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The Genesis of Rare Earth Element Ore Deposits

By

A.E. Williams-Jones

Department of Earth and Planetary Sciences
McGill University, Montreal, Canada

The REE and the Periodic Table

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub	114 Uuq					

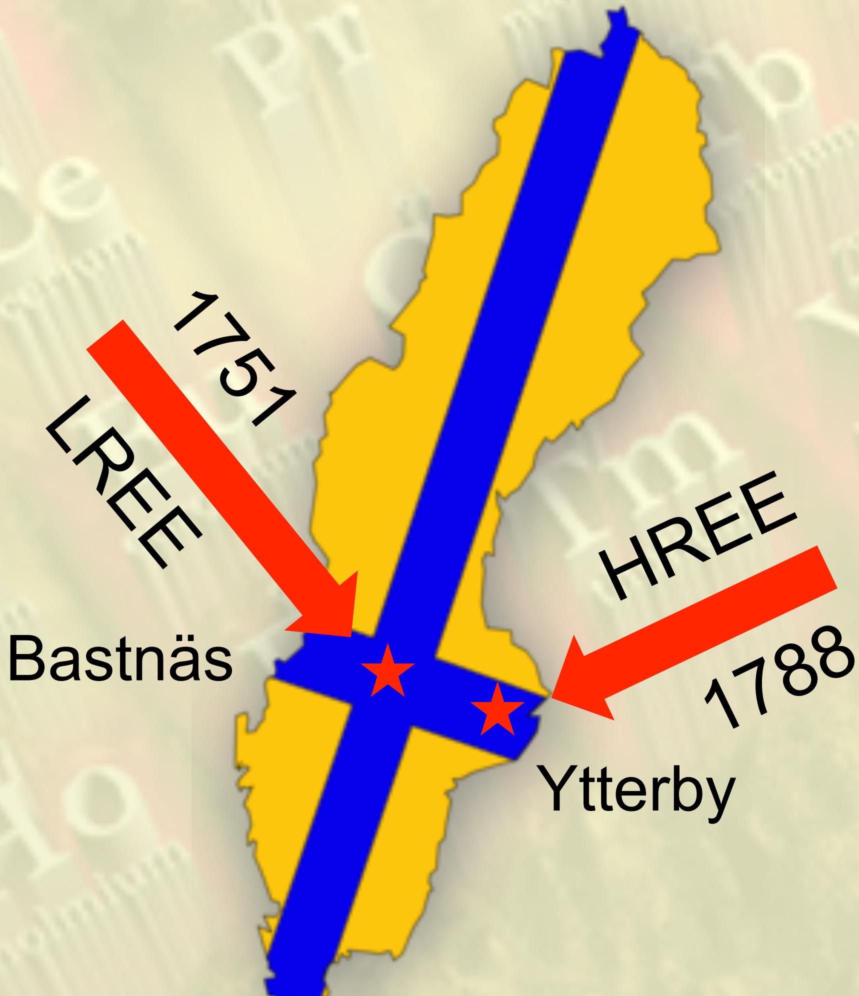
Light REE **Heavy REE**

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Ytterby and Bastnäs

"Ceria"

Wilhelm Hisinger



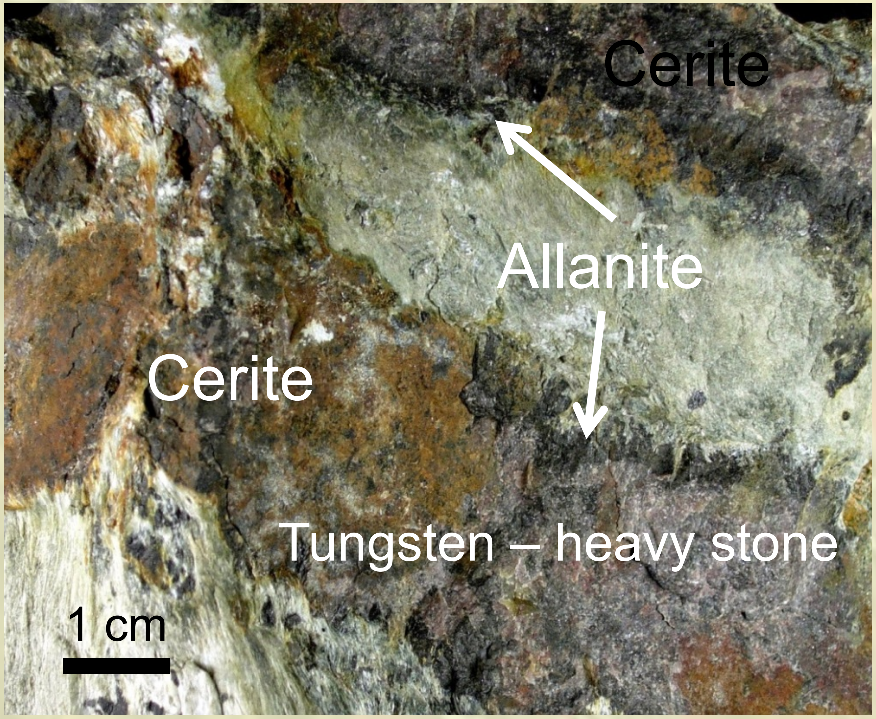
"Yttria"

Johan Gadolin

A Tale of Ceria and Yttria

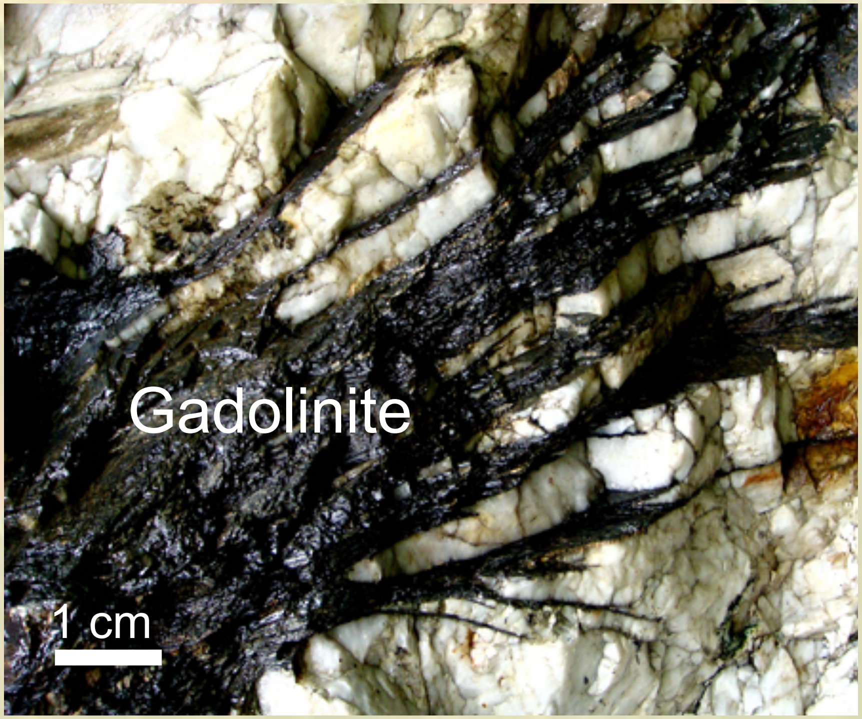
Bastnäs (Skarn)

Cerite $\{Ce_9(Fe,Mg)Si_7O_{27}(OH)_4\}$

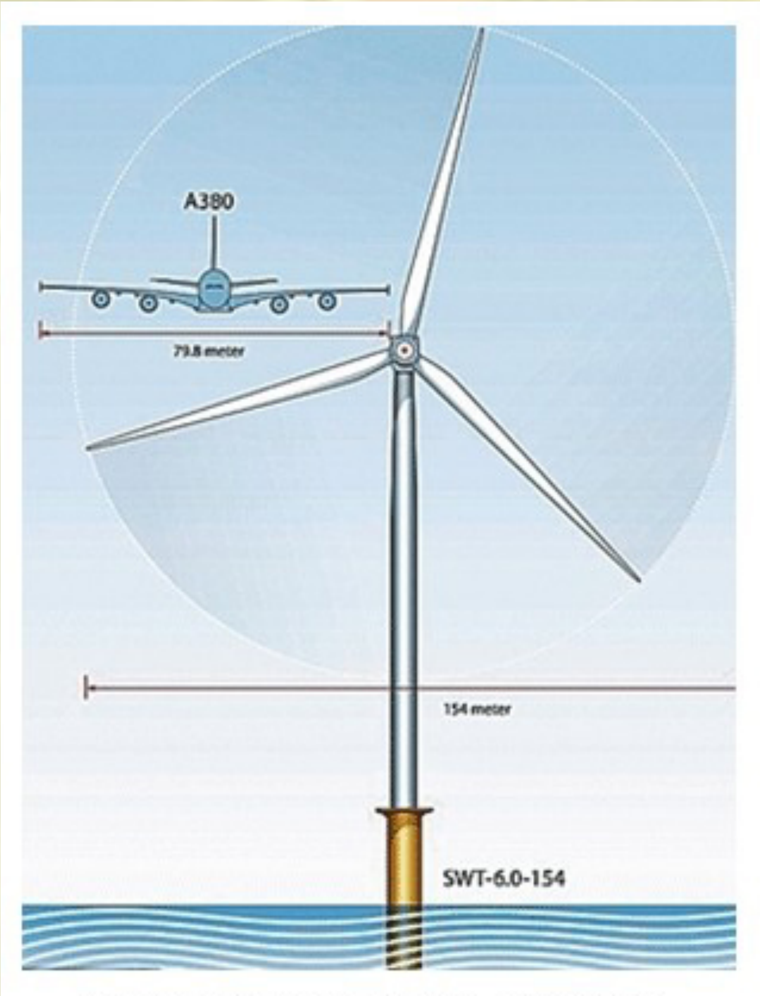


Ytterby (Pegmatite)

Gadolinite $\{Y_2FeBe_2Si_2O_{10}\}$



The REE and Wind Power



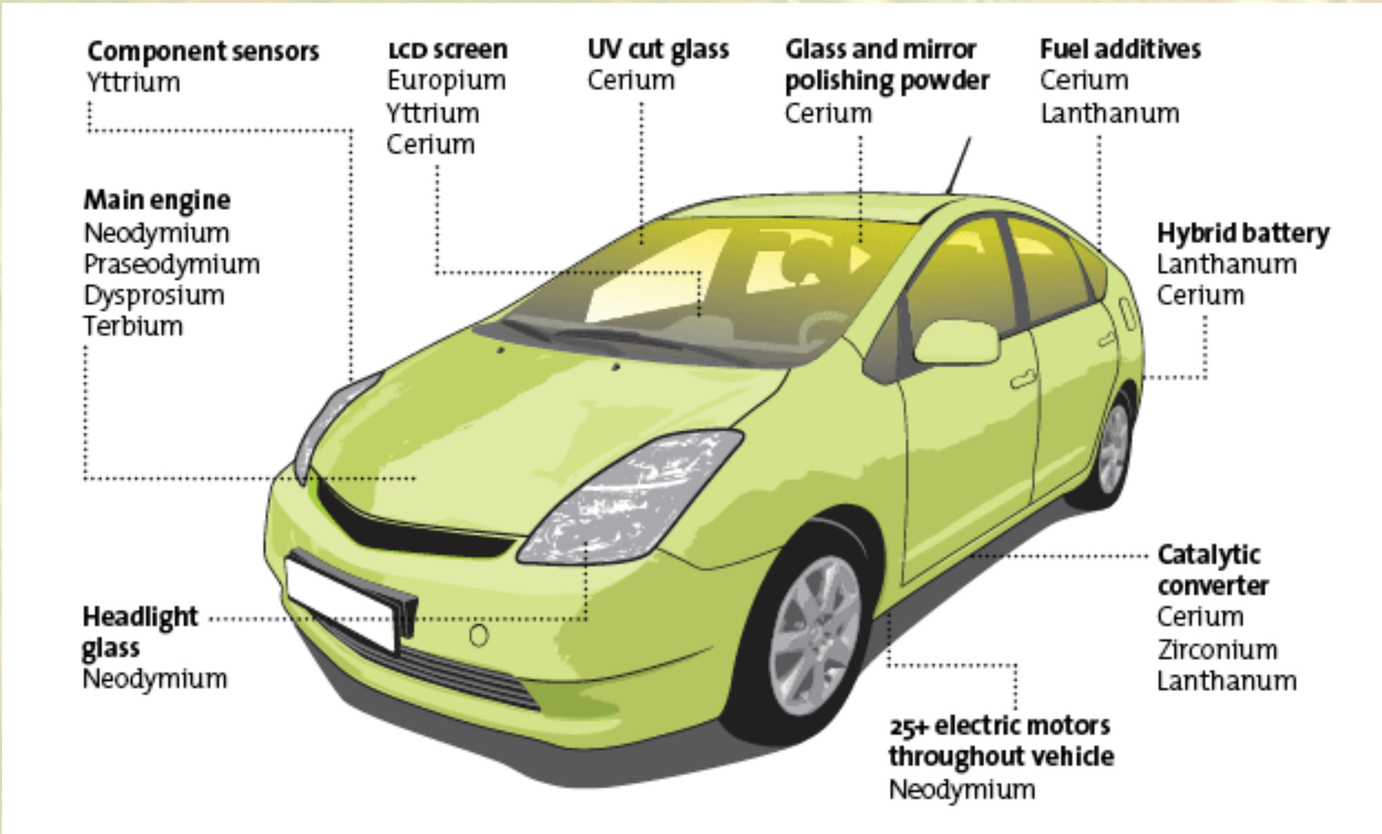
Wind power now supplies 11.4% of the European Union's electricity (128,752 MW); growing at 15.6% /yr.

In the U.S., it supplies 4.4% of electrical energy (65,879 MW); also growing at 15.6%/yr.

In Canada, it supplies 4% of electrical energy (9,694 MW); growing at 19.3%/yr.

Wind turbines are driven by $(Nd,Dy)_2Fe_{14}B$ magnets that require 730 Kg of Nd and Dy per MW.

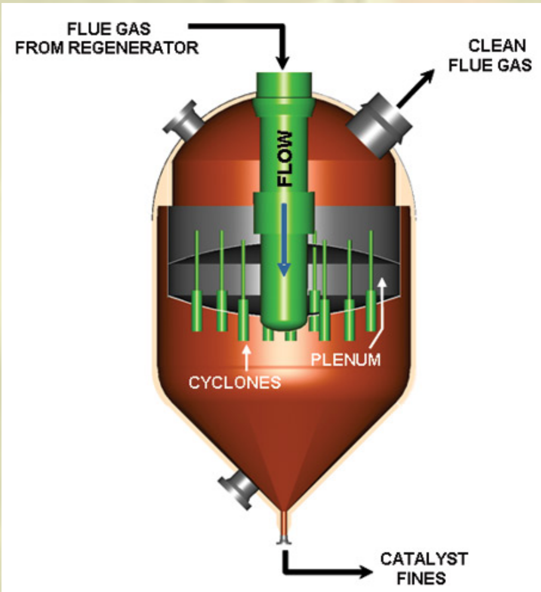
The REE and Hybrid Cars

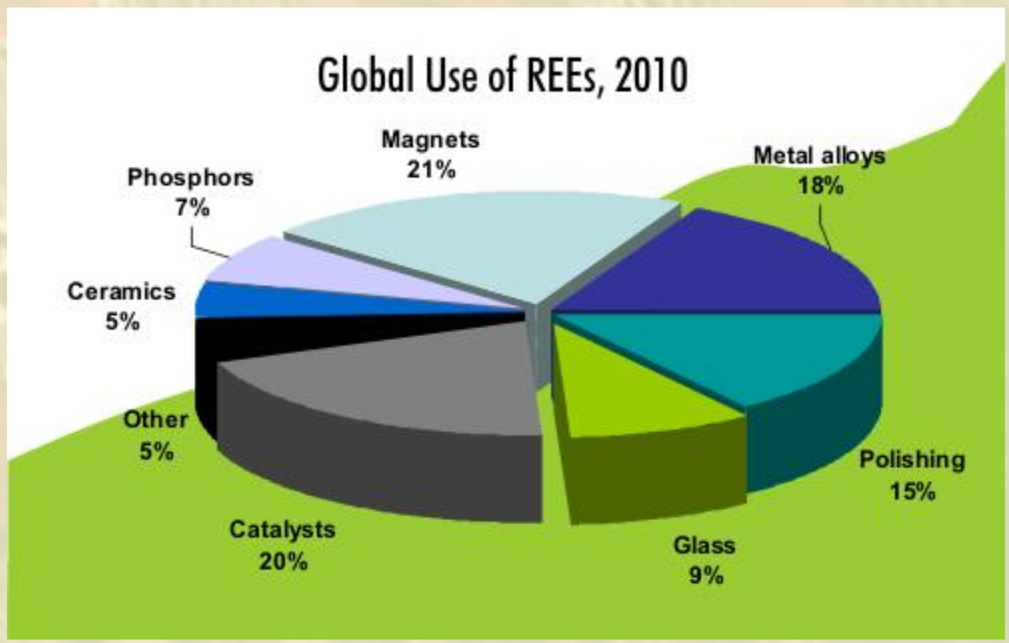


Each hybrid / electric car consumes ~28 Kg of REE mainly in magnets and La-Ni-hydride batteries

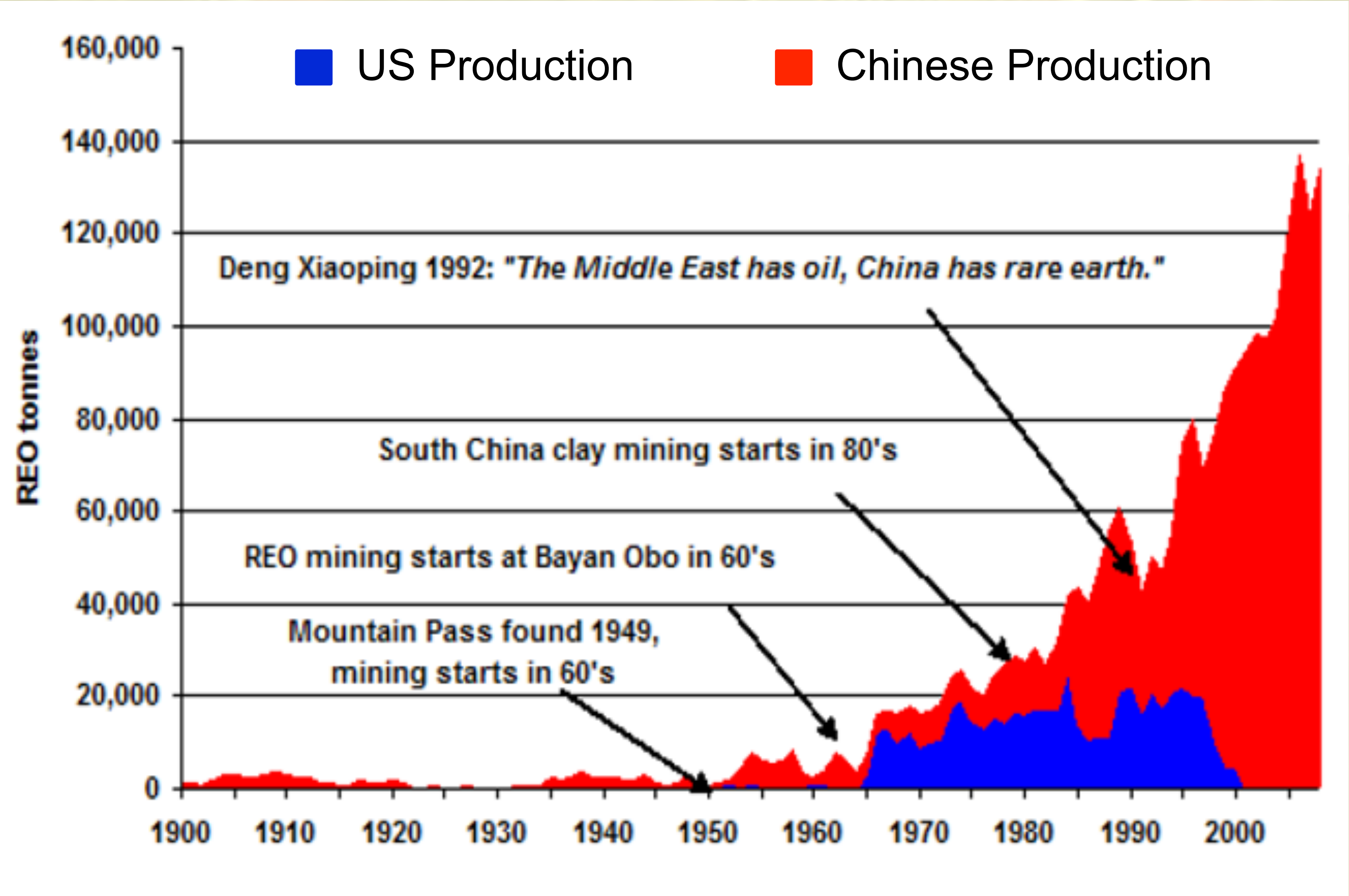
During 2013 hybrid car sales in the US totalled 500,000 units up 14% from 2012 , representing 3% of new car sales.

Some Other Uses of the REE





The Strategic Importance of the REE

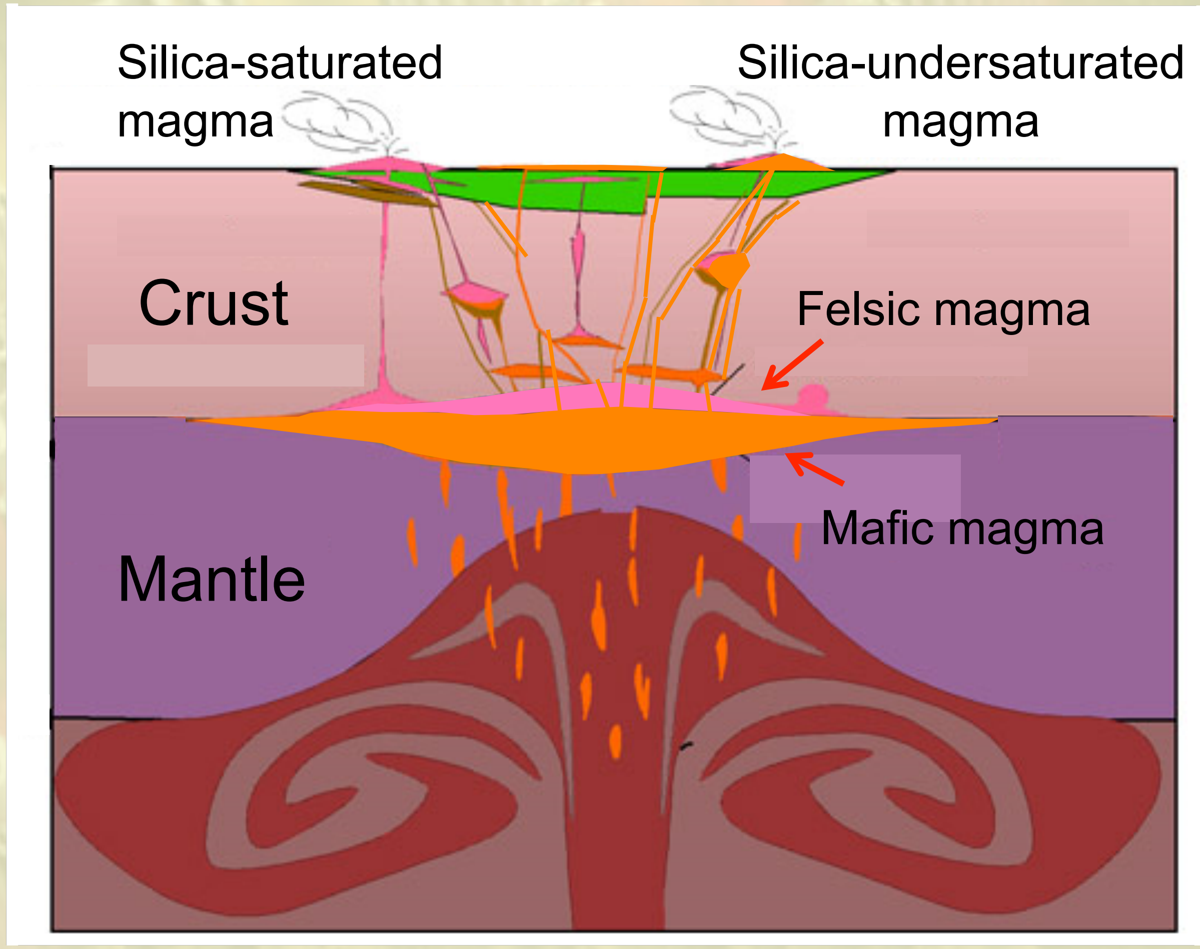


Rifts, Mantle Plumes and the REE

1. A REE/HFSE, volatile rich (H_2O,CO_2, Cl, F,) mantle.
2. Low degrees of partial melting, produces F-REE-HFSE-rich peralkaline mafic silicate magmas, carbonatites,
3. Crust metasomatised by mantle fluids produces REE/HFSE felsic melts

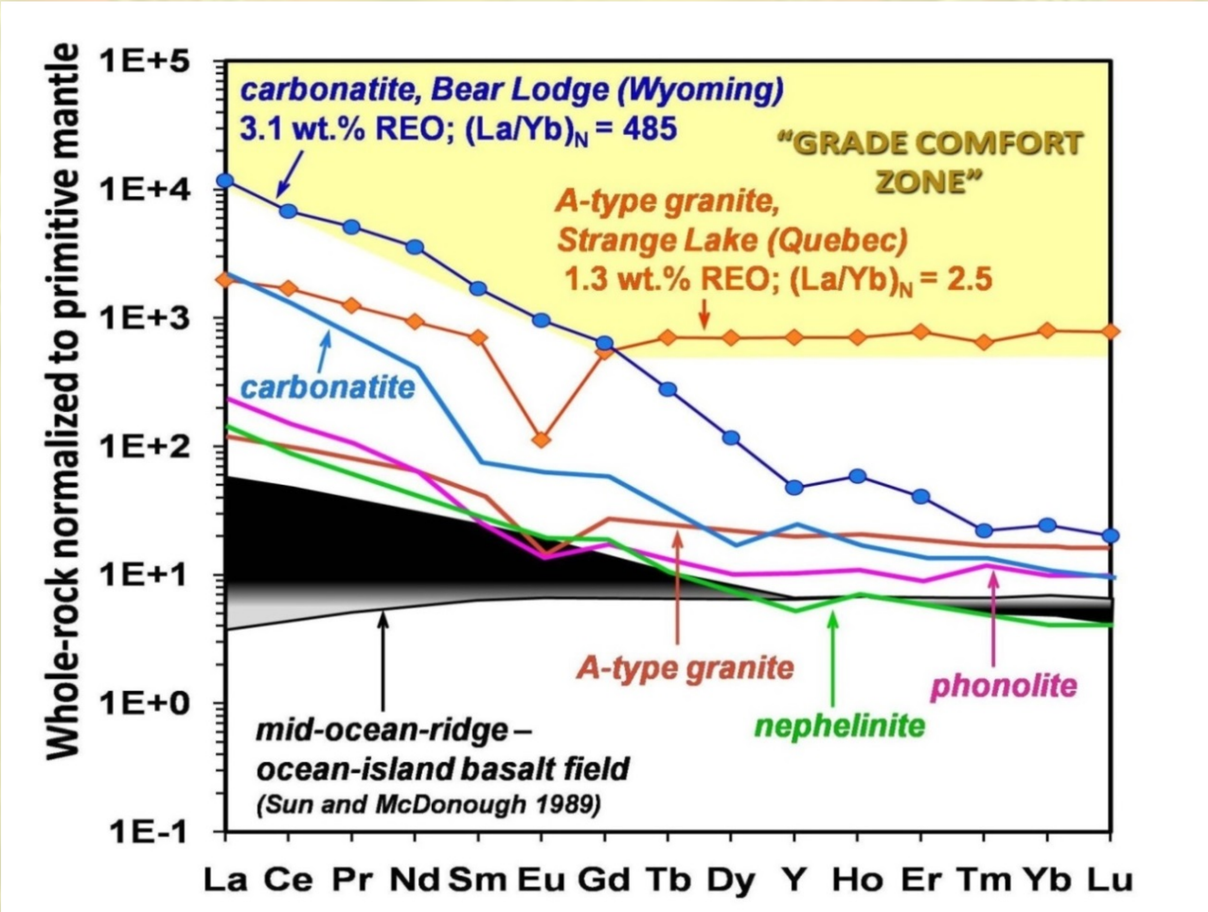
Peralkaline Granites

Carbonatites, Nepheline Syenites



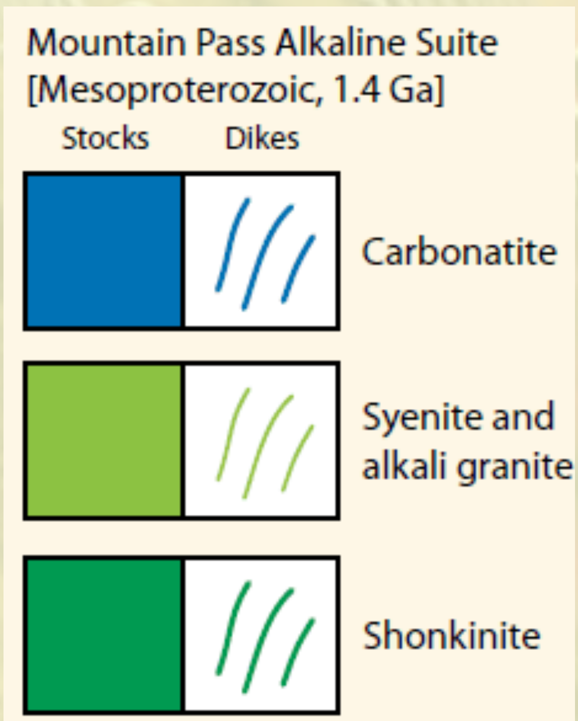
LREE and HREE – Carbonatites and Peralkaline Silicate Igneous Rocks

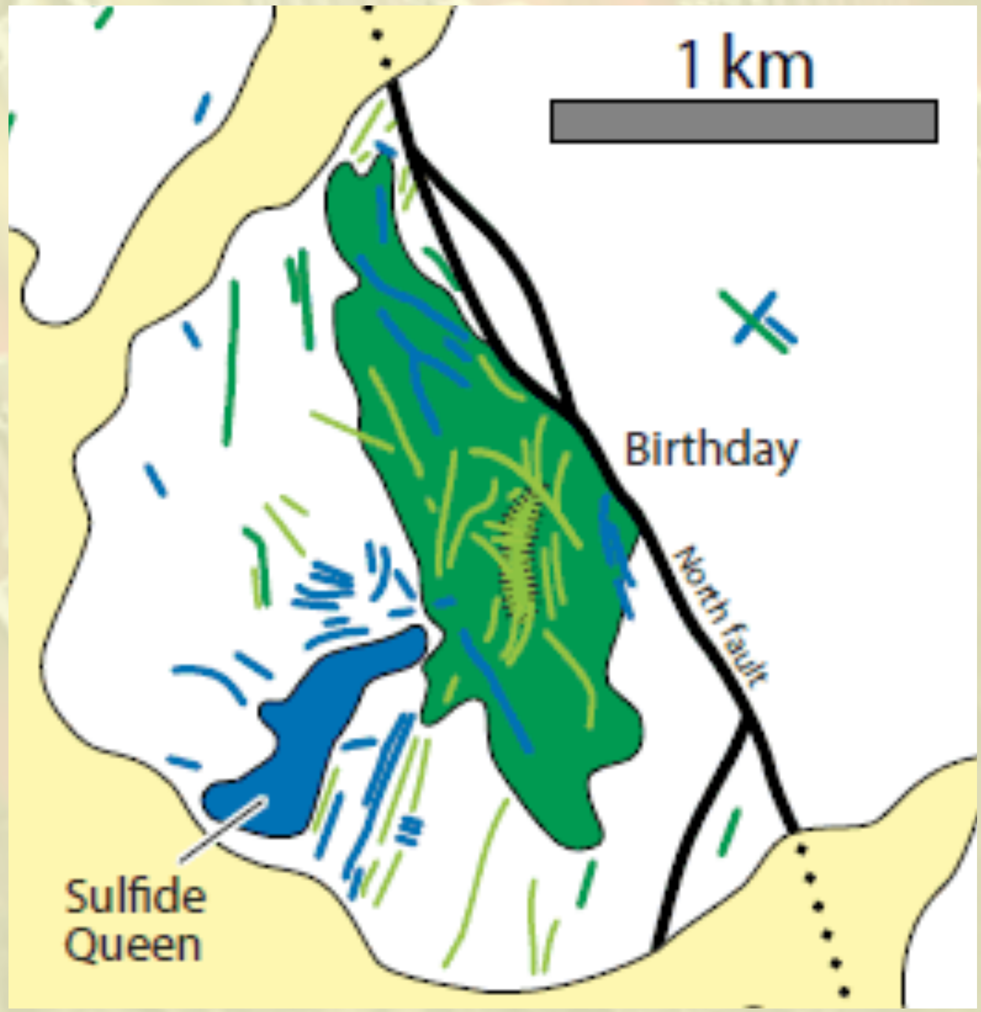
LREE are more incompatible (higher Z/r) than HREE and will concentrate in the first partial melts or last residual liquids of crystallisation – carbonatites.



The Mountain Pass LREE Deposit

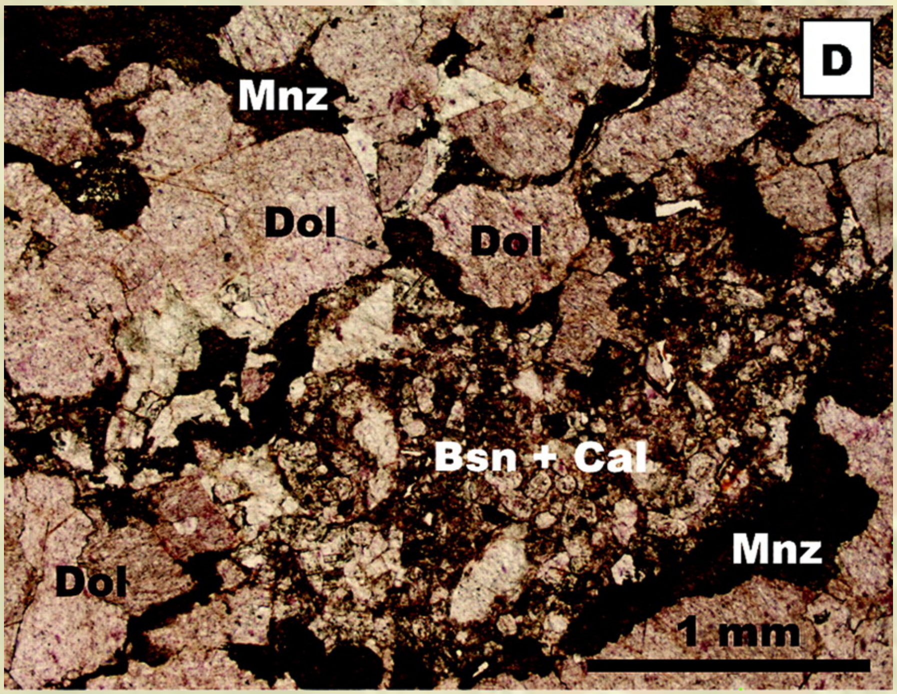
Reserves: 18.4×10^6 tons @ 7.98 wt.% $TREE_2O_3$

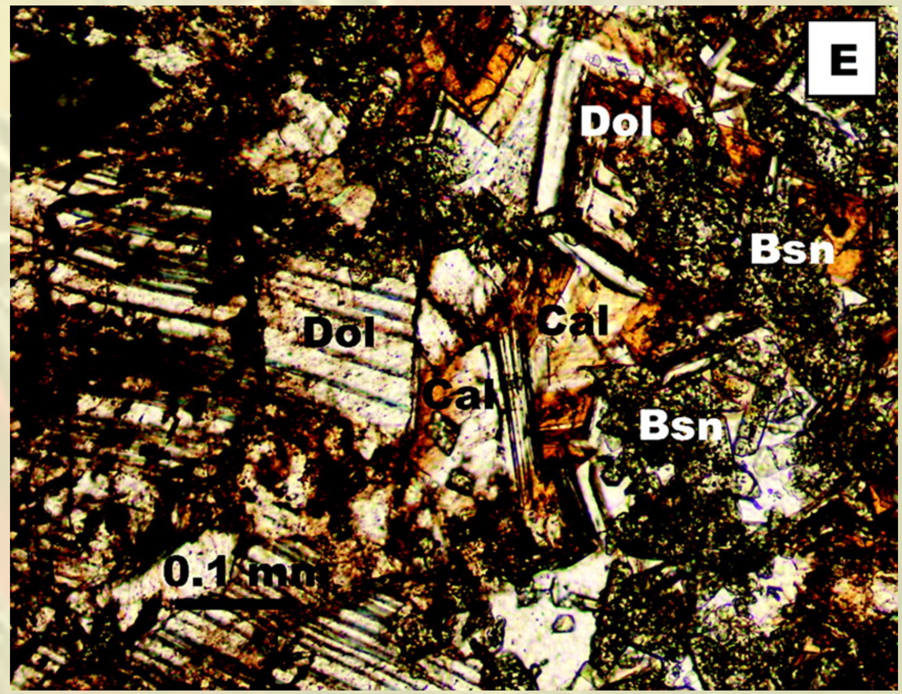




Dolomite Carbonatite LREE Ore

Bsn: Bastnäsite-(Ce) {$REECO_3F$}   Mnz: Monazite-(Ce) ($REEPO_4$)



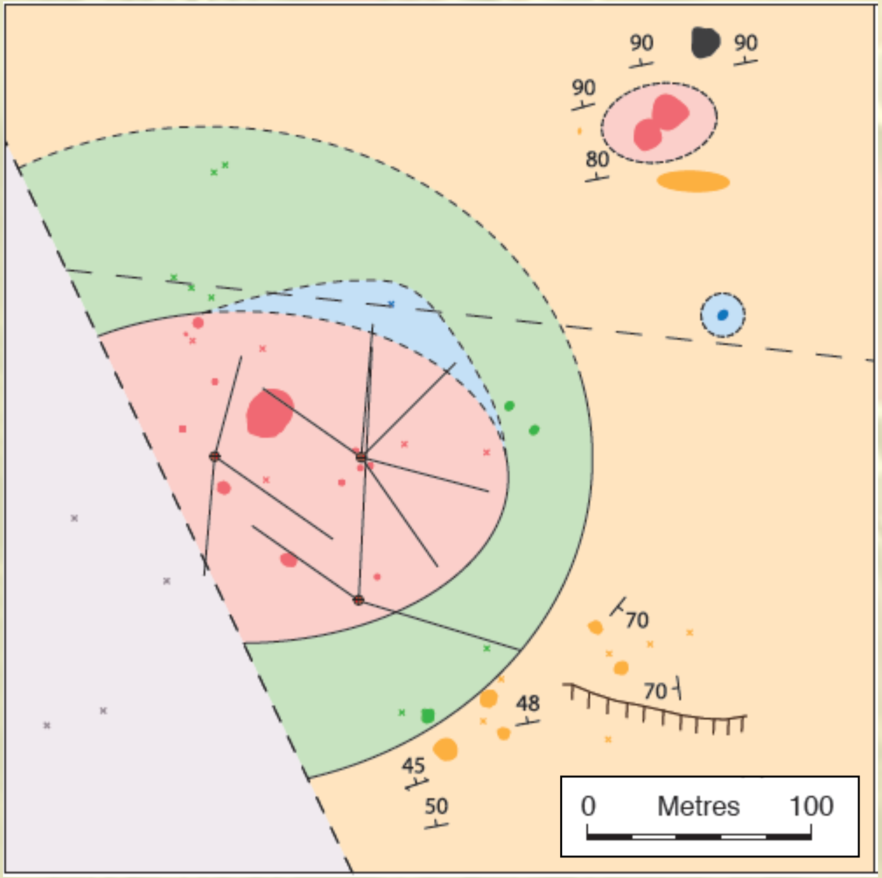


Castor (2008)

The REE mineralisation is generally thought to be magmatic, e.g., Castor (2008). However, an experimental study by Gysi and Williams-Jones (2015) shows that bastnäsite-(Ce) decomposes at 338 °C!!

The Wicheeda LREE Deposit, British Columbia

Resource: 11.3 million Mt grading 1.95 wt.% TREO



Late Jurassic

Wicheeda Complex

- Grey sodic fenite with blue amphibole, rare biotite, and altered apatite
- Grey potassic fenite with brownish monazite-rich zones
- White to grey medium-grained calcite carbonatite with flow banded biotite
- (Dsy) Cream to white coarse-grained dolomitic carbonatite with rare biotite and rare chloritized xenoliths up to 10 cm in diameter
- Medium green flow-banded felsic dyke

Cambrian to Ordivician

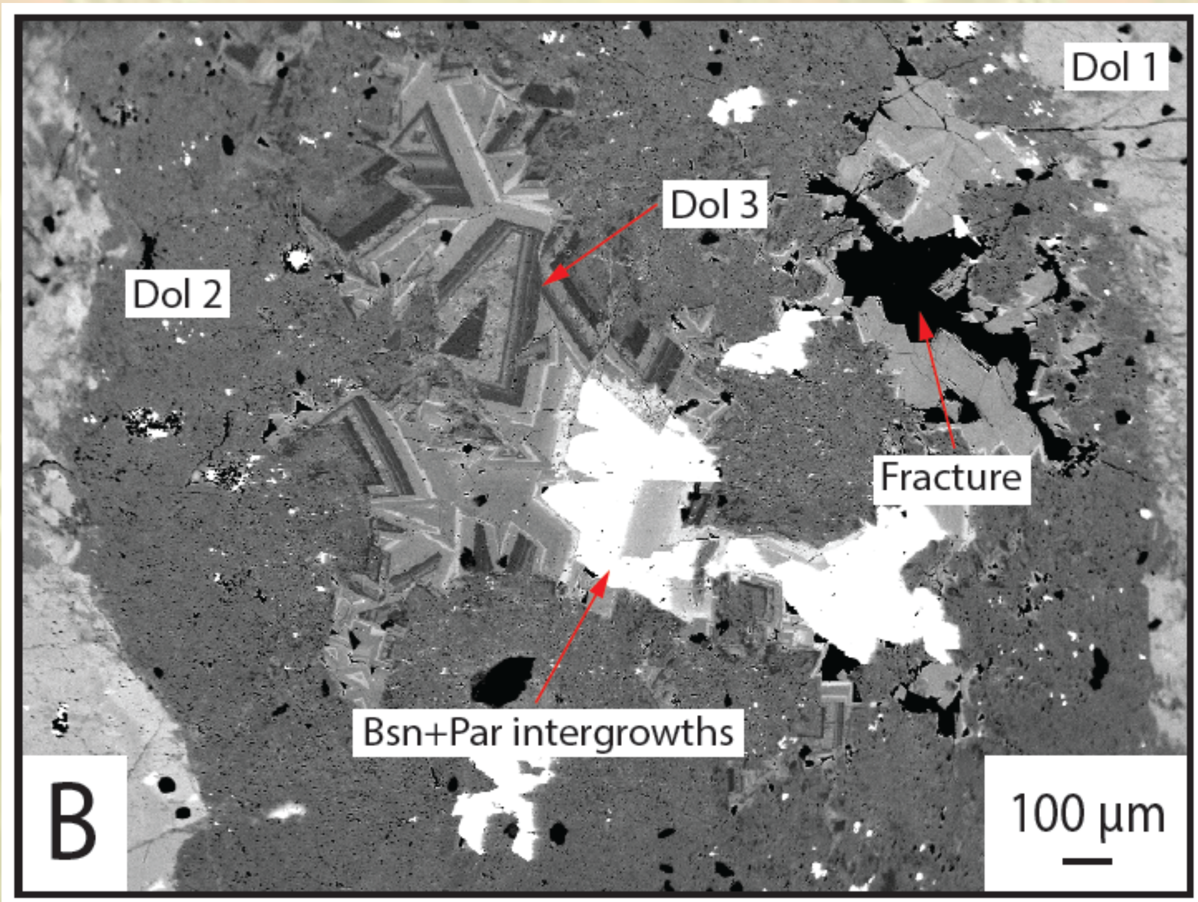
Kechika Group

- (CmOKlc) Grey slate with rare dolomite infill on slatey cleavages

Three Stages of Dolomite

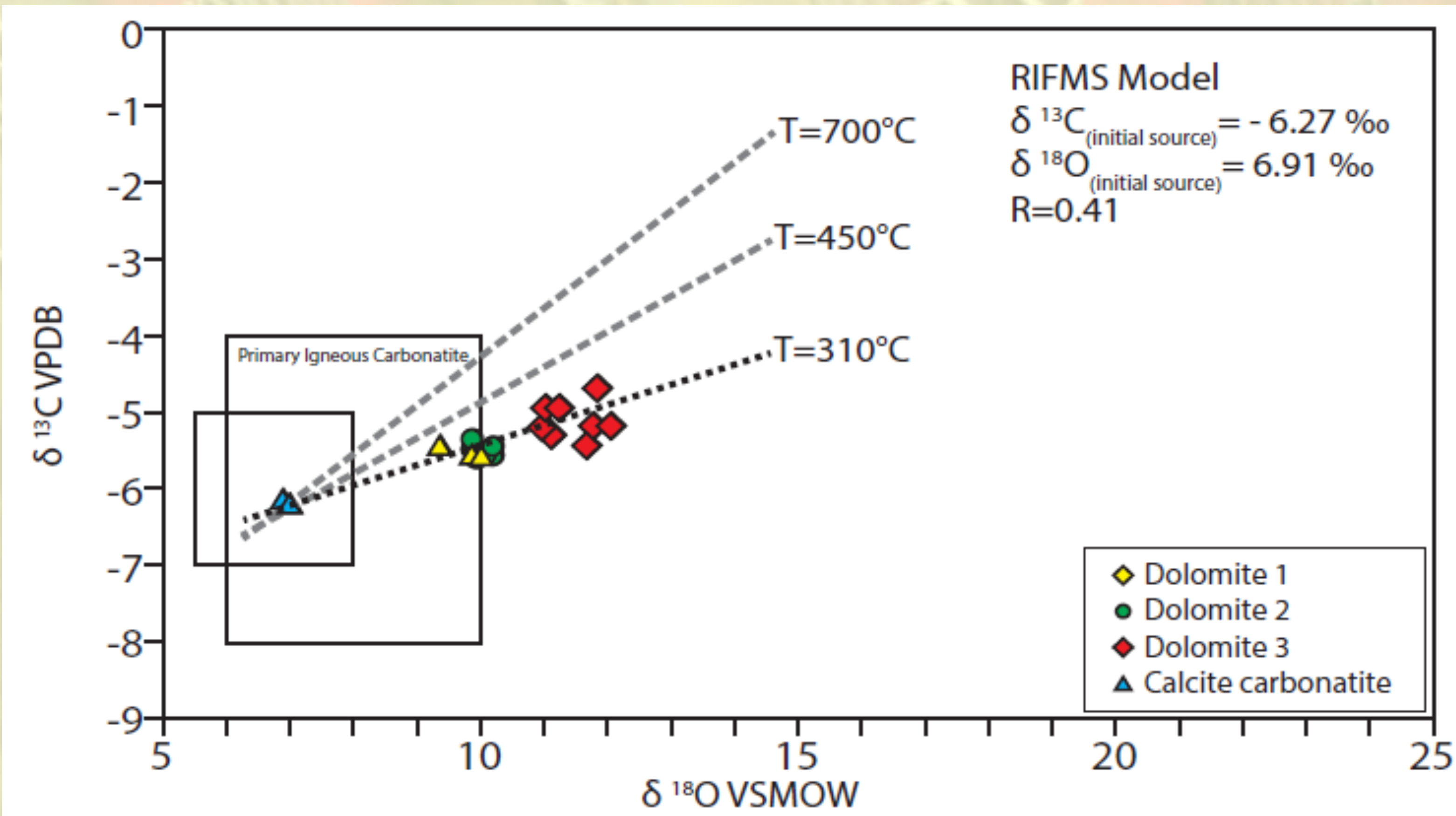
Dolomite 1 (Primary); Dolomite 2 (Hydrothermally altered Dolomite 1); and Dolomite 3 (Hydrothermal dolomite filling vugs)

Bastnäsite-(Ce) {$REECO_3F$} and parisite-(Ce) {$CaREE_2(CO_3)_3F_2$}



Isotopic Evolution of the Carbonates

Application of the Raleigh Distillation Model of Ray and Ramesh (2000) assuming that the carbonatite "stewed in its own juices" and that the fluid. contains equal proportions of H_2O and CO_2.



Trofanenko et al.. (in press)

Lofdal, a HREE-rich Deposit Classified as Carbonatite-Hosted

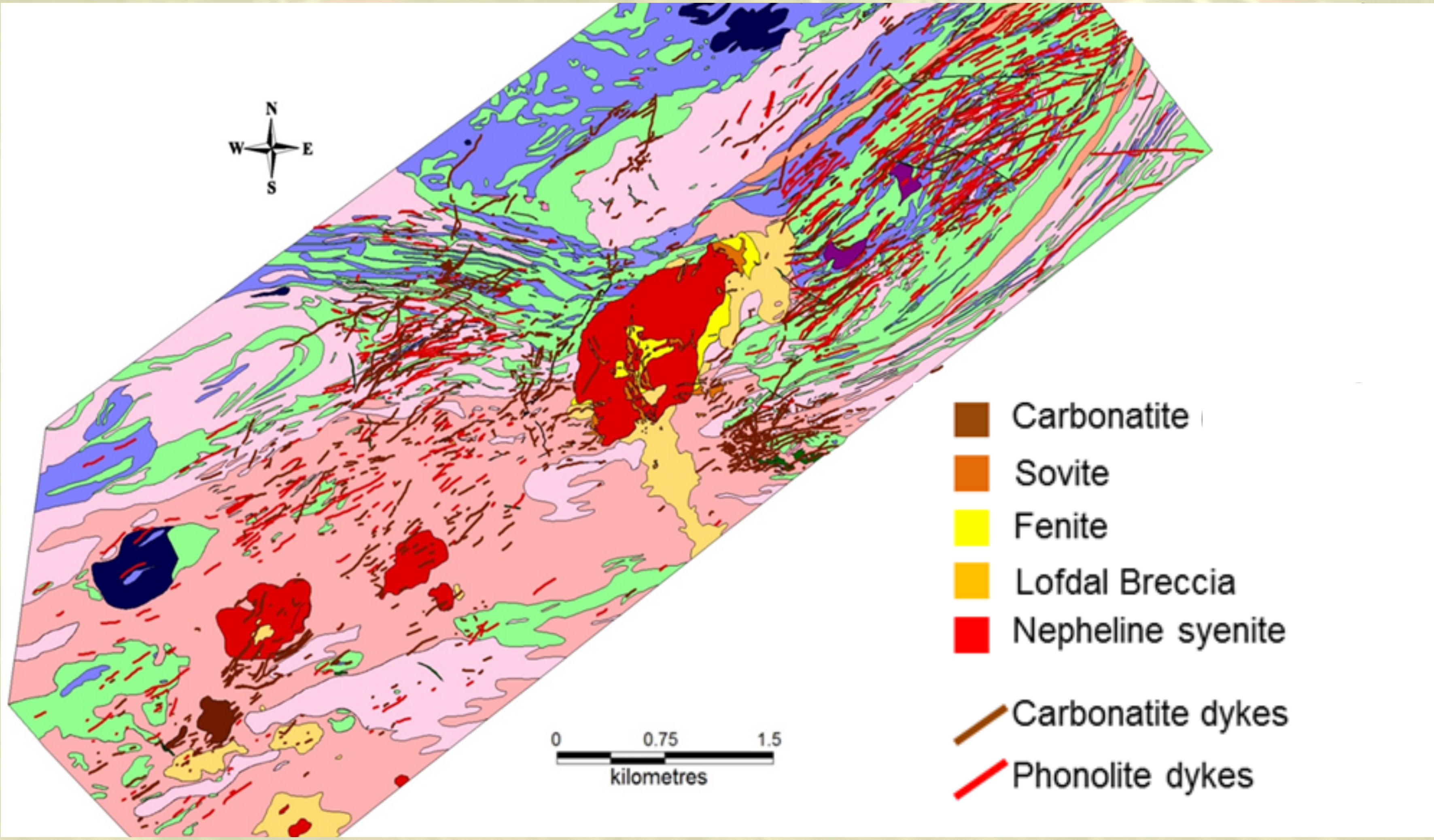
In-situ **Indicated Mineral Resource**

Cut-Off %TREO	Tonnes million	LREO %	HREO %	TREO %	REO Tonnes	HREO Proportion
0.1	2.88	0.08	0.24	0.32	9,234	76.3%
0.2	1.62	0.09	0.37	0.45	7,358	80.9%
0.3	0.90	0.09	0.53	0.62	5,594	85.6%
0.4	0.58	0.09	0.69	0.78	4,477	88.3%
0.5	0.39	0.09	0.84	0.93	3,673	90.3%
0.6	0.28	0.09	1.00	1.09	3,039	91.8%
0.7	0.20	0.08	1.18	1.26	2,524	93.5%

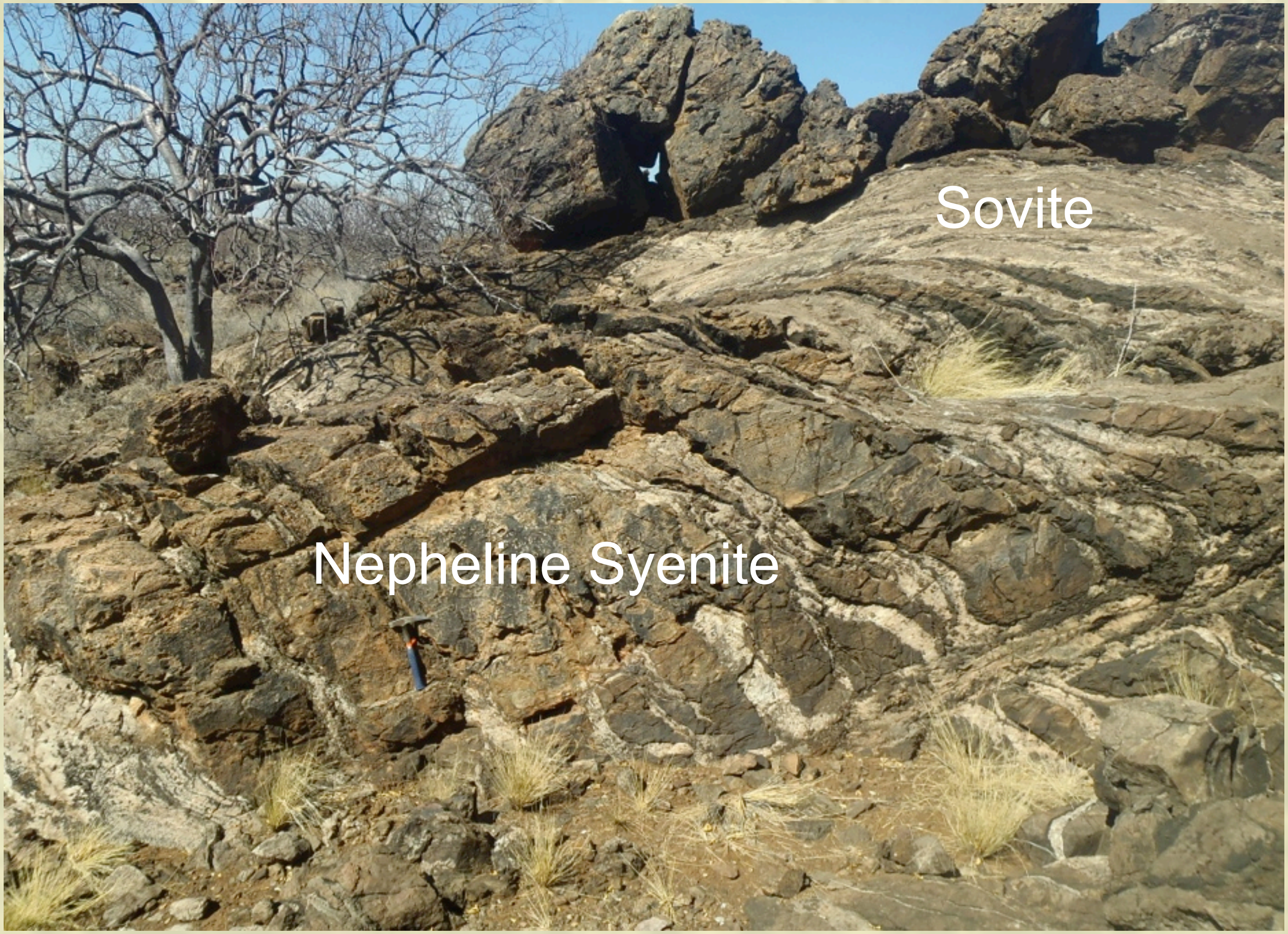
In-situ **Inferred Mineral Resource**

Cut-Off %TREO	Tonnes million	LREO %	HREO %	TREO %	REO Tonnes	HREO Proportion
0.1	3.28	0.07	0.20	0.27	8,973	74.7%
0.2	1.80	0.08	0.30	0.37	6,748	79.3%
0.3	0.75	0.08	0.47	0.56	4,180	85.1%
0.4	0.42	0.08	0.64	0.72	3,071	88.8%
0.5	0.27	0.08	0.81	0.89	2,377	90.9%
0.6	0.21	0.08	0.91	0.99	2,049	92.1%
0.7	0.16	0.07	1.03	1.10	1,717	93.5%

Lofdal Geology



Sovite Dykes Intruding Nepheline Syenite in the Main Intrusion

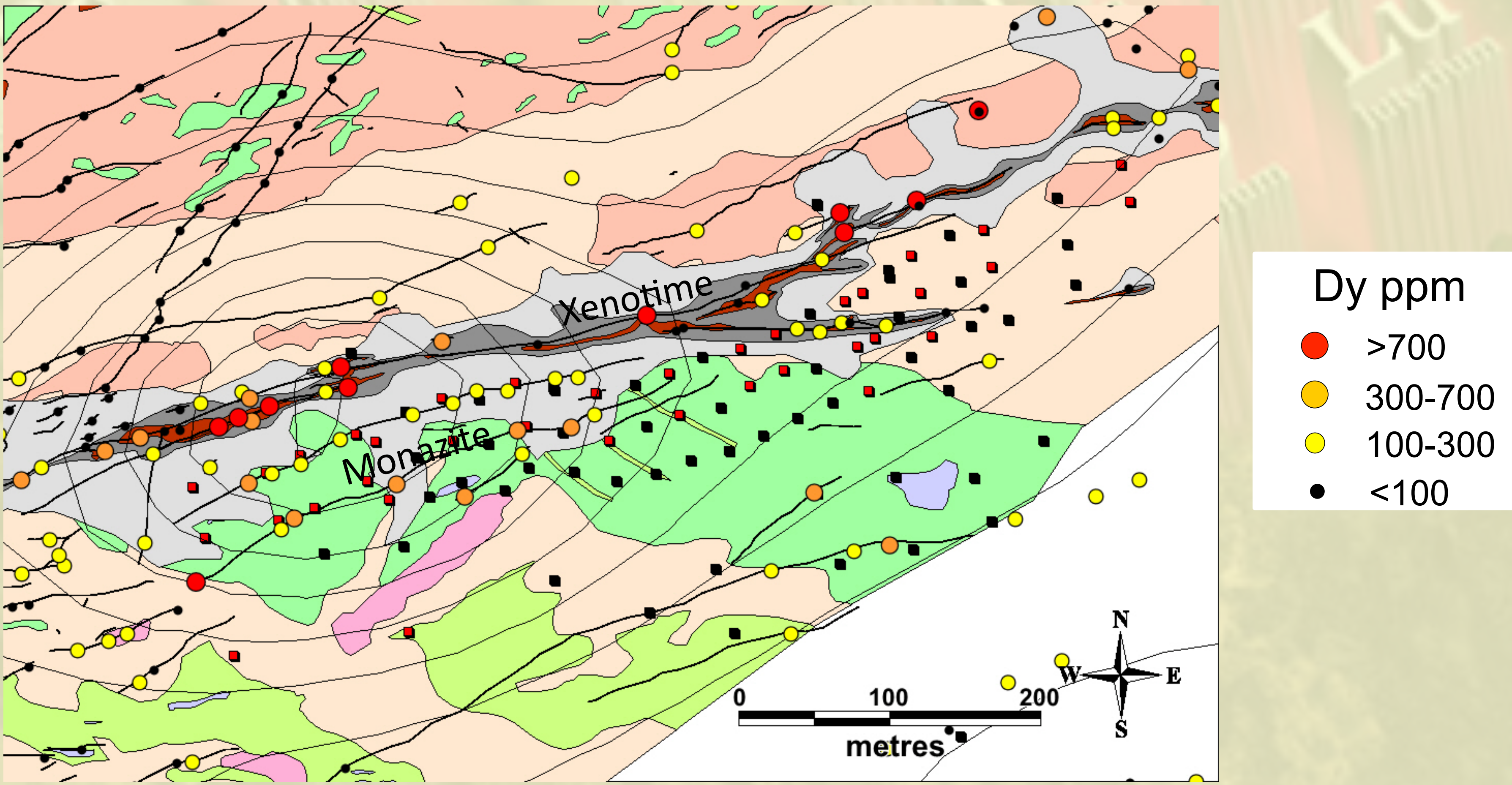


REE-Mineralised Structures

The REE mineralised structures give the appearance of ferrocarbonatite dykes but are instead fault-controlled sodic fenites (albitites) that have been altered to calcite and/or ankerite. The red colour reflects pyrite oxidation.

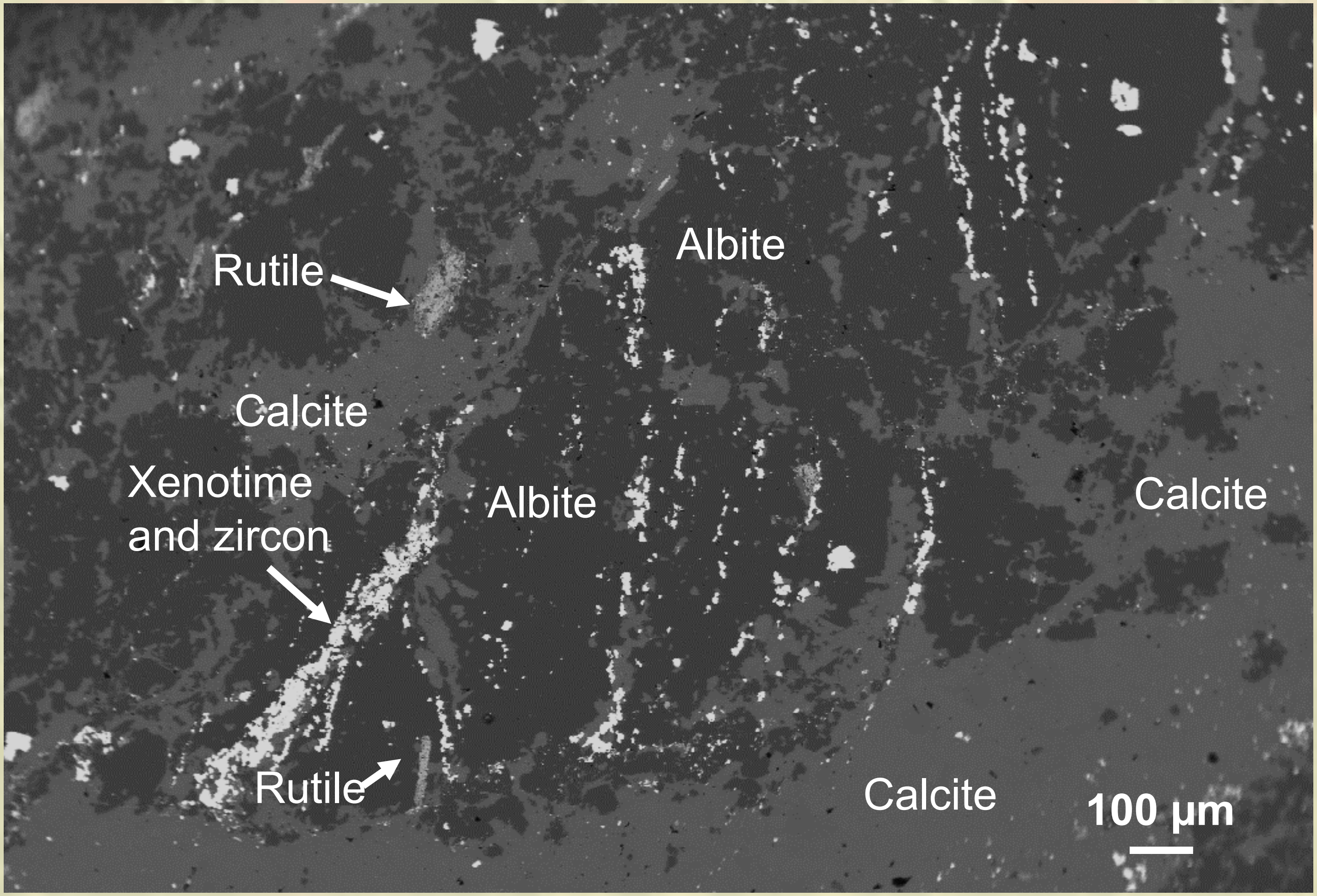
Lithogeochemical Survey

Structure with zones of strong fenitisation and carbonate alteration (dark grey); weaker fenitisation (light grey). Coloured dots show distribution of Dy. Xenotime-(Y) concentrates in the structure and monazite-(Ce) distally from it.



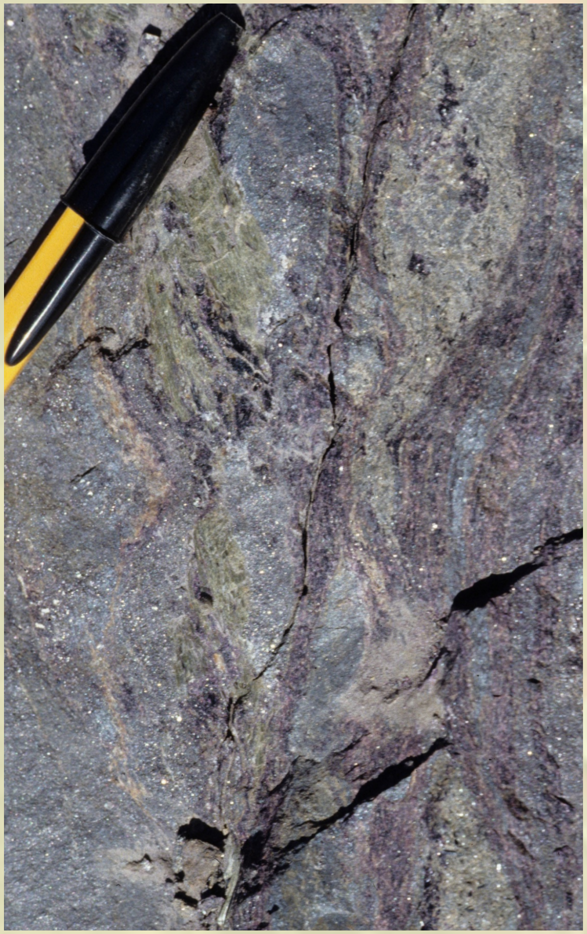
Xenotime-(Y) Mineralisation

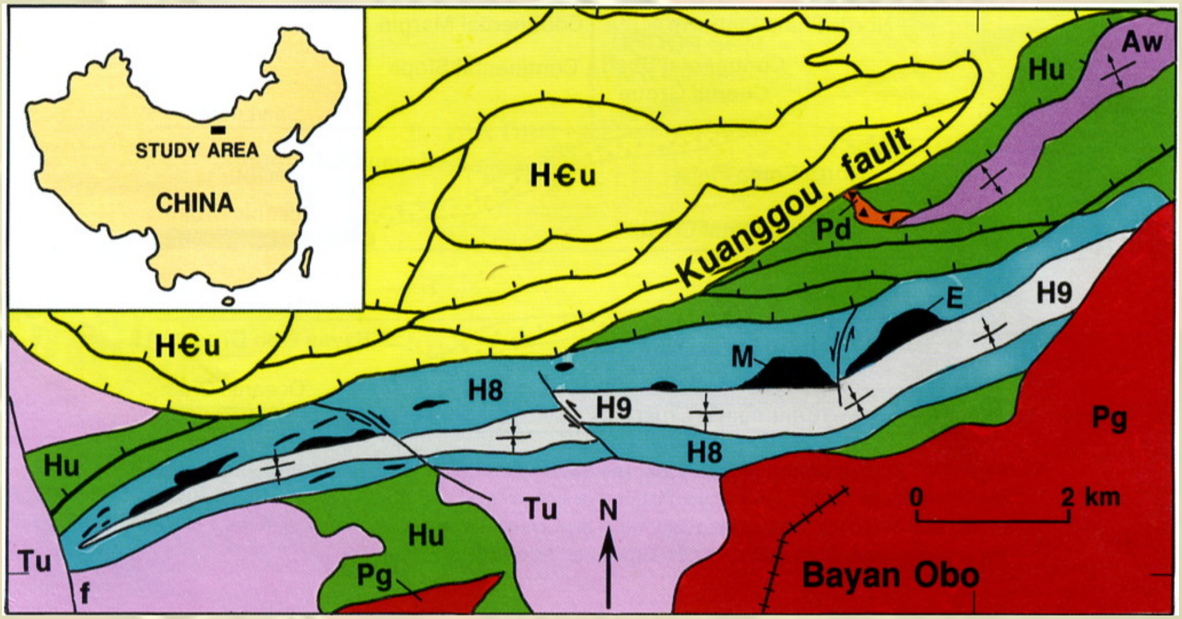
Albitite cut by xenotime-(Y)-zircon-biotite veins and then replaced by calcite. Xenotime-(Y) {$HREEPO_4$}



The Bayan Obo LREE Deposit, China

The world's richest REE deposit with reserves of 48 million tonnes grading 6 wt.% REE_2O_3, Bayan Obo, is responsible for 70% of global REE production





Monazite ($LREEPO_4$) and bastnäsite ($LREECO_3F$), together with magnetite, hematite and fluorite replaced H8 dolomite . Fluids 5 – 15 wt% NaCl eq., T ~ 400 °C.

Smith and Henderson (2000)

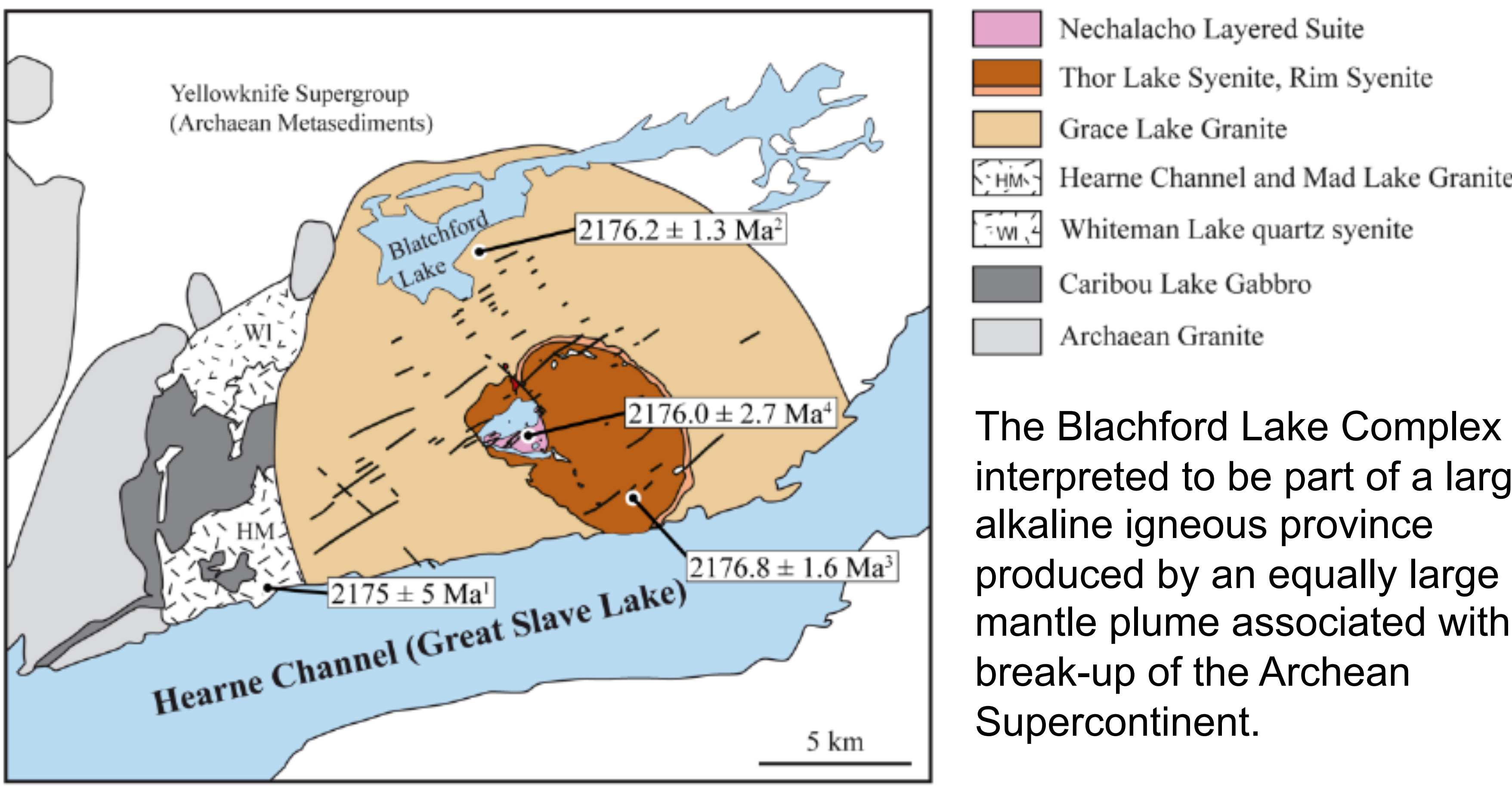
The Nechalacho Deposit: Potential HREE Producer

Measured and Indicated Resources in the Basal Zone at Various NMR Cut-offs

(August 2013)

Basal Zone	Tonnes (millions)	% TREO	% HREO	% HREO/ TREO	% ZrO_2	% Nb_2O_5	% Ta_2O_5
US$345 NMR Cut-Off (Reflects entire Basal Zone)							
Measured	12.56	1.71	0.38	22.50	3.20	0.405	0.0404
Indicated	49.33	1.62	0.35	21.27	3.07	0.405	0.0398
US$800 NMR Cut-Off (Approximately Reflects High Grade "Basin")							
Measured	5.11	2.20	0.58	26.17	4.23	0.52	0.0544
Indicated	16.15	2.20	0.55	24.87	4.13	0.52	0.0542

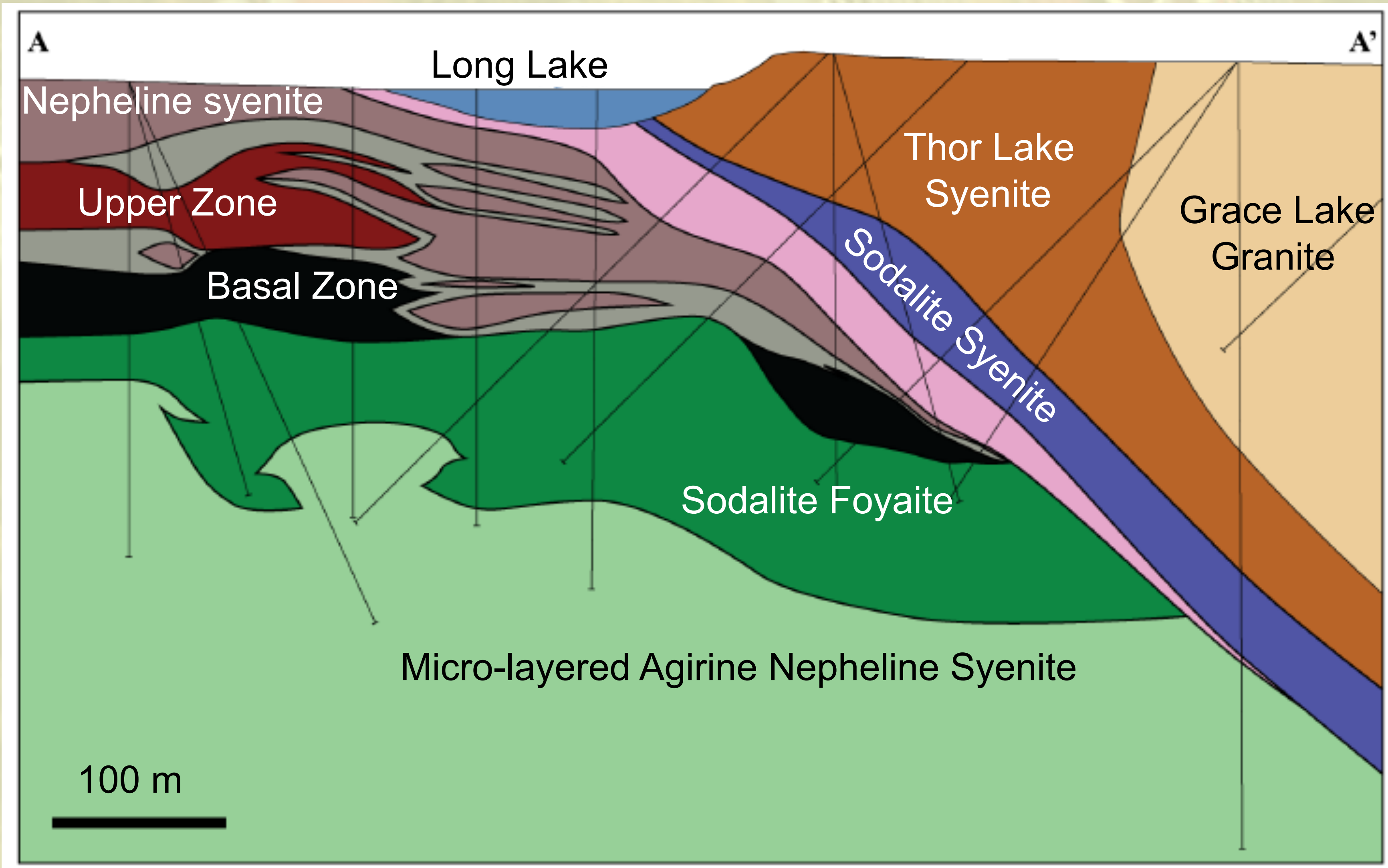
Geological Setting of the Nechalacho Layered Suite, Blachford Lake Complex



The Blachford Lake Complex is interpreted to be part of a large alkaline igneous province produced by an equally large mantle plume associated with the break-up of the Archean Supercontinent.

Sheard et al. (2012); Möller and Williams-Jones (2014)

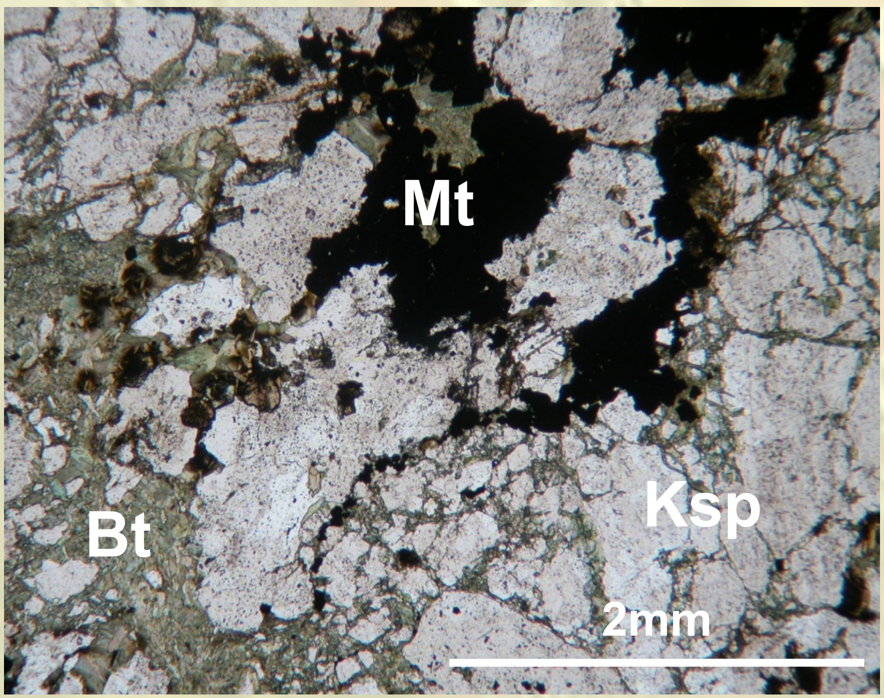
Cross-Section through part of the Nechalacho Layered Suite



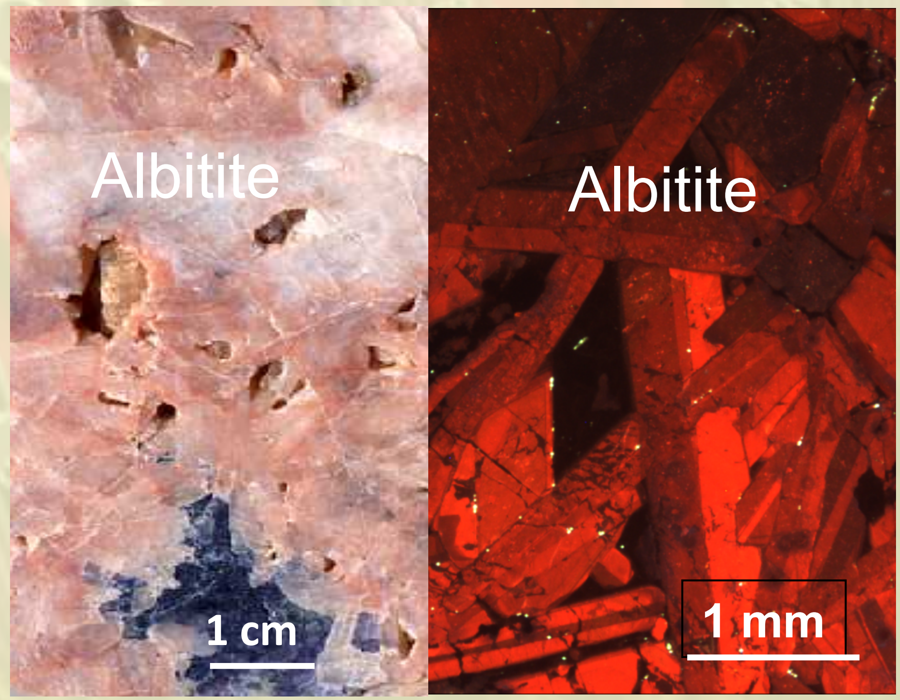
Hydrothermal Alteration

The upper 250-300 m of the layered suite has been intensely altered, largely obliterating primary igneous textures

Biotite-magnetite alteration - early



Albitisation - late



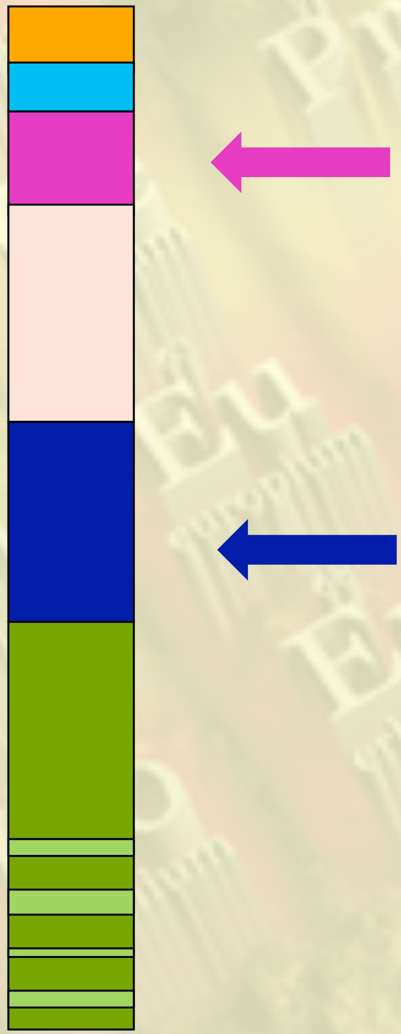
The Ore Zones

Upper
ore zone

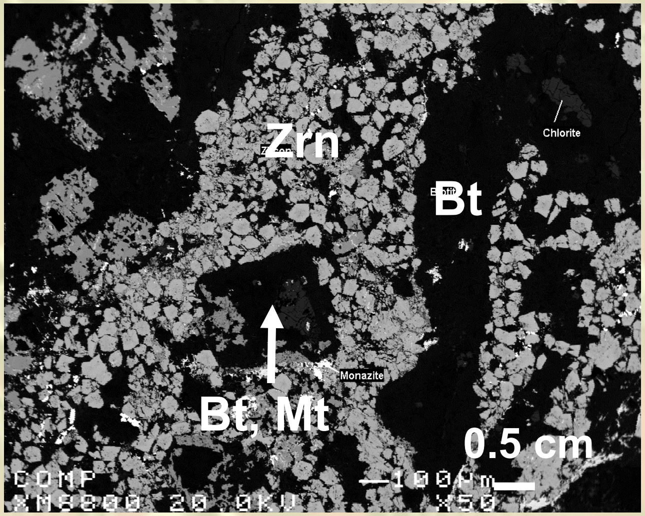
Albitite

Basal
ore zone

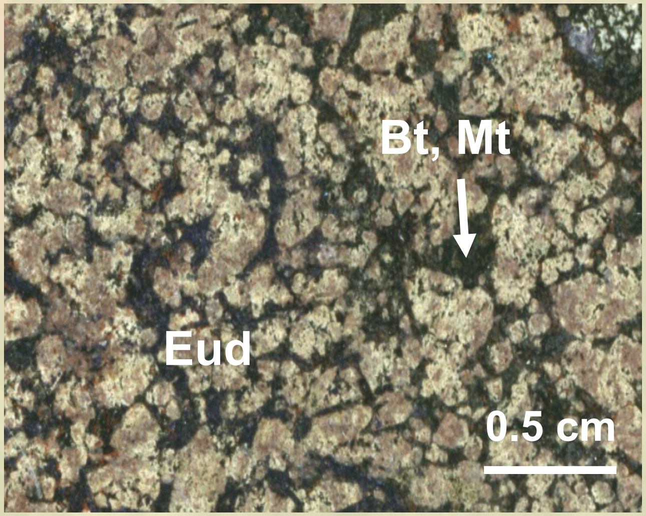
Unaltered
aegirine
nepheline
syenite



Zircon cumulates



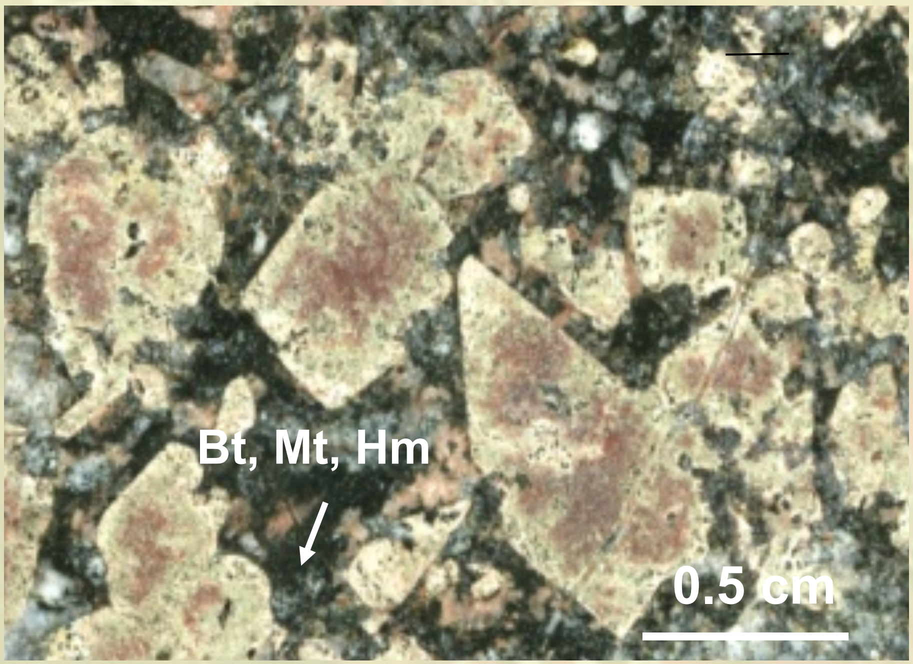
Pseudomorphs after Eudialyte cumulates



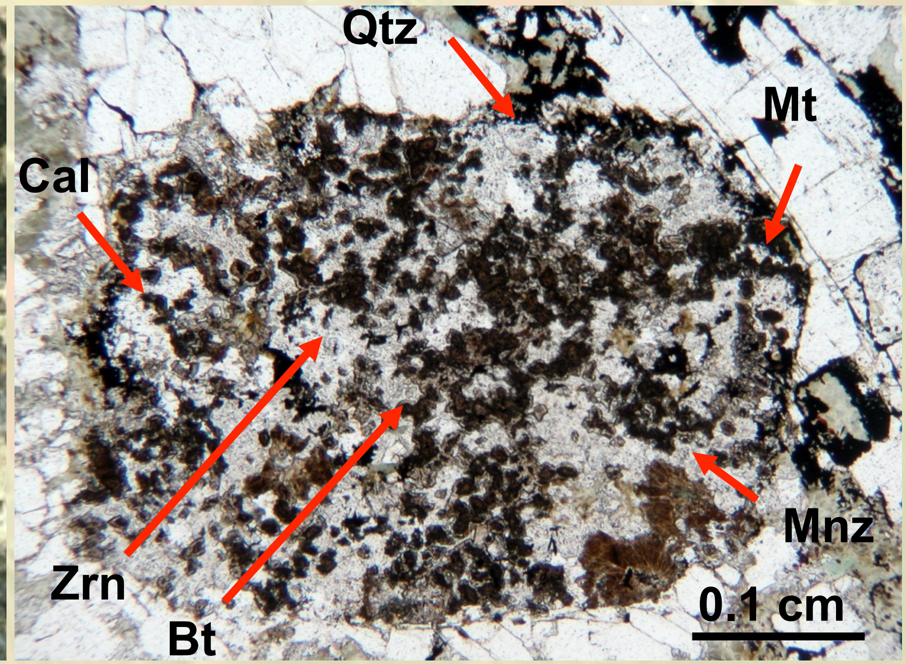
Basal Zone REE Mineralization

Pseudomorphs after eudialyte

$Na_{15}(Ca, REE)_6(Fe,Mn)_3Zr_3NbSi_{25}O_{72}(O,OH,H_2O)_3$



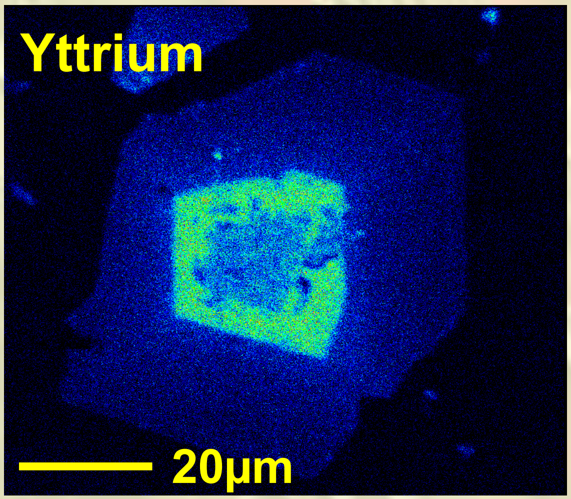
Pseudomorph after eudialyte
in plane polarised light

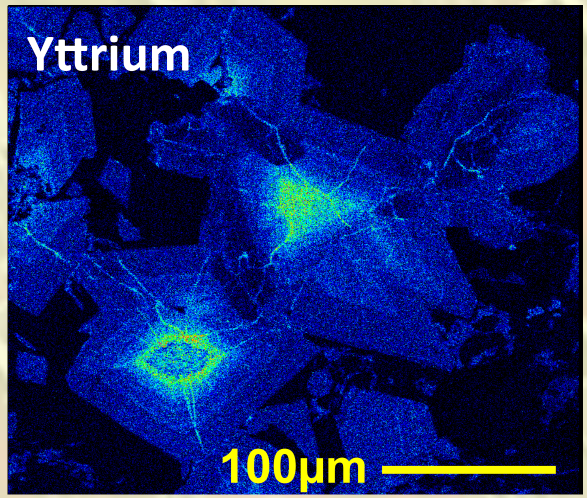


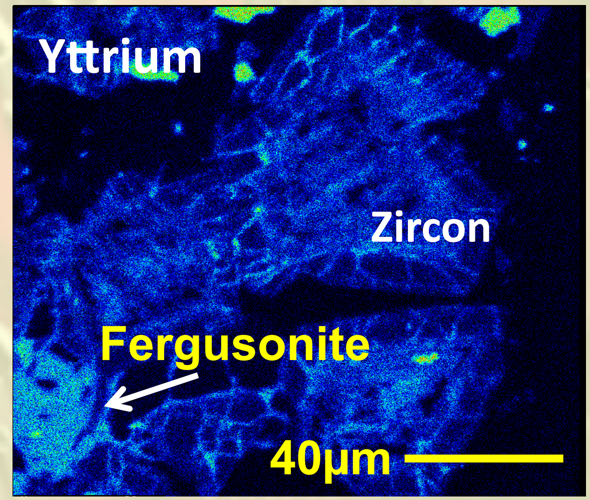
Mnz - monazite ($LREEPO_4$)

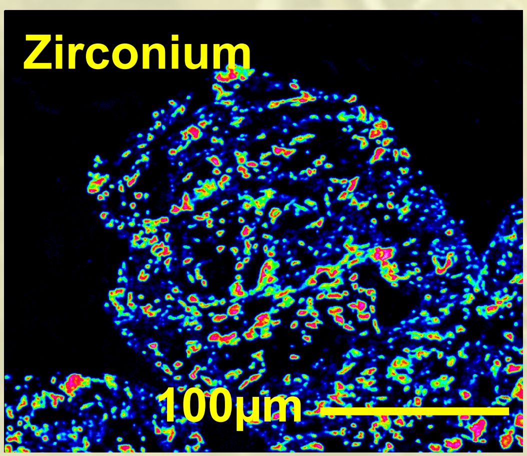
Hydrothermally unlocking and concentrating the REE

Progressive alteration of zircon to fergusonite-(Y) ($HREENbO_4$)

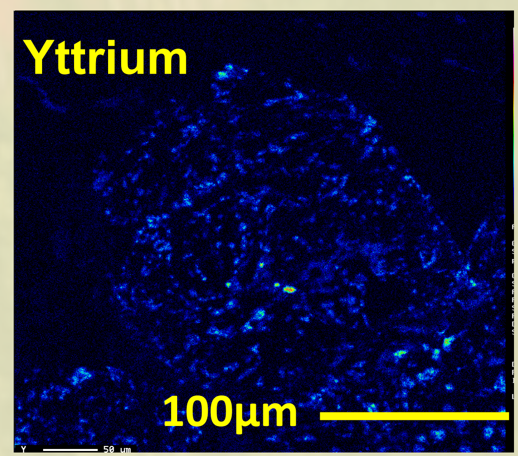




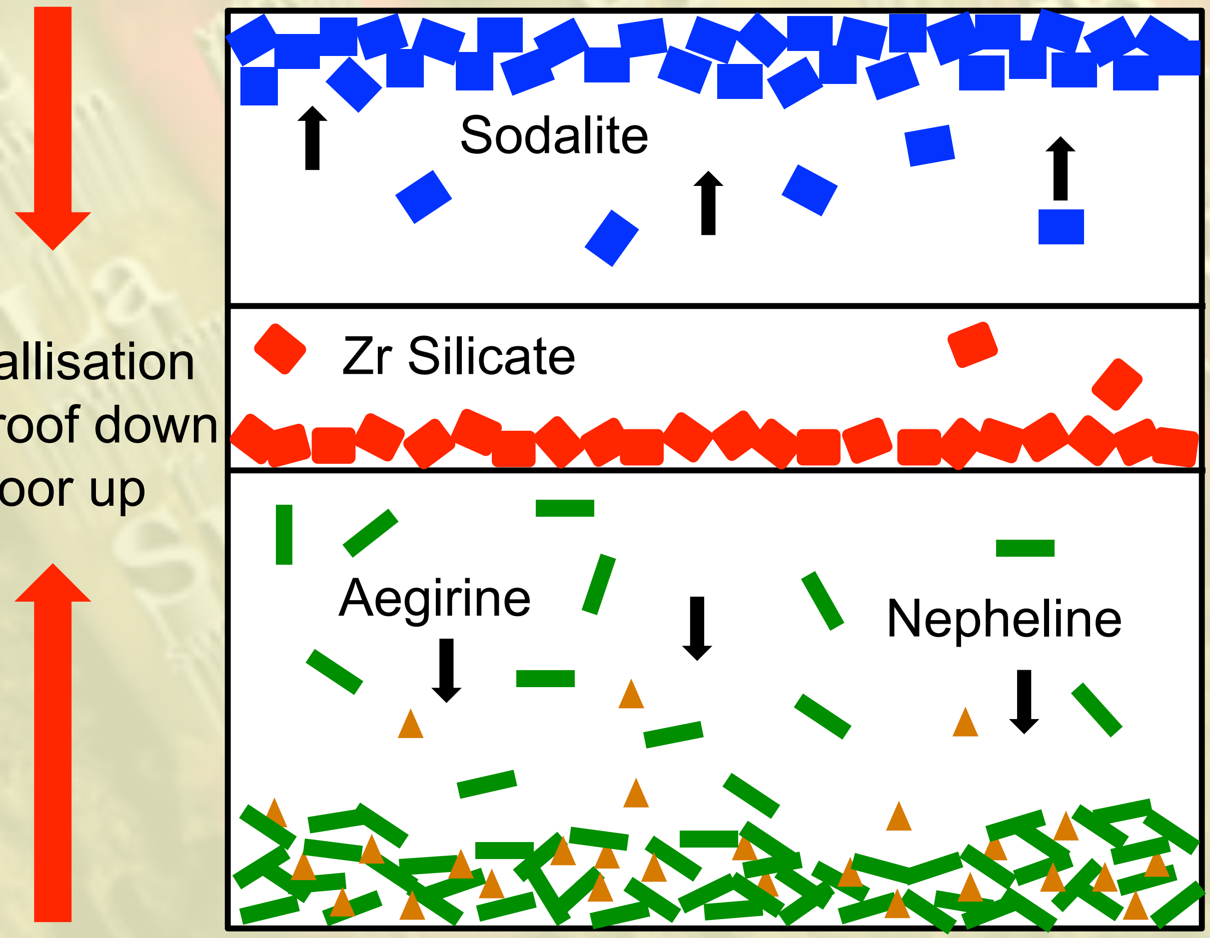




Alteration of eudialyte to zircon and other minerals



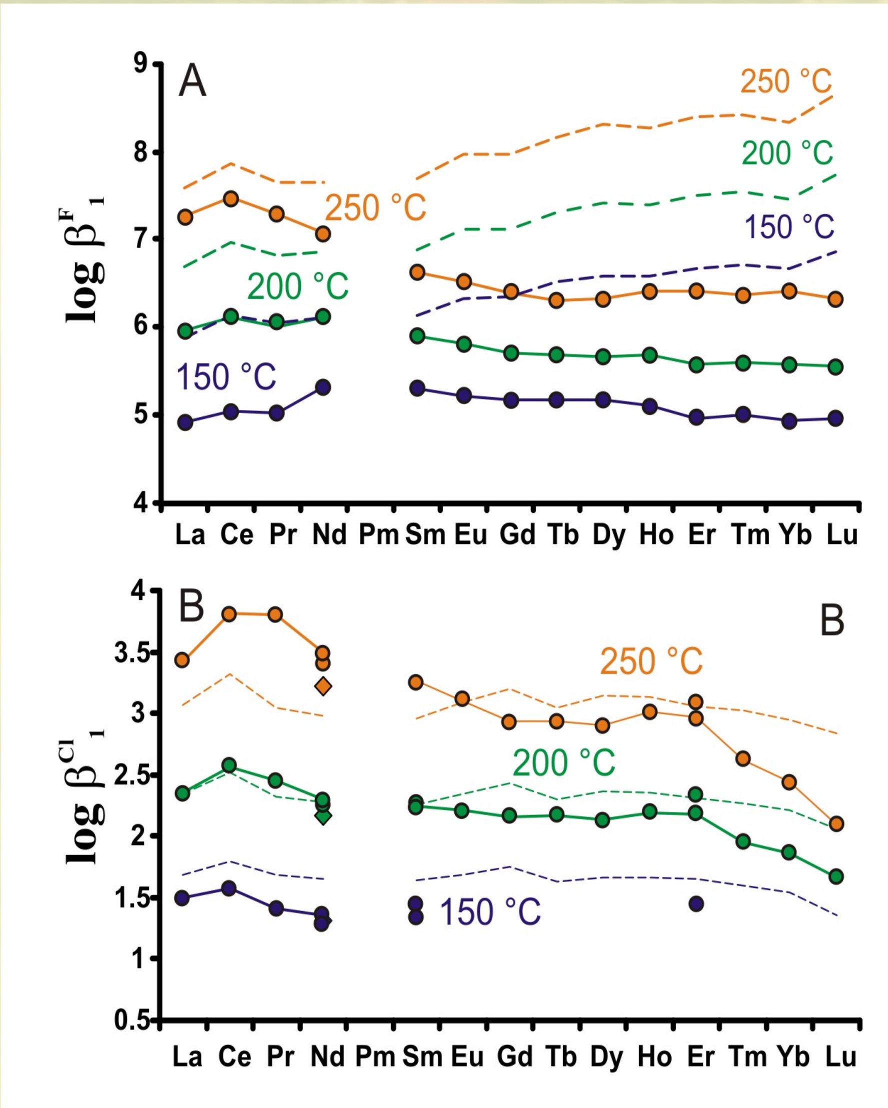
Magmatic concentration of the REE in the Nechalacho Layered Suite



Crystallisation from roof down and floor up

Residual, volatile- and HFSE-rich magma(s) saturates with REE-bearing zirconosilicates (zircon, eudialyte); soon afterwards it exsolves a hydrothermal fluid

The Stability of REE F & Cl Complexes



Log K $REEF^{2+}$

Stability of $REEF^{2+}$ complexes high, decreases with increasing atomic number.

Log K $REECl^{2+}$

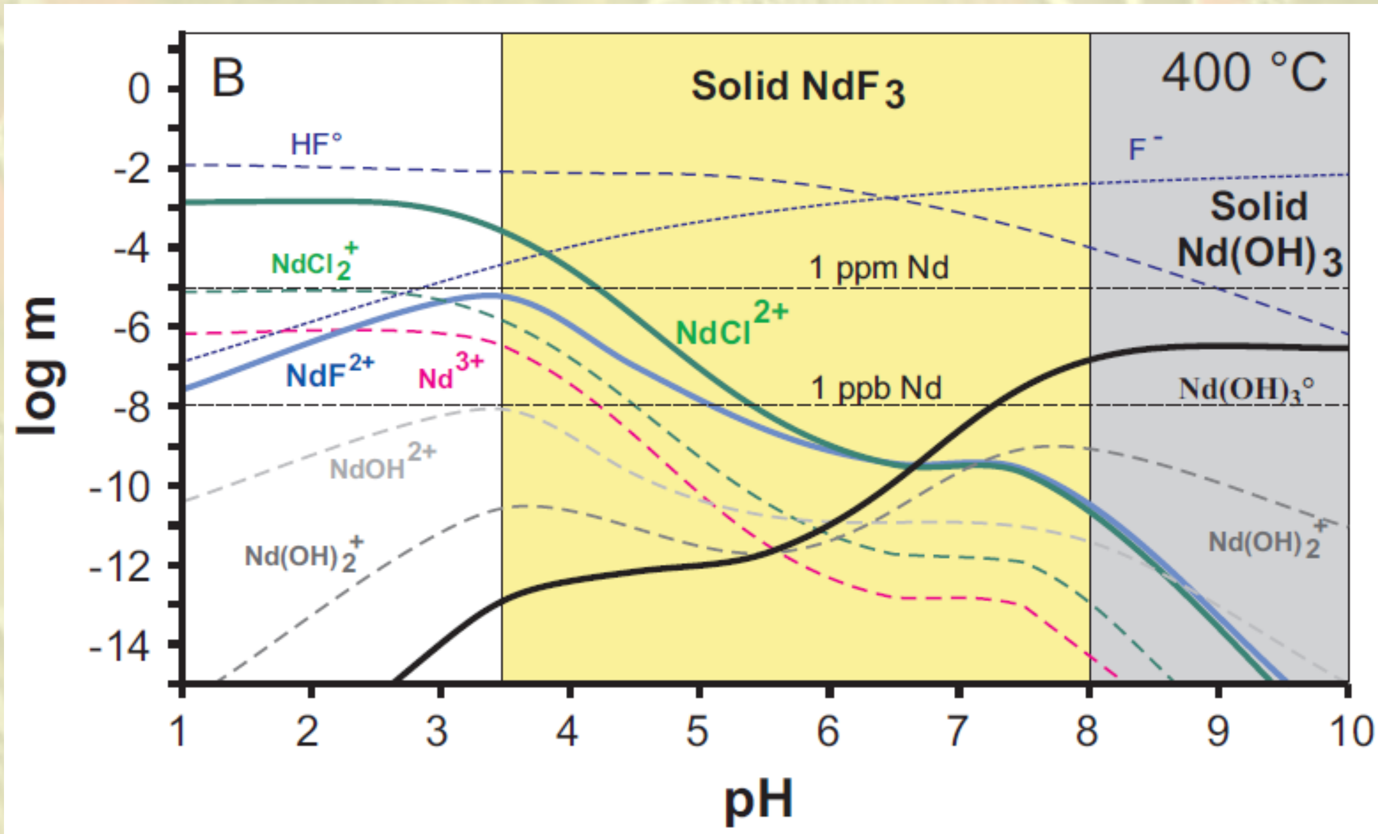
Stability of $REECl^{2+}$ complexes, moderate, decreases with increasing atomic number.

Solid lines – experimental data of Migdisov et al. (2009)
Dashed lines – theoretical predictions of Haas et al. (1995)

Migdisov et al. (2009)

Modelling REE Mineral Solubility in a F-Bearing Brine

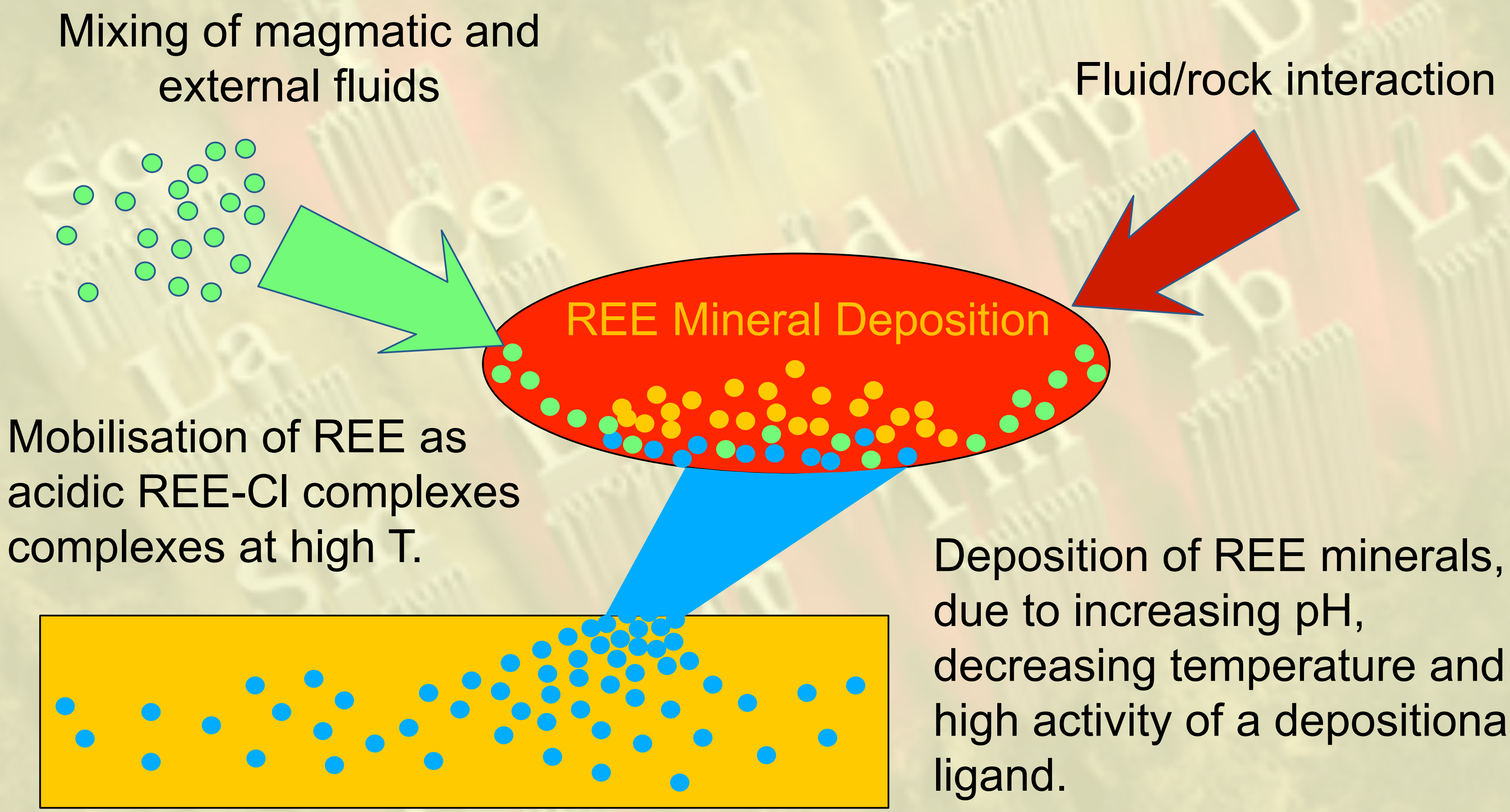
10 wt.% NaCl,
500 ppm F,
200 ppm Nd

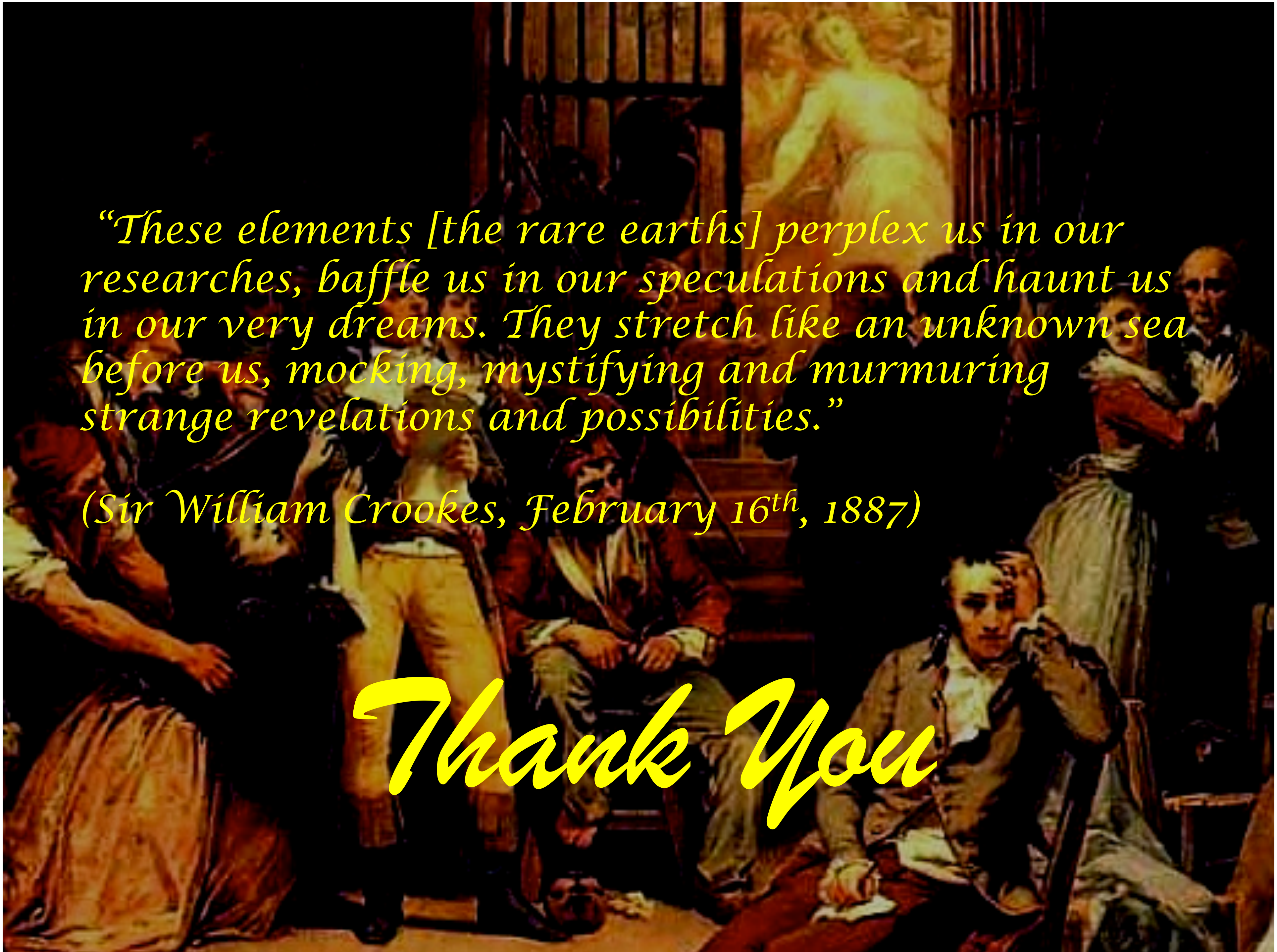


The REE are transported dominantly as chloride complexes despite the greater stability of REE fluoride complexes, because HF is a weak acid and REE fluoride is relatively insoluble.

Migdisov and Williams-Jones (2014)

Simplified Model for the Hydrothermal Transport and Deposition of REE




"These elements [the rare earths] perplex us in our researches, baffle us in our speculations and haunt us in our very dreams. They stretch like an unknown sea before us, mocking, mystifying and murmuring strange revelations and possibilities."
(Sir William Crookes, February 16th, 1887)
Thank You