LITHIUM: FROM EXPLORATION TO END-USER,
GEOLOGICAL SOCIETY, LONDON – 9-10 APRIL 2018

FAME

FAME: HELPING TO VALORISE EUROPEAN LITHIUM RESOURCES

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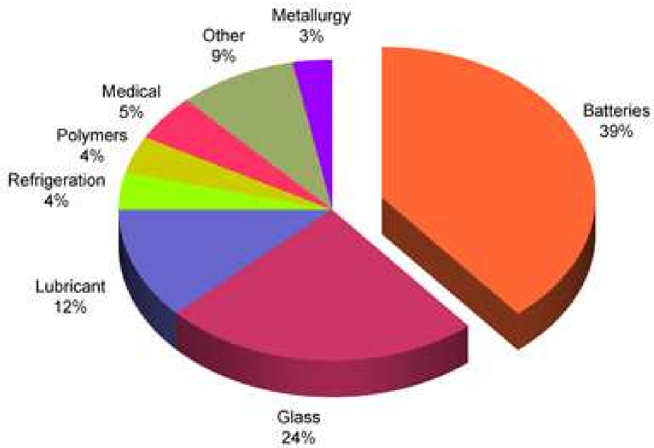
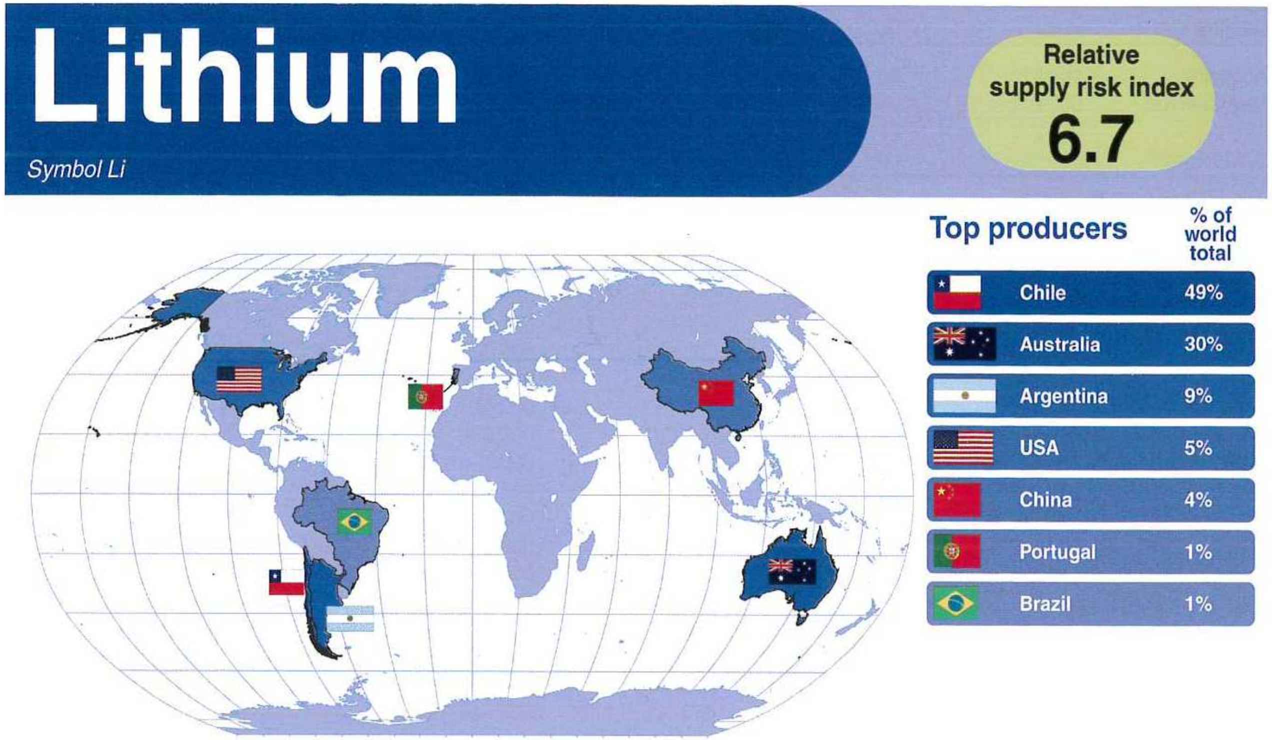
LITHIUM DEMAND

"In terms of new lithium supply the industry needs all the supply it can get. SQM, traditionally conservative of its lithium estimates, is expecting an 800,000tpa LCE market by 2027. These numbers are staggering considering the market was at 180,000tpa LCE in 2017."

Source: Mining Journal – Interview with Simon Moores – MD Benchmark Mineral Intelligence – 5th September 2017



CURRENT LITHIUM PRODUCERS



Source: BGS World Mineral Production

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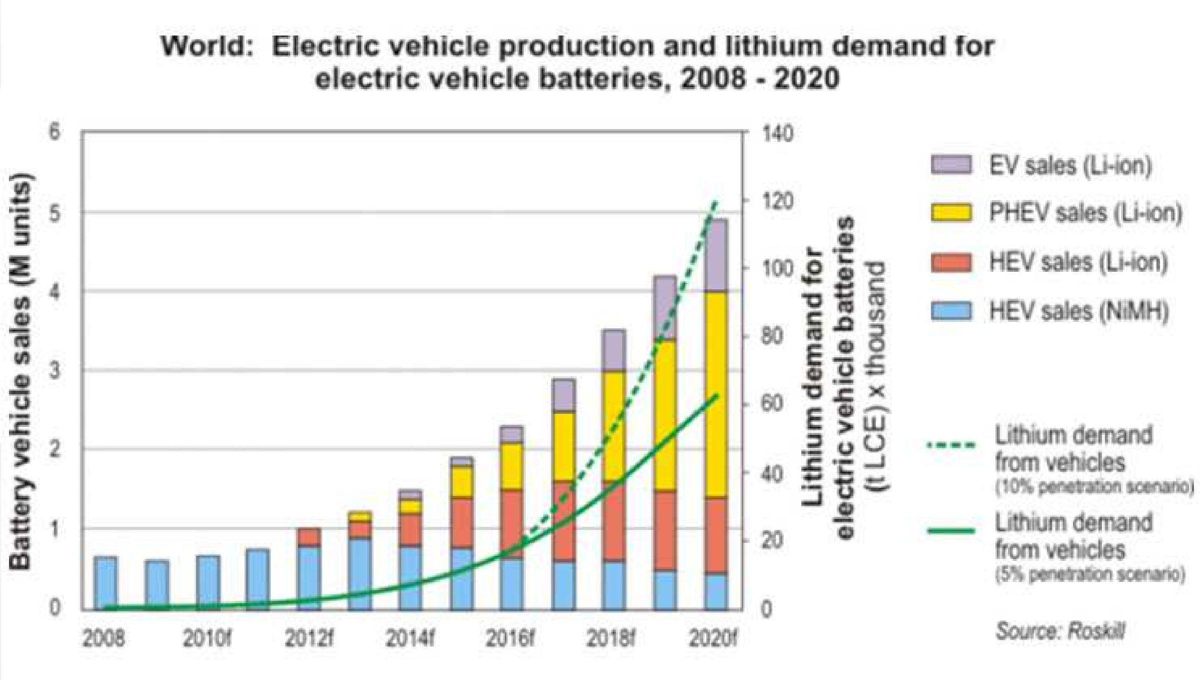
LITHIUM DRIVER

ELECTRIC CAR PRODUCTION IS DRIVING LITHIUM DEMAND



Note: WHILST Li-ION BATTERY TECHNOLOGY MAY BE REPLACED;
IN SHORT – MID TERM – DEMAND FOR Li WILL REMAIN

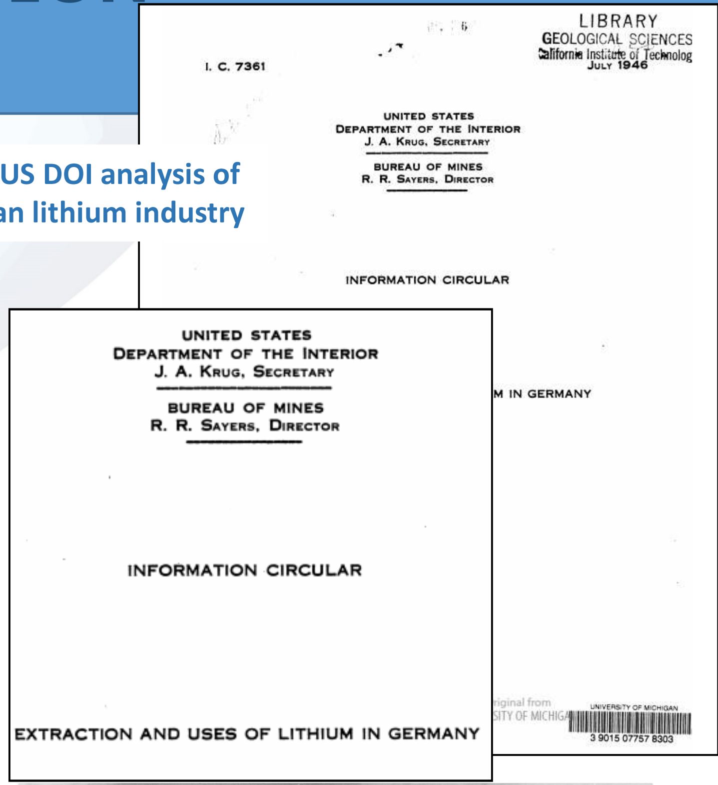
EUROPEAN Li POTENTIAL

HARD ROCK POTENTIAL

Country	Company	Deposit	Main mineral	Stage	Production 2016 t LCE	Resources		Reserves	
						Mt	Li2O %	Mt	Li2O %
Austria	European Lithium	Wolfsberg	Spod	PFS o	-	12.6	1.17	-	-
Czech Republic	European Metals	Cinovec	Zinn	PFS f	-	656.5	0.40	-	-
Finland	Keliber	Several	Spod	DFS o	-	8.1	1.19	4.5	1.10
Portugal	Sociedad Mineira de Pegmatites	Castanho	Spod?	Prod	1200	?	?	?	?
Portugal	FELMICA	Gondiães	Pet	Prod	150	?	?	?	?
Portugal	Imery Ceramics Portugal SA.	Mina do Barroso	Spod	Prod	190	?	?	?	?
Portugal	José Aldeia Lagoa & Filhos	Gonçalo Sul	Lep	Prod	50	?	?	?	?
Portugal	Sociedade Mineira Carolinos	Alvarrões	Lep	Prod	150	?	?	?	?
Serbia	Rio Tinto	Jadar	Jad	PFS o	-	136.0	1.80	-	-
Spain	Imerys	Alberto	Lep?	Prod	100	?	?	?	?
Total					1840	813.2	0.65	4.5	1.10

Source: P Lamberg, Keliber, October 2017

HISTORY OF LITHIUM PRODUCTION IN EUROPE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INFORMATION CIRCULAR

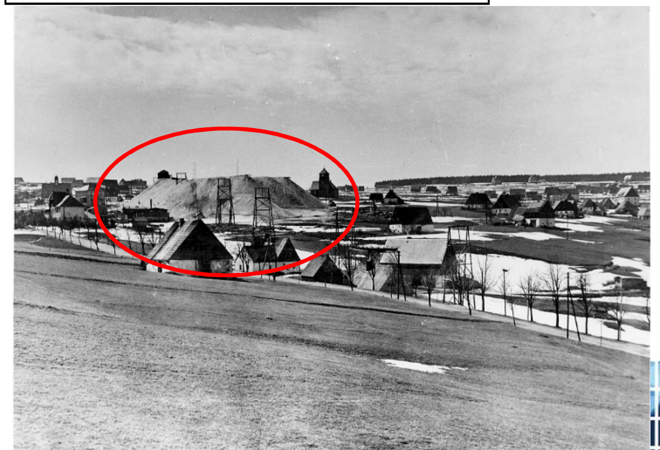
EXTRACTION AND USES OF LITHIUM IN GERMANY

I. C. 7361

1945: US DOI analysis of German lithium industry

First large scale Lithium production in the world: Zinnwald / Germany

Start in 1922: Re-mining of Tin-Tungsten tailings for lithium mica (Zinnwaldite)



Processing plant

Tin-Tungsten tailings containing Li mica

WHAT IS FAME

- Horizon 2020 PROJECT
  Flexible And Mobile Economic Processing EU Research and Innovation Project co-ordinated by Wardell Armstrong
- 7.4 Million Euros
- 16 Partners – 7 countries
- Start Date 01/01/2015
- End Date 31/12/2018

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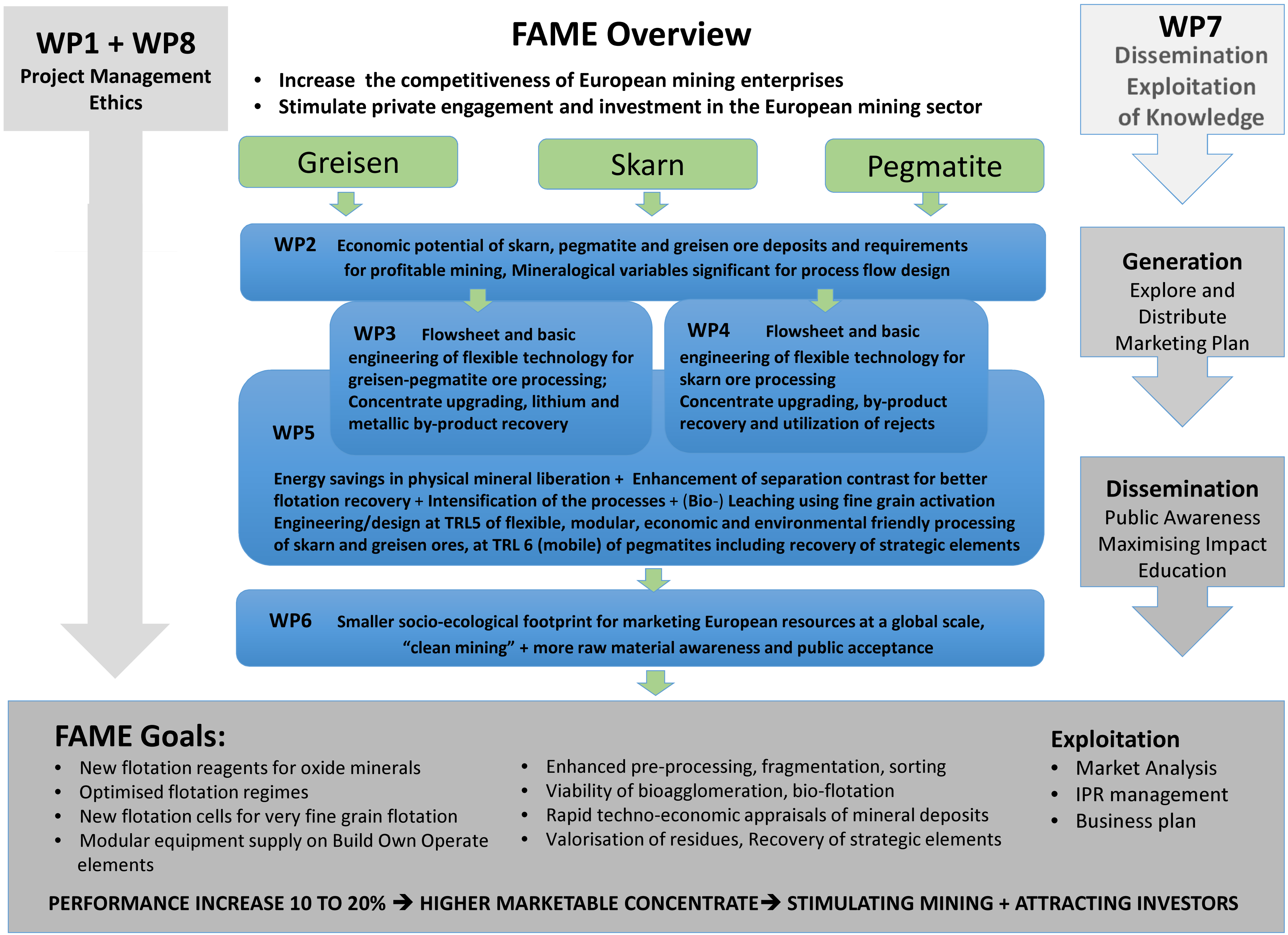

WP1 + WP8
Project Management
Ethics
FAME Overview
• Increase the competitiveness of European mining enterprises
• Stimulate private engagement and investment in the European mining sector
WP7
Dissemination
Exploitation
of Knowledge
Greisen
Skarn
Pegmatite
WP2 Economic potential of skarn, pegmatite and greisen ore deposits and requirements for profitable mining, Mineralogical variables significant for process flow design
WP3 Flowsheet and basic engineering of flexible technology for greisen-pegmatite ore processing; Concentrate upgrading, lithium and metallic by-product recovery
WP4 Flowsheet and basic engineering of flexible technology for skarn ore processing
Concentrate upgrading, by-product recovery and utilization of rejects
WP5
Energy savings in physical mineral liberation + Enhancement of separation contrast for better flotation recovery + Intensification of the processes + (Bio-) Leaching using fine grain activation
Engineering/design at TRL5 of flexible, modular, economic and environmental friendly processing of skarn and greisen ores, at TRL 6 (mobile) of pegmatites including recovery of strategic elements
Generation
Explore and
Distribute
Marketing Plan
Dissemination
Public Awareness
Maximising Impact
Education
WP6 Smaller socio-ecological footprint for marketing European resources at a global scale, “clean mining” + more raw material awareness and public acceptance
FAME Goals:
• New flotation reagents for oxide minerals
• Optimised flotation regimes
• New flotation cells for very fine grain flotation
• Modular equipment supply on Build Own Operate elements
• Enhanced pre-processing, fragmentation, sorting
• Viability of bioagglomeration, bio-flotation
• Rapid techno-economic appraisals of mineral deposits
• Valorisation of residues, Recovery of strategic elements
Exploitation
• Market Analysis
• IPR management
• Business plan
PERFORMANCE INCREASE 10 TO 20% → HIGHER MARKETABLE CONCENTRATE→ STIMULATING MINING + ATTRACTING INVESTORS

FAME REFERENCE ORES

LITHIUM RESEARCH IN FAME
MINERALOGICAL CHARACTERISATION - 1

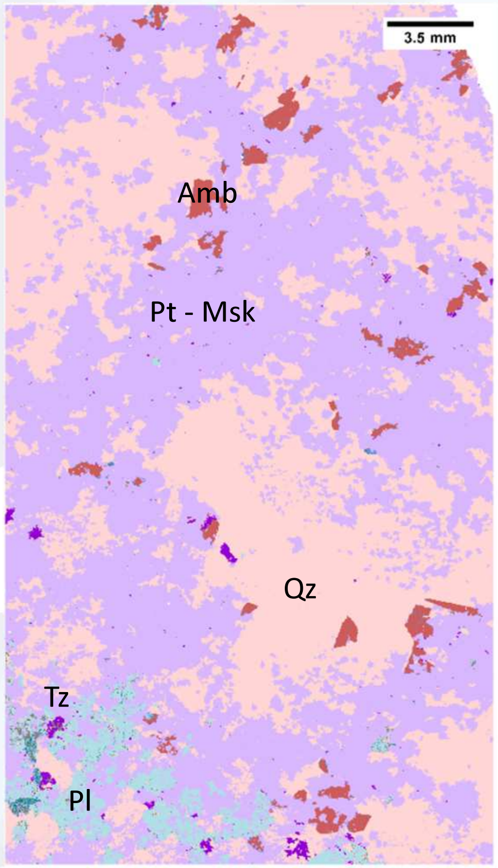
COMMON LI-PHASES AND ASSOCIATED MINERALS

Abbreviation	Li-minerals	Mineral formulae
Pt (Lpd)	Polylithionite-trilithionite *	$KLi_2Al[Si_4O_{10}][F,OH]_2$ – $K[Li_{1.5}Al_{1.5}][AlSi_3O_{10}][(F,OH]_2$
Zwd	Zinnwaldite	$KLiFe^{2+}Al[AlSi_3O_{10}][F,OH]_2$
Spd	Spodumene	$LiAlSi_2O_6$
	Petalite	$LiAl[Si_4O_{10}]$
Lt	Lithiophilite-triphylite	$Li[Mn,Fe]PO_4$
Am	Amblygonite-montebrasite	$LiAl[PO_4][F,OH]$
Brl	Beryl	
Qz	Quartz	
Pl	Plagioclase	
Kfs	K-feldspar	
Ap	Apatite	
Chl	Chlorite	
Kao	Kaolinite	
Tz	Topaz	

** Note: "Lepidolite" is a loosely defined name commonly used for Li-mica of the Pt-series*

LITHIUM RESEARCH IN FAME – MINERALOGICAL CHARACTERISATION - 2

GONCALO, PORTUGAL (FELMICA MINERAIS INDUSTRIAIS S.A.)



Mineralogical composition (vol %)[2]

Lpd	54.08	Bt	Tr.
Qtz	39.39	Zrc	Tr.
Pl	3.06	Cst	Tr.
Amb	2.46	Urn	Tr.
Tz	0.46	Chl	Tr.
Als	0.22	Tur	Tr.
2ndP	0.19	REE	Tr.
Ap	0.10	FeOx	Tr.
Kao	0.03	Rt	Tr.
Fl	0.01	MnOx	n.d.
Clb	Tr.	Ilm	n.d.

Size distribution (max | min| mean)[3]

Lepidolite	1 mm	≤10 µm	609 µm
Amblygonite	2.2 mm	≤10 µm	248 µm
Aluminium silicates	250 µm	≤10 µm	33 µm
Apatite	300 µm	≤10 µm	27 µm
Cassiterite	-	-	20 µm
Columbite-tantalite	-	-	29 µm
Zircon	-	-	17 µm

Ore dominated by lepidolite with significant amblygonite-montebrasite

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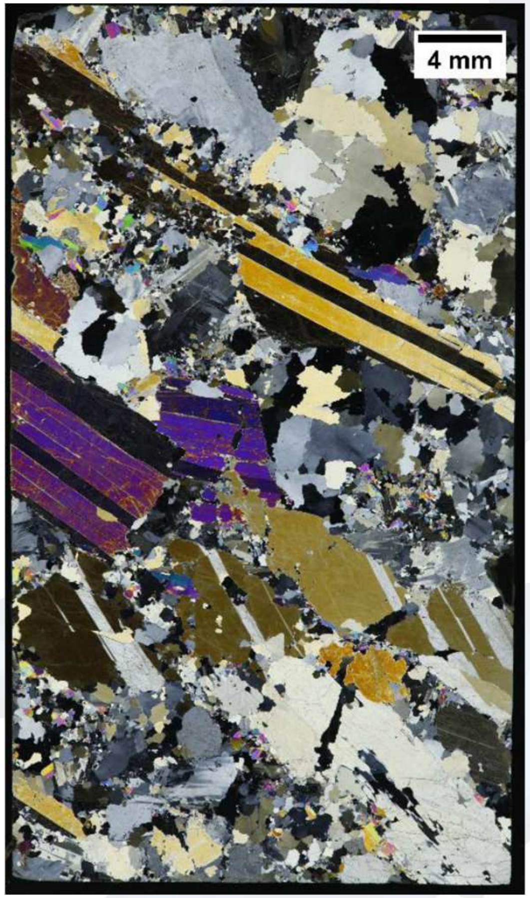
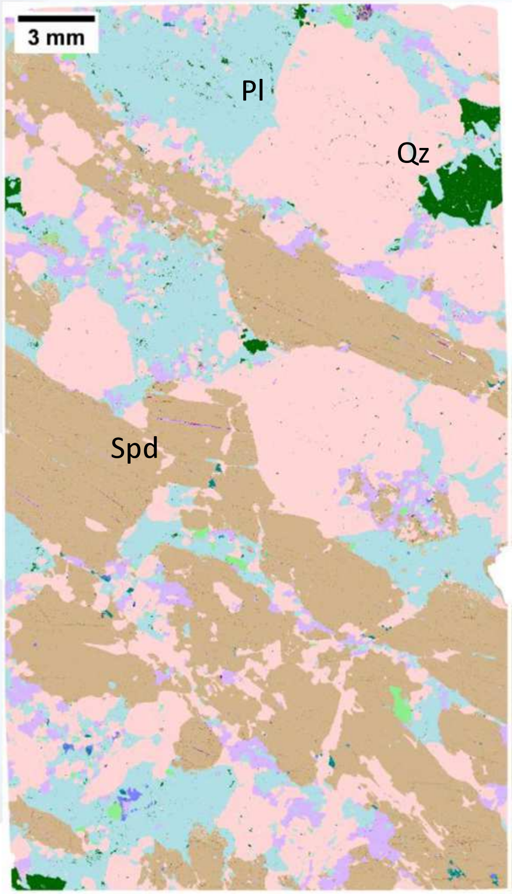
LITHIUM RESEARCH IN FAME – MINERALOGICAL CHARACTERISATION - 3

KAUSTINEN PEGMATITE FIELD, FINLAND (KELIBER OY)





Mineralogical composition (vol %)[2]

Qtz	35.88	Clb	0.01
Spd	34.56	Amb	Tr.
Pl	20.68	Cal	Tr.
Ms / Lpd	5.39	Sp	Tr.
Kfs	1.66	Zrc	Tr.
Brl	0.83	Sps	Tr.
Kao	0.45	Cst	Tr.
Ap	0.22	Others	Tr.
Lth	0.12	Py	Tr.
Tz	0.07	Urn	Tr.
Chl	0.06	FeOx	Tr.
Bt	0.02	Apy	Tr.
Tur	0.01		

Size distribution (max | min| mean)[3]

Spodumene	11 mm	≤10 µm	395 µm
Beryl	1.7 mm	≤10 µm	43 µm
Columbite	110 µm	≤10 µm	26 µm
Cassiterite	-	-	24 µm
Apatite	400 µm	≤10 µm	39 µm
Lithiophilite	650 µm	≤10 µm	89 µm

Ore dominated by spodumene with significant lepidolite (and/or muscovite)

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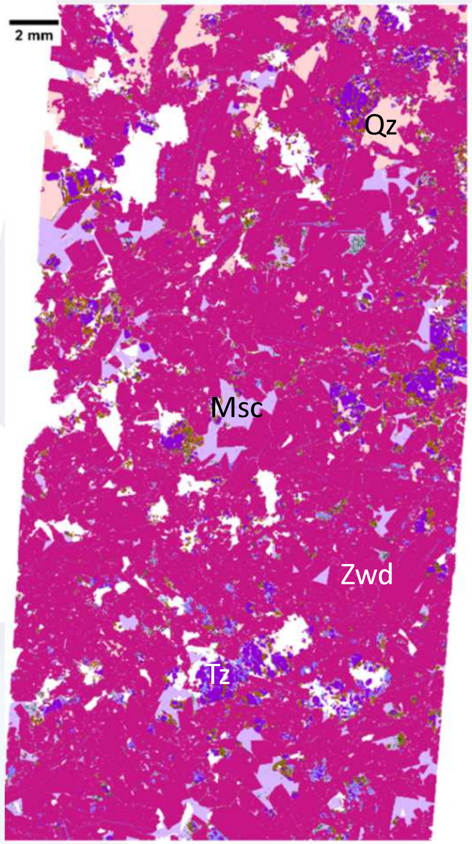
LITHIUM RESEARCH IN FAME – MINERALOGICAL CHARACTERISATION – 4

CINOVEC, CZECH REPUBLIC (EUROPEAN METALS HOLDINGS LTD.)



Ore dominated by zinnwaldite with potential for by-product of cassiterite, wolframite and scheelite

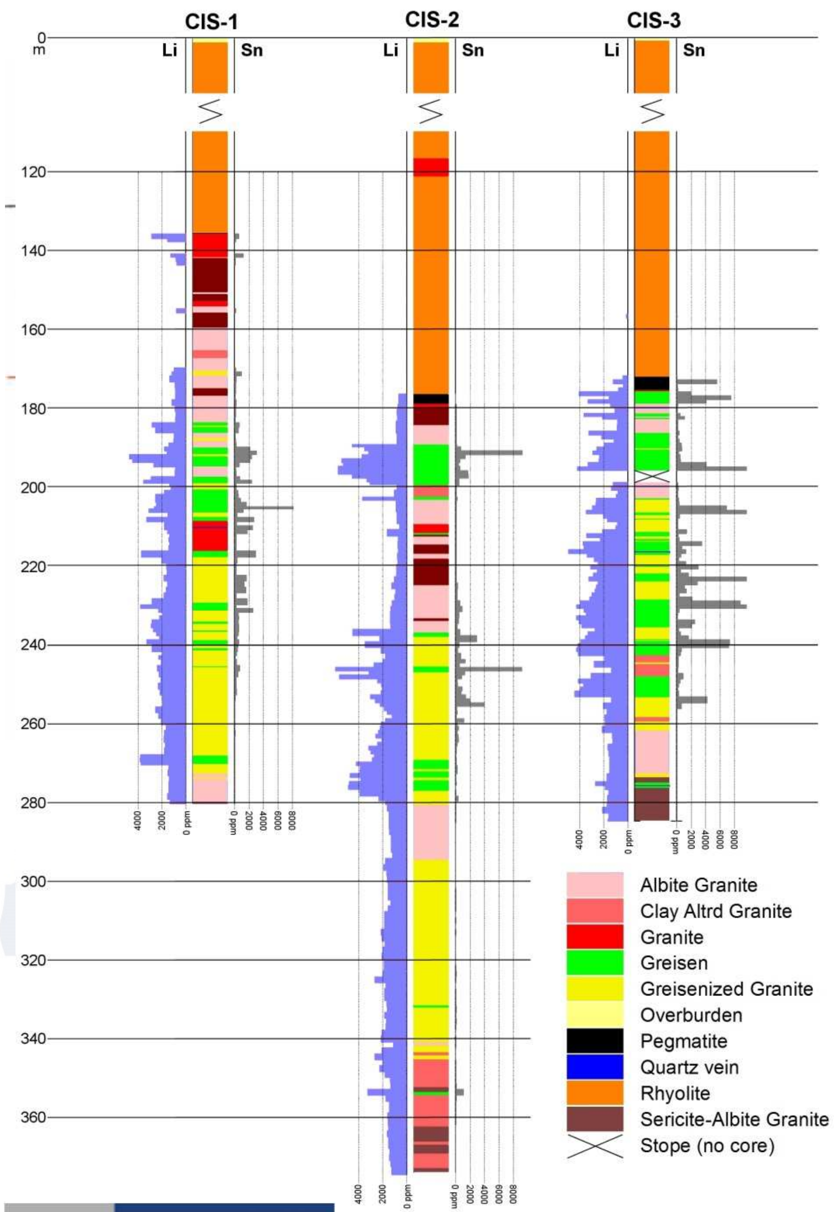
Mineralogical composition (vol %)[2]

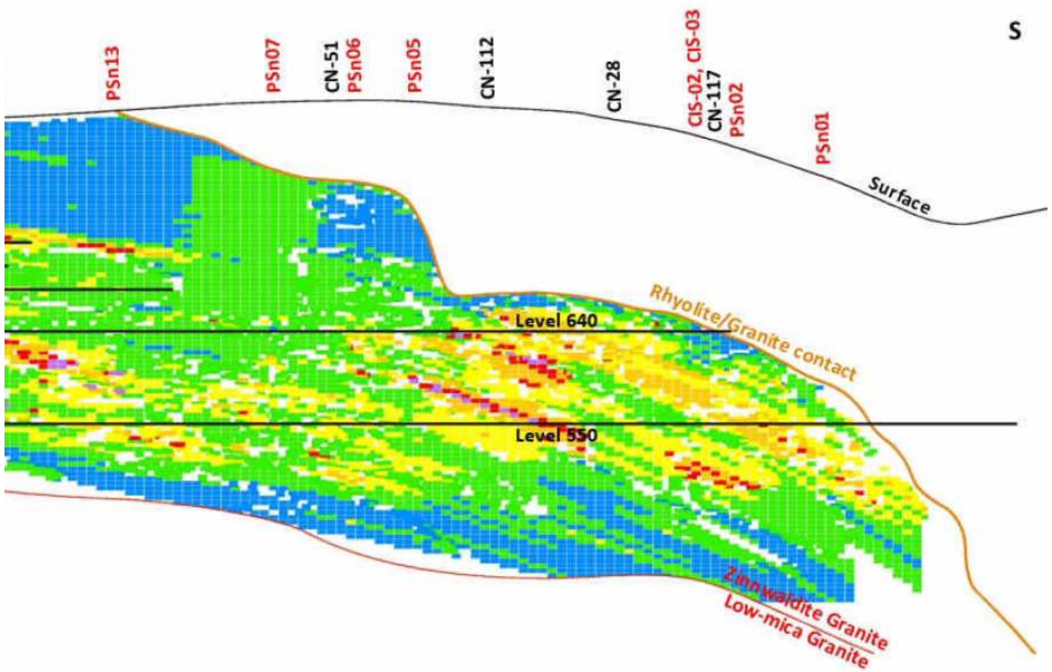
Zinnwaldite	75.67	Apatite	Tr.
Muscovite / illite*	8.78	Fe-Ox/CO3	Tr.
Topaz	5.51	Uraninite	Tr.
Quartz	4.15	Others	Tr.
Kaolinite	3.35	Galena	Tr.
Fluorite	1.11	Columbite	Tr.
K-Feldspar	0.98	Rutile	Tr.
Plagioclase feldspar	0.39	Scheelite	Tr.
Tourmaline	0.02	Wolframite	Tr.
Calcite	0.01	Bismuthinite	Tr.
Cassiterite	0.01	Sphalerite	Tr.
REE minerals	0.01	Chalcopyrite	n.d.
Chlorite	0.01	Cu arsenides	n.d.
Zircon	Tr.	Cobaltite	n.d.
Pyrite	Tr.		

Size distribution (max | min | mean)[3]

Zinnwaldite	6 mm	10 µm	521 µm
Cassiterite	145 µm	<10 µm	26 µm
Wolframite (Tr.)	-	-	≤15 µm
Scheelite (Tr.)	-	-	32 µm
Columbite (Tr.)	-	-	≤15 µm
REE minerals	120 µm	<10 µm	32 µm

Grade Distribution Li%, Interim Block Model Cinovec Deposit





Challenges for processing and impacting recovery:

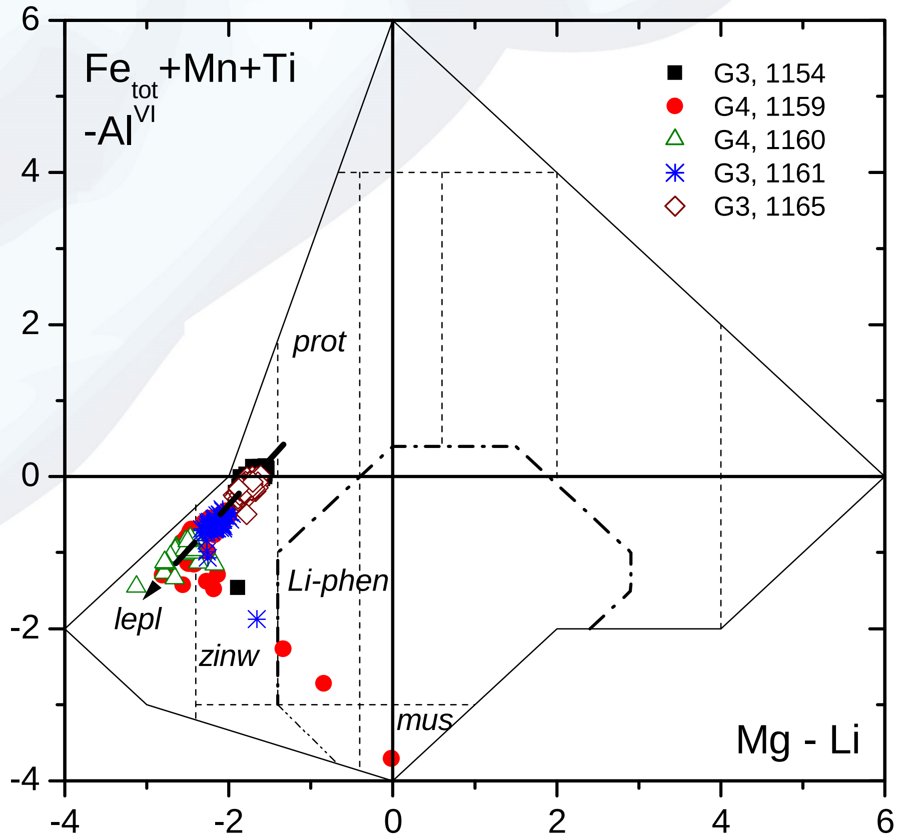
- Subhorizontal thin-layered anatomy

(sheeted laccolite, alteration zones, flat ore bodies)

- Strong petrographic-mineralogical variability
- Contrasting magnetic properties of mica phases
- Variable grain size and strong Li zonation of mica
- LT clayey alteration hosted in intergranular space

→ Potential loss of Li in slimes

Cinovec Sn-Li Deposit



Mineralogic & Petrographic Variability of Granites and Greisens (**qtz, kfs, alb, top, di- / trioctahedral mica, clay, accessories**)

Mineralogical Variability of Lithium Mica:
Li-Phengite - Zinnwaldite - Lepidolite
(plot after Tischendorf et al. 1997)

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LITHIUM RESEARCH IN FAME – ISSUES IDENTIFIED FROM MINERALOGY

Lithium deportment issues:

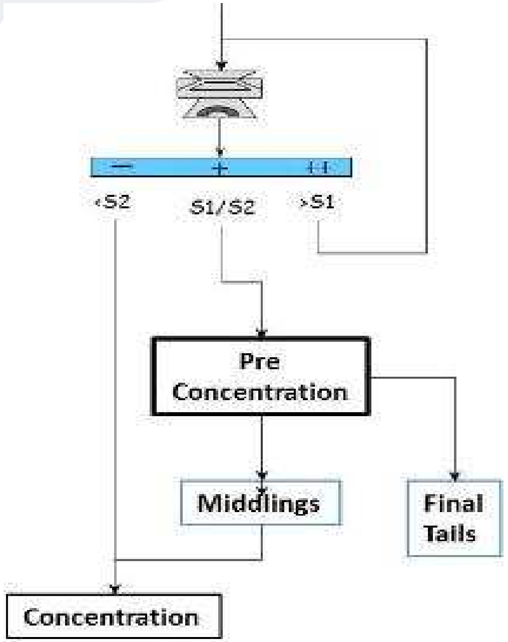
- Is it possible to generate selective recovery of Li-mica in the presence of muscovite?
- Presence of minor minerals may require separate processing stream (e.g., amblygonite-montebrasite at Goncalo; lepidolite at Kaustinen)

Problematic (or penalty) minerals:

- Topaz – extremely hard, excessive wear on crushing/grinding equipment
- Uraninite and pitchblende – trace minerals, radioactive

LITHIUM RESEARCH IN FAME – PRE-CONCENTRATION

- Removal of barren rock (i.e. PRECONCENTRATION) will be important for successful Li Processing
- There may be uses for the barren rock (gangue) – otherwise tailings for disposal with low Li content
- If pre-concentration is possible at coarse sizes, the reduced amount of ore going for crushing leads to significant energy savings and increases head grade (Li Content) of feed



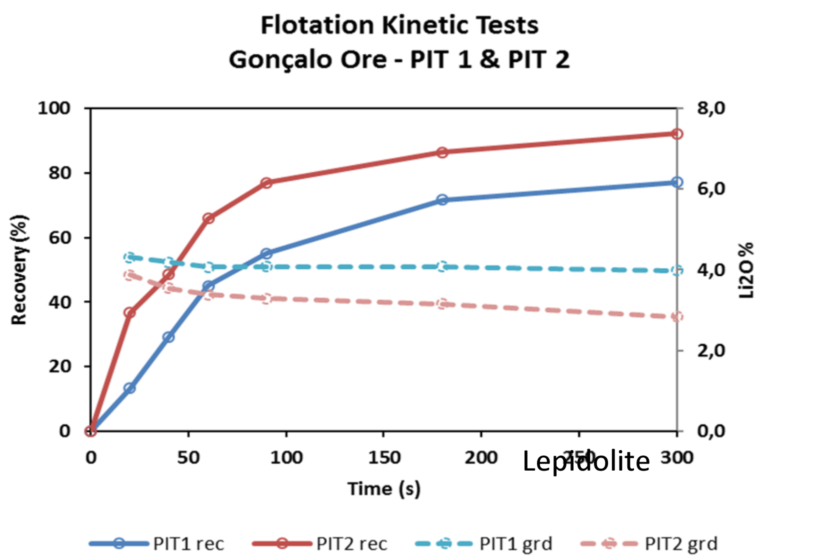
- A number of Different Sorting Techniques Considered:

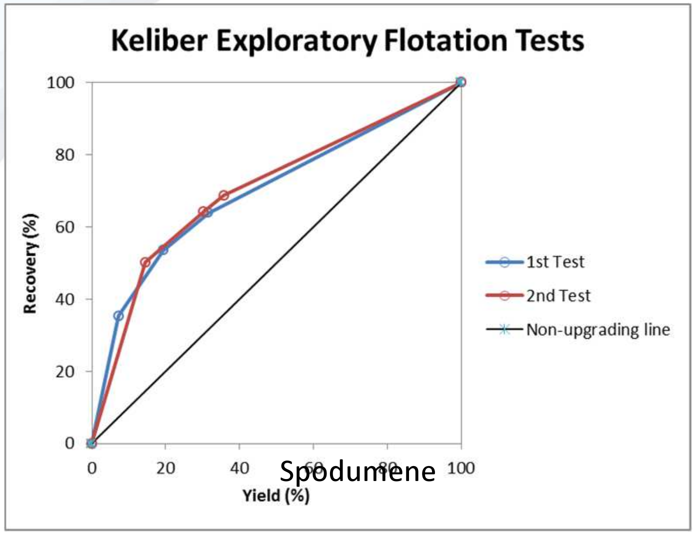
Good results using Optical sorter (colour differences between Li-rich minerals and gangue)

Pre-concentration of Lepidolite using an optical sorter

LITHIUM RESEARCH IN FAME FLOTATION

- (Almost all) Li minerals can be upgraded to Concentrates of Higher Li content using Froth Flotation (However – Max Li Content 6-8%)
- FAME has developed intensive Flotation to improve Li recovery from lepidolite and spodumene ores





- Comminution down to k_{80} ~ 150μm;
- Flotation in acidic media, using specific collectors
- Li recoveries = 80-90%; concentrates upgrade above 4.5 – 5 %Li_2O

RECOVERY NEEDS TO BE AS CLOSE TO 100% AS POSSIBLE

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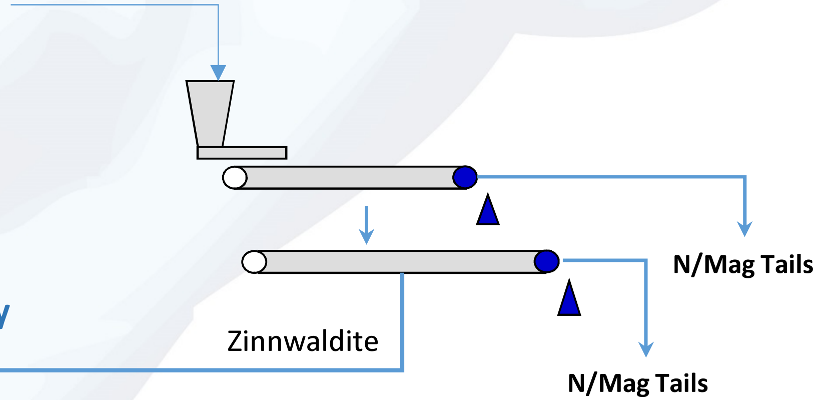
LITHIUM RESEARCH IN FAME
MAGNETIC SEPARATION FOR ZINNWALDITE RECOVERY

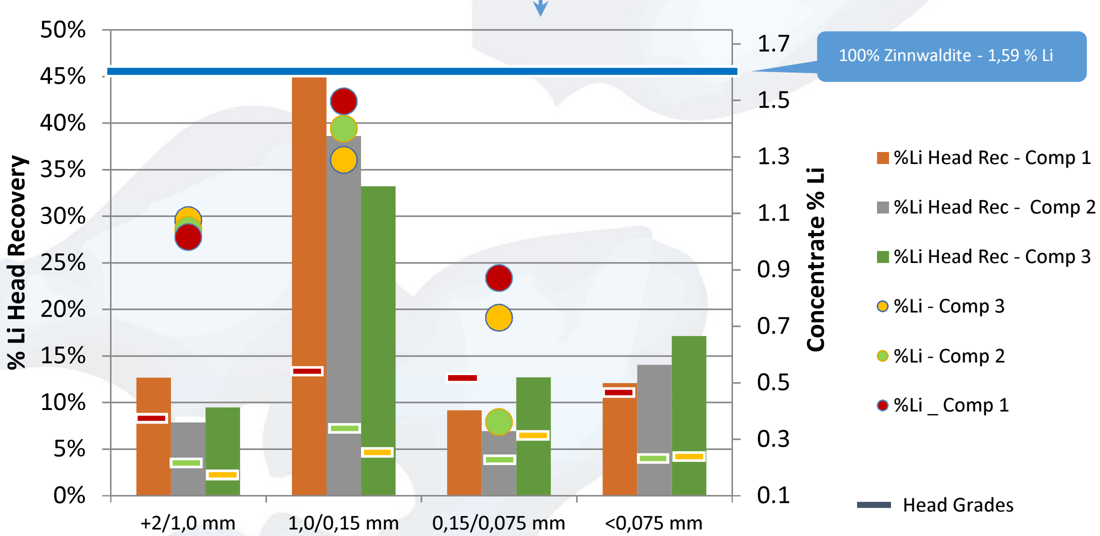
SAMPLES FROM CINOVEC

Lithium Recovery:

- Fraction 1/0,5 mm collects 40% Li
- Recovery decreases with size
- Fines (<0,075mm) represent 14% Li losses

Concentrate of size fraction 1/0,5 mm is a high purity zinnwaldite product





Particles crushed to around 1mm

Higher entrapment in size fractions below 0,5 mm leads to low grades and low recoveries

Dry Medium Intensity Magnetic Separation (Permroll type) seems to be suitable for zinnwaldite recovery

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LITHIUM RESEARCH IN FAME – BIOLEACHING 1

BIOLEACHING FOR LITHIUM MICA PROCESSING? THE FIRST APPROACH

$$2S^0 + 3\,O_2 + 2\,H_2O \xrightarrow{A.\ thiooxidans} 2\,H_2SO_4$$

$$2\ KLiFeAl(AlSi_3)O_{10}F_{1,5}(OH)_{0,5} + 10\ H_2SO_4 \rightarrow K_2SO_4 + Li_2SO_4 + 2\ FeSO_4 + 2\ Al_2(SO_4)_3 + 0.75\ SiF_4 + 5.25\ SiO_2 + 10.5\ H_2O$$

$$4FeSO_4 + O_2 + 2\,H_2SO_4 \xrightarrow{A.\ ferrooxidans} 2\,Fe_2(SO_4)_3 + 2\,H_2O$$

Advantages:

- No roasting process
- Use of sulfur instead of sulfuric acid (availability)
- Accompanied oxidation of ferrous iron

Challenges:

- Inhibition of acidophiles
- Release of silica

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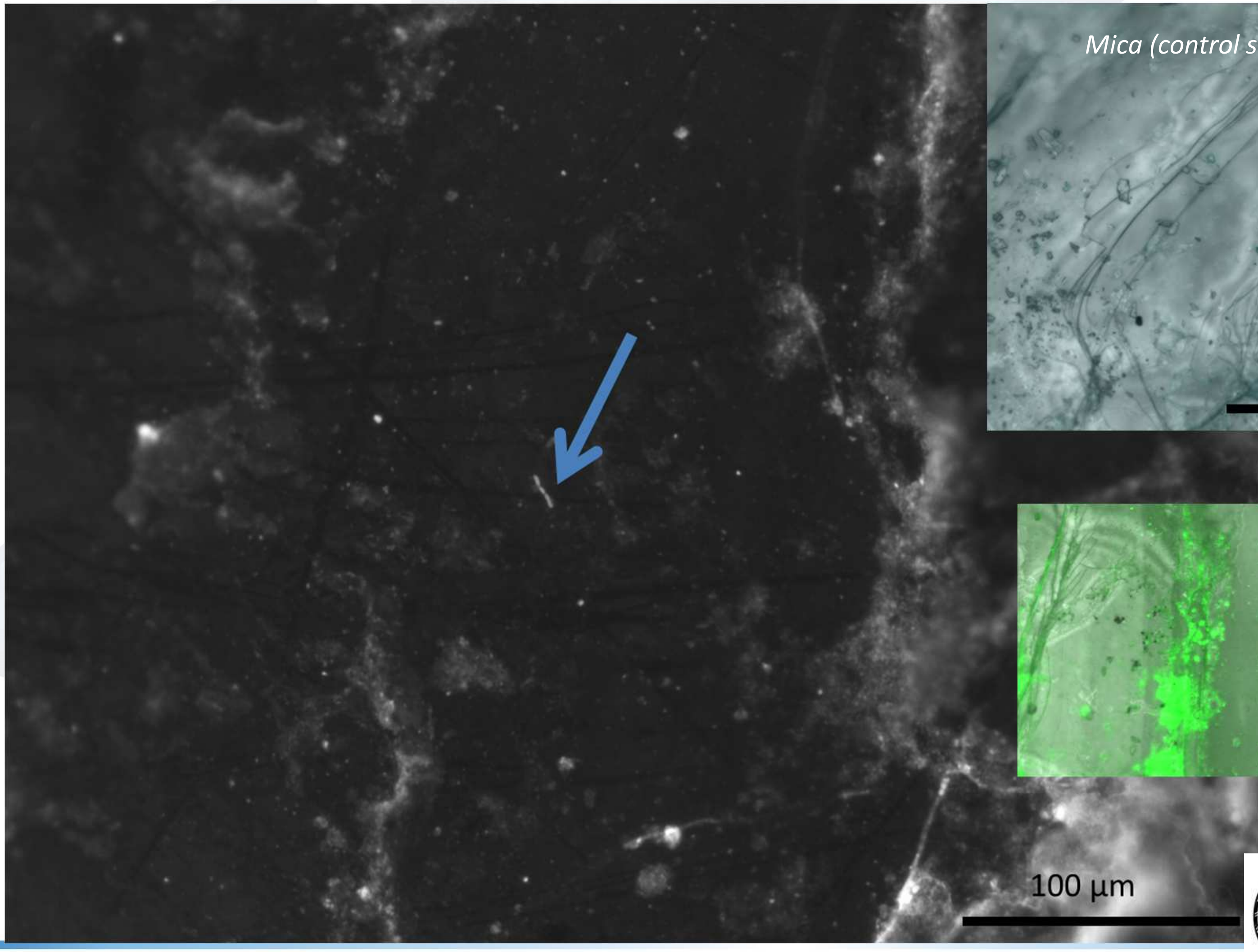
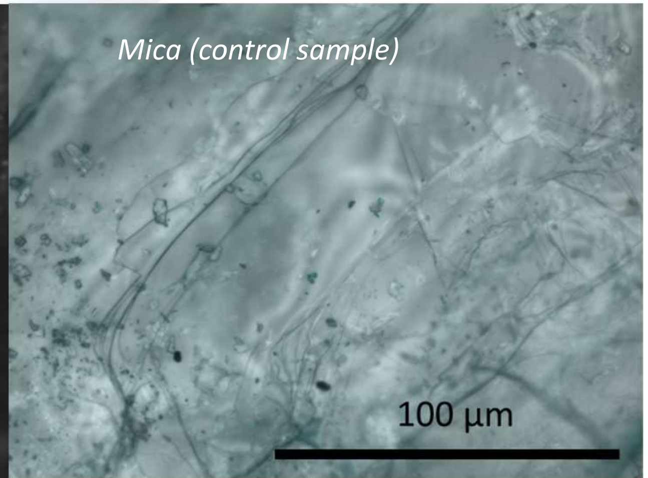
LITHIUM RESEARCH IN FAME – BIOLEACHING 2

BIOLEACHING – BIOFILM FORMATION





Stained microbes on surface of mica blade

Stained microbes on mica blade visualized by epifluorescence microscopy (Bellenberg, UDE)

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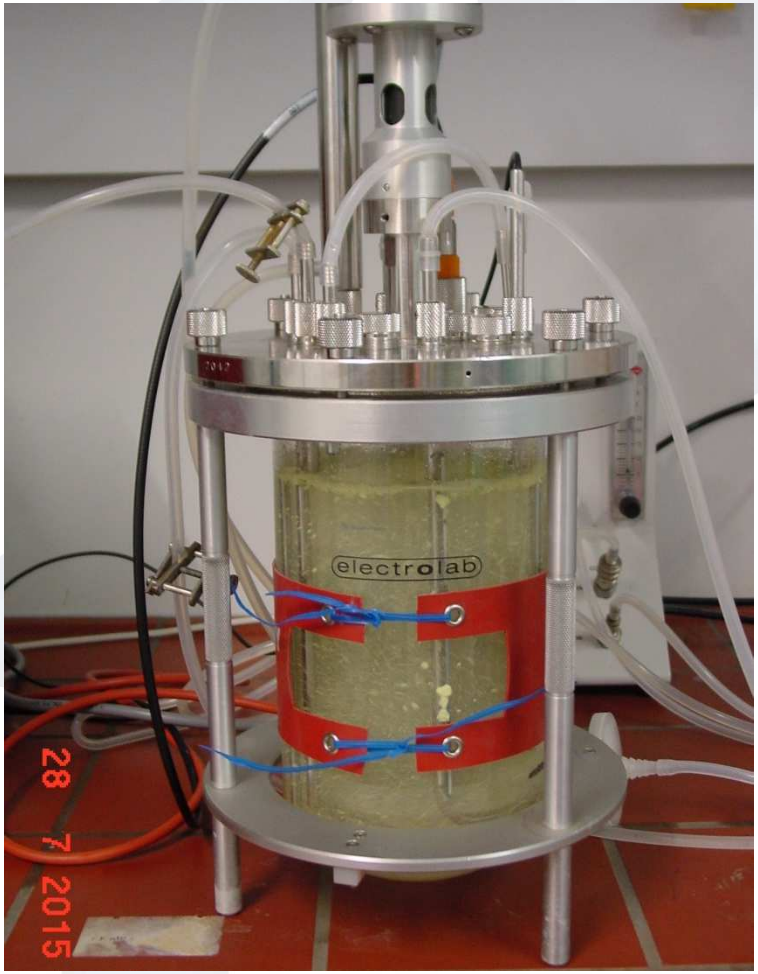
LITHIUM RESEARCH IN FAME – BIOLEACHING 3

BIOLEACHING – BATCH BIOREACTOR



Volume:	2 to 4 l
Pulp density:	5 % (zinnwaldite added at exponential growth phase)
Temperature:	30 °C
Medium:	DSMZ 71 + elemental sulfur (5 g/l)
Grain fraction:	<45 µm
Innoculation:	acidophilic mixed culture ($6.5\ 10^{-7}$)

Pure minerals (mica blade and crystalline sulfur) added to investigate biofilm formation)

Zinnwaldite (mica) grinded < 45 µm

Zinnwaldite (blade) and sulfur

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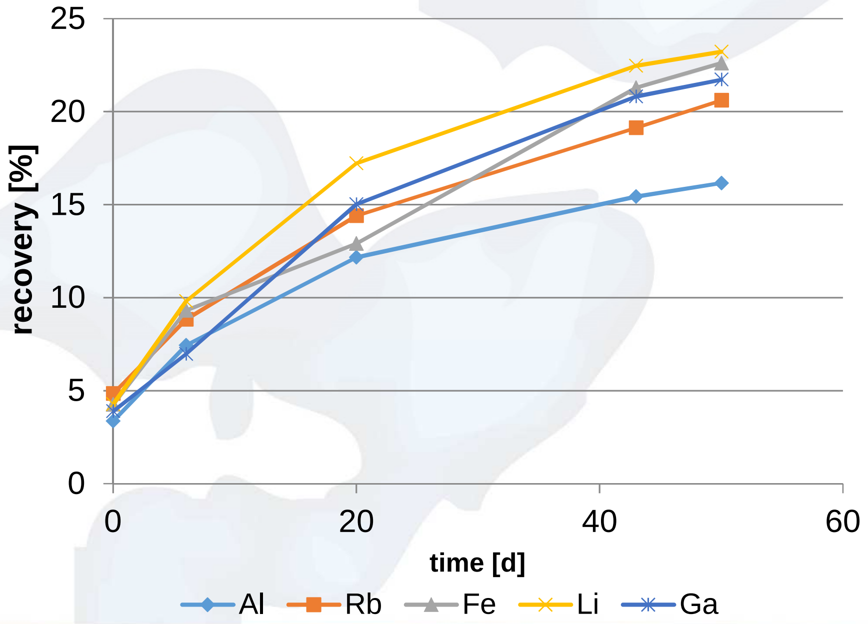
LITHIUM RESEARCH IN FAME – BIOLEACHING 4

BIOLEACHING – BATCH BIOREACTOR RESULTS

- Higher recovery of Lithium – 23 to 28%
- 50% of released Fe^{2+} oxidized to Fe^{3+}
- Final pH 1.4

Average results of two reactor runs:



Element	PLS bioleaching [mg/l]	Recovery bioleaching [%]	Recovery chemical leaching [%]
Al	1010	16.16	11.62
Rb	98	20.61	16.92
Fe	850	22.61	14.61
Li	155	23.22	15.82
Cs	2.5	20.92	10.39
Ga	1.2	21.72	11.4

PLS processing:

- Increase of pH
- precipitation of aluminium and iron hydroxides
- Alongside: precipitation of gypsum
- Membrane filtration
- Li_2CO_3 precipitation

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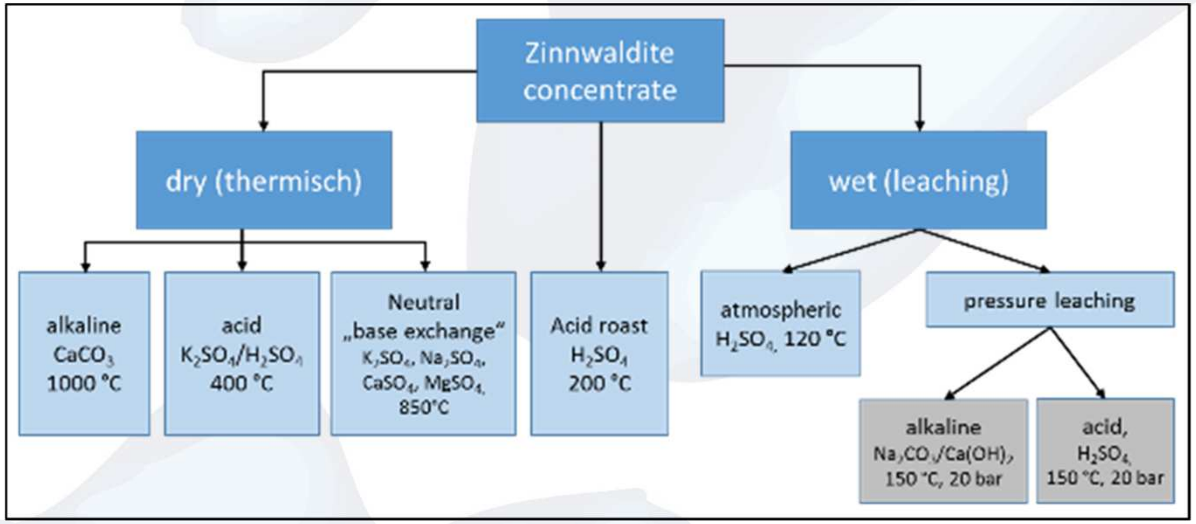
LITHIUM RESEARCH IN FAME CHEMICAL PROCESSING – 1

Overview of Potential Chemical Processing Routes for Lithium Processing from Micas or Spodumene



Overview of the technologies for lithium silicate digestion

FAME EXAMPLE: SULFURIC ACID LEACHING TESTS ON ZINNWALDITE MICA:

Leaching recovery (%)	
<u>Li</u>	<u>96</u>
Fe	73
K	58
Ga	78

→ Good Li recovery

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LITHIUM RESEARCH IN FAME
CHEMICAL PROCESSING – 2

DRY ROAST PROCESSING OF LEPIDOLITE

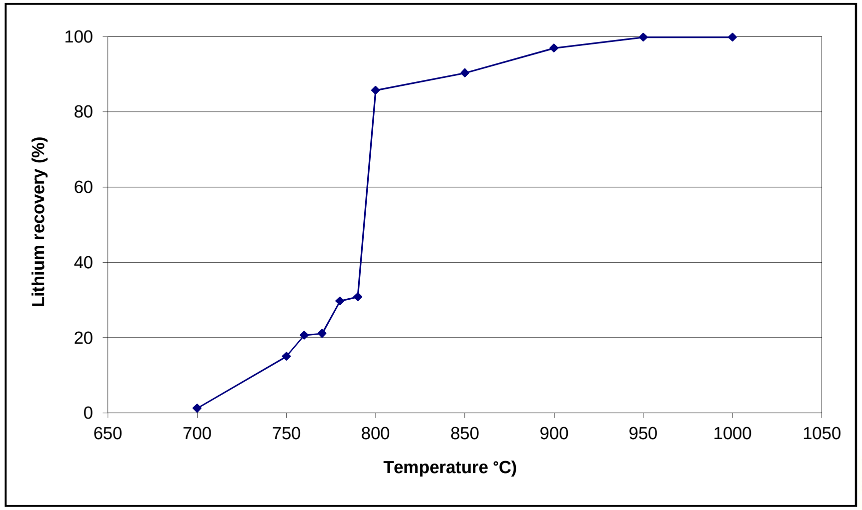
Testing Procedure:

- Mixing of lepidolite with additives
- Roasting in muffle furnace
- Cooling
- Crushing
- Leaching with water (90°C)
- Analysis for Li to determine recovery rate
- Evaporating
- Hot precipitation of Li_2CO_3

Digestion with CaSO4 / CaCO3 (950 °C)

Digestion with Na2SO4 (1050 °C) → partial melting!

Example: Roasting of lepidolite with $CaSO_4$ / Na_2SO_4



Lithium recovery related to roast temperature

LITHIUM RECOVERY REACHES 100 %

Lithium Carbonate from Gonçalo Lepidolite

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FUTURE WORK

PILOT TESTING OF GONÇALO ORE Li-MICA FLOTATION

- BENCH SCALE FLOTATION TESTS
  SUCCESSFUL IN PRODUCING 6% $Li_2 0$ CONCENTRATE
- PILOT TESTS OF Li-MICA FLOTATION TO CONFIRM ECONOMIC VIABILITY
  AS WELL AS FINANCIAL VIABILITY
- TESTS PLANNED FOR Q2 2018 ON SITE IN PORTUGAL

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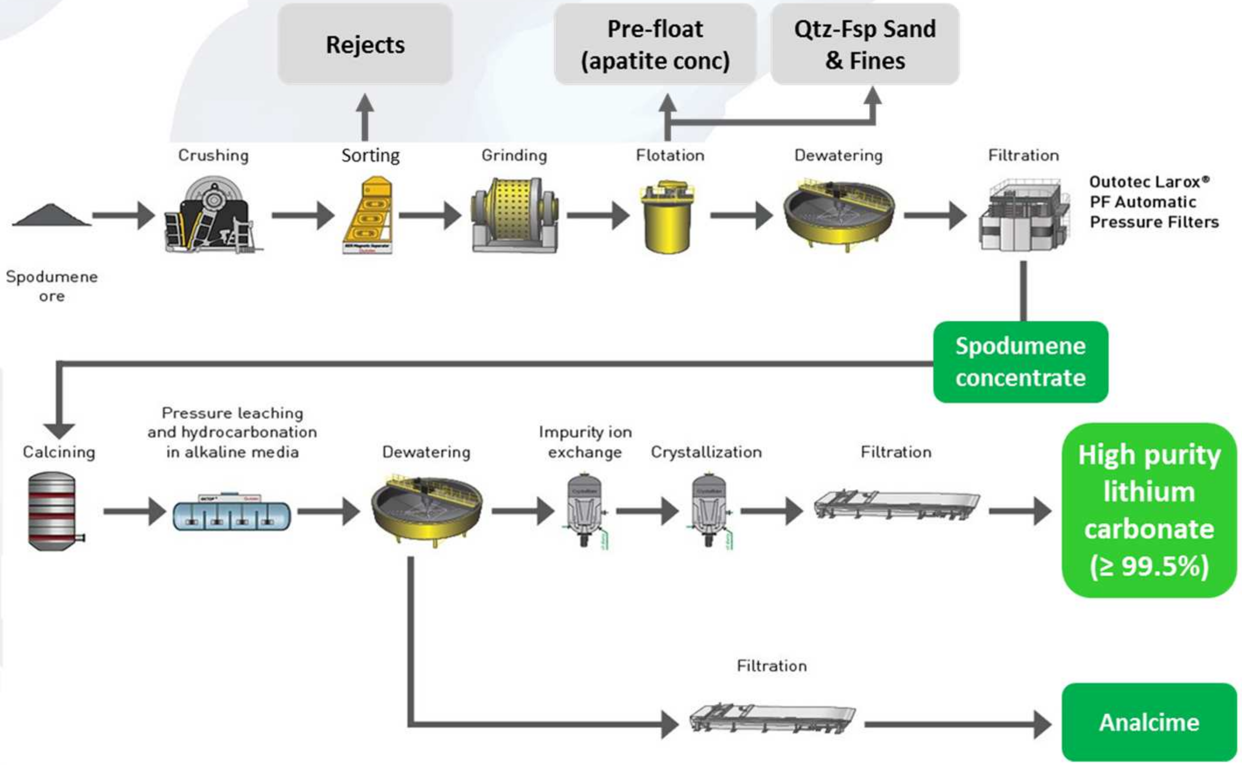
CURRENT KELIBER PROCESS FLOWSHEET

- LATE STAGE EXPLORATION COMPANY AND FAME PARTNER
- AIM TO ENTER PRODUCTION 2019/20
- Ca. 10% of Current World Supply



Proposed flowsheet for Keliber, from P. Lamberg, October 2017

CONCLUSIONS

- FAME: ACTIVE IN THREE REFERENCE ORES WHICH CONTAIN Li
- KELIBER: ON SCHEDULE TO BECOME A EUROPEAN Li PRODUCER IN 2019
- CINOVEC: PFS CONCLUDES POTENTIAL TO BE ONE OF LOWEST COST HARD ROCK Li PROJECTS
- MICA FLOTATION: TO BE TESTED AT PILOT SCALE 2018 ON GONÇALO ORE
- FAME WILL HAVE CONTRIBUTED SIGNIFICANTLY TO THE VALORISATION OF EUROPEAN LITHIUM ORES

Samples showing spodumene from Keliber

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THANKS FOR YOUR ATTENTION

CHEERS FROM THE FAME TEAM

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