Primary raw materials for the Sc industry - a geological perspective

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GeoAfrica Prospecting Services cc/HiTech AlkCarb Project

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Workshop - Europe's critical raw materials data management & the European Scandium inventory.

26-27th November, 2018, Berlin, Germany

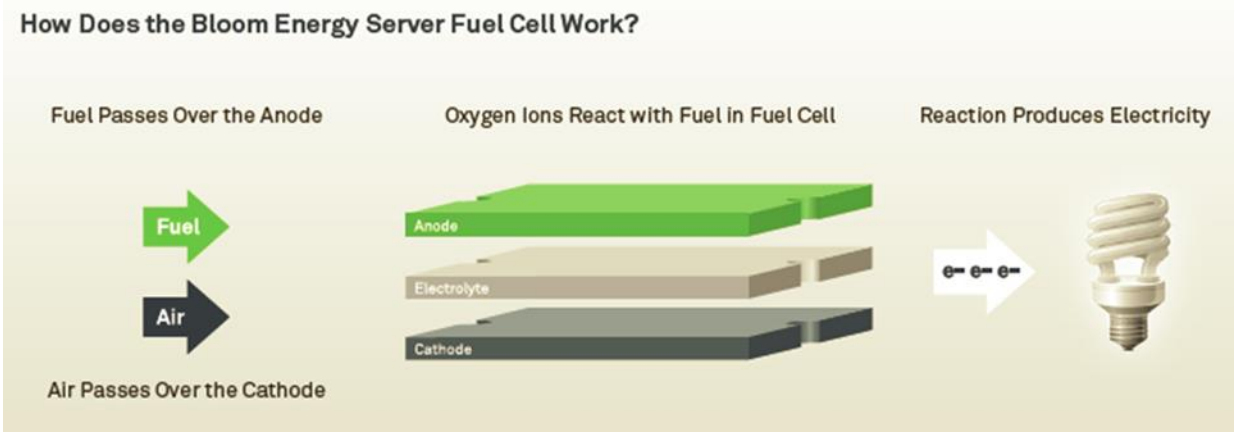
BAM Bundesanstalt für Materialforschung und -prüfung

scale SCANDIUM ALUMINIUM EUROPE

Scandium …..the forgotten REE

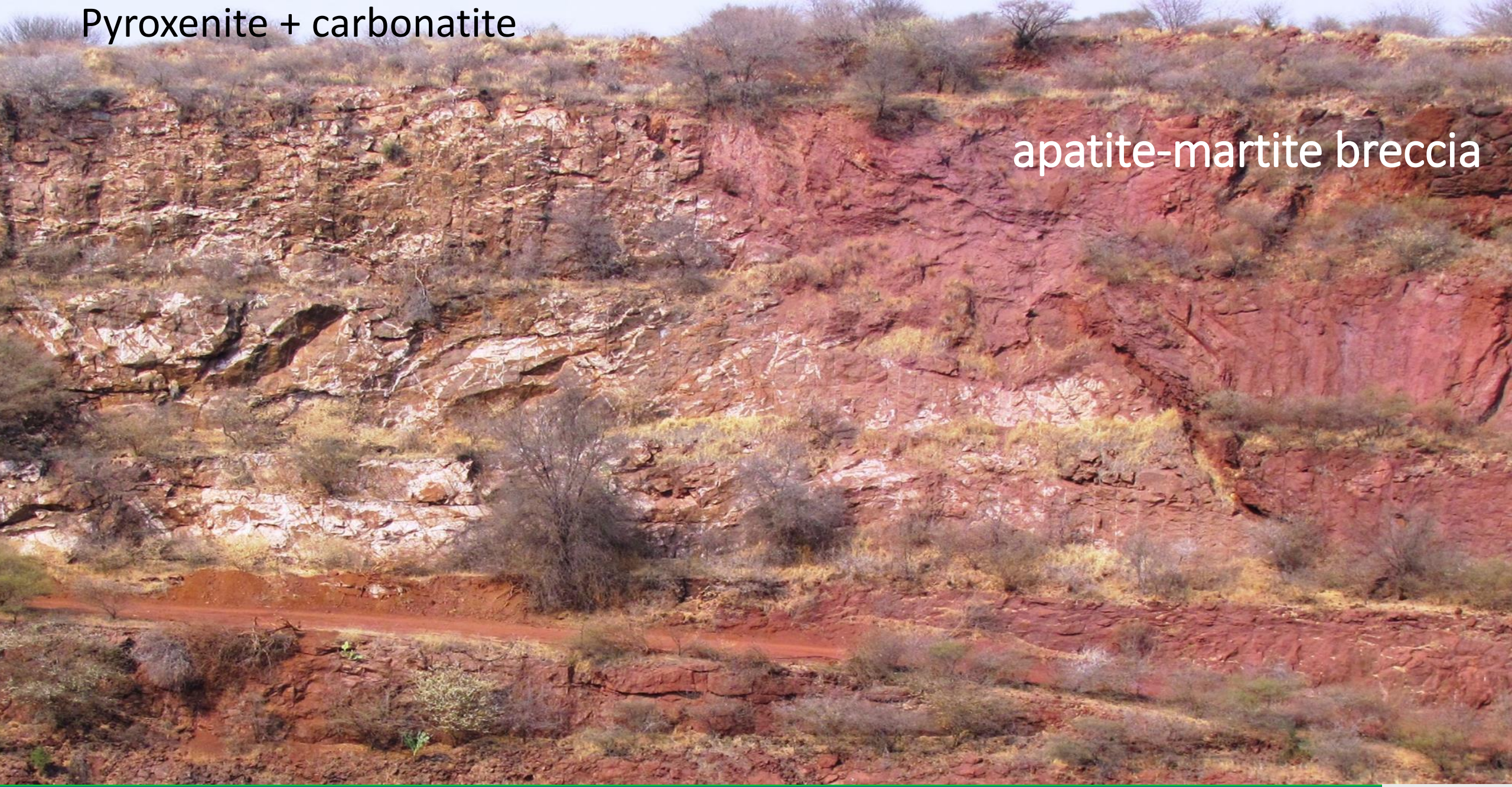
Scandium what is all the fuss about?

- **Current interest in scandium (Sc) is driven by:**
- Strong but weldable, and light (estimated 15% - 20% lighter) Al-Sc alloys in the aerospace industries.
- Solid Fuel Cells



Mikoyan MiG29

Bloom Energy founder, president and CEO K.R. Sridhar is applauded as he raises the gavel after ringing a ceremonial bell on the New York Stock Exchange (25 July, 2018)

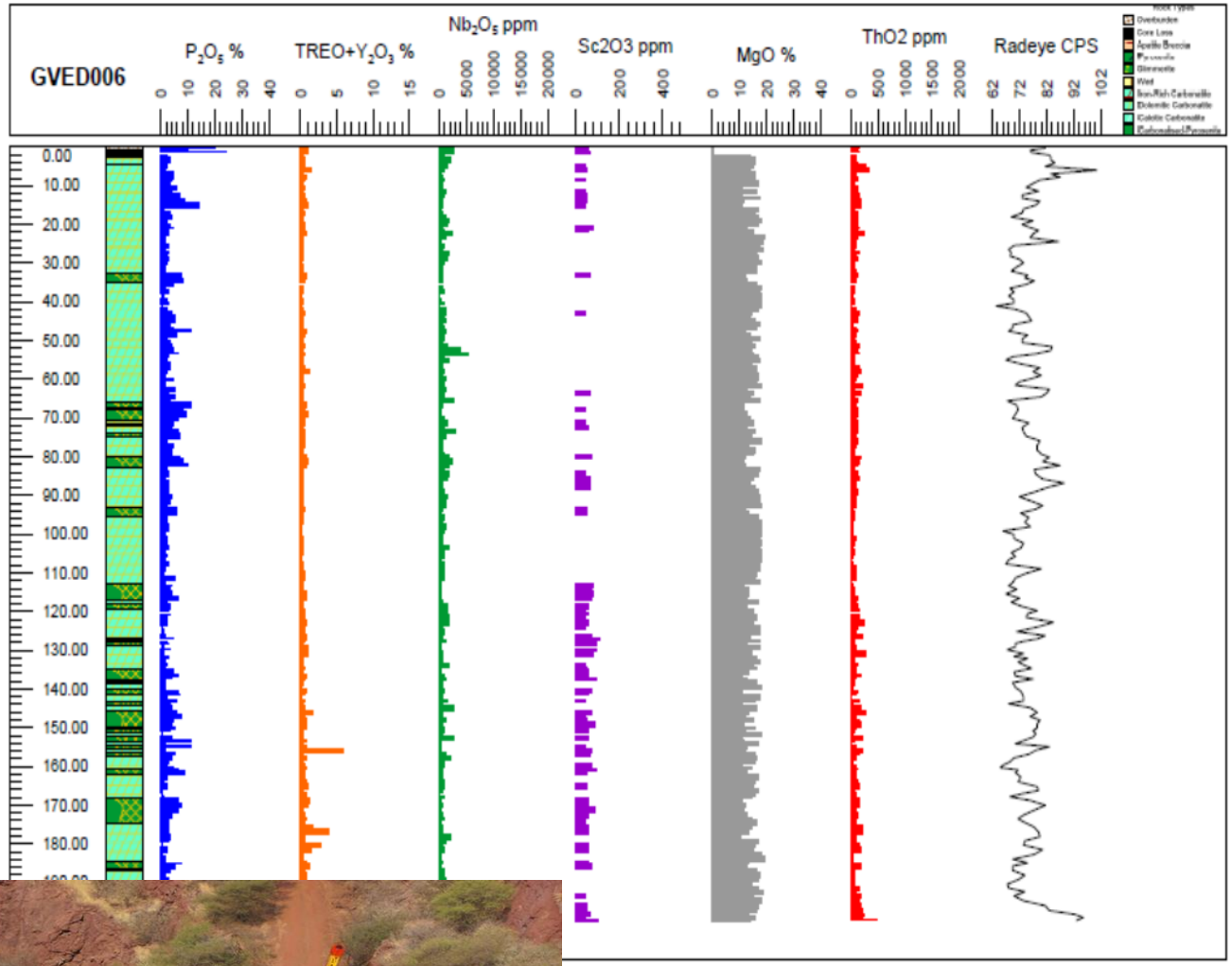

Pyroxenite + carbonatite
apatite-martite breccia

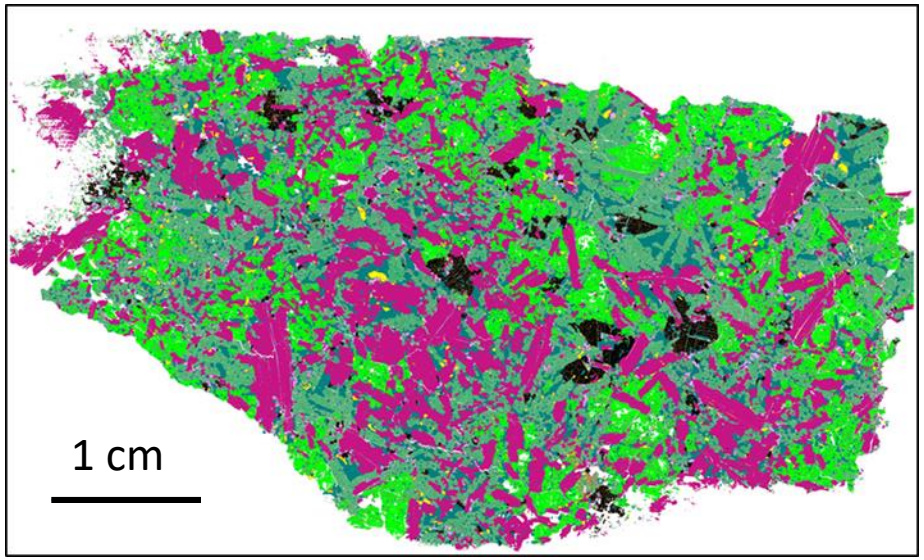
Glenover Complex

The apatite breccia has no Sc in the major rock forming minerals: apatite, magnetite and clay.

Much greater proportion of Sc in the following minerals albeit in trace amounts:

Zr oxides / silicates	7400 ppm
Aeschinite	700 ppm
Columbite -Fe oxides	5300 ppm
Pyrochlore	3100 ppm
Rutile	600 ppm





	Apt mgt breccia	Pxt
Sc_2O_3ppm	180	130
TREO%	1.57	0.25
Fe_2O_3%	29.7	13.6
P_2O_5%	21.5	2.76

Diopside	32%	0 Sc
Aegirine	1.5%	2600 ppm
Mica (phlogopite)	17%	0 Sc
Magnetite	12%	0 Sc
Apatite	16%	0 Sc (0.26% REO)
Zircon	0.03%	400 ppm

Chemistry of pyroxenite shows Sc deportment primarily in aegerine

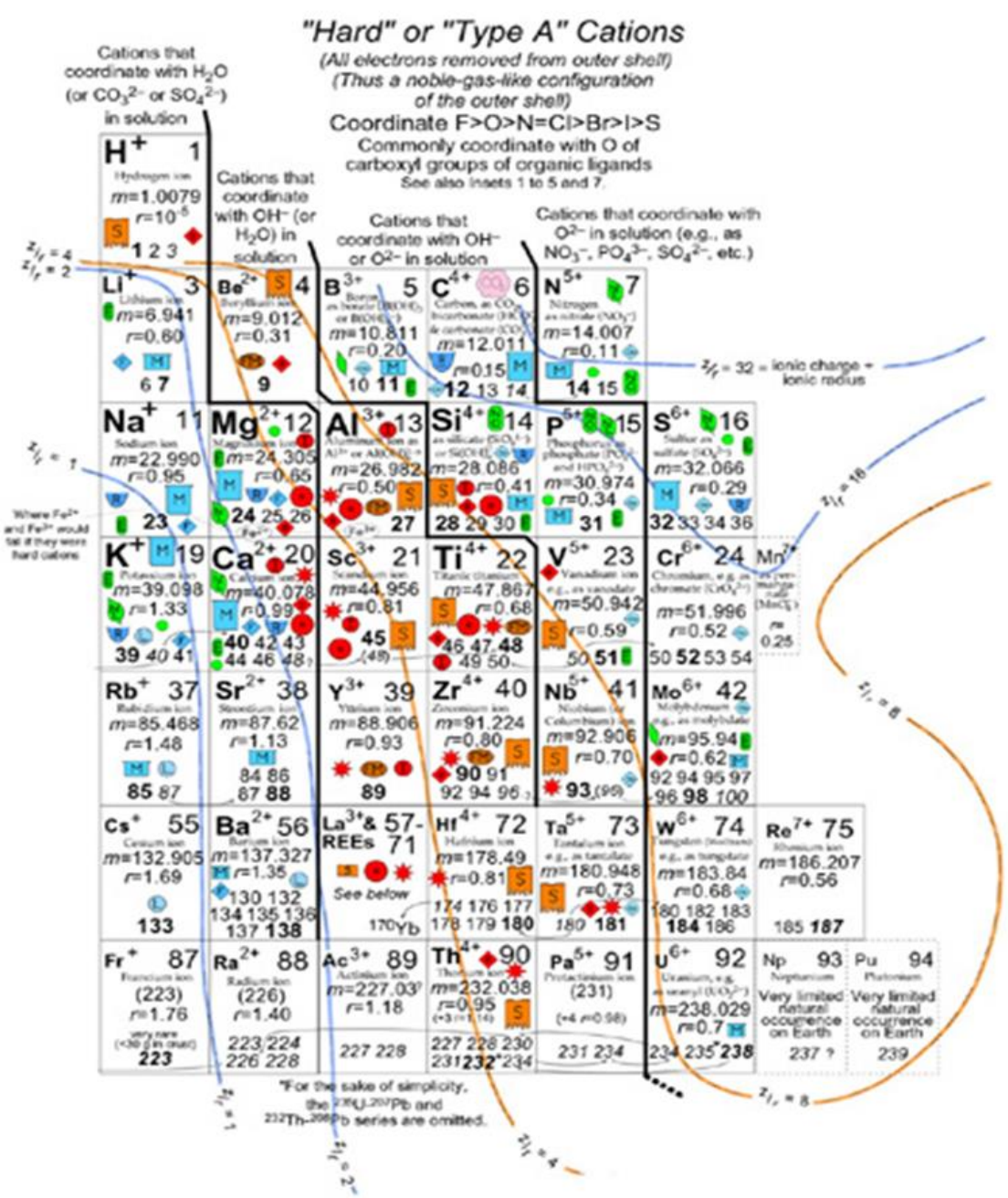
Literature Review….

- Review of carbonatites, REE and Sc content using GEOROC, CARBONATITE databases.
- Many localities of alkaline silicate rocks and carbonatites lack Sc analyses.
- GeoRoc (http://georoc.mpch-mainz.gwdg.de/georoc) igneous geochemical database was searched for anomalously high (>100 <500 ppm) Sc values.
- Almost all of the 116 analyses returned were found to be the result of errors in transferring data from the original published papers to the database!
- A single carbonatite sample from Pakkanadu, India revealed a Sc content of 237 ppm.
- Searching the CARBONATITE database located 743 analyses that included Sc and a mean concentration in these of just 15 ppm. The highest values were again a sample from Pakkandu (265 ppm) and a sample from Bayan Obo, China (111 ppm).
- To compare …..6000 individual samples of basalt from the North Atlantic Igneous Province had a maximum Sc content of 94 ppm!

Scandium minerals rare and uncommon

- Scandium is included with the REE but is hardly ever found in REE minerals.
- Over 400 minerals contain Scandium.
- So Sc is VERY compatible.
- Primary pegmatite mineral concentrates including davidite, tantalite, columbite, samarskite, ixiolite, rutile, Ti-aeschynite all contain significant Sc (>7000ppm).

- Extra-terrestrial.



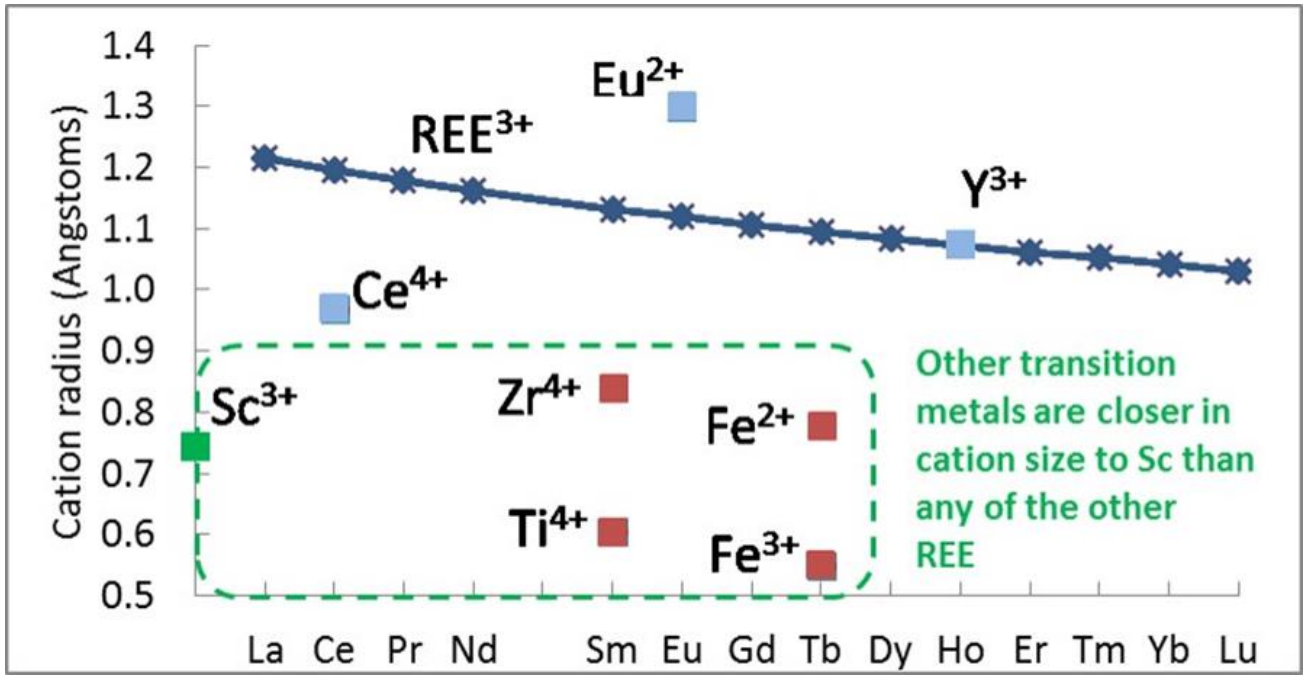
- Atomic weight 44.95555910
- Melting point 1541 ^{o}C
- Density 3.0 g/cm^{-3}
- Oxide Sc2O3

- It is the 35th most common element in the Periodic Table with a crustal abundance of 16 - 22 ppm, comparable to Pb.
- According to the International Union of Pure and Applied Chemistry, Sc is a member of the 17 strong rare earth element (REE) family. However, most reviews of REE geochemistry start by mentioning this fact, but then promptly exclude Sc from further consideration (Chakhmouradian and Wall, 2012).

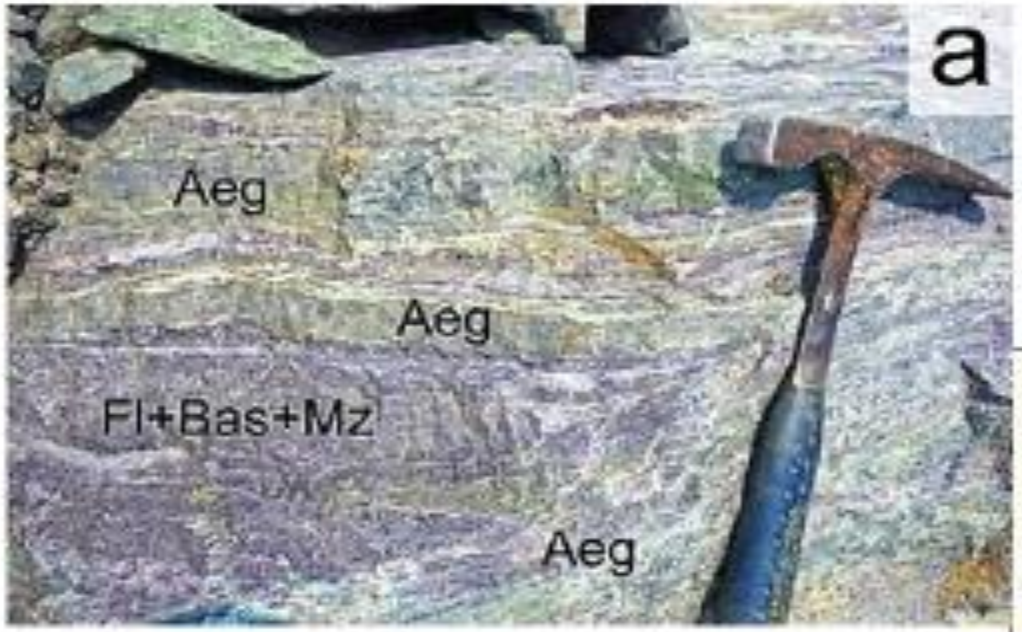
www.gly.uga.edu/railsback/PT.html

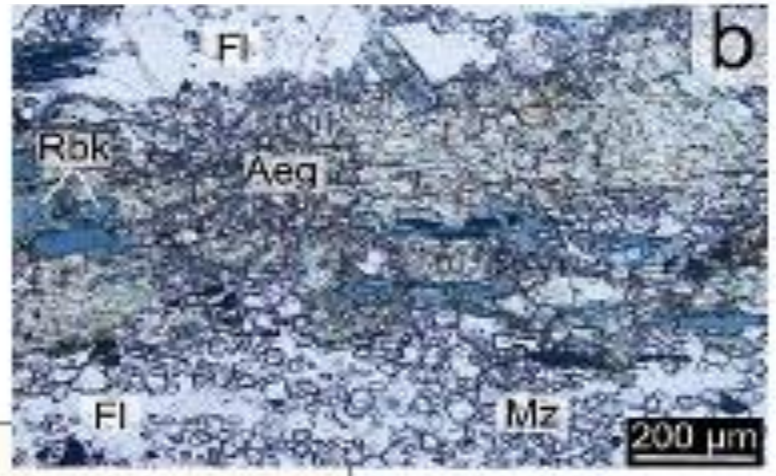
Scandium …..as an REE

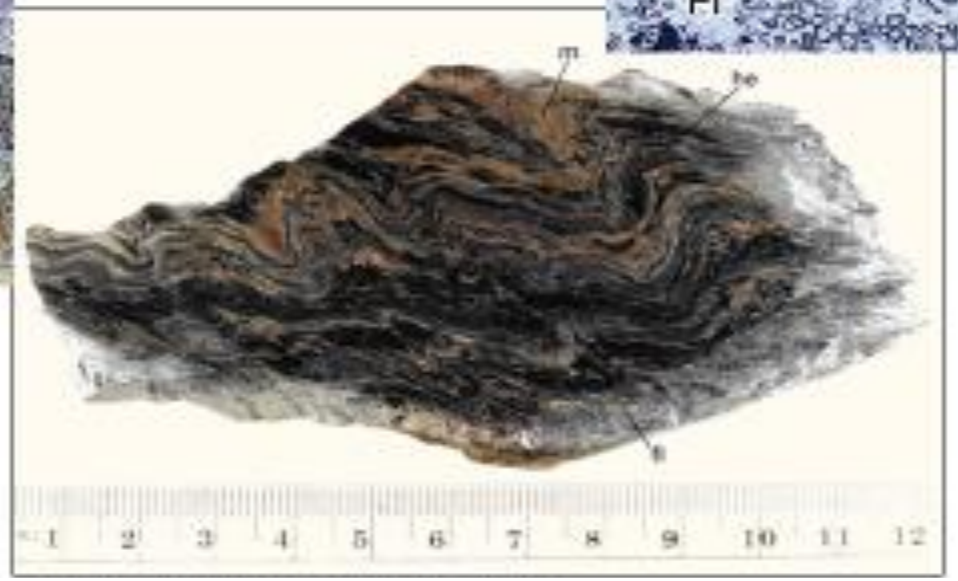
- The smaller size of the Sc^{3+} cation means that it is unlikely to behave similarly to the other larger cations in the REE family and so the general observations applied to the geochemistry of REE do not necessarily apply to Sc.



Bayan Obo – REE Deposit







(plates from Williams-Jones and Vasyukova, 2018, Chao et al., 1997)

Bayan Obo

Is Cracking Possible? China says yes!

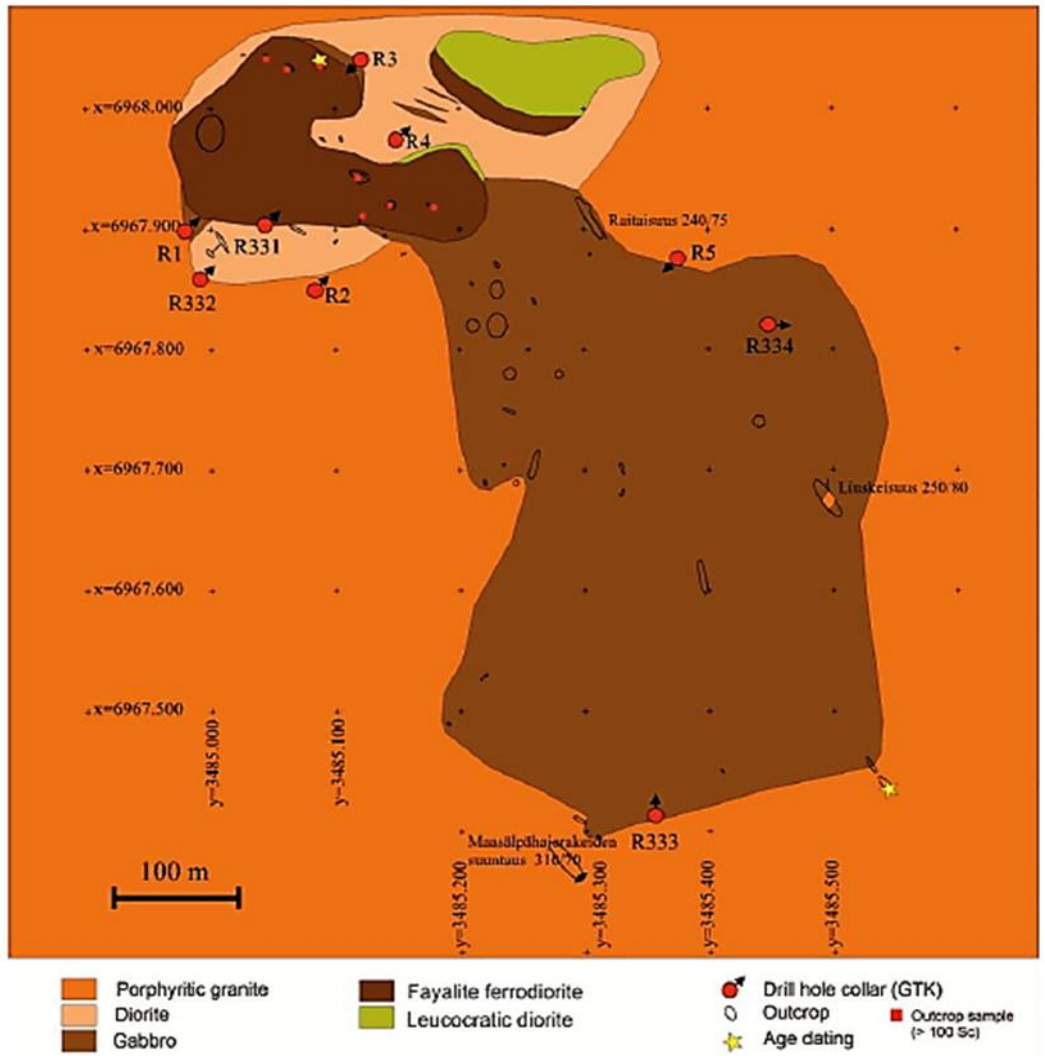
- 1. Roast with Sodium Hydroxide
- 2. Leaching with HCl (100 °C) or H_2SO_4 (300 °C) at elevated temperature (Li, et al., 2013)

Aegerine appears variable in Sc content:

- 155 ppm in aegerine of 'banded ores' (Zhao, et al., 2016)
- 165 ppm in aegerine of magnetite ores

- Aegerine appears most favorable because of higher Sc content….but is it the best?
- Plans to produce 20t/a

Hard Rock Deposits in Europe…….Kivienemi, Finland

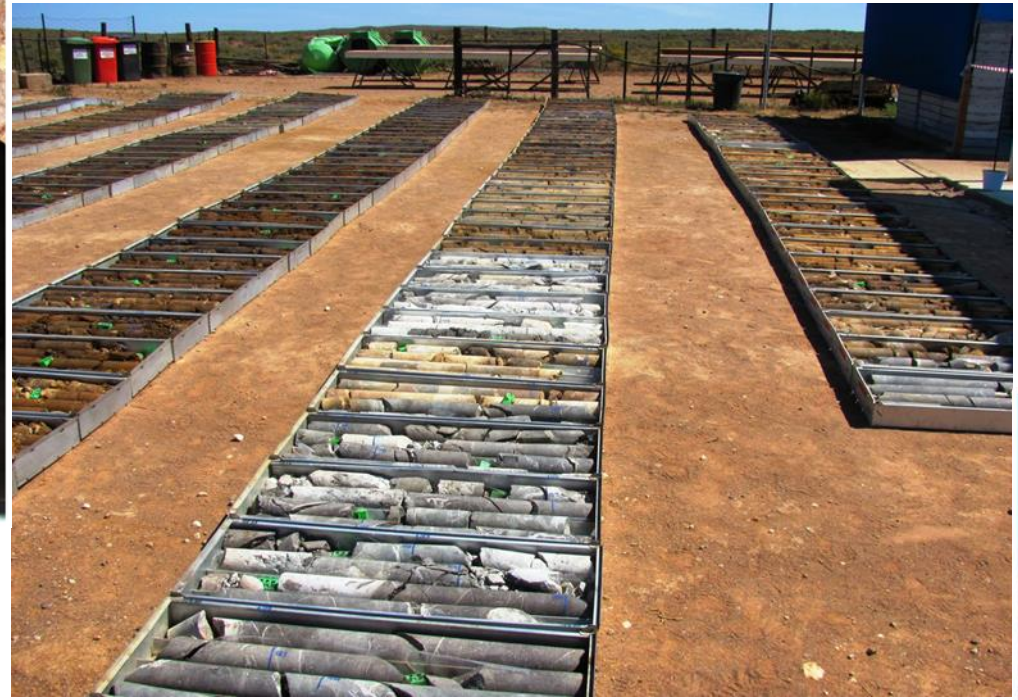


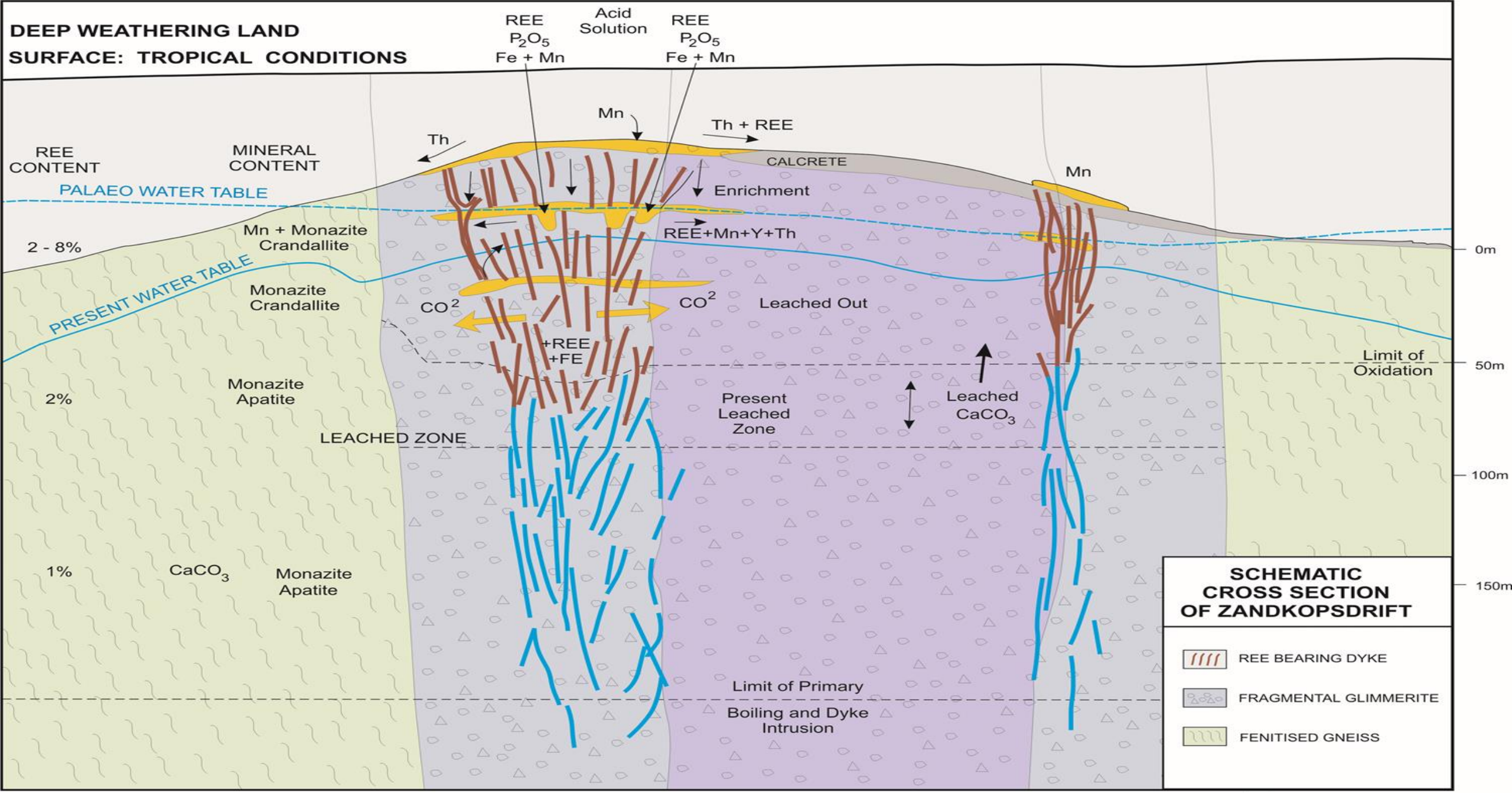
- Contains 14.3Mt at 154 ppm Sc.
- Most scandium occurs in a fayalitic ferro-diorite.
- Mineralogy not well constrained but appears to be Fe-rich silicates including pyroxene (59%) and amphibole (40%). Are we dealing with hedenbergite, riebeckite?
- Propose magnetic separation, HF + HCl crack, metal chelation recovery.
- NOT alkaline silicate or carbonatite related.

Scandium …..the laterite question

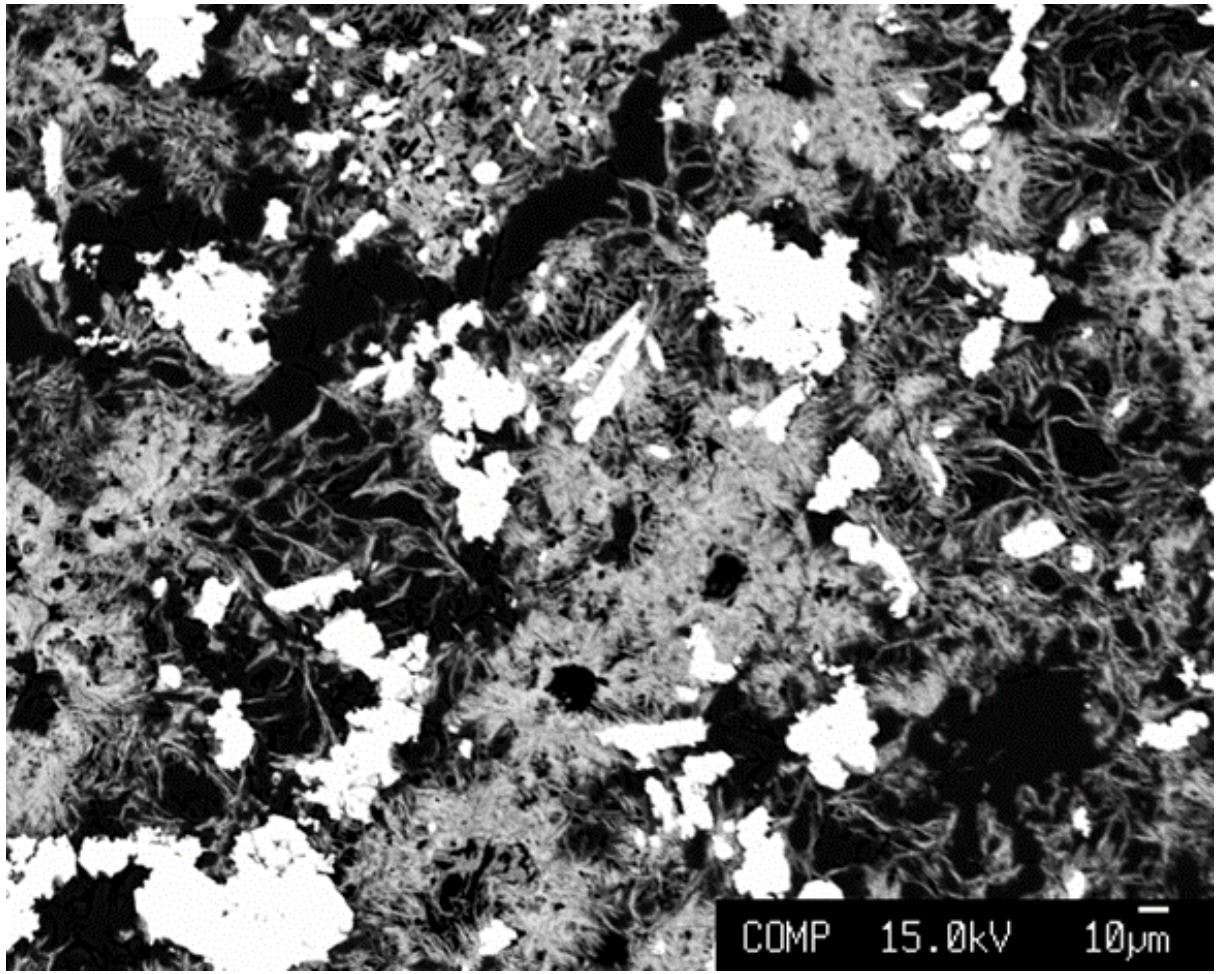
- Currently four Sc projects on mafic/ultramafic rocks (eastern Australia) are undergoing feasibility and related studies.
- Scandium was hosted originally in clinopyroxene and then released and adsorbed onto iron oxides during the weathering process.
- Syerston–Flemington is a Co+Ni+Sc deposit, which contains about 1350 t of Sc at an average concentration of 434 ppm Sc. Deposit formation requires a high concentration of Sc in clinopyroxenes, which are then weathered (Chasse et al., 2016)
- Seasonal precipitation of goethite allows the adsorption of Sc^{3+} onto goethite and then during dry periods, the goethite recrystallizes to hematite, incorporating part of the adsorbed Sc in its crystal structure
- Concentration of Sc in lateritic deposits requires a combination of three circumstances:
- (1) anomalously high Sc concentration in the parent rock,
- (2) long time scales of alteration in stable tectonic environment and
- (3) lateritic conditions during weathering, allowing the trapping of Sc by Fe oxides.
- The Nyngan deposit has grades up to 409 ppm in parts of the resource and is a stand alone Sc laterite deposit.

Laterites…..REE……Zandkopsdrift




DEEP WEATHERING LAND
SURFACE: TROPICAL CONDITIONS
REE
P_2O_5
Fe + Mn
Acid
Solution
REE
P_2O_5
Fe + Mn
Mn
Th
Th + REE
REE
CONTENT
MINERAL
CONTENT
CALCRETE
Mn
PALAEO WATER TABLE
Enrichment
REE+Mn+Y+Th
Mn + Monazite
Crandallite
2 - 8%
PRESENT WATER TABLE
Monazite
Crandallite
CO^2
CO^2
Leached Out
+REE
+FE
Limit of
Oxidation
Monazite
Apatite
2%
Present
Leached
Zone
Leached
$CaCO_3$
LEACHED ZONE
1%
$CaCO_3$
Monazite
Apatite
Limit of Primary
Boiling and Dyke
Intrusion
0m
50m
100m
150m
SCHEMATIC
CROSS SECTION
OF ZANDKOPSDRIFT
REE BEARING DYKE
FRAGMENTAL GLIMMERITE
FENITISED GNEISS

Laterites…..Karingarab



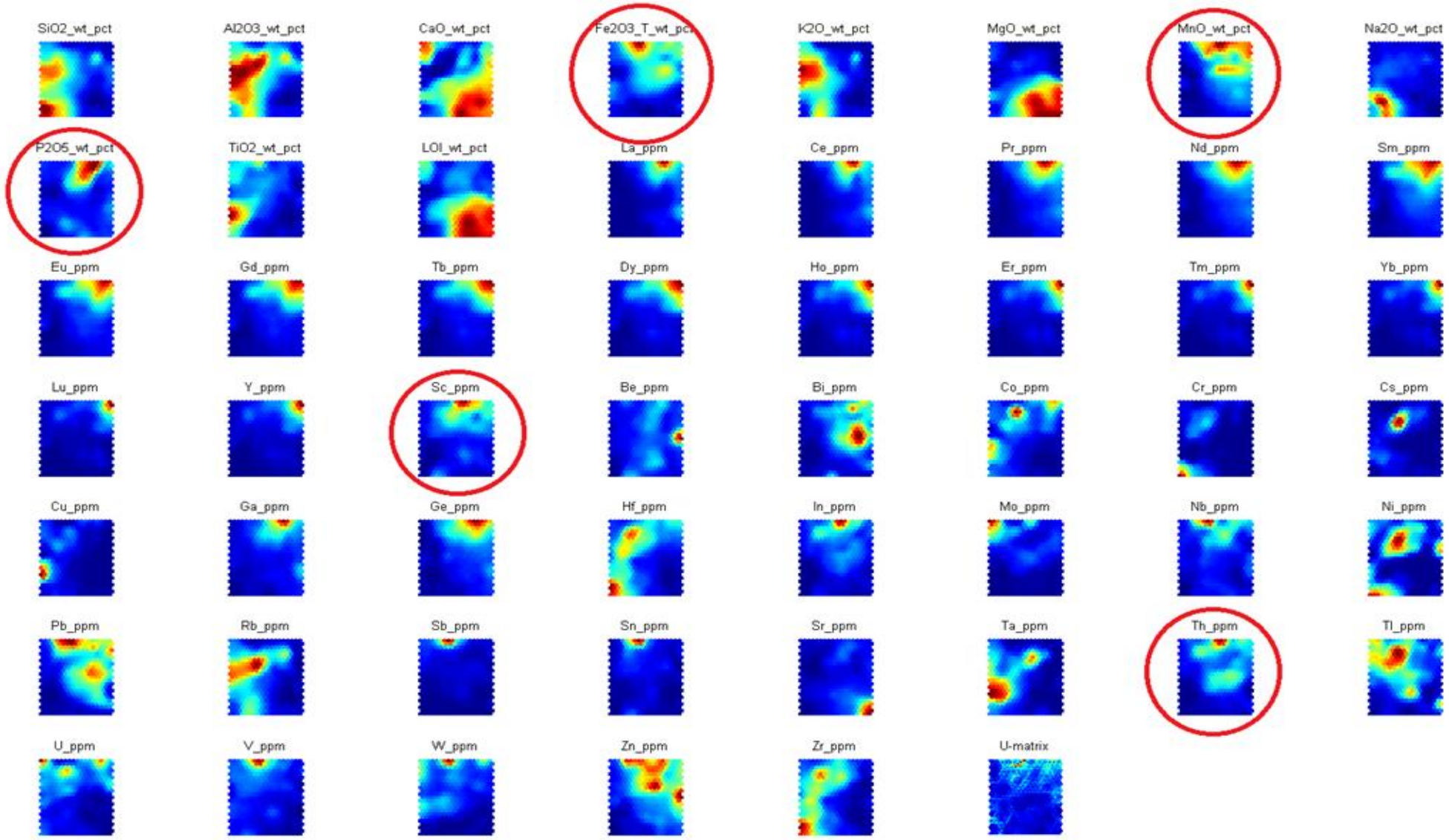
Laterites….Karingarab

REE project on a carbonatite in Namibia.

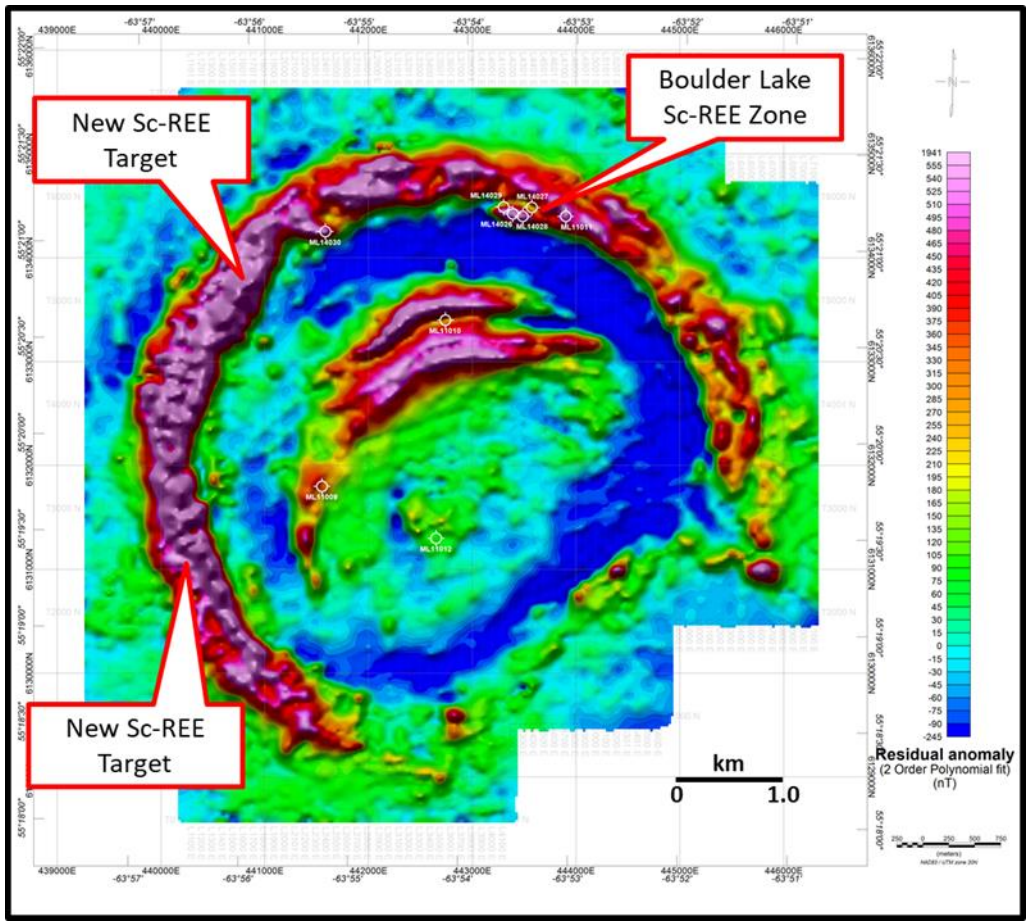
Over 5 000 samples of drill core and RC chips were analysed ICP-MS during the last 2 years for their REE content.

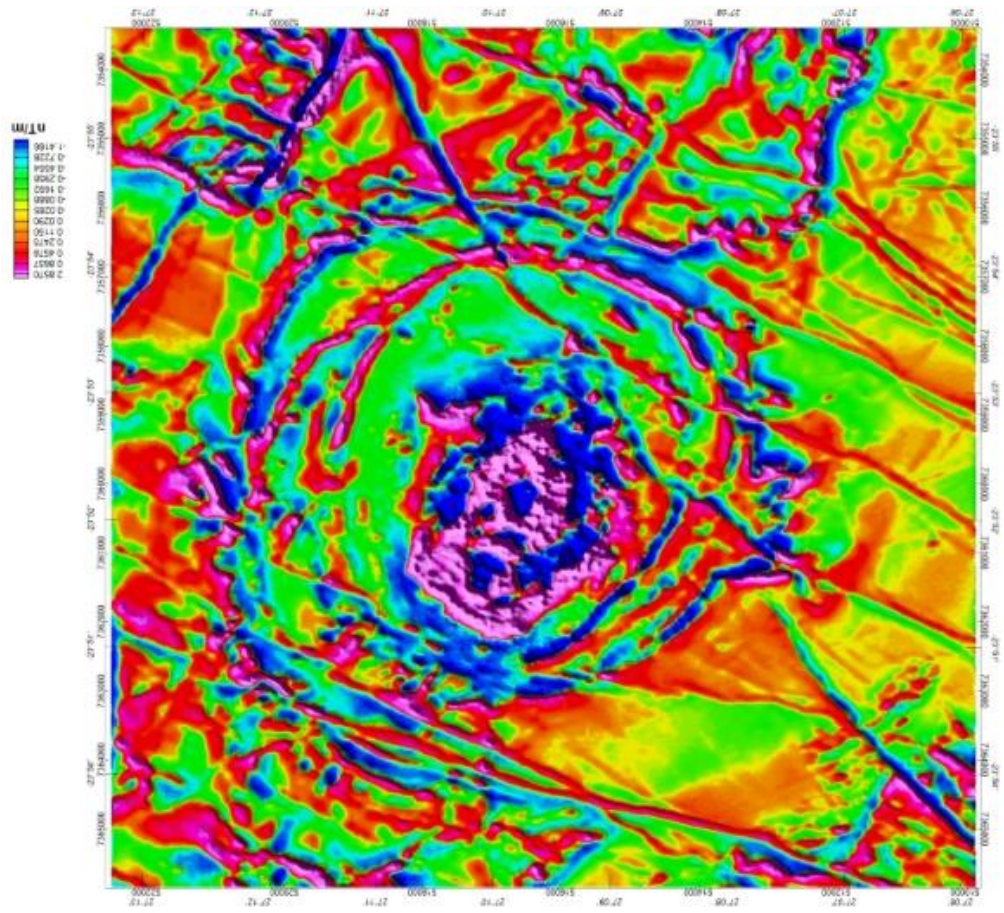
Analyses included REE, P, Zr, Fe, Mn and Th but not Sc. QA/QC failure on a subset saw re-analysis of approximately 1500 samples using borate fusion rather than sodium peroxide fusion.

These analyses importantly ALSO included Sc in the results and significant intersections of > 250 ppm Sc were noted. (best intersection 330ppm Sc over 27m)

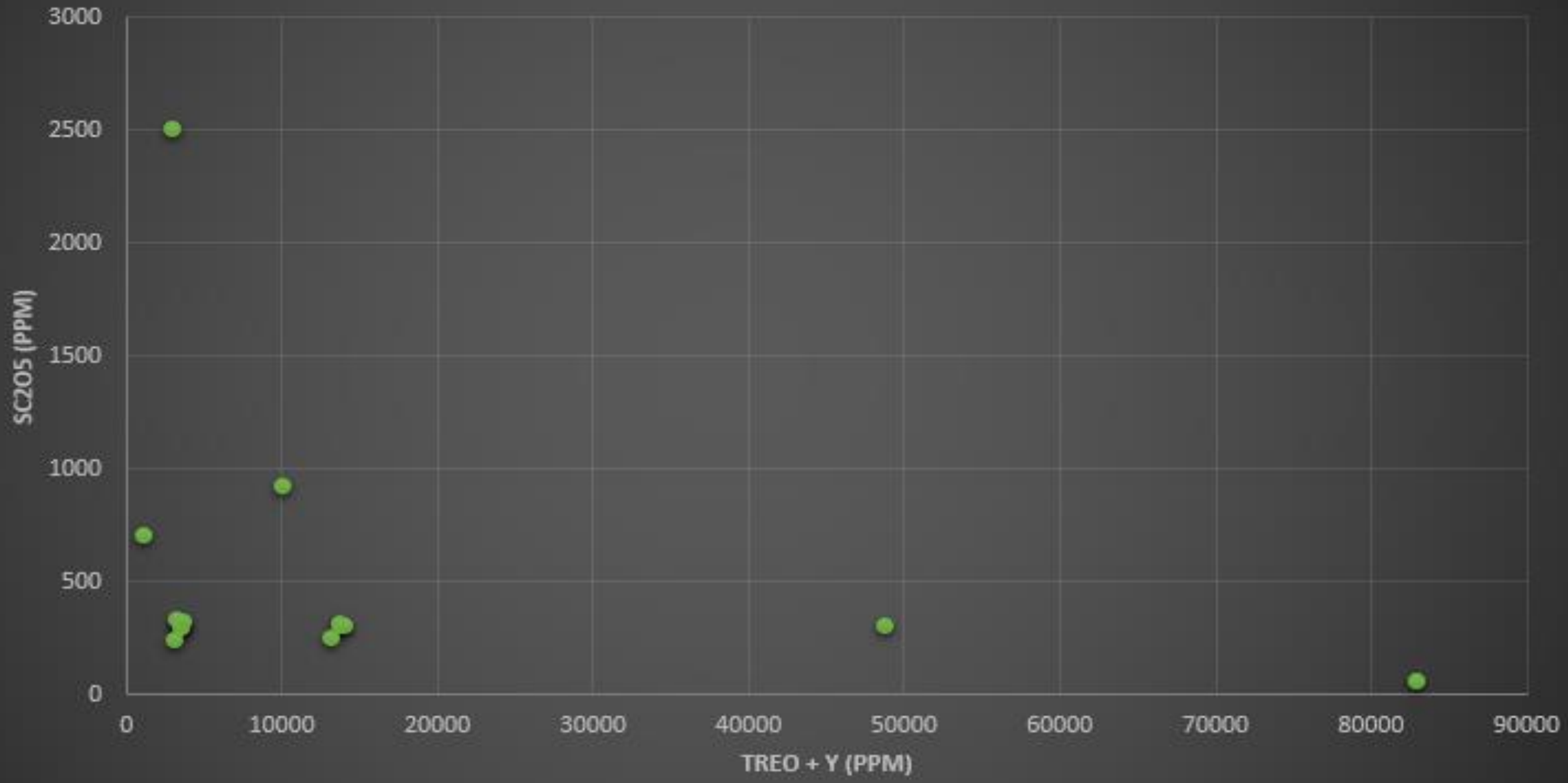

SiO2_wt_pct
Al2O3_wt_pct
CaO_wt_pct
Fe2O3_T_wt_pct
K2O_wt_pct
MgO_wt_pct
MnO_wt_pct
Na2O_wt_pct
P2O5_wt_pct
TiO2_wt_pct
LOI_wt_pct
La_ppm
Ce_ppm
Pr_ppm
Nd_ppm
Sm_ppm
Eu_ppm
Gd_ppm
Tb_ppm
Dy_ppm
Ho_ppm
Er_ppm
Tm_ppm
Yb_ppm
Lu_ppm
Y_ppm
Sc_ppm
Be_ppm
Bi_ppm
Co_ppm
Cr_ppm
Cs_ppm
Cu_ppm
Ga_ppm
Ge_ppm
Hf_ppm
In_ppm
Mo_ppm
Nb_ppm
Ni_ppm
Pb_ppm
Rb_ppm
Sb_ppm
Sn_ppm
Sr_ppm
Ta_ppm
Th_ppm
Tl_ppm
U_ppm
V_ppm
W_ppm
Zn_ppm
Zr_ppm
U-matrix

Similar styles…..Crater Lake and Glenover



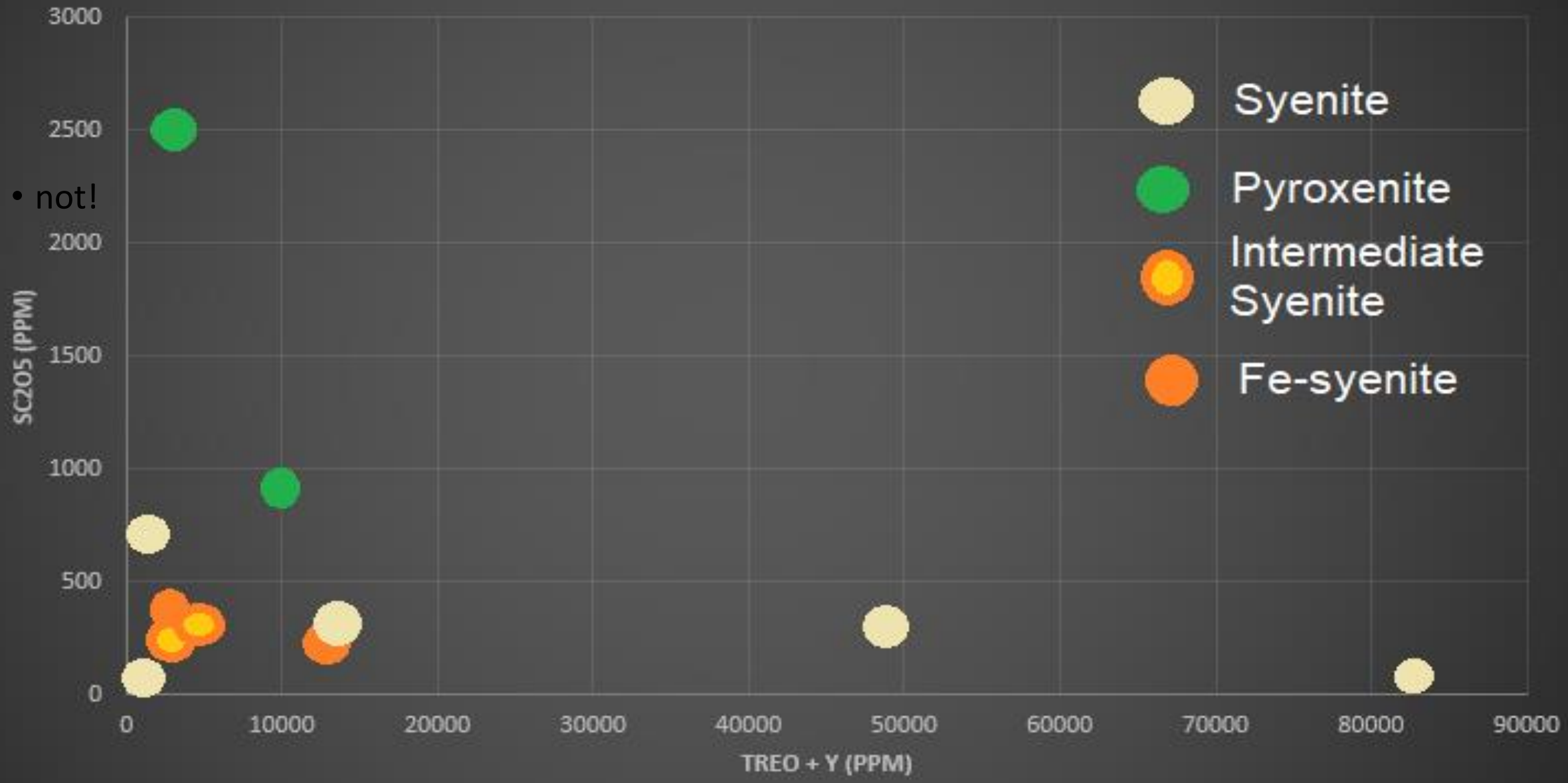


Crater Lake Sample Results (News Release: Imperial Mining, 2018-10-30)



Crater Lake Rock Sample Results (News Release: Imperial Mining, 2018-10-30)

- not!



CONCLUSIONS

Scandium occurs in significant quantities in some alkaline silicate rocks and carbonatites

Scandium does not appear to be associated with other REE due to its cationic radius and therefore – it's 'compatibility'

Exploration for Sc focusing on REE-enriched areas may therefore not be helpful

Scandium appears to be preferentially enriched in early pyroxenitic rocks, and is contained in alkali clinopyroxene such as aegerine, or amphibole such as riebeckite

In the secondary weathering environment scandium becomes enriched through lateritic weathering.

A crucial lack of mineralogical and chemical data in the literature is apparent and should be addressed urgently for Europe to identify potential sources of scandium in the region