Indicator minerals analytical techniques

Part I: Identification

Marja Lehtonen GTK

Indicator minerals

- Indicate the presence of a mineralization
- Visually and chemically distinct (heavy minerals)
- Chemically and physically resistant
- Target depended
- In Finland conventionally applied to gold and diamond exploration, but also several other targets (base metals, critical metals etc.)
- Sample media usually till
- Several indicator mineral projects carried out at GTK (Hightech metals, NovTecEx, INDIKA, MinExTarget)

Photo: Kari A. Kinnunen

Commonly used indicator minerals (McClenaghan, 2013) (mod).

Commodity / Deposit	Indicator minerals	Chemical composition	Average density (gcm^{-3})	Typical size range (mm)
Diamond[1]	Cr-pyrope garnet	$(Mg,Fe)_3(Al,Cr)_2(SiO_4)_3$	3.7	0.25-0.5
	Eclogitic garnet	$(Fe{+}{+},Mg)_3Al_2(SiO4)_3$	4.0	0.25-0.5
	Mg-ilmenite	$(Fe{+}{+},Mg)TiO_3$	4.7	0.25-0.5
	Cr-diopside	$CaMg(Fe,Cr)Si_2O_6$	3.3	0.25-0.5
	Chromite	$(Fe{+}{+}, Mg)(Cr,Al)_2O_4$	4.8	0.25-0.5
	Forsteritic olivine	$(Mg,Fe)_2SiO_4$	3.3	0.25-0.5
	Diamond	C	3.5	0.25-0.5
Gold[2]	Gold	Au	17.6	0.01-0.25
	Scheelite	$CaWO_4$	6.0	0.01-0.25
	Rutile	TiO_2	4.3	0.01-0.25
	Sulphides		>4.0	0.01-0.25
Magmatic Ni-Cu-PGE[3]	Cr-diopside	$CaMg(Fe,Cr)Si_2O_6$	3.3	0.25-2.0
	Forsteritic olivine	$(Mg,Fe)_2SiO_4$	3.3	0.25-2.0
	Enstatite	$(Mg,Fe)_2Si_2O_6$	3.2	0.25-2.0
	Chromite	$(Fe{+}{+}, Mg)(Cr,Al)_2O_4$	4.8	0.25-2.0
	Pentlandite	$(Fe,Ni)_9S_8$	4.8	0.01-0.25
	Pyrrhotite	$Fe_{(1-x)}S$ (x=0-0.17)	4.6	0.01-0.25
	Chalcopyrite	$CuFeS_2$	4.2	0.01-0.25
	Pyrite	FeS_2	5.0	0.01-0.25
	Platinum group minerals (PGM)		>8.0	0.001-0.1

Continues…

VMS deposits[4]	Chalcopyrite	$CuFeS_2$	4.2	0.01-0.25
	Galena	PbS	7.4	0.01-0.25
	Sphalerite	(Zn,Fe)S	4.1	0.01-0.25
	Pyrrhotite	$Fe_{(1-x)}S$ (x=0-0.17)	4.6	0.01-0.25
	Pyrite	FeS_2	5.0	0.01-0.25
	Gahnite	$(Zn,Fe)Al_2O_4$	4.3	0.25-2.0
	Spessartine	$(Mn{+}{+},Fe)_3Al_2(SiO_4)_3$	4.2	0.25-2.0
	Staurolite	$(Fe{+}{+},Mg)_2Al_9(Si,Al)_4O_{20}(O,OH)_4$	3.7	0.25-2.0
Pb-Zn deposits[5] (Mississippi Valley type)	Galena	PbS	7.4	0.01-2.0
	Sphalerite	(Zn,Fe)S	4.1	0.01-2.0
Porphyry Cu deposits[6]	Sulphides		> 4.0	0.25-2.0
	Andradite	$Ca3Fe{+}{+}{+}_2(SiO_4)_3$	3.9	0.25-2.0
	Diaspore	AlO(OH)	3.4	0.25-2.0
	Barite	$BaSO_4$	4.5	0.25-2.0
	Alunite	$KAl_3(SO_4)_2(OH)_6$	2.7	0.25-2.0
	Dravite	$NaMg_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$	3.1	0.25-2.0
	Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$	3.2	0.25-2.0
W-Mo deposits[7]	Scheelite	$CaWO_4$	6.0	0.01-0.25
	Wolframite	$(Fe,Mn)WO_4$	7.3	0.01-0.25
	Sulphides		>4.0	0.01-0.25
	Bi minerals		>6.0	0.01-0.25
"High tech metals"	Pyrochlore	$(Na,Ca)_2Nb_2O_6(OH,F)$	5.3	0.01-0.25
e.g. Nb, Ta, REE	Columbite	$Fe{+}{+}Nb_2O_6$	6.3	0.01-0.25
	Ta-minerals		>8.0	0.01-0.25
	Allanite	$(Ce,Ca,Y)_2(Al,Fe{+}{+}{+})_3(SiO_4)_3(OH)$	3.75	0.01-0.25

References:
1. McClenaghan & Kjarsgaard (2007) 2. McClenaghan & Cabri (2011) 3 and 6. Averill (2011) 4. Averill (2001) 5. Oviatt et al. (2013) 7. McClenaghan et al. (2013)

Indicator mineral work flow

Sampling

Pre-treatment

Concentration

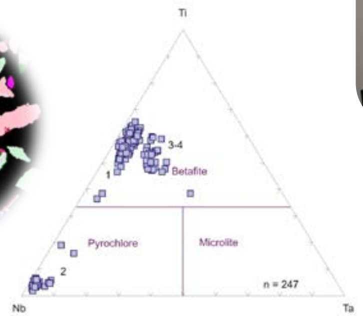
Separation

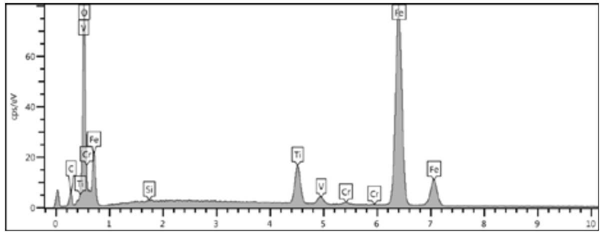
MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

Indicator mineral workflow

Microscopy

Mineral analysis

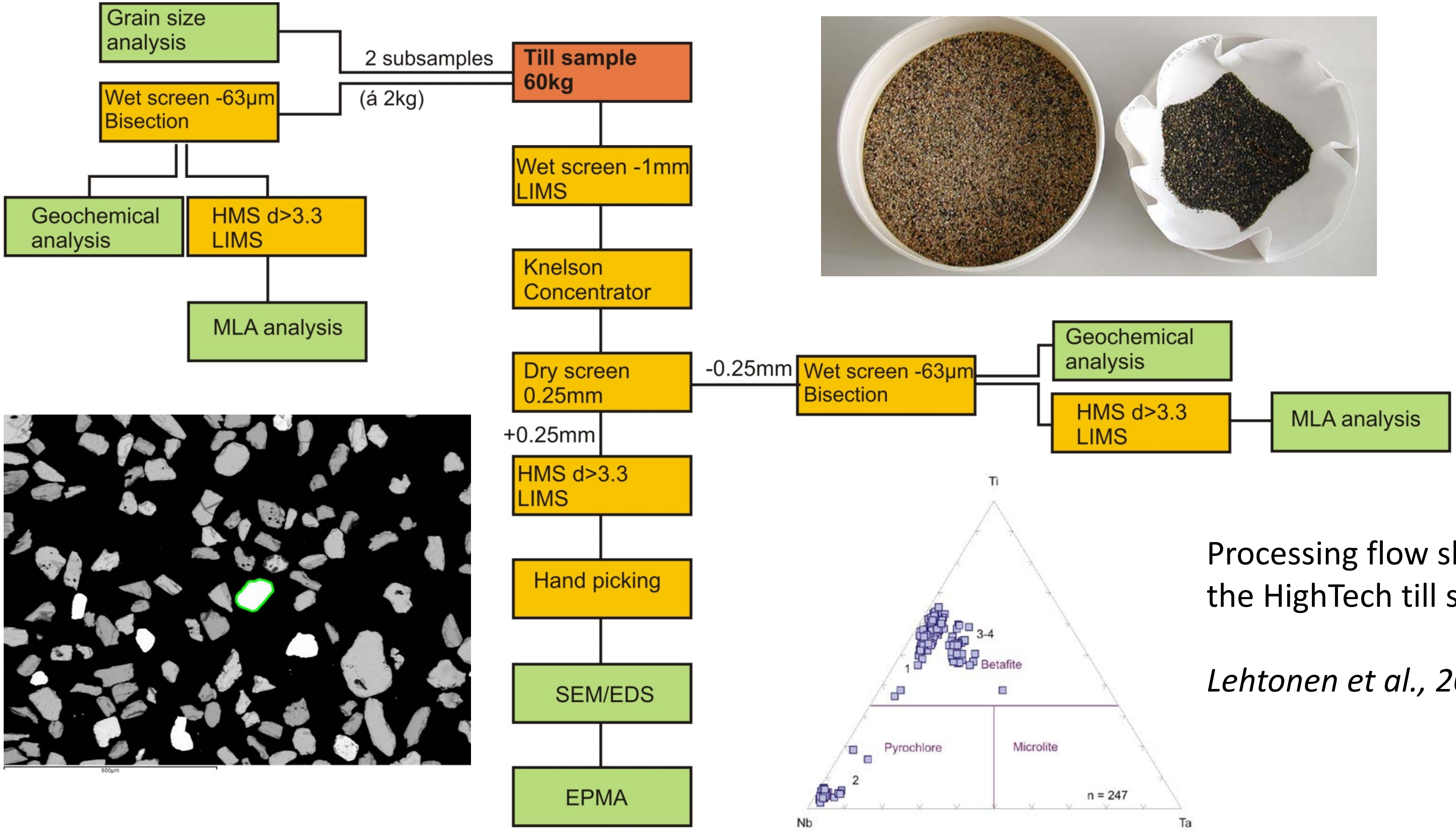




MinExTarget

eit RawMaterials
Connecting matters

Funded by the European Union



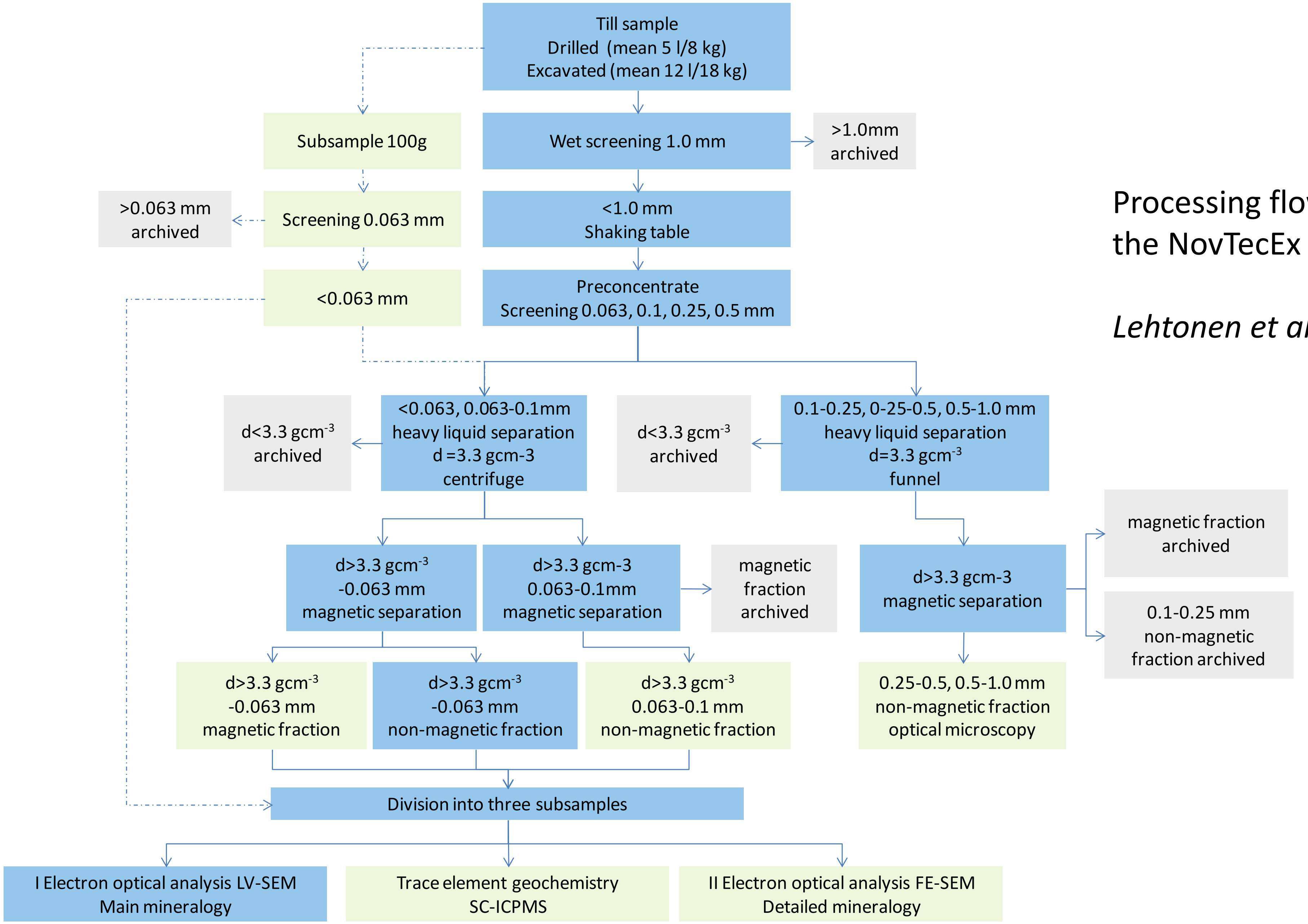
Hogarth (1977)

Processing flow sheet for the HighTech till samples

Lehtonen et al., 2011

Processing flow sheet for the NovTecEx till samples

Lehtonen et al., 2015



Funded by the European Union

Optical Microscopy

Strengths

- Experience and intelligence of the observer

Weaknesses

- Human error: tiredness, loss of focus when observing several indicators simultaneously, results may vary according to the observer
- Some minerals are impossible to identify in grain sizes below <100-200 µm
- SEM-EDS / EPMA is needed for confirmation
- Requires large original sample sizes to obtain enough sand-sized heavy mineral grains to obtain statistically meaningful results

Automated Mineralogy

Strengths

- Accuracy; very small contents of indicator minerals can be detected
- Optimal grain size range 10-200 µm
- Considerable reduction of the original sample size possible (savings in sample processing, less-invasive sampling methods)
- Can solve host mineral phases of trace elements detected by geochemical analysis (elemental deportment)

Weaknesses

- Tedious sample preparation

MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

GTK processed	Weight < 1 mm table feed (kg)	Microscopy 0.25-1.0 mm: mineral assemblage
RM_POS$-2012-36.2	10.9	Almandine-ilmenite/staurolite-epidote
RM_POS$-2012-39.1	18.5	Almandine/epidote-staurolite-kyanite
RM_POS$-2012-41.2	8.3	Almandine-ilmenite/epidote-staurolite
RM_POS$-2012-43.3	8.4	Almandine/staurolite-epidote
RM_POS$-2012-48.2	11	Almandine-ilmenite/staurolite-epidote
RM_POS$-2012-55.2	7.5	Almandine-ilmenite-hornblende/epidote- staurolite
RM_POS$-2012-66.1	19.7	Hematite-almandine-ilmenite/staurolite- epidote-kyanite
RM_POS$-2012-77.2	9.5	Almandine-ilmenite-hematite/epidote- staurolite-kyanite
RM_POS$-2012-82.1	22.2	Almandine-hematite-ilmenite/epidote- staurolite
RM_POS$-2012-97.2	11.6	Almandine-hematite/epidote-staurolite

GTK processed	Microscopy 0.25-1.0 mm: accessories								
	Chalcopyrite	Pyrite	Low Cr-diopside	Ruby Corundum	Sapphire Corundum	Mn epidote	Gahnite	Red Rutile	Chromite
RM_POS$-2012-36.2	1	1	3	0	0	0	0	55	55
RM_POS$-2012-39.1	0	0	1	0	0	0	0	22	108
RM_POS$-2012-41.2	1	0	0	0	0	0	0	48	72
RM_POS$-2012-43.3	0	0	0	0	0	0	31	36	36
RM_POS$-2012-48.2	0	0	1	0	0	0	1	36	73
RM_POS$-2012-55.2	0	1	0	0	0	0	0	53	53
RM_POS$-2012-66.1	0	0	0	0	0	0	0	20	9
RM_POS$-2012-77.2	0	0	0	0	0	0	0	63	32
RM_POS$-2012-82.1	0	0	0	0	0	0	0	27	68
RM_POS$-2012-97.2	0	0	0	0	0	0	0	34	34

Lehtonen et al., 2015 (NovTecEx project)
Microscopy results from ODM Laboratory

MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

SEM-EDS data	RM_POS$-2012-36.2		RM_POS$-2012-43.3	
Class	**Grains**	**% Total grains**	**Grains**	**% Total grains**
Monazite	2 991	1.20	21 142	8,81
Xenotime	529	0.21	64	0.03
Scheelite			1	0.00
Bismuth	1	0.00	2	0.00
Gold	4	0.00	1	0.00
Pyrochlore	39	0.02		
Columbite	8	0.00	2	0.00
Thorite	4	0.00	1	0.00
Galena	16	0.01	7	0.00
Sperrylite	2	0.00		
Total	250 000		240 000	
SC-ICPMS data				
Y ppm	277		2 152	
Bi ppm	2		5	
W ppm	12		58	
Nb ppm	284		416	
Au ppb	127		146	
Pt ppb	902		608	
Picking results (ODM)				
Gold	18		13	
Sperrylite	4			

NovtecEx project, Lehtonen et al. (2015)

Funded by the European Union

Particle size vs. Sample preparation

Particle Size		Approximate Number of Heavy Mineral Grains		Approximate No. of Epoxy Blocks per Gram
Class	µm	Per Gram	Per Expoxy Block	
Very coarse sand	1000-2000	170	125	1.5
Coarse sand	500-1000	1,400	500	3
Medium sand	250-500	11,000	2,000	5.5
fine sand	125-250	88,000	8,000	11
Very fine sand	63-125	700,000	32,000	22
Very coarse silt	32-63	5,600,000	130,000	45
Coarse silt	16-32	45,000,000	500,000	90

Table 1. Variation with particle size in the number of epoxy blocks required for automated analysis of 1 gram of heavy minerals.

Averill & Huneault, 2016

Different size materials have different transportation distances in glacial systems.
Important to evaluate what size fraction to focus.

Grain size distribution of minerals: Example from till heavy mineral concentrates

Grain size mm Density gcm-3	0.1-0.5 mm d>3.3	0.063-0.1 mm d>3.3	<0.063 mm d>3.3
Class	Grains / mass%	Grains / mass%	Grains / mass%
Titanite	655 / 5.5	411 / 3.4	542 / 1.7
Almandine	384 / 3.9	411 / 4.2	514 / 1.9
Ilmenite	1010 / 9.3	1895 / 19.2	7341 / 31.2
Zircon	73 / 0.8	371 /4.1	1352 / 5.7
Monazite	3 / 0.0	9 / 0.1	82 / 0.4
Gold	0 / 0.0	0 / 0.0	1 / 0.0

Lehtonen et al., 2015 (NovTecEx project)
SEM-EDS Modal mineralogy data

Funded by the European Union

Grain size distribution of minerals: Example from heavy mineral concentrates

Mäkärä	63-100 µm	100-160 µm
RM_JOV-2017-4.1*	**Zr**, Mnz, Ap, (Bdy), (Aln), (Xtm)	Zr, Mnz, (Xtm), (Ap)
RM_JOV-2017-6.2	Zr, Mnz, (Ap)	(Mnz), (Zr)
RM_JOV-2017-8.2*	**Zr**, Mnz, Xtm, (Aln)	**Zr**, Mnz, Xtm, (Aln), (Au)
RM_JOV-2017-9.2	Zr, (Mnz)	(Aln), (Mnz)
Sokli		
RM_JOV-2017-11.2*	**Zr**, Ap, Mnz, Pcl, (Bdy)	**Zr**, Mnz, Pcl, Ap, (Aln), (Bdy), (Xtm), (Zrc)
RM_JOV-2017-12.2	**Zr**, Ap, Mnz, Pcl, (Bdy)	**Zr**, Ap, Mnz, (Pcl), (Bdy)
RM_JOV-2017-13.2*	**Zr, Pcl, Bdy, Ap, Mnz**, Zrc, (Aln), (Thr), (Bas)	**Zr, Pcl, Bdy, Mnz**, Ap, Zrc, (Aln)
Rautuvaara		
RM_AMPE-2017-150.4	W-Rt, Mnz, Cbl, (Ap), (Aln), (Xtm), (Zr)	W-Rt, Mnz, Aln, (Ap), (Cbl)
RM_AMPE-2017-150.6	W-Rt, Mnz, (Zr), (Aln), (Xtm), (Cbl)	W-Rt, (Mnz), (Ap), (Cbl)
RM_AMPE-2017-151.2	W-Rt, Mnz, Xtm, Aln, (Ap), (Zr)	W-Rt, Mnz, Ap, (Aln), (Cbl), (Xtm), (Thr), (Zr)
RM_AMPE-2017-151.5	W-Rt, Mnz, (Ap), (Zr), (Xtm), (Cbl), (Bdy), (Aln)	W-Rt, Zr, Mnz, Aln, (Xtm)

Lukkari & Lehtonen 2018 (INDIKA project)

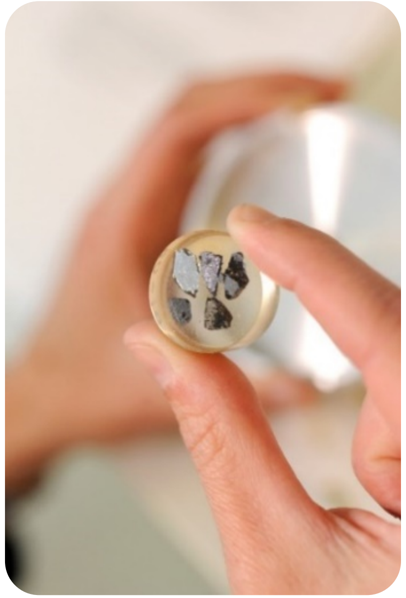
*Frantz 0.3 ja 0.5 A, **bold** = concetration over 5 %, () = trace amount

Aln = allanite, Ap = apatite, Bdy = baddeleyite, Bas = bastnäsite, Cbl = cobaltite, Mnz = monazite, Pcl = pyrochlore, Thr = thorite, W-Rt = W-rutile, Xtm = xenotime, Zrc = zircelite, Zr = zircon

MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

Sample preparation for electron optical studies

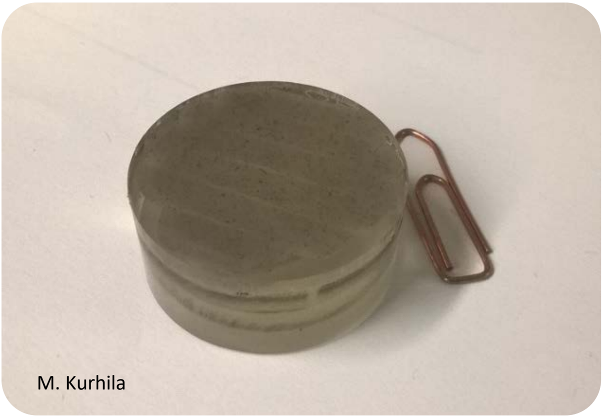
- Standard sample types
  - Polished epoxy mounts (Ø 25 mm or 30 mm)
  - Polished thin/thick sections (28 x 48 mm)
- Coating by carbon, gold, copper etc. for conductivity to achieve optimal quality of image & analysis
- Grain preparates for morphological studies (semiquantitative analysis)



MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

Sample preparation for electron optical studies

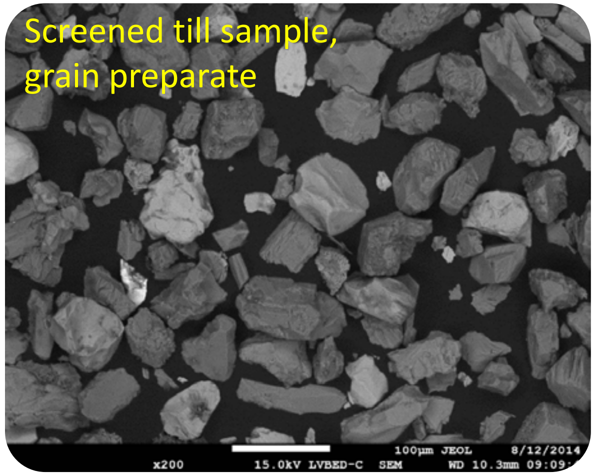
- Vertical polished mounts can be prepared to avoid gravitational differentiation in the epoxy
- Horizontal mount is cut into a few mm thick slices, each turned 90 degrees, glued back together & polished

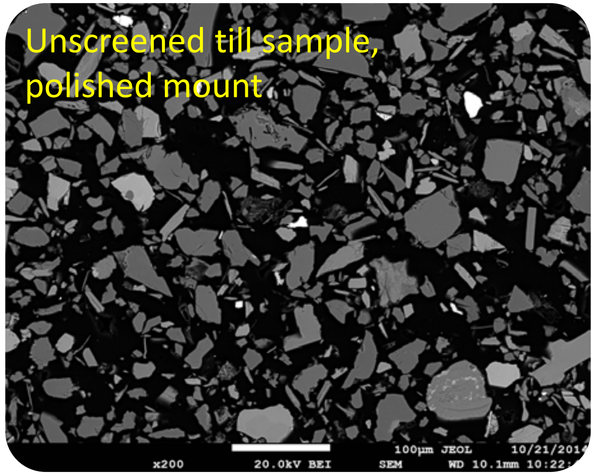


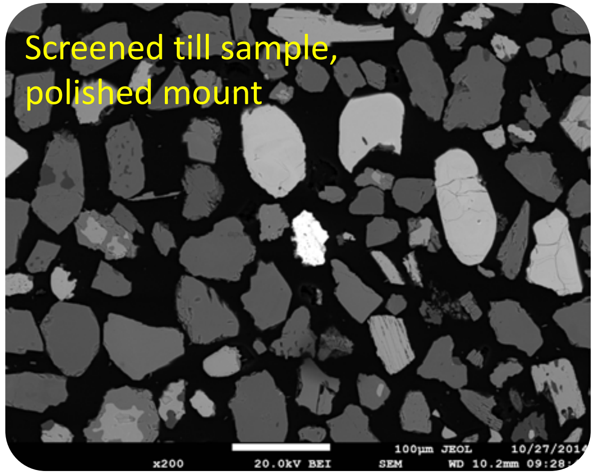
Vertical polished mounts (30 mm) of mineral powder. Each slice approximately 5 mm.

Sample preparation for electron optical studies

- Optimal set-up
  - Narrow grain size distribution
  - Mineral grains are not touching each other
- Pre-treatment of sample material
  - Sieving
  - Fine grained graphite powder to grain separation







Automated/semi-automated mineralogy (SEM-EDS)

Funded by the European Union

minerals

MDPI

Article

Exploration Potential of Fine-Fraction Heavy Mineral Concentrates from Till Using Automated Mineralogy: A Case Study from the Izok Lake Cu–Zn–Pb–Ag VMS Deposit, Nunavut, Canada

H. Donald Lougheed [1,*], M. Beth McClenaghan [2], Dan Layton-Matthews [1] and Matthew Leybourne [1,3]

1 Queen's Facility for Isotope Research, Department of Geological Sciences and Geological Engineering, Queen's University, 36 Union St., Kingston, ON K7L 3N6, Canada; dlayton@queensu.ca (D.L.-M.); m.leybourne@queensu.ca (M.L.)
2 Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8, Canada; beth.mcclenaghan@canada.ca
3 McDonald Institute, Canadian Particle Astrophysics Research Centre, Department of Physics, Engineering Physics & Astronomy, Queen's University, 64 Bader Lane, Kingston, ON K7L 3N6, Canada
* Correspondence: 5hdl@queensu.ca

Received: 15 February 2020; Accepted: 26 March 2020; Published: 30 March 2020

check for updates

Well-established method & widely used for indicator mineral surveys.

Feature

Unlocking the applications of automated mineral analysis

Identifying and quantifying the relative abundance of minerals is a fundamental part of many aspects of both pure and applied geology. Historically, quantitative mineralogy could be achieved using optical microscopy and point counting. This is a slow and operator dependent process, and practically impossible to achieve in, for example, very fine grained samples. Over the last decade a range of automated mineralogy technologies have arisen from the global mining industry and are being increasingly used in other branches of geology. These technologies, based on scanning electron microscopy with linked energy dispersive spectrometers, have the potential to revolutionise how we quantify mineralogy. In addition, during measurement, the sample textures are also captured, providing a wealth of valuable data for the geologist. In this article we review the current state of automated mineralogy and highlight the many areas of application for this technology.

Duncan Pirrie[1] & Gavyn K. Rollinson[2]

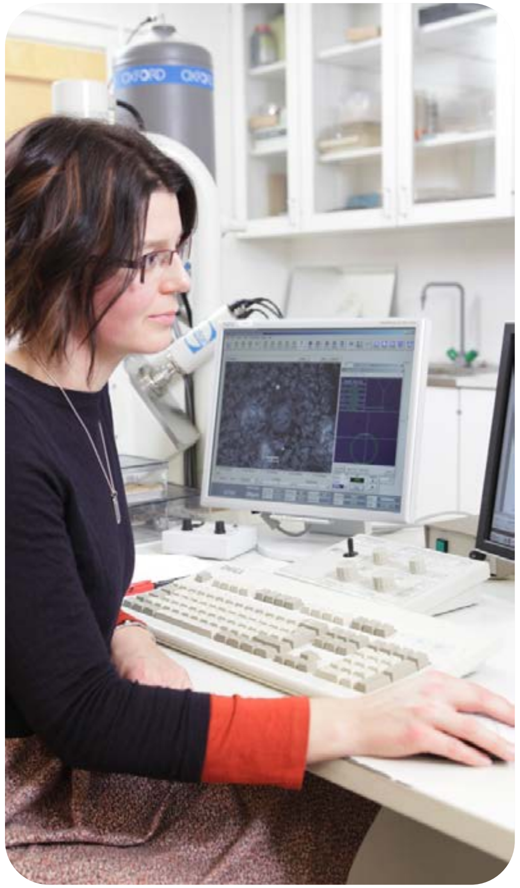
[1]Helford Geoscience LLP, Menallack Farm, Treverva, Penryn, Cornwall, TR10 9BP, UK
dpirrie@helfordgeoscience.co.uk
[2]Camborne School of Mines, CEMPS, University of Exeter, Tremough Campus, Penryn, Cornwall, TR10 9EZ, UK

MinExTarget

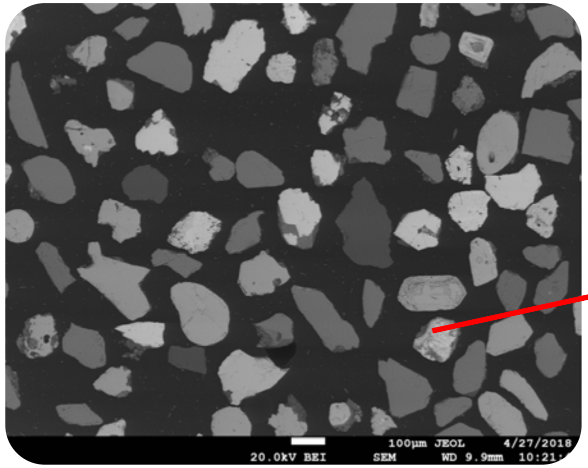
eit RawMaterials Connecting matters

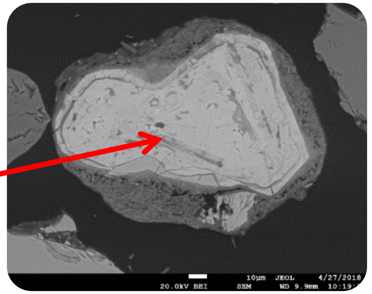
Funded by the European Union

Modal Mineralogy Measurement



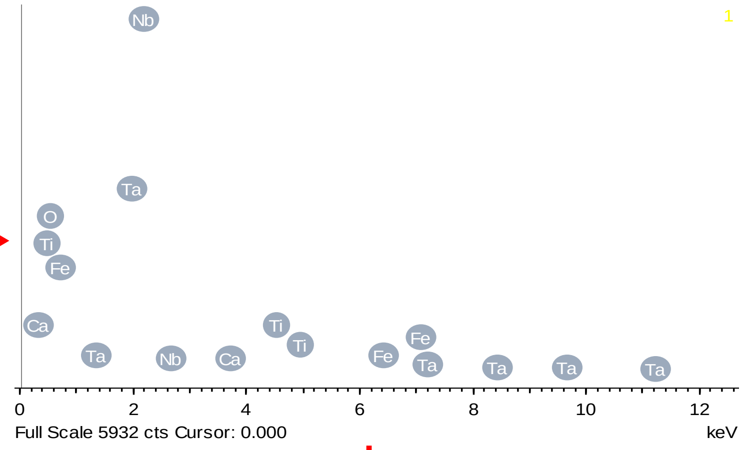
BSE image





Single grain

EDS spectrum



Chemical composition

GTK Database

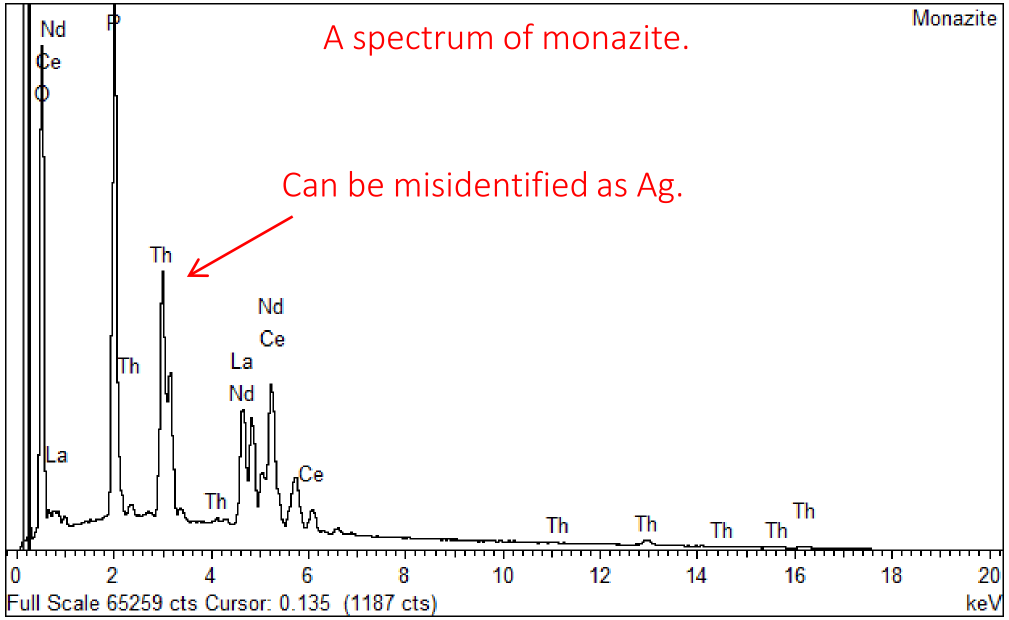
Columbite

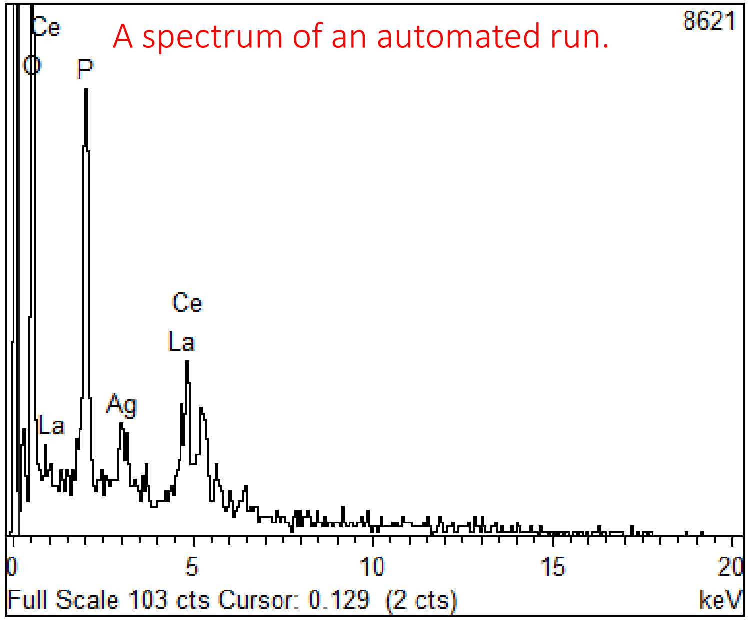
(Mg,Fe,Mn)(Nb,Ta)$_2$O$_6$

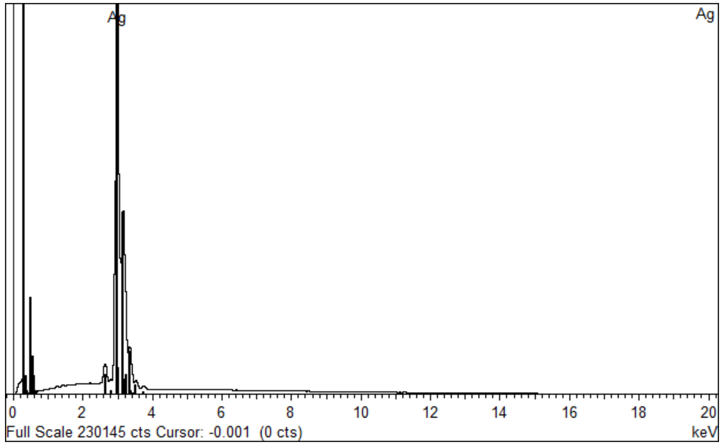
Mineral	Grain count	Vol-%
Monazite	**1800**	**11.70**
Fe-oxide	1708	16.28
Zircon	**1666**	**11.45**
Baddeleyite	877	6.69
Columbite	32	0.02
.		
.		
Total	9226	100

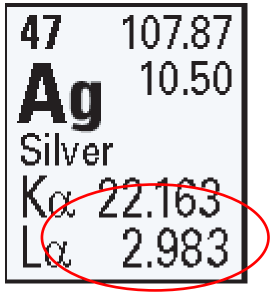
MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

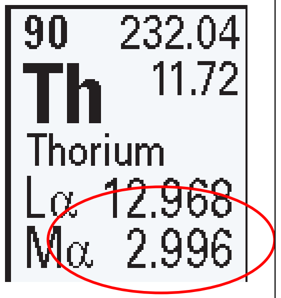
EDS software is not infallible –
It is **crucial** to check the data quality!

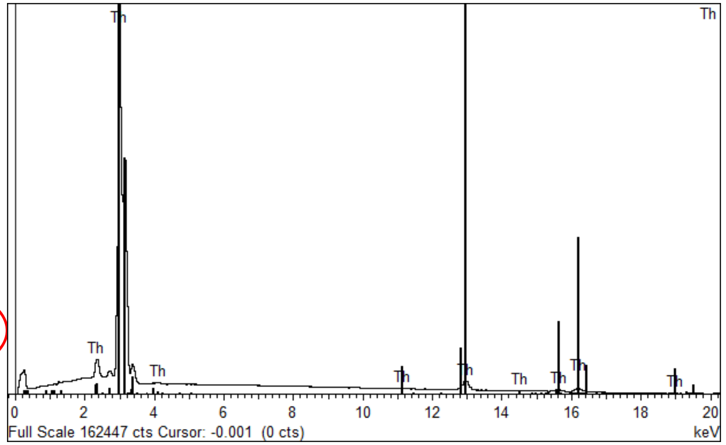






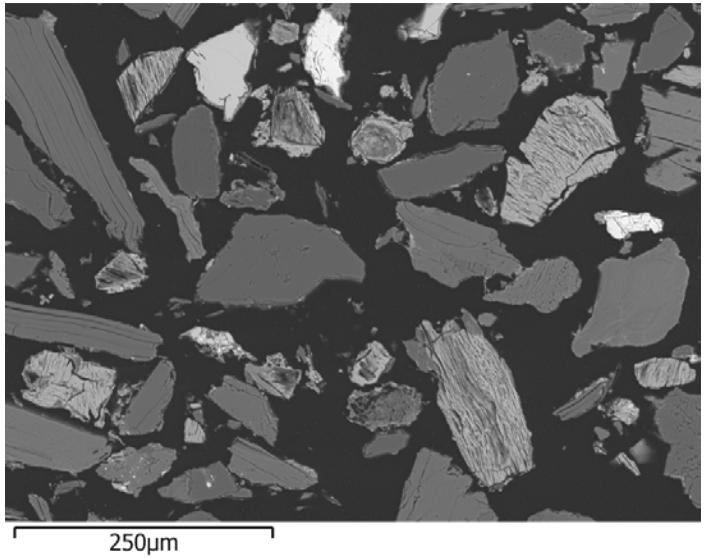


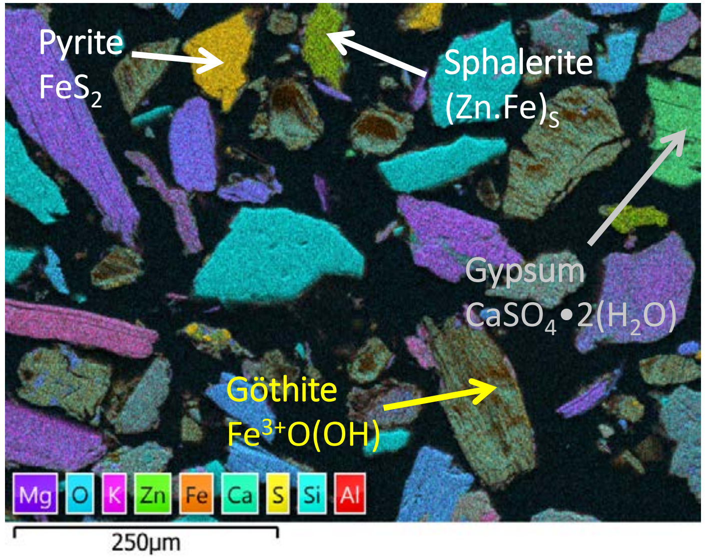


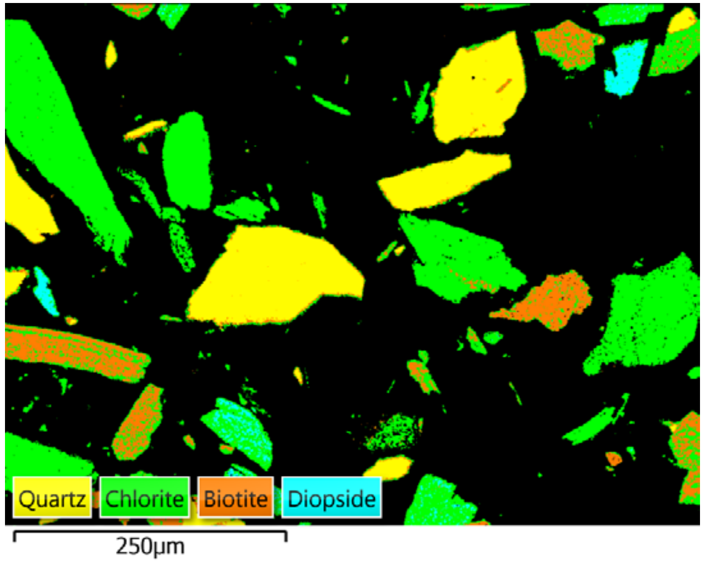


MinExTarget
eit RawMaterials
Connecting matters
Funded by the European Union

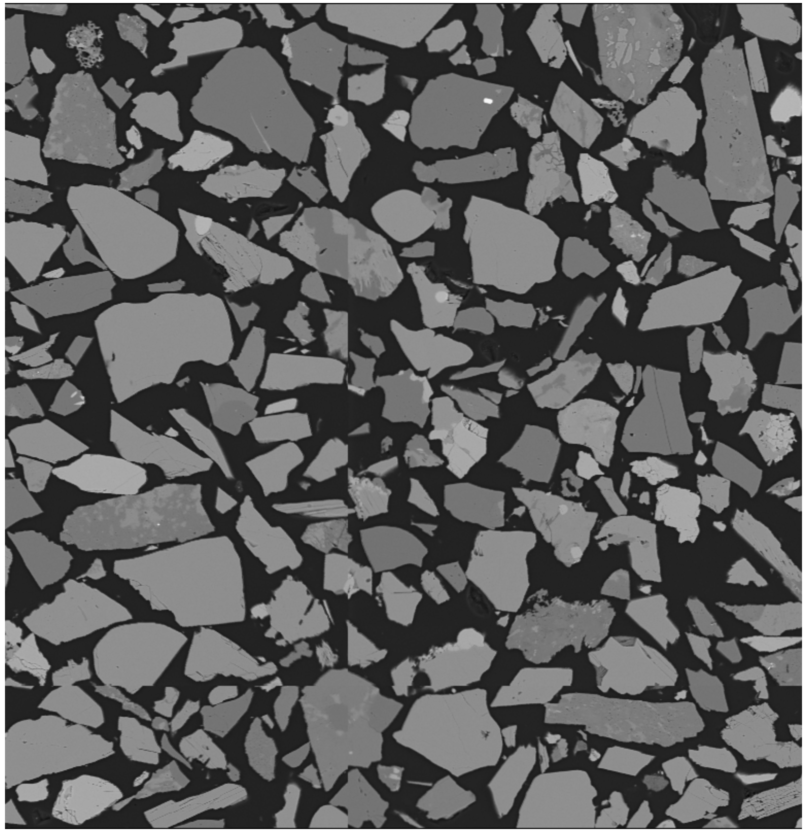
Elemental and Phase Mapping

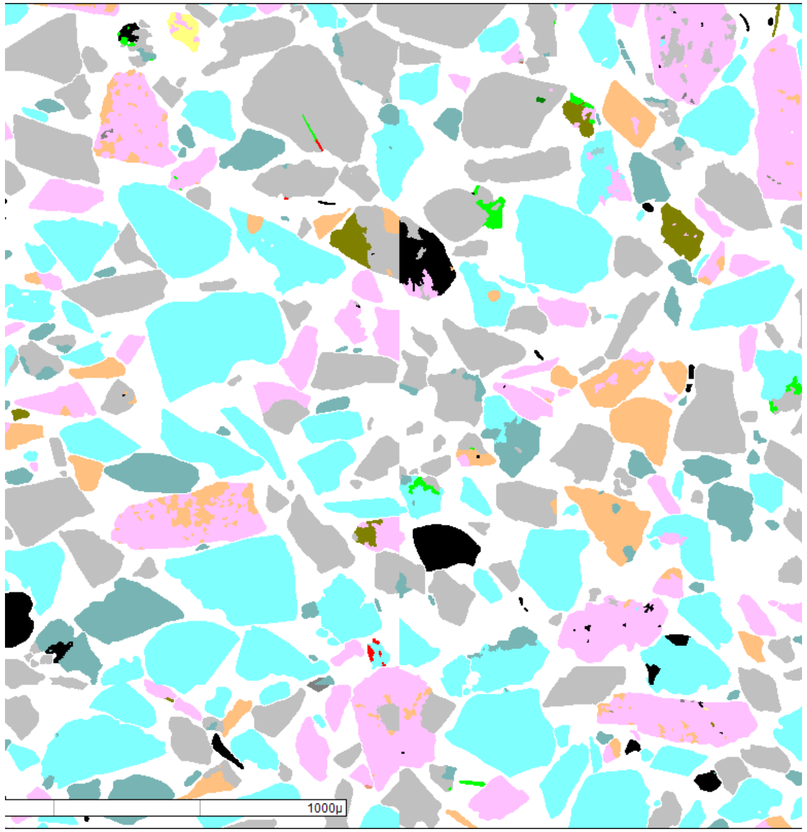


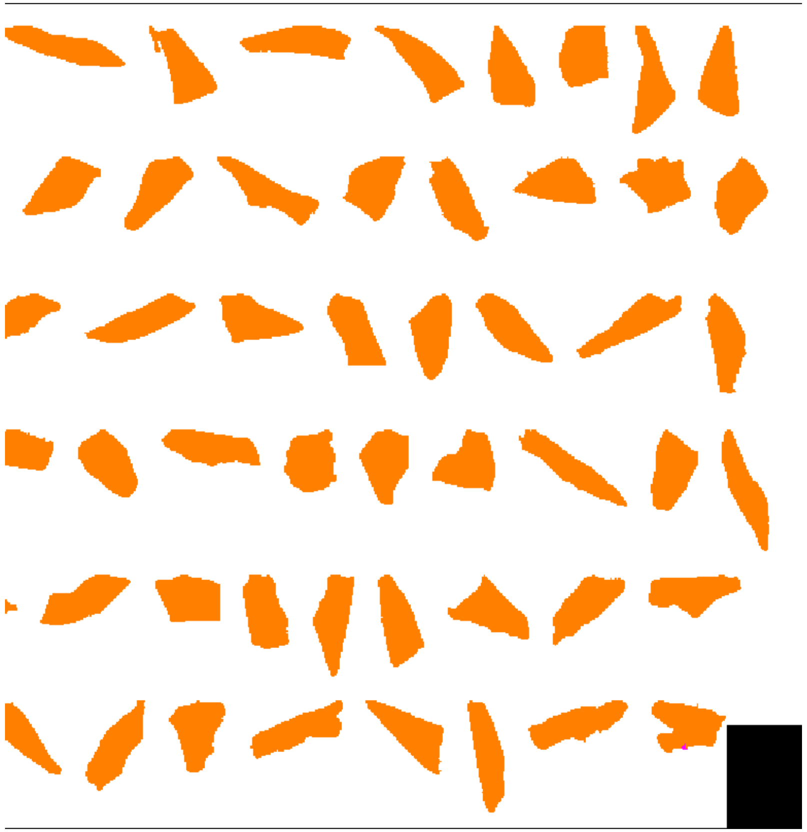




MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union







Phase Mapping & Particle listing

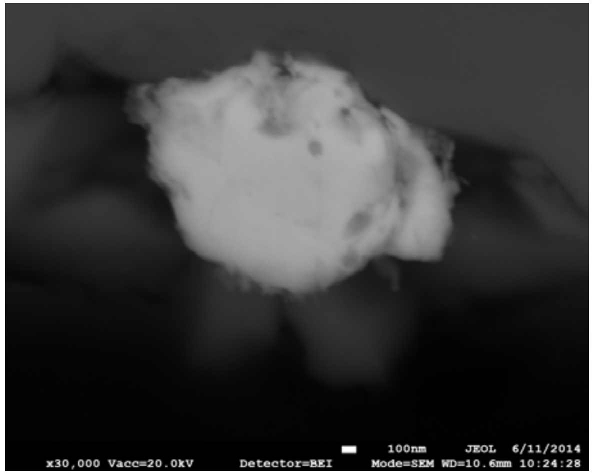
Courtesy: Matti Kurhila

MinExTarget eit RawMaterials Connecting matters Funded by the European Union

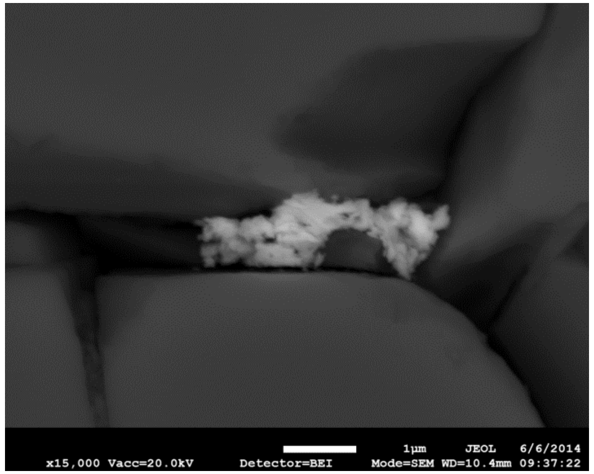
Automated Search for Trace Mineral Phases: BSE Thresholding

A heavy mineral concentrate of till (20-63 μm).

	RM_POS$-2012-36.2		
Class	**Grains**	**% analyzed grains**	**% total grains**
Monazite	2 991	83.13	1.20
Xenotime	529	14.70	0.21
Scheelite	0	0.00	0.00
Bismuth	1	0.03	0.00
Gold	4	0.11	0.00
Pyrochlore	39	1.08	0.02
Thorite	8	0.22	0.00
Galena	4	0.11	0.00
Pb-oxide	16	0.44	0.01
Sperrylite	4	0.11	0.00
Uraninite	2	0.06	0.00
Total	3 598	100.00	1.44
Total features (est.)	250 000		



Sperrylite $PtAs_2$

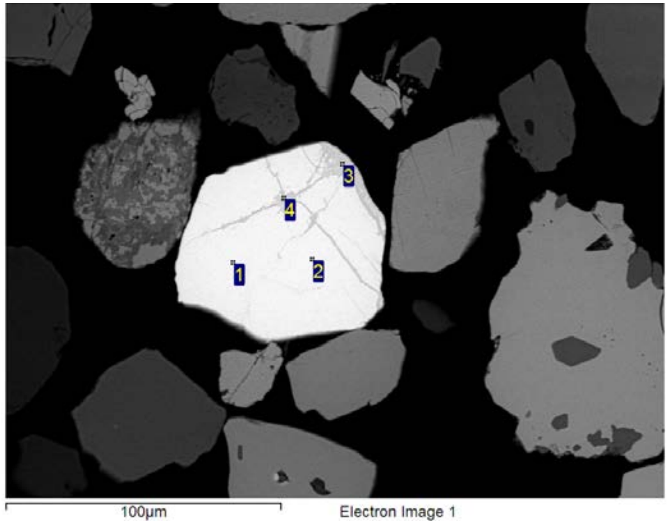


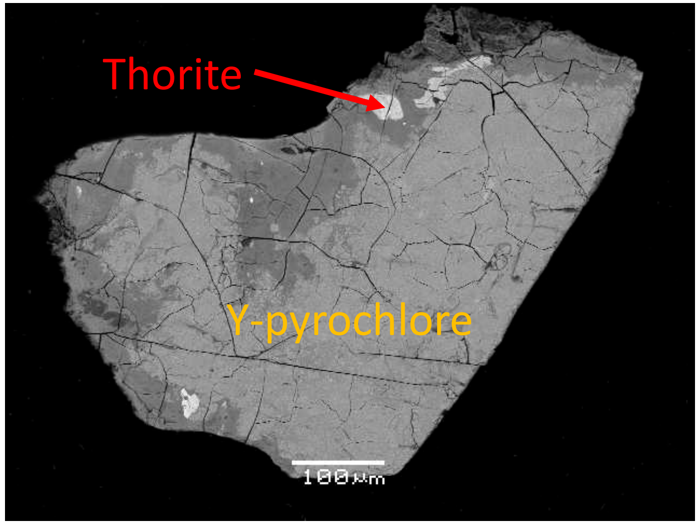
Gold Au

MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

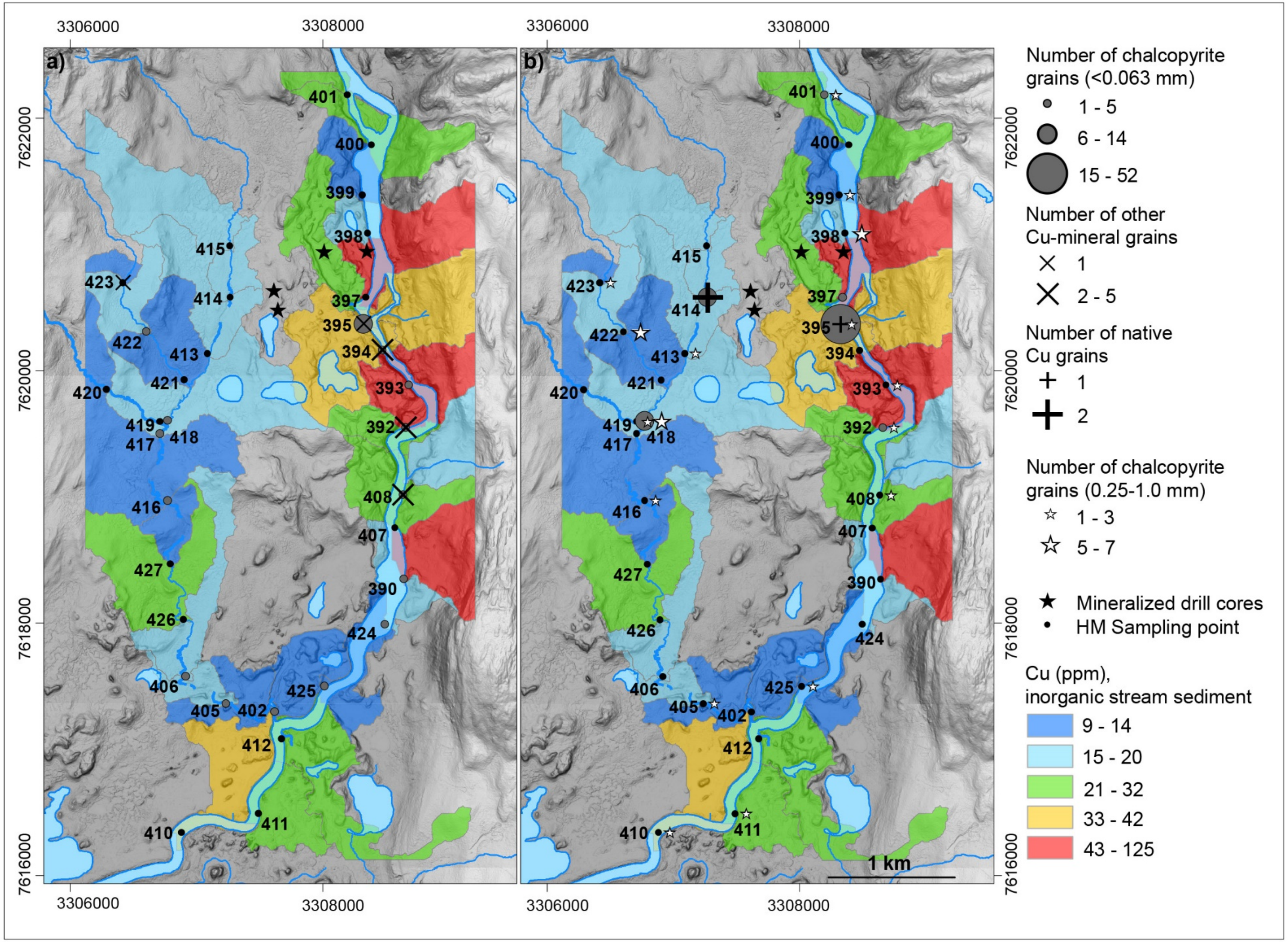
	426U_06MR	426_U_Pin09	426U_10MR	426_U_Kes09	426U_17MR	426_U_Poh09
Sample type	Till	Till precon	Till	Till precon	Till	Till precon
Original sample size kg	2	45	2	45	2	45
Density gcm-3	>3.3	>3.3	>3.3	>3.3	>3.3	>3.3
Grain size µm	-63	-63	-63	-63	-63	-63
Mineral	Grain Count	Grain Count	Grain Count	Grain Count	Grain Count	Grain Count
Yttro-pyrochlore-(Y)	3	4	2	12	23	24
Other_pyrochlores						
Columbite_tantalite	2	5	1	10		6
Gold		1				1
Bismuth						1
Hedleyite				1		
Scheelite		1	2	11	1	24
Thorite	9	15	41	29	16	25
Baddeleyite	3	28	2	8		4
Monazite	656	3635	1046	1317	560	1289
Bastnasite	5	11	14	27	16	30
Xenotime	73	148	75	65	56	81
Allanite		6	1	20		27
Zirconolite				1		1
Chamosite				1		
Total	**751**	**3854**	**1184**	**1502**	**672**	**1513**
Total grain count (ca)	400 000	800 000	800 000	800 000	600 000	800 000

Hand picking of 0.25-0.5 mm						
Yttro-pyrochlore-(Y)		0		0		66





Lehtonen et al., 2011



Hulkki et al., 2018

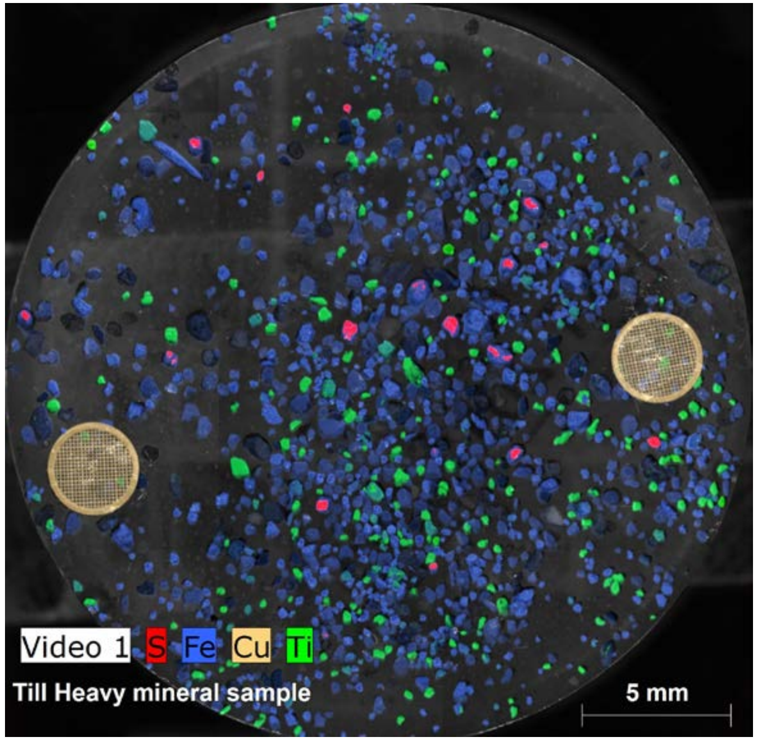
MinExTarget

eit RawMaterials Connecting matters

Funded by the European Union

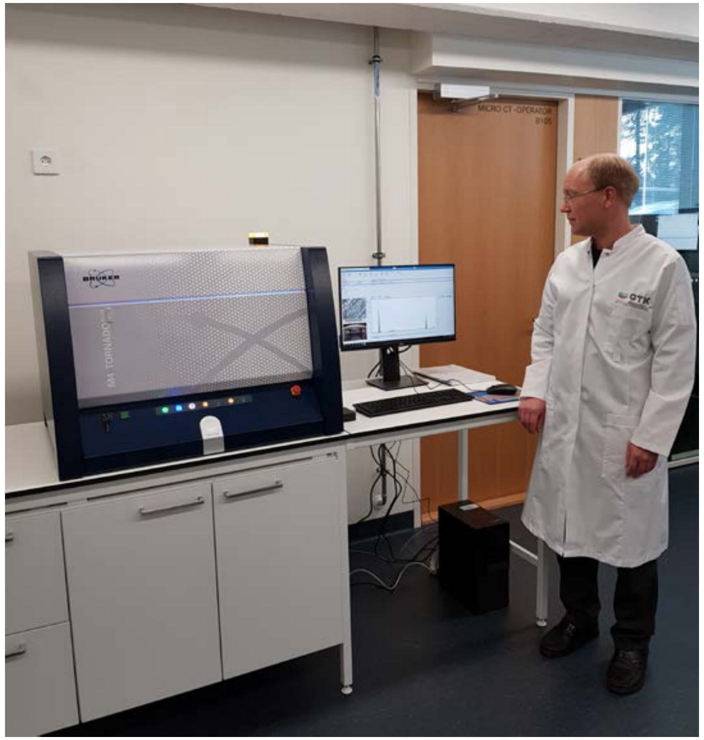
Micro-XRF Technique

- Recently installed at GTK
- Validation period on-going
- Benefits for indicator mineral work
  - Large sample chamber
  - Fast scanning of elemental distribution maps
  - Possibility to study coarser grain size fractions
  - No (or minimal) sample preparation needed
- Testing on-going for MinExTarget samples



Micro-XRF map of a MinExTarget heavy mineral concentrate
Beam size 20 µm

Courtesy: Hugh O'Brien, GTK



Extremely fast scanning techniques also available

Maia Mapper: high definition XRF imaging in the lab

C.G. Ryan,[a,1] R. Kirkham,[a] G.F. Moorhead,[a] D. Parry,[a] M. Jensen,[a] A. Faulks,[a] S. Hogan,[a] P.A. Dunn,[a] R. Dodanwela,[a] L.A. Fisher,[a] M. Pearce,[a] D.P. Siddons,[b] A. Kuczewski,[b] U. Lundström,[c] A. Trolliet[c] and N. Gao[d]

[a] *Commonwealth Scientific and Industrial Research Organisation, Normanby Road, Clayton VIC 3168, Australia*
[b] *National Synchrotron Light Source II, Brookhaven National Laboratory, Upton NY 11973, U.S.A.*
[c] *Excillum AB, Torshamnsgatan 35, 164 40 Kista, Sweden*
[d] *XOS, 15 Tech Valley Drive, East Greenbush, U.S.A.*

E-mail: Chris.Ryan@csiro.au

MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

Quantitative chemical analysis of minerals (EPMA)

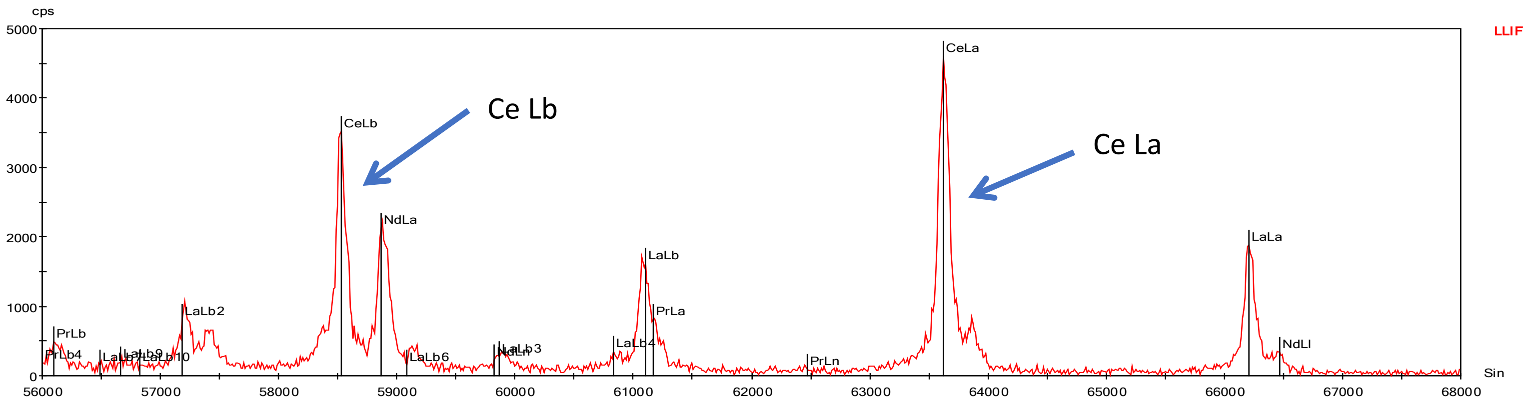
MinExTarget
eit RawMaterials
Connecting matters
Funded by the European Union

Quantitative mineral analysis of indicators

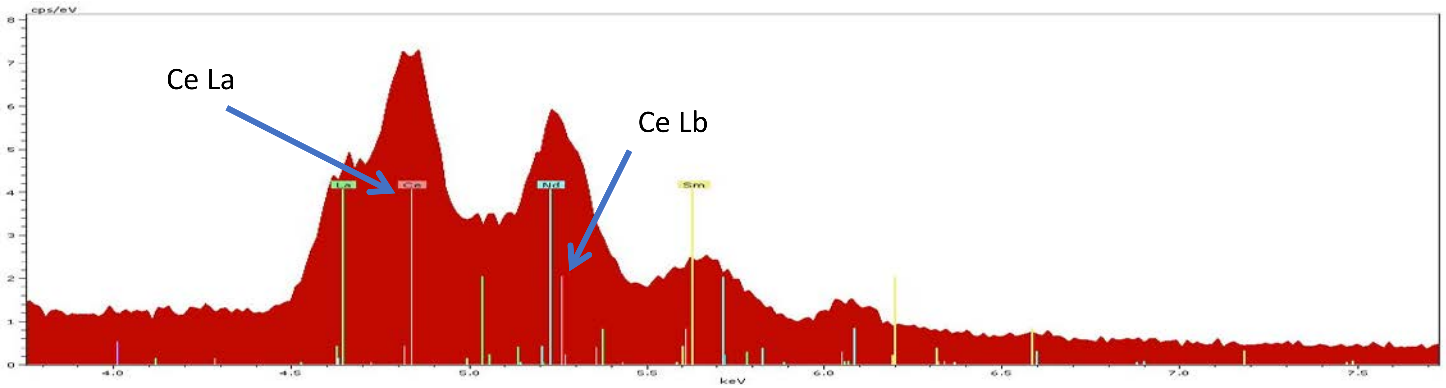
- Quantitative chemical analyses of indicator minerals needed for source characterization (finger-printing)
- Routinely obtained by electron microprobe (WDS based analysis)
    - DL of EDS 0.1-0.5w%; DL of WDS down to a few ppm's but routinely ca 0.05w% (element and matrix depended)

MinExTarget
eit RawMaterials
Connecting matters
Funded by the European Union

WDS-EDS spectral resolution (Monazite)



WDS

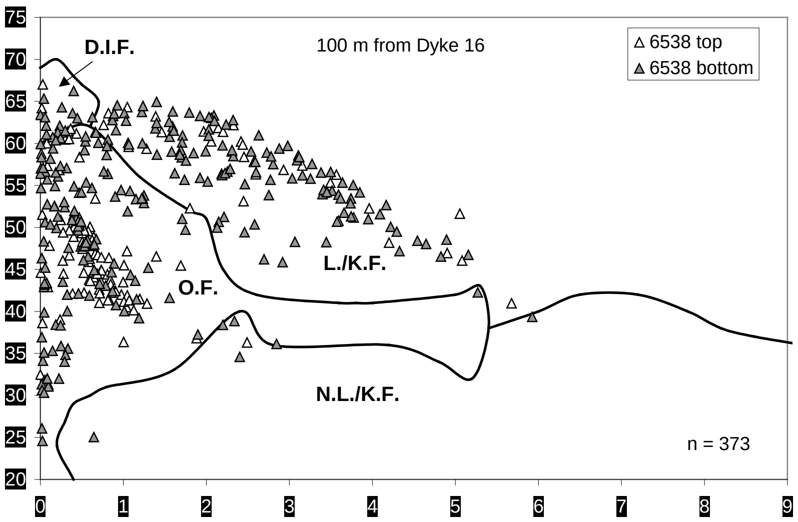


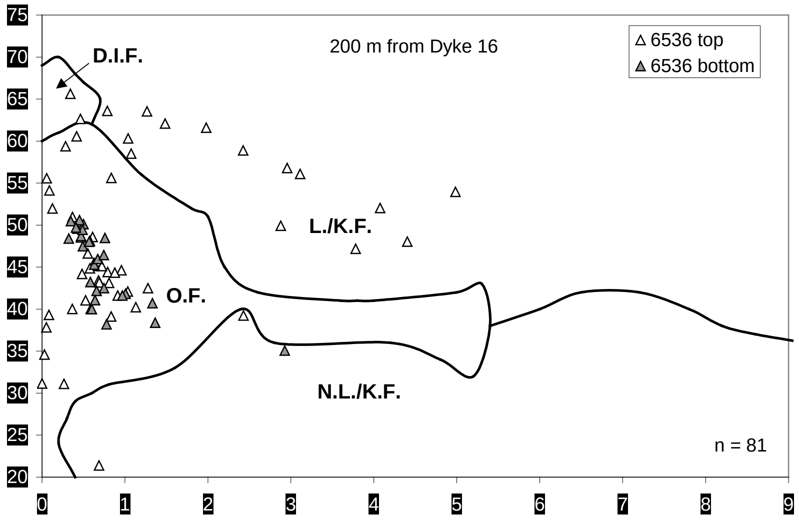
EDS

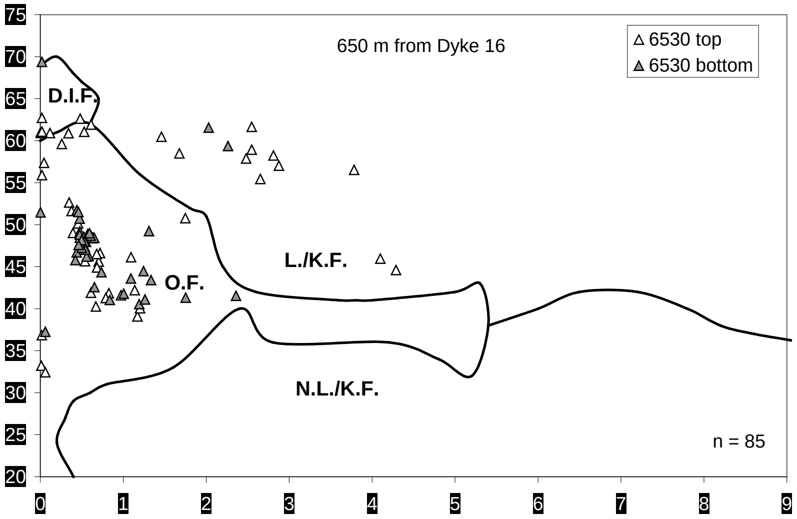
Courtesy: Bo Johanson, GTK

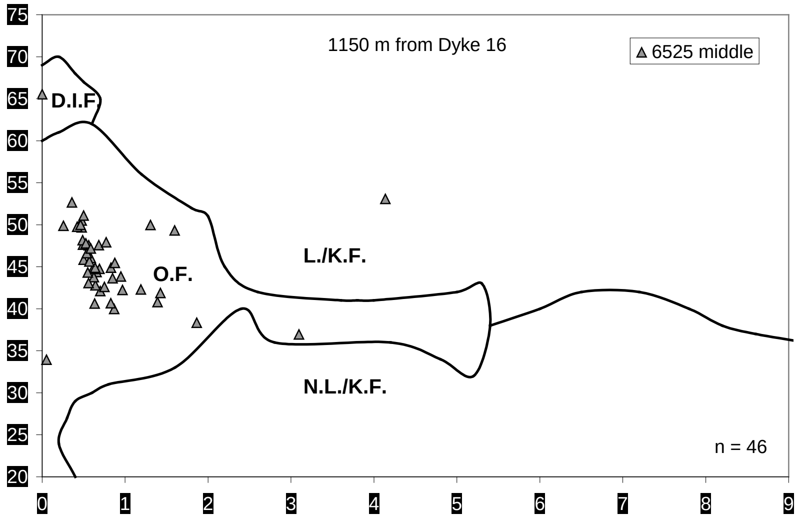
MinExTarget
eit RawMaterials Connecting matters
Funded by the European Union

Classification of indicators: Example of kimberlitic / non-kimberlitic chromite



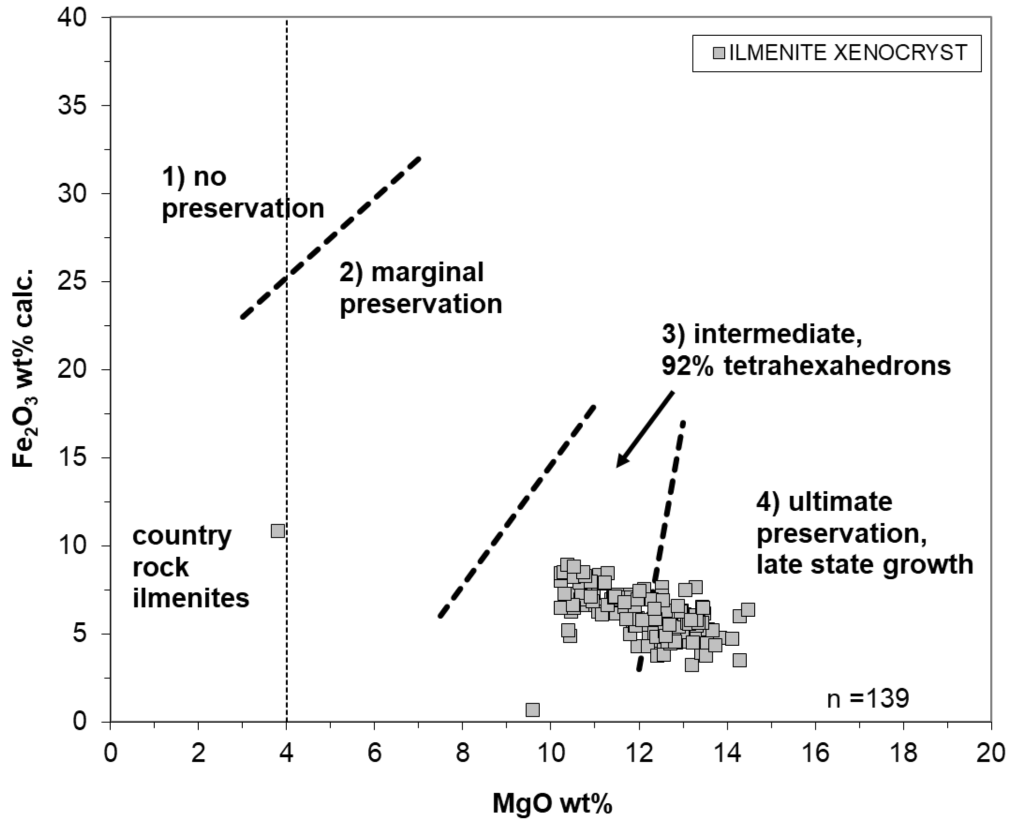




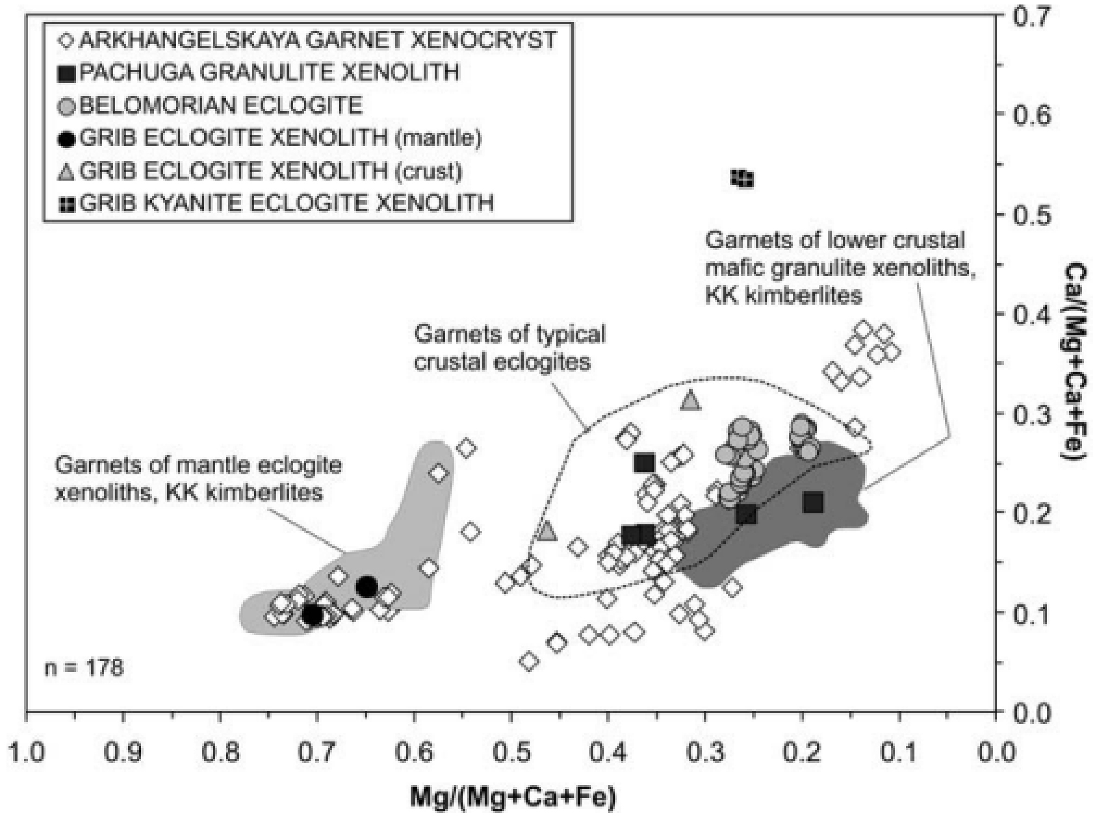


Classification by Fipke et al. (1995);
Data from Lehtonen et al. (2005)

Source characterization based on indicator minerals

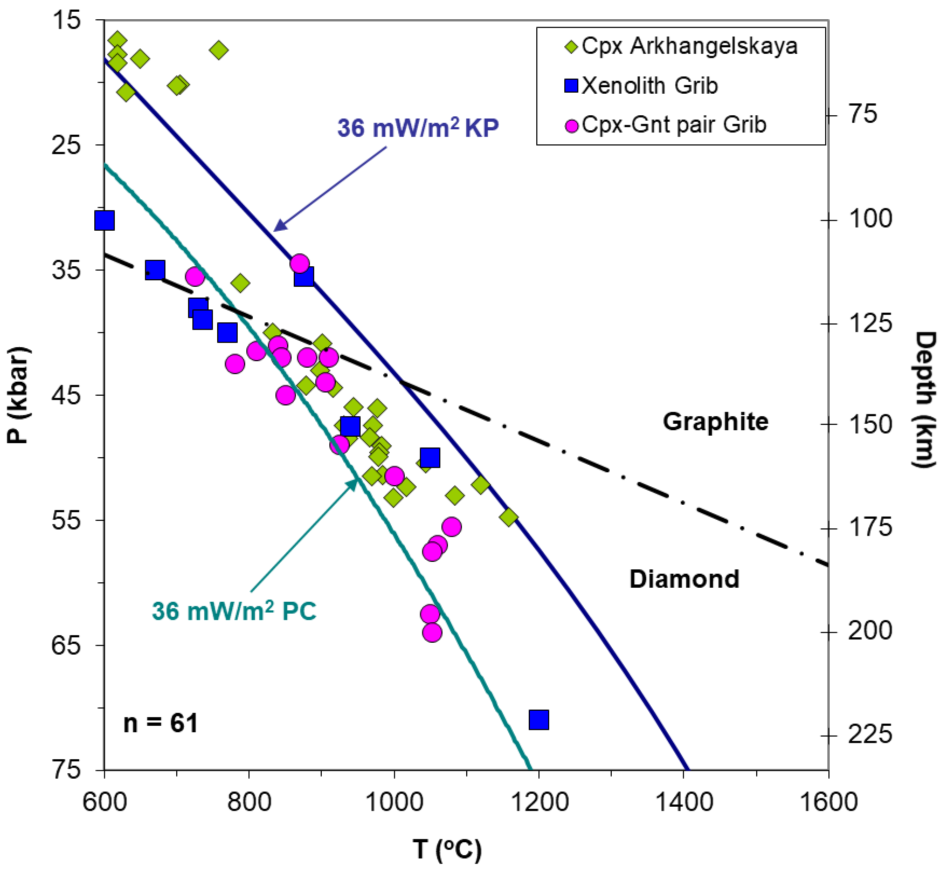


Diamond preservation index by Gurney & Zweistra (1995); Data from Lehtonen et al. (2009)



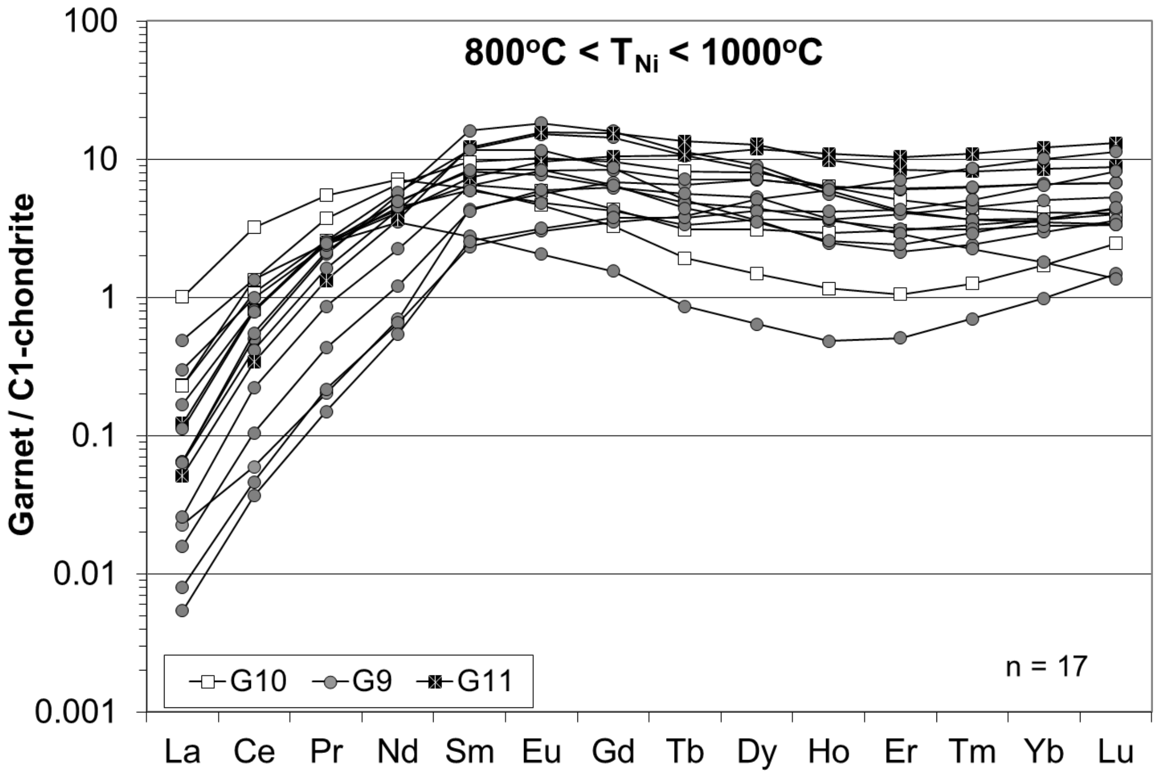
Eclogitic garnet classification; Data from Lehtonen et al. (2009) and references therein

Thermometry and Thermobarometry



p-T data from CPX xenocrysts (Lehtonen et al., 2009); mantle xenoliths (Malkovets et al., 2003; Sablukova et al., 2003); garnet-cpx data from Kostrovitsky et al., 2004; reference geotherms Pollack & Chapman (1977); Kukkonen & Peltonen (1999), diamond – graphite transition Kennedy & Kennedey 1976

Trace element data by LA-SC-ICPMS



Stay tuned for Yann Lahaye's presentation!

C1-Chondrite normalized (McDonough and Sun, 1995) REE profiles of garnet xenocrysts .
The samples are subdivided according to rock type (Grütter et al., 2004). Data from Lehtonen et al. (2009).

MinExTarget eit RawMaterials Connecting matters Funded by the European Union

Thank you – Kiitos!

Acknowledgements: Hugh O'Brien, Bo Johanson, Leena Järvinen, Sari Lukkari, Yann Lahaye, Pertti Sarala, Anne Taivalkoski, Helena Hulkki & other GTK co-workers