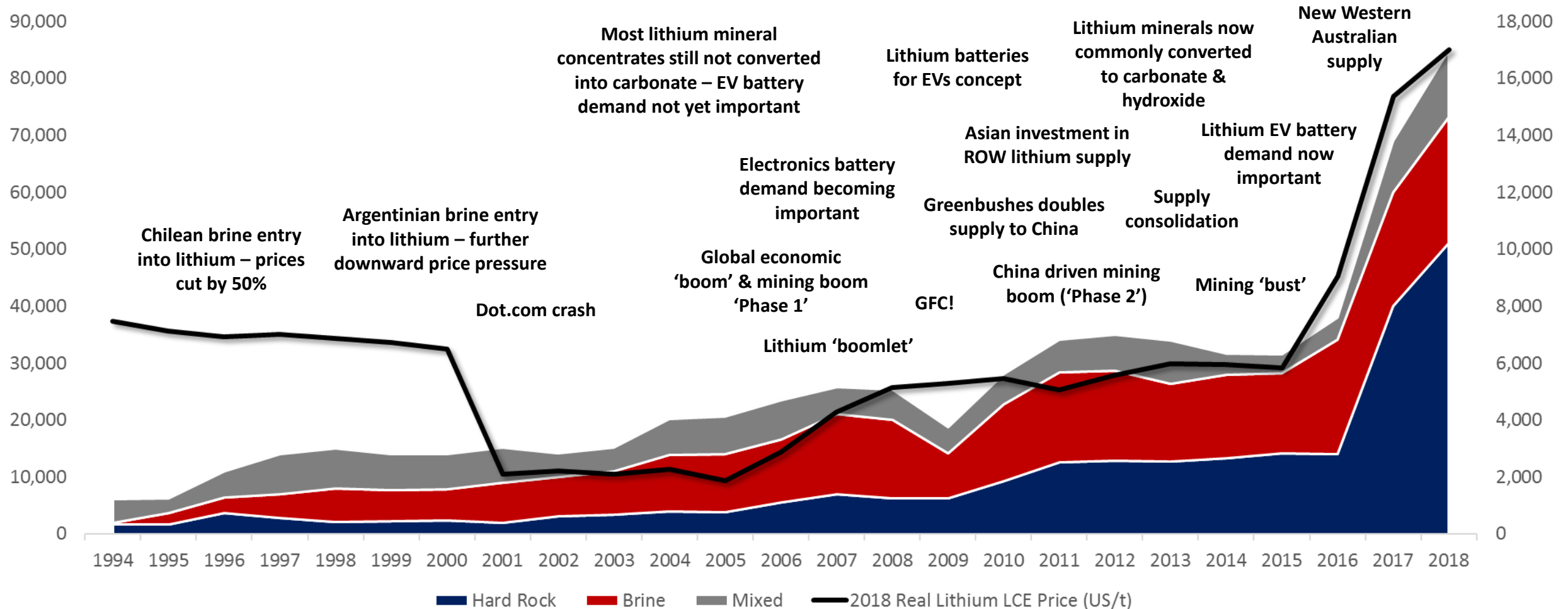


**A global overview of the geology and economics of lithium production**

# **ECONOMICS OF PEGMATITES VERSUS 'SALARS'**

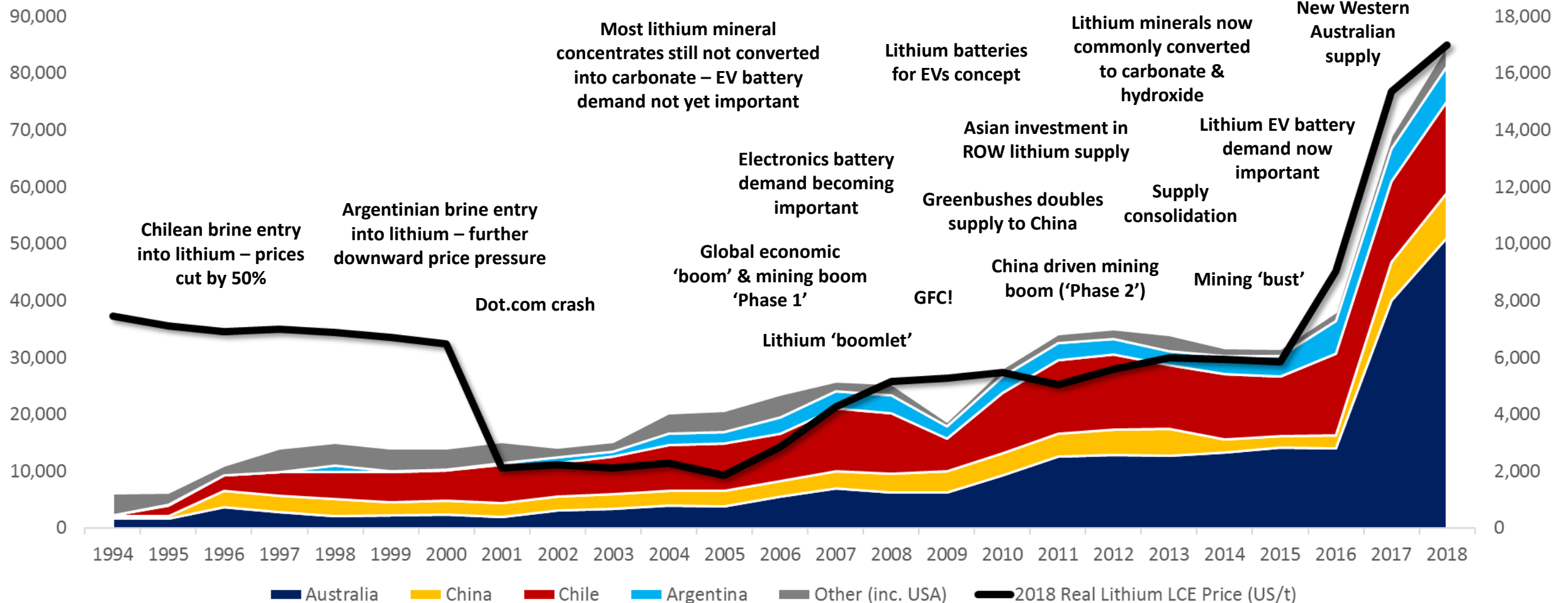
# The recent 'story' in lithium has been fast growing hard rock spodumene concentrate supply...

Estimate of lithium production by country, based on inferences from latest USGS data, 1994-2018



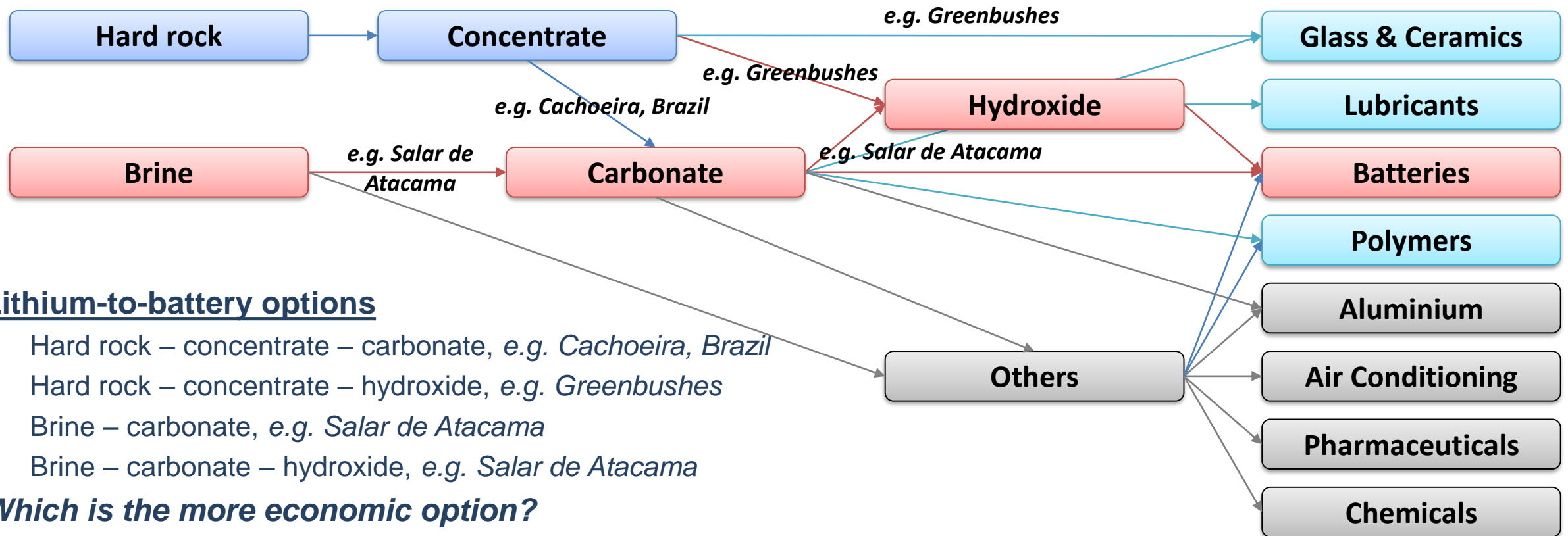
# ...from Western Australia

Estimate of lithium production by country, based on inferences from latest USGS data, 1994-2018





# Both hard rock and brine operations can produce carbonate and hydroxide



## Lithium-to-battery options

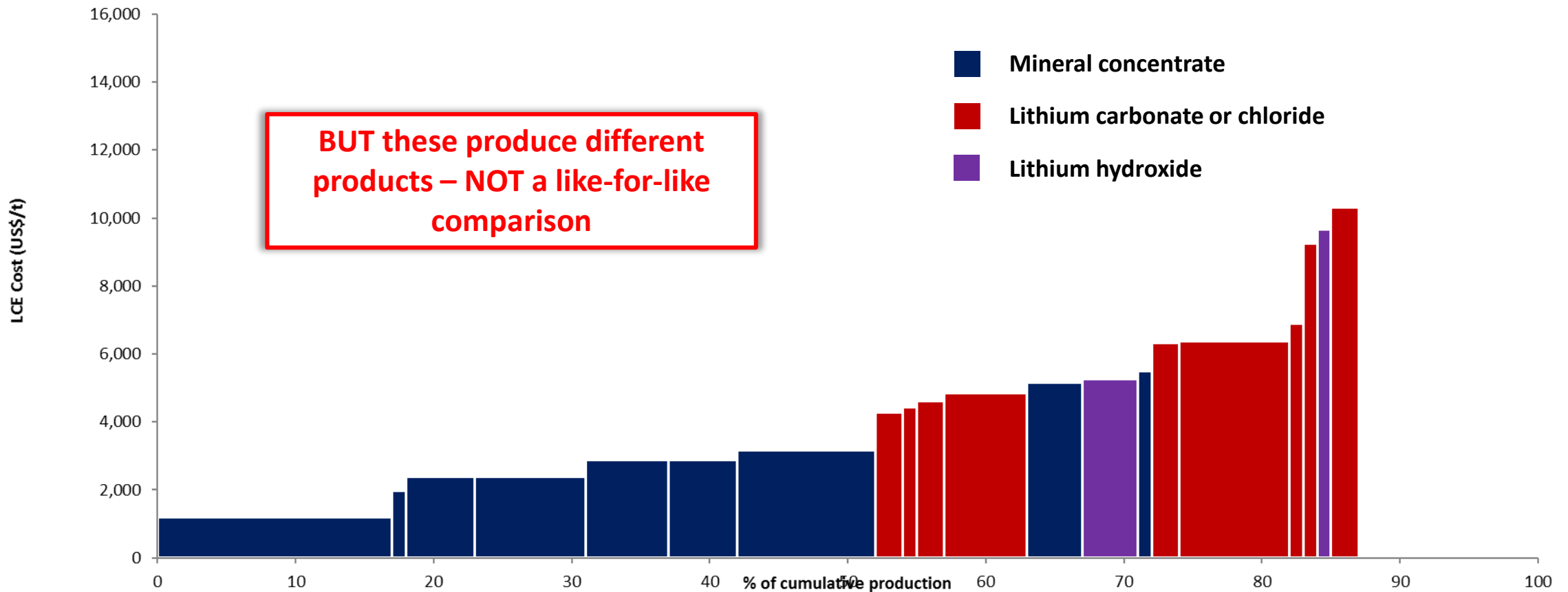
- Hard rock – concentrate – carbonate, *e.g. Cachoeira, Brazil*
- Hard rock – concentrate – hydroxide, *e.g. Greenbushes*
- Brine – carbonate, *e.g. Salar de Atacama*
- Brine – carbonate – hydroxide, *e.g. Salar de Atacama*

## ***Which is the more economic option?***

- *Lithium overall: Hard rock or brine?*
- *Carbonates: Hard rock or brine?*
- *Hydroxide: Hard rock or brine?*

# Initially it appears the spodumene producers are most competitive...

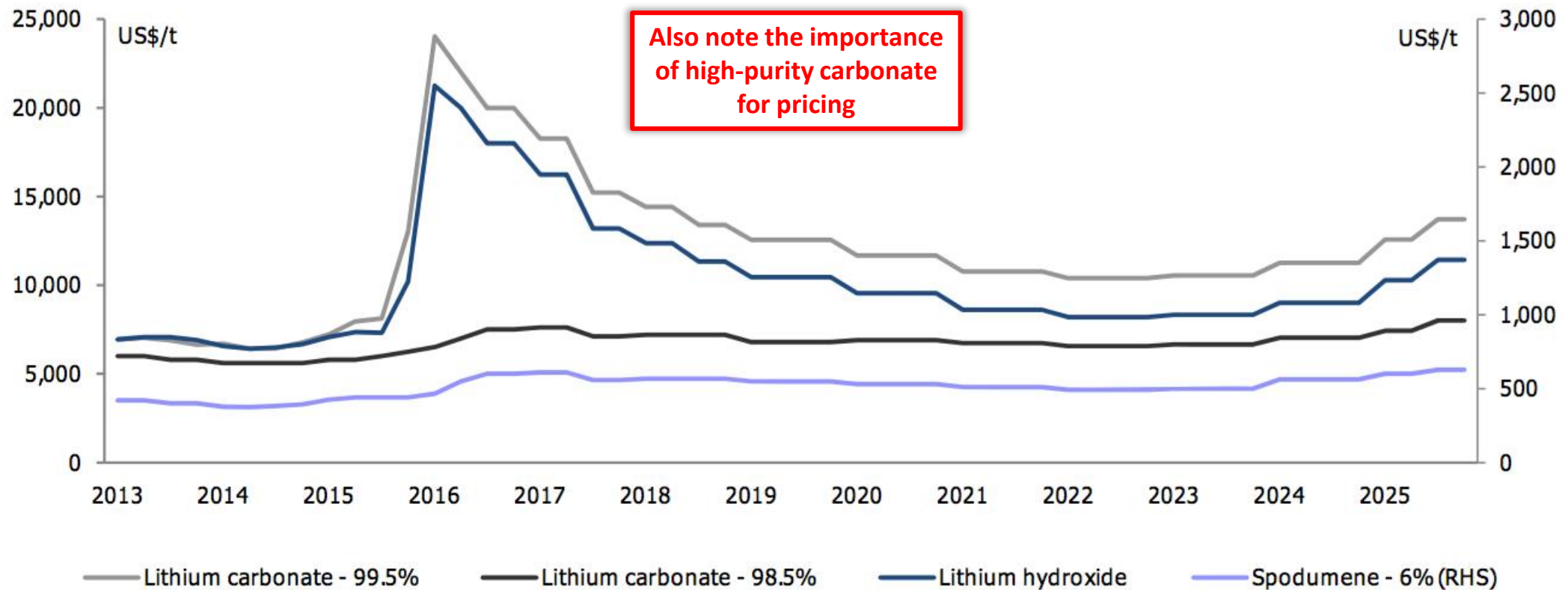
**Unnormalised** lithium carbonate equivalent (LCE) cost curve, 2019 (From SNL)



*NB: MinEx is reliant on the SNL cost data for this analysis, as well as some very general assumptions. The aim is to show the general strategic picture, rather than accurate break-down of costs.*

# Mineral concentrate and downstream lithium products have very different prices

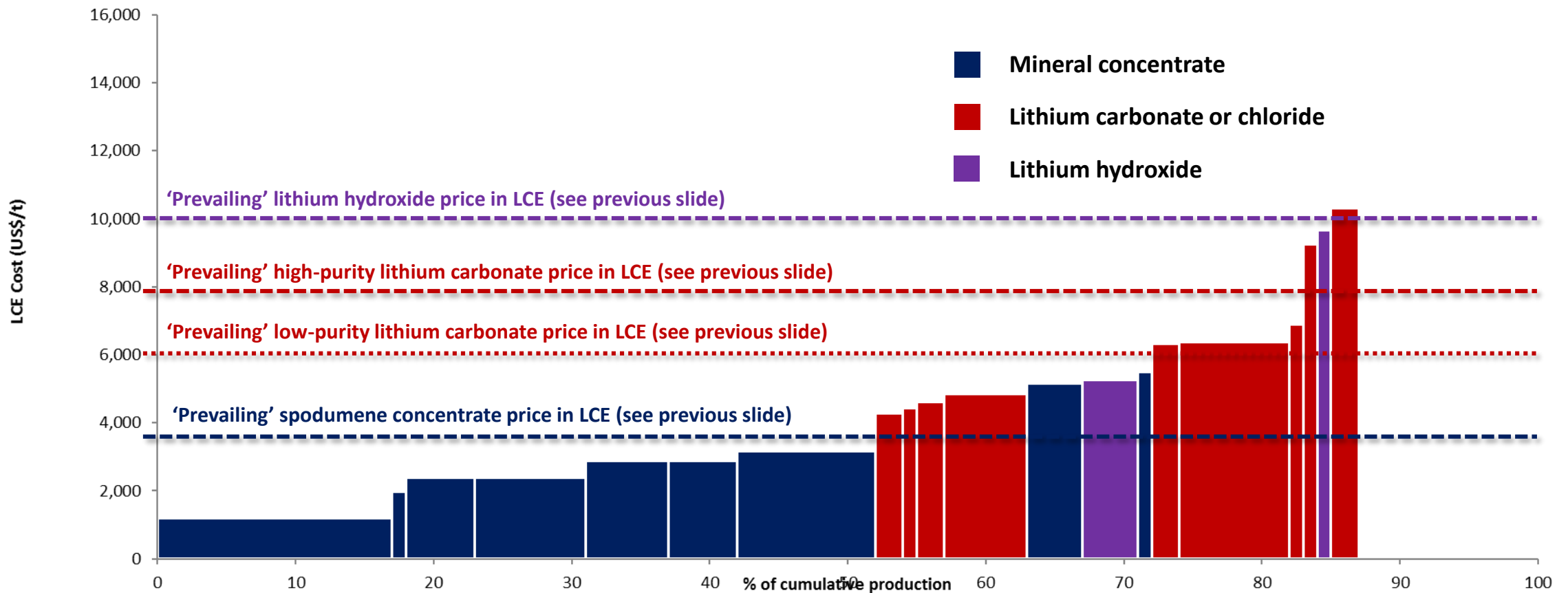
Figure 13: DB price forecasts for 99.5% & 98.5% lithium carbonate, lithium hydroxide and 6% spodumene concentrate



Source: Deutsche Bank, Asian Metal, company data

# Mineral concentrate and downstream lithium products have very different costs and prices

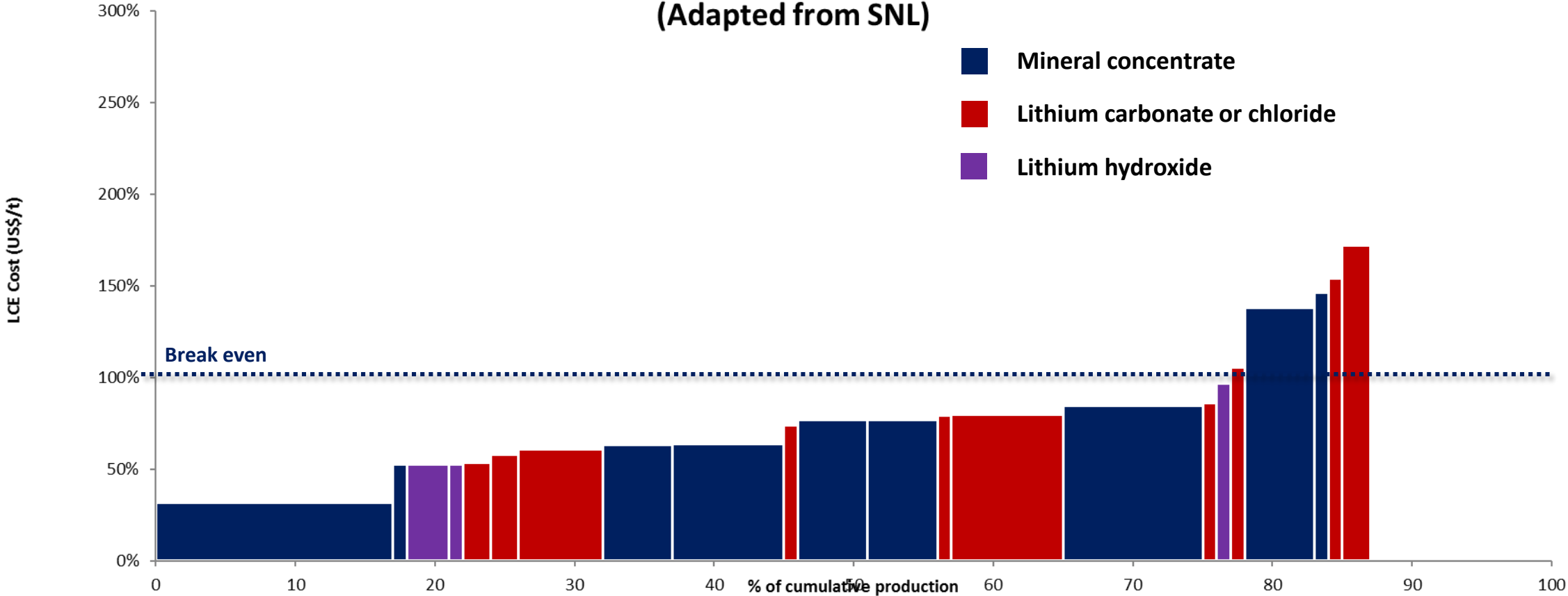
**Unnormalised** lithium carbonate equivalent (LCE) cost curve, 2019 (From SNL)



**NB: MinEx is reliant on the SNL cost data for this analysis, as well as some very general assumptions. The aim is to show the general strategic picture, rather than accurate break-down of costs.**

# Normalised for product price the spodumene miners become less competitive... integrating more economic

Normalised lithium cost curve - as % of product price (LCE), 2019  
(Adapted from SNL)



NB: MinEx is reliant on the SNL cost data for this analysis, as well as some very general assumptions. The aim is to show the general strategic picture, rather than accurate break-down of costs.



A global overview of the geology and economics of lithium production

# SOME THOUGHTS ON THE WESTERN AUSTRALIAN 'LITHIUM VALLEY' CONCEPT

# WA's 'Lithium Valley' and 'cluster economics'

- Clustering is a well-established economic concept, where companies (and a local industry) gain a competitive advantage due to proximity;
- They have better access to relevant resources, suppliers, infrastructure, education, expertise, innovations, economies of scale, brand, and often favourable (but relevant) business climates;
- The complex, intangible nature of a cluster creates very high 'barriers to entry';
- The advantage endures long after initial 'cost advantages' may have dissipated;
- Classic examples include:
  - Silicon Valley, San Francisco;
  - Hollywood, Los Angeles
  - Napa Valley wine – all French wine – and Margaret River nearer home;
  - German car manufacturing;
  - British F1 car manufacturing;
  - Italian leather manufacturing;
  - Swiss watches;
  - Biotech in Massachusetts;
  - Finance in London & New York;
  - Outsourcing in/to India;
  - 'Factory Asia' (see right)

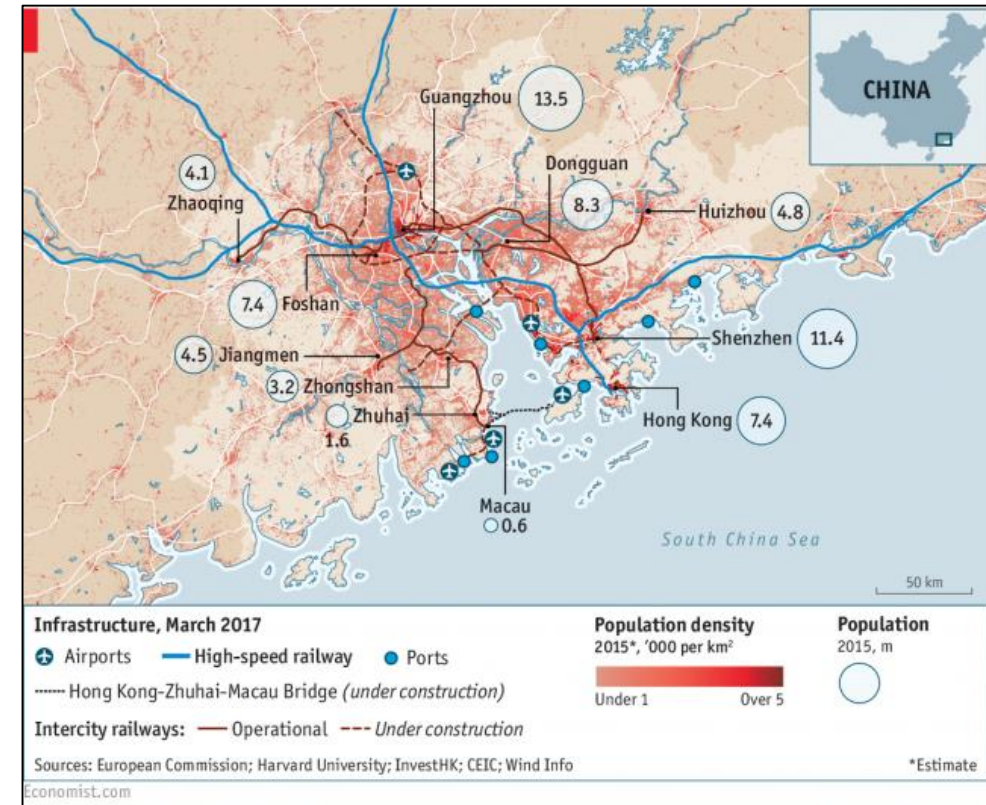
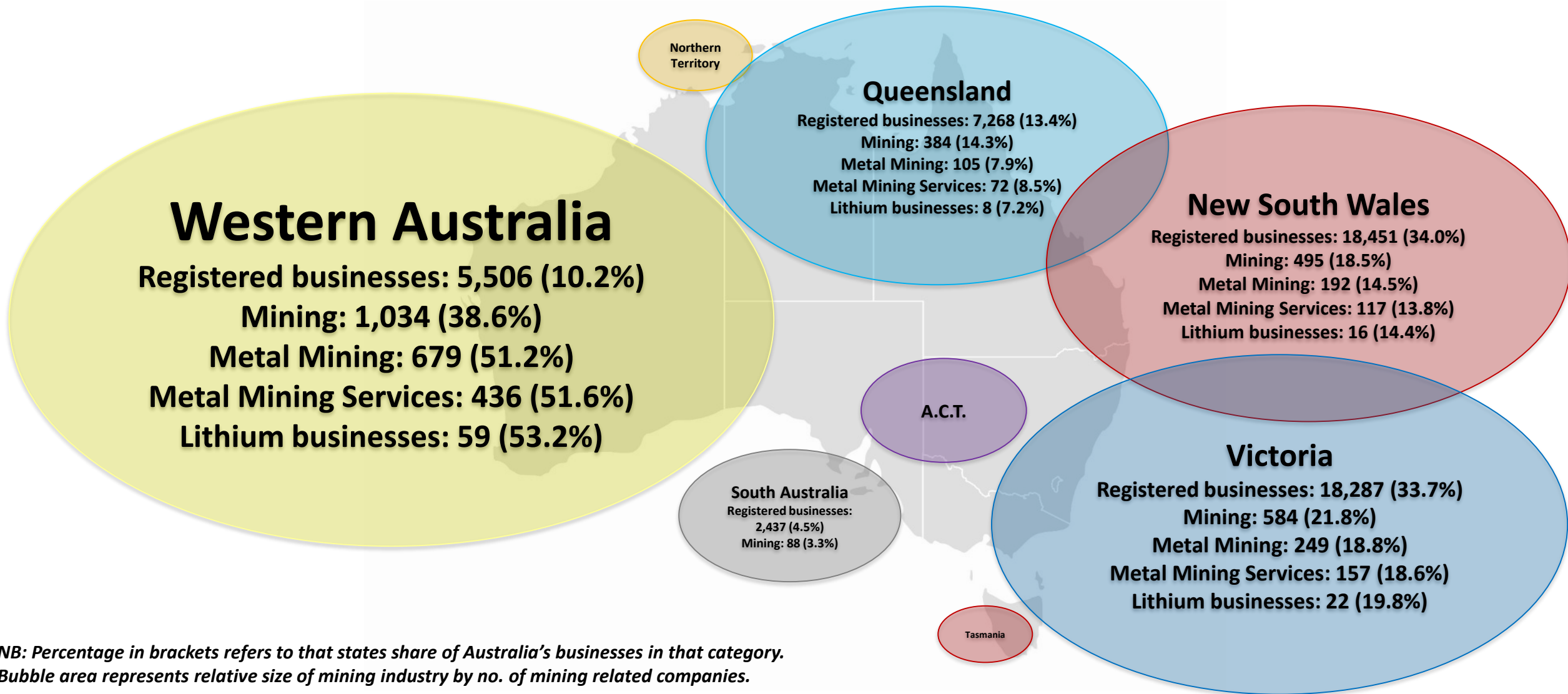


Image: The Pearl River Basin, China – this increasingly high cost manufacturing location still sits at the centre of 'Factory Asia' co-ordinating a massive SE Asian manufacturing cluster managing and outsourcing low-cost manufacturing, and implementing high-end and innovative, automated manufacturing at the centre. It is a substantial barrier to entry for non-Asian manufacturers. 'Cluster economics' now explains China's manufacturing dominance better than 'low costs'.

# WA is already a 'mining and exploration' cluster





# The WA 'Lithium Valley' concept is realistic (but still a challenge)

- **Good lithium deposits!**
- **Low-grade of spodumene concentrate (freight cost);**
- Minerals industry infrastructure, suppliers and expertise;
- Economies of scale (for once);
- Supportive academic communities;
- Supportive local government;
- **Proximity to China – a chance to join 'Factory Asia';**
- *Or potentially some geopolitical linkages with other Asian battery clusters;*
- ***But more realistically battery raw materials, rather than 'batteries' (so not quite 'Factory WA'.***

Image: Western Australia's hard rock lithium deposits, with bubble size reflecting relative size by contained lithium. Source: MinEx Consulting, 2019.





A global overview of the geology and economics of lithium production

# A NOTE ON STRATEGIC COHERENCE

# Lithium mining, the ‘green revolution’ and strategic coherence

- The mining industry is facing real pressure to genuinely implement more sustainable practices;
- In addition, lithium is seen as a ‘**green metal**’ suggesting such pressures may be greater;
- *e.g. The Whabouchi lithium project in Quebec (see left) was designed to go underground ‘early’ for environmental and social reasons;*
- This is likely more due to its location (in Quebec) than because it is a lithium project;
- BUT the ‘green’ focus of lithium will likely create stakeholder demand for ‘green’ coherence in lithium mining strategy.

## 1.14 Mining Methods

The Whabouchi deposit characteristics make open pit mining more favourable from an economic and technical standpoint because of its proximity to surface. Open pit mining will therefore be favoured for the upper portions of the deposit. However, open pit mining is commonly associated with more significant environmental and social impacts than underground mining, essentially because of the associated larger surface footprint. In order to mitigate environmental and social effects of the projected mine, where geological characteristics and economic factors made it feasible to switch to underground mining, the latter was favored. Consequently, from Year 24, the mine will be operating from underground, thus not only limiting the surface footprint of the ultimate open pit, but also minimizing the amount of waste rock to be managed and stockpiled at the surface. Such an approach also enables a longer mine life without significantly increasing the surface area impacted by mining activities, something which extends the duration and cumulative importance of the Project's economic spin-offs for local, regional and provincial stakeholders.

Image: Section from Whabouchi Feasibility Study (2018) with author highlights

# An example of 'bad' strategic coherence: Coles and plastic

- 2003: Ireland & Denmark ban plastic bags;
- 2015: England bans plastic bags;
- 
- **4<sup>th</sup> June 2018:** Following campaign pressure, Coles begins reducing packaging on fresh produce;
- **1<sup>st</sup> July 2018:** Coles ends free supply of 'single use' plastic bags, offering a thick plastic 'Better Bag' for 15c or 'Community Bags' for \$1 (only some of which are recyclable), but with a transition period with plastic 'Better Bags' given away for free until 8<sup>th</sup> July;
- **11<sup>th</sup> July 2018:** Free give away of complimentary plastic bags extended to end of July;
- **18<sup>th</sup> July 2018:** Launches 'Little Shop' promotion giving away plastic toys – ***criticised by environmentalists (and some customers);***
- **20<sup>th</sup> July 2018:** Introduces recyclable packaging for fresh meat;
- **2<sup>nd</sup> August 2018:** Free give away of complimentary plastic bags extended to end of August – ***criticised by rival Woolworths – and academics – and environmentalists;***
- **29<sup>th</sup> August 2018:** Coles begins charging 15c for thick plastic 'Better Bags' again;
- 
- **February 2019:** Coles launches 'Strikeez' promotion giving plastic toys of fruits and veg – ***more criticism from customers;***



Image: Truu, 2019 citing Coles


# An example of 'good' strategic coherence: Shell and CO<sub>2</sub>

Net Carbon Footprint  
**Our ambition**

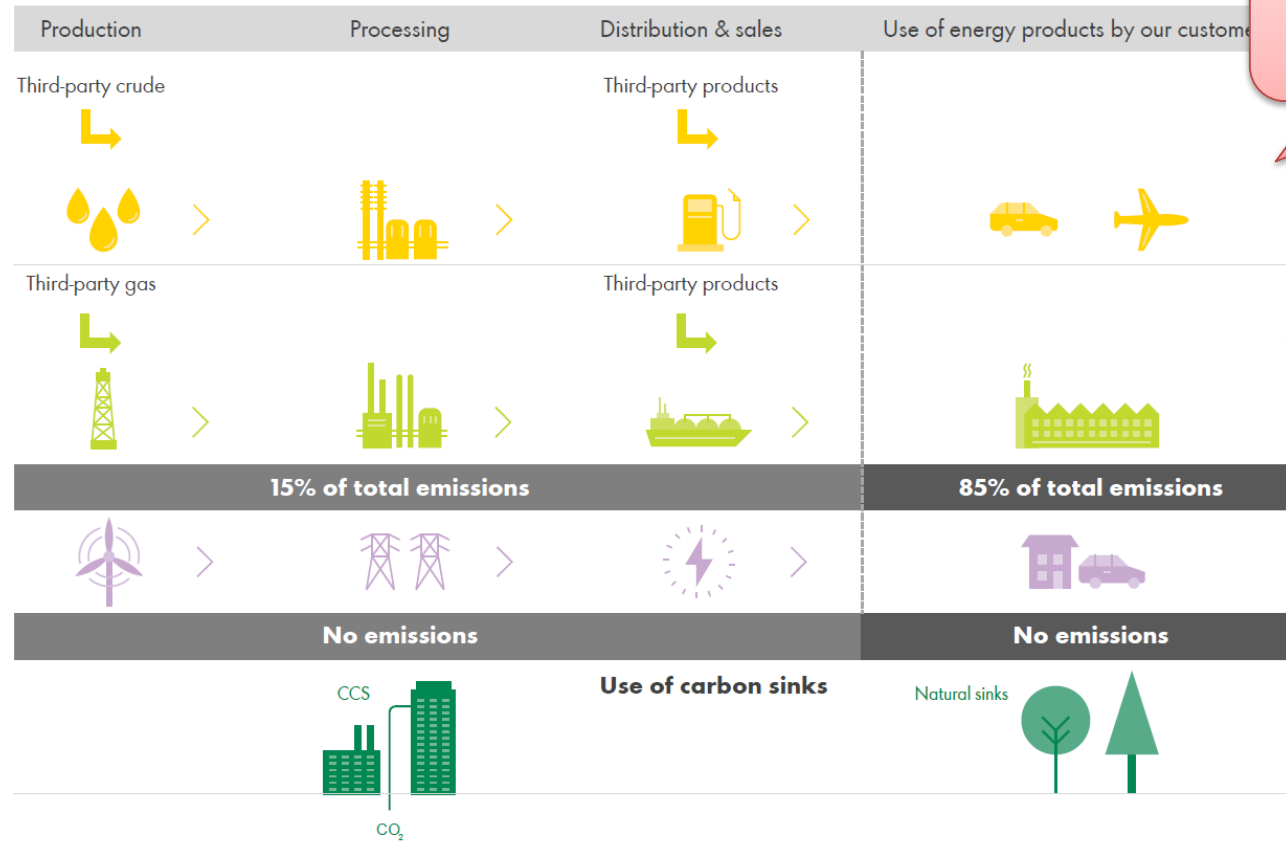
It is not Shell's CO<sub>2</sub> emissions that are the problem (15% of their CO<sub>2</sub> footprint)...

...but this is where some petroleum companies are focusing

Full life cycle of energy products, including consumption

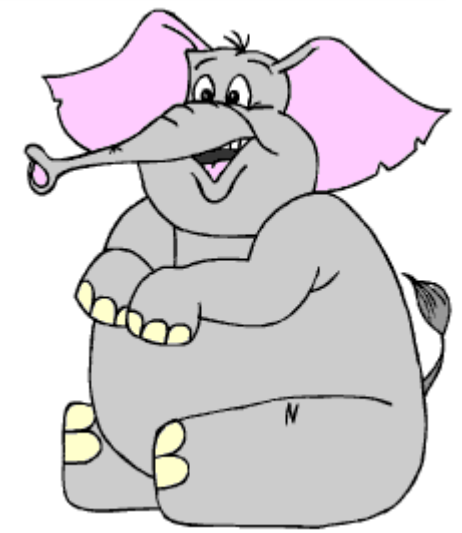
 Royal Dutch Shell | June 4-5, 2019

## The scope of Shell's Net Carbon Footprint ambition



It is Shell's customers' CO<sub>2</sub> emissions that are the problem (85% of their CO<sub>2</sub> footprint)...

As well as trying to reduce its own CO<sub>2</sub> emissions, Shell is also trying to reduce its customers' CO<sub>2</sub> emissions (or at least accounting for it)



# What is a coherent lithium mining strategy?

## Potential components of a 'coherent' lithium mining strategy:

- Operations
  - Renewable power plants? *e.g. Sandfire Resources*;
  - EV fleets (Anglo American is looking at hydrogen) – also good for H&S;
  - Going underground early, *e.g. Whabouchi*;
  - EV company cars? Especially the CEO & Chairman!
  - What about tailings and waste? Water use? Electricity use? Recycling bins?
- Exploration
  - Remote, low impact exploration?
  - BUT maintaining good local stakeholder contact (explorers as anthropologists);
  - Exploring in EVs? 'What would Elon do?'
- Investors
  - Targeting ESG investors? Governance important is important too.
  - Targeting millennials? Bitcoin, crowdfunding, gamification?
  - Targeting Tesla, Apple, Toyota etc., Supply chain transparency is important;
- Government & Social
  - Most lithium projects in countries such as Canada, Australia, Germany, Finland, Spain etc., where environmental and social concerns are commonplace;
  - Land values are often higher leading to land-use conflict;
  - Lithium is often seen as 'strategic' which may create requirements for socio-politically or geopolitically appropriate off-takers, a desire for downstream integration, low content use, or local employment rules.
- Leadership
  - *Not pale, stale and grey?*



Image: [Threadsquad on Amazon](#)

## The mining industry: Home of the 'bad strategy'

STRICTLY Boardroom suggests the concept of 'strategic coherence' should help the mining industry overcome a track-record of 'bad strategies'.

For more on  
'strategic coherence' in  
mining...



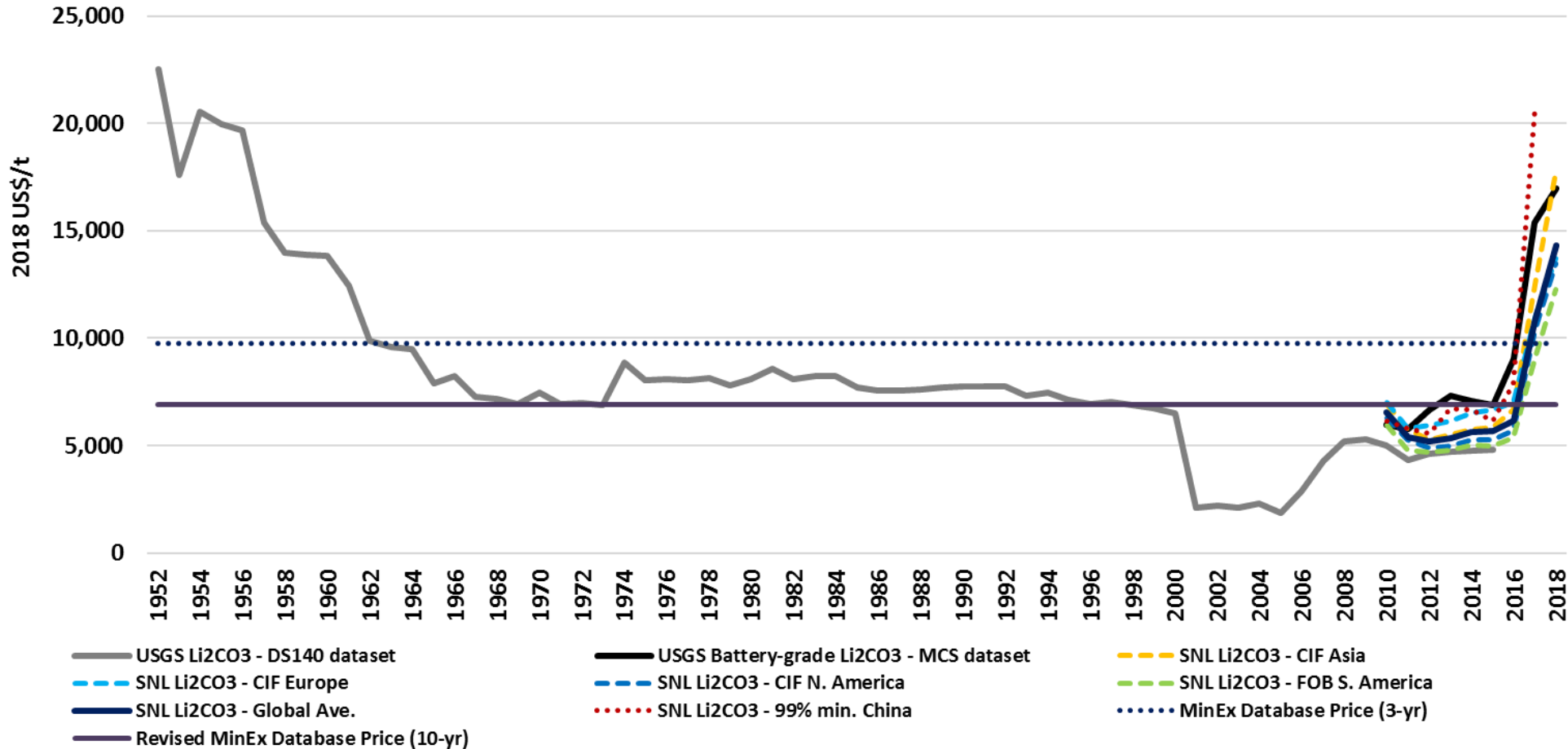


A global overview of the geology and economics of lithium production

# A NOTE ON LITHIUM PRICES, BOOMS AND LONG-TERM MARKET GROWTH

# The recent lithium prices are a historical anomaly

Historic lithium carbonate prices from the USGS & SNL



Li <sub>2</sub> CO <sub>3</sub> Historic Ave. Price*	2018 US\$/t
67-yr	8,424
20-yr	5,273
10-yr	6,924
5-yr	8,257
3-yr	9,870
MinEx (3-yr)	9,735
MinEx (10-yr)	6,924

*NB: Generally, MinEx uses 3-year average prices in its database, however, the lithium price spike means a 10-year price is more appropriate for understanding the quality of a mine or project through the full price cycle.*



# For the industry to grow prices will need to moderate

*We are in an unusual 'Lithium Boom' ('Party') market at the moment – with growing volumes and high prices – this will be temporary;*

*Either volumes will grow and prices will fall ('Parents');*

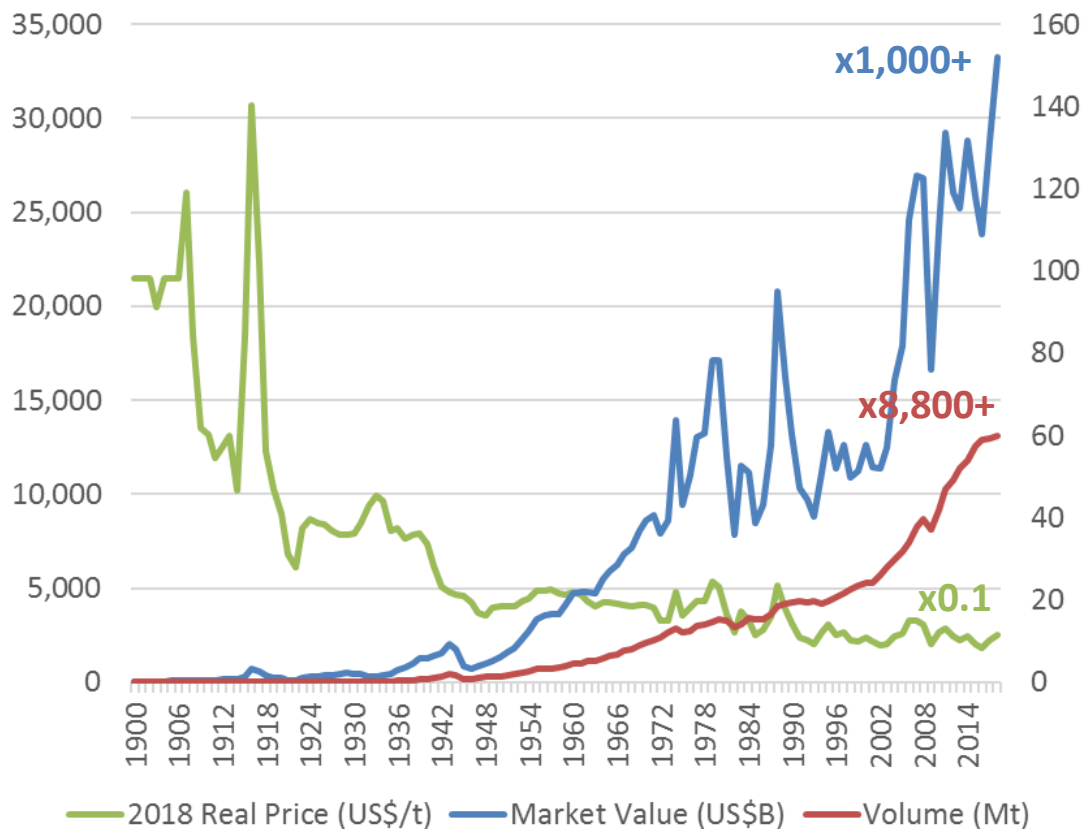
*Or high prices will choke demand and normalise prices (the 'Hangover');*

*Or high prices and high demand will encourage politicians to get involved (the Policemans market).*



# Small mineral markets do sometimes grow into large ones

Aluminium Real Price, Volume & Value, 1900-2018



## Factors in place prior to 20th century



## Key supply & demand innovations in late 19<sup>th</sup> & early 20<sup>th</sup> century

Bulk open pit mining

Bayer & Hall-Heroult processes

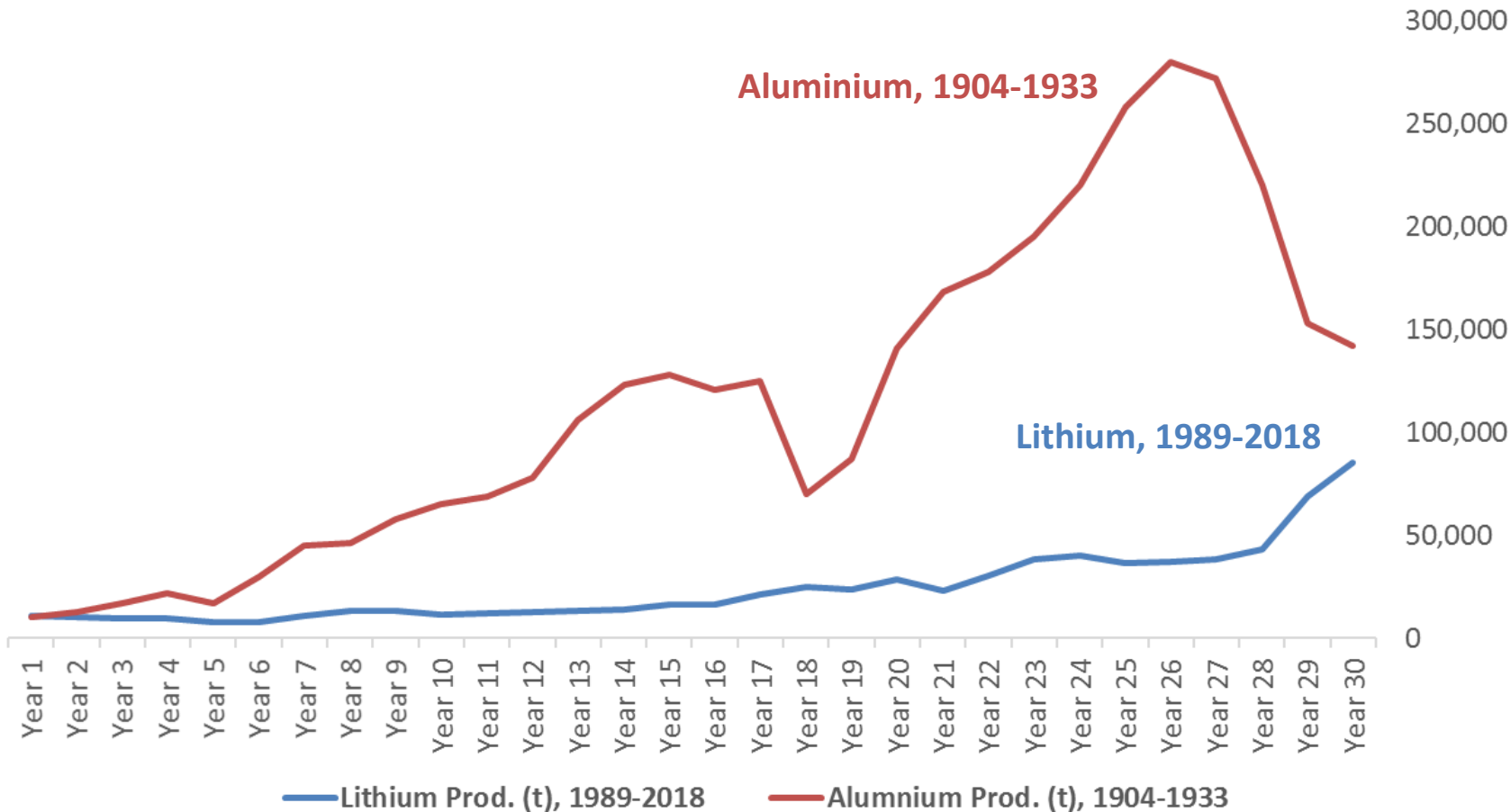
New uses

Cheap energy

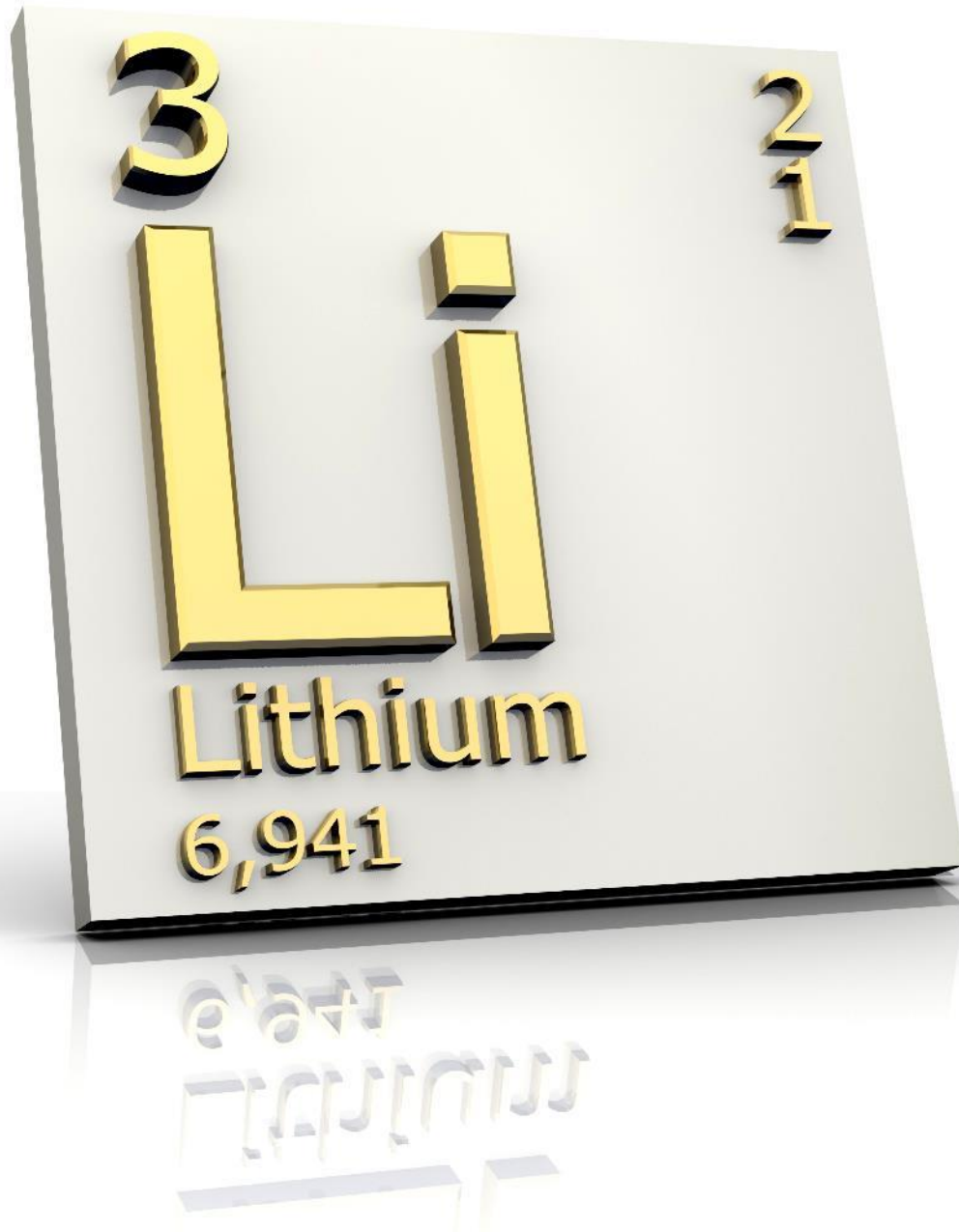
Images: Alcoa; Shutterstock

# Is lithium on this growth track? Only with lower prices...

Aluminium vs Lithium Production Growth, various years



Metal	Crustal Abundance (ppm)
Aluminium	84,300
Zinc	72
Nickel	59
Copper	27
Cobalt	27
<b>Lithium</b>	<b>17</b>
Lead	11
Tin	2
Molybdenum	1



A global overview of the  
geology and economics of  
lithium production

## **IN SUMMARY**

# In summary: The global geology & economics of lithium

- Lithium demand is growing fast, driven by a wide range of battery applications, which are in turn changing the structure of demand, the lithium supply chain and potentially raw material requirements – though much still remains uncertain;
- Geologically ‘brine’ salars and ‘hard rock’ pegmatites remain the most important lithium deposit types in terms of production and undeveloped resources, however, there are some interesting emerging sedimentary / clay deposits and unconventional brine concepts – and lithium remains very ‘under explored’ globally;
- Spodumene pegmatites in Australia are the fastest growing source of supply, however, long-term competitiveness may be dependent on successful downstream integration targeting the battery industry;
- The concept of a Western Australian ‘Lithium Valley’ is possible, despite high costs, due to the number of quality mines, proximity to Asia, and the unit reduction in freight costs associated with the low grade spodumene concentrate, in addition to the ‘cluster effect’ of many minerals businesses, specialists and students;
- The ‘green’ association of lithium use presents a challenge of ‘strategic coherence’ to explorers and miners impacting decisions around exploration, mining, investors, stakeholders, and leadership;
- But remember, we are in an unsustainable ‘lithium boom’ of high prices and high volume growth – future long-term growth of the industry is reliant on structurally lower prices, and thus structurally lower costs.

# Thank You!

## Contact details

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Website: [www.MinExConsulting.com](http://www.MinExConsulting.com)

Copies of this and other similar presentations can be downloaded from our website



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