GEOLOGICAL SURVEY OF NORWAY

- NGU -

THE BJERKREIM-SOKNDAL LAYERED INTRUSION

APATITE FACTS

- Igneous apatite and sedimentary phosphorite are the main sources for phosphate rocks (commodity) mainly used in agriculture and food production
- Igneous apatite is a necessity for the production of high-quality phosphate fertilizers by nitric acid process yielding agriculture-$CaCO_3$ as waste/byproduct
- EU regard phosphate rocks as a critical commodity. Yara Suomi Oy, Siilinjärvi in Finland is the only producer of apatite in western Europe
- Igneous apatite concentrates are largely used domestically; limited export. Norway has two phosphate fertilizer plants, but no deposits
- In spite of large resources of apatite, the demand is high due to growing world population and standard of living, leading to depletion of high-grade ores and lowering of average producing grades at a rate of 0.45 wt.% P_2O_5 or 1 wt.% apatite per decade
- Present lower limits for an economic deposit of igneous apatite is about 60-100 Mt containing 5 wt.% P_2O_5 or 12 wt.% apatite

History of research and surveys

- **Esmark 1824: Norite**
- **Dahll 1863: Mapping, Fe-Ti**
- **Kjerulf, Reusch, Vogt, Kolderup 1870-1910s: Fe-Ti**
  - **1910 -> no future**
  - **1916 -> yes future**
- **Michot, Michot, Duchesne a.o. (Liège) 1930s-present: anorthosite, BKSK, Fe-Ti**
- **Krause a.o. (Clausthal) 1970-80s: anorthosite, BKSK, Fe-Ti**
- **Robins a.o. 1980s-present (UiB): BKSK+**
- **Wilson a.o. 1980s-present (ÅU): BKSK+**
- **NGU w/wo YARA, Titania, Ekberg**
  - **Mid 1990s: Fe-Ti**
  - **Late 1990-early 2000s: anorthosite, apatite, magnetic mineralogy, Fe-Ti**
  - **Future: apatite, ilmenite, vanadium??**

Ideal sequence:

plagioclase

ilmenite

(olivine)

orthopyroxene

magnetite

clinopyroxene and apatite

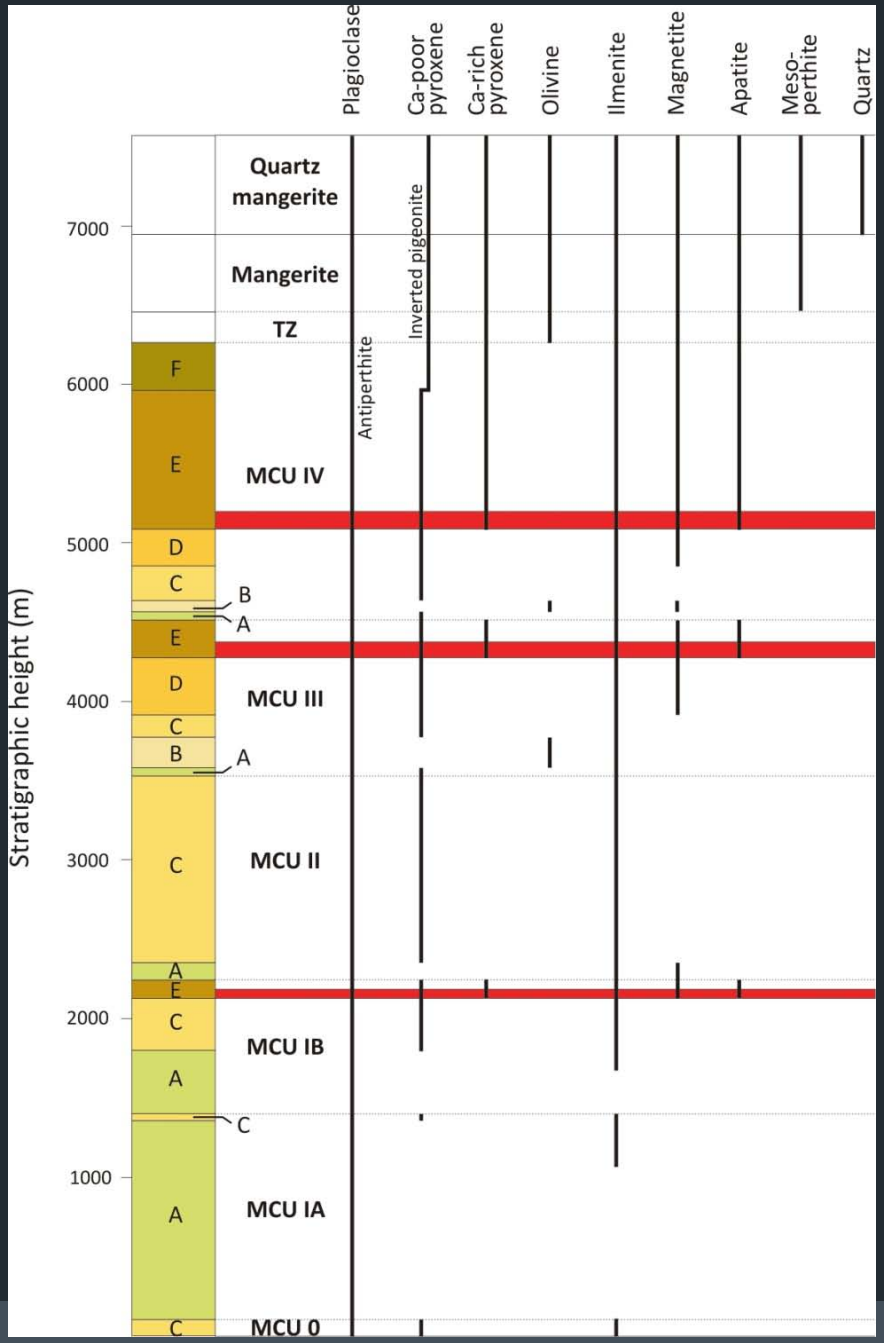
antiperthite

invertet pigeonite

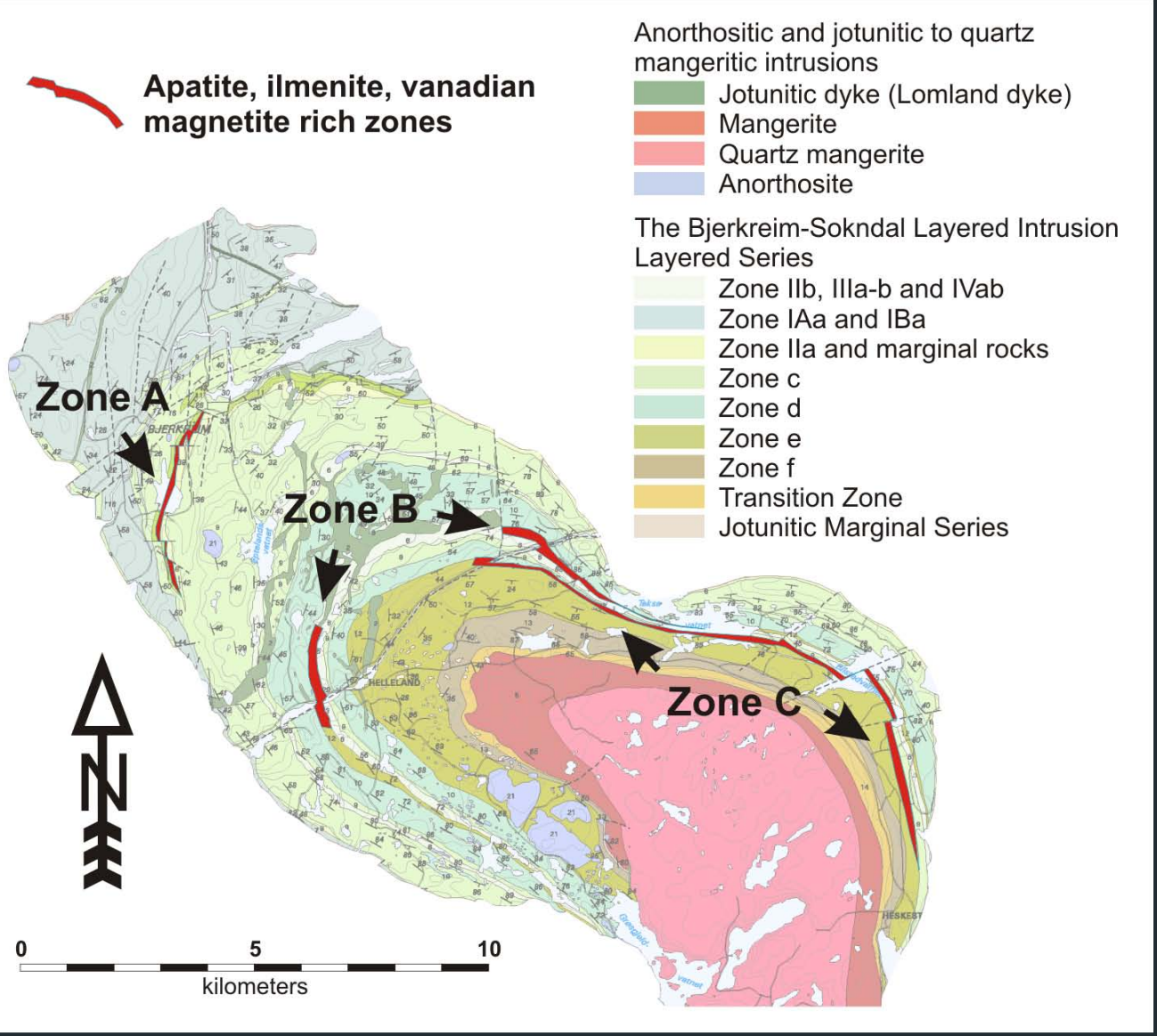
iron-rich olivine

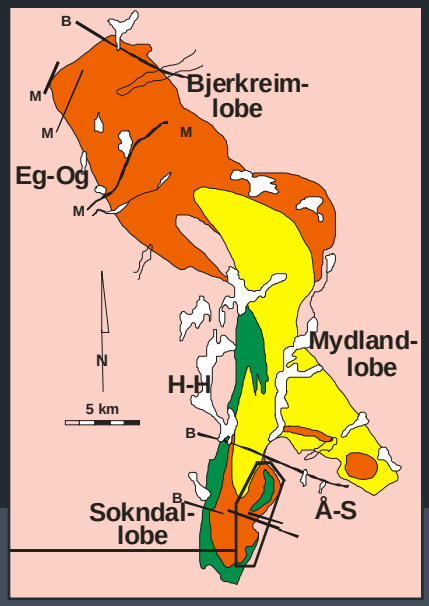
quartz

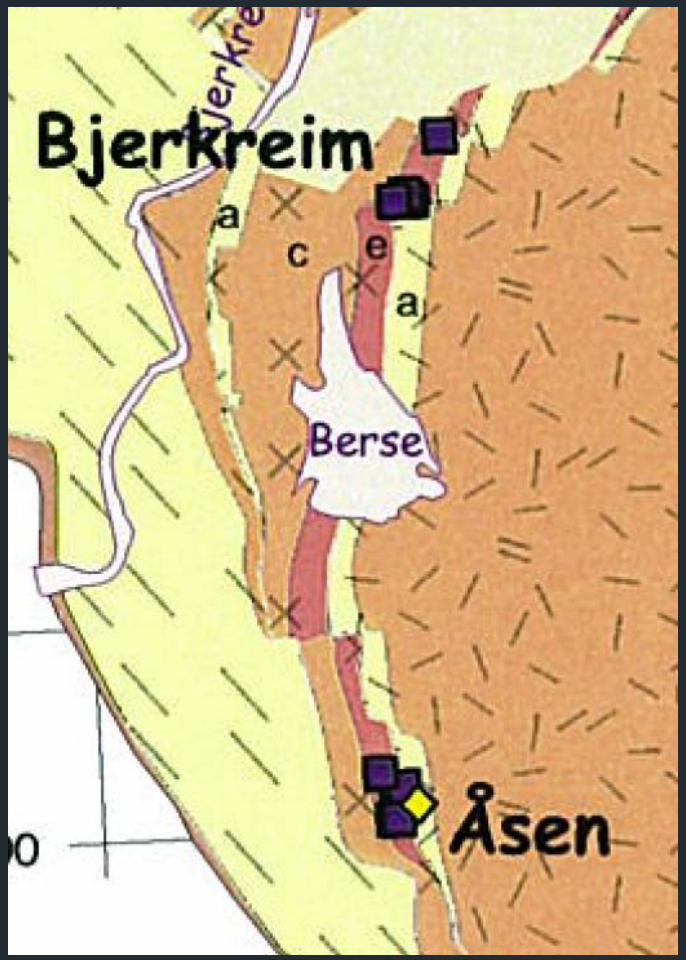
Apatite-rich zones in RED



The Bjerkreim-Sokndal Layered Intrusion







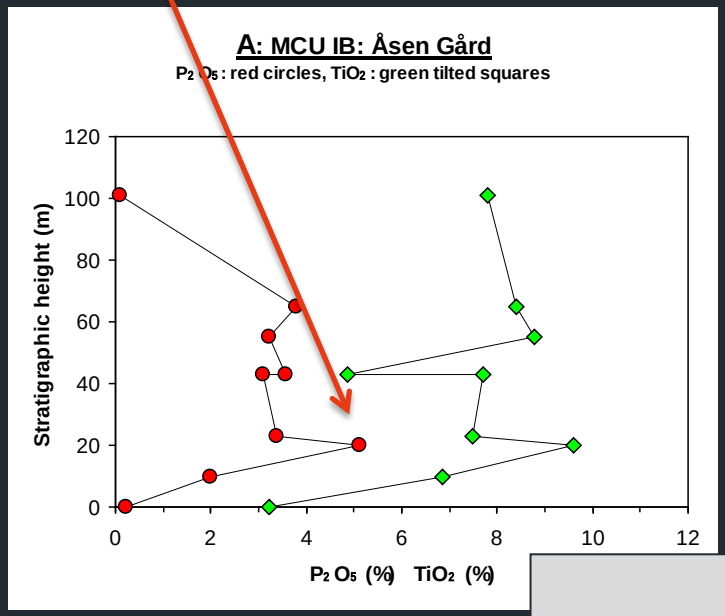
AREA A

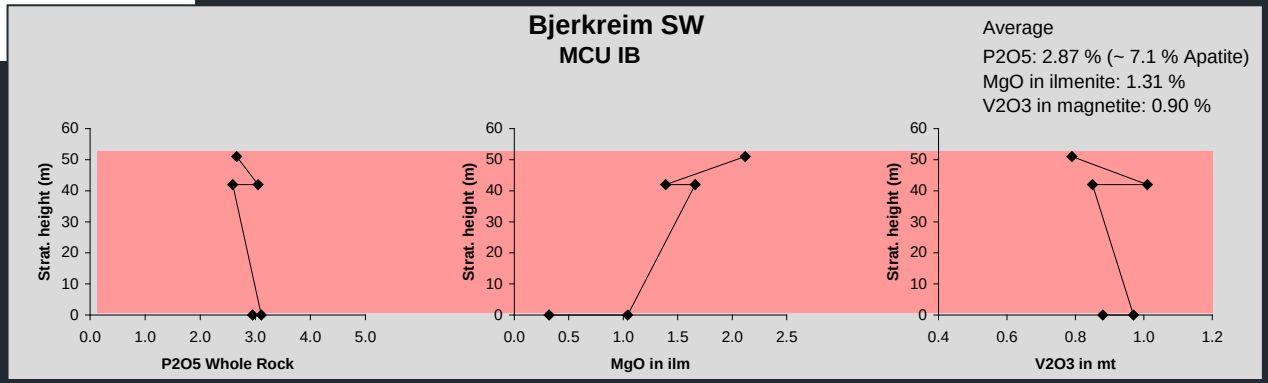
severely covered

mt + ap entering simultaneously

AREA A

5.11 % P_2O_5





AREA A, MCU IB:

Resource area: 15-20 – 60 m x 3000 m

~ 50 - 100.000 m^2

Estimated value mineral content:

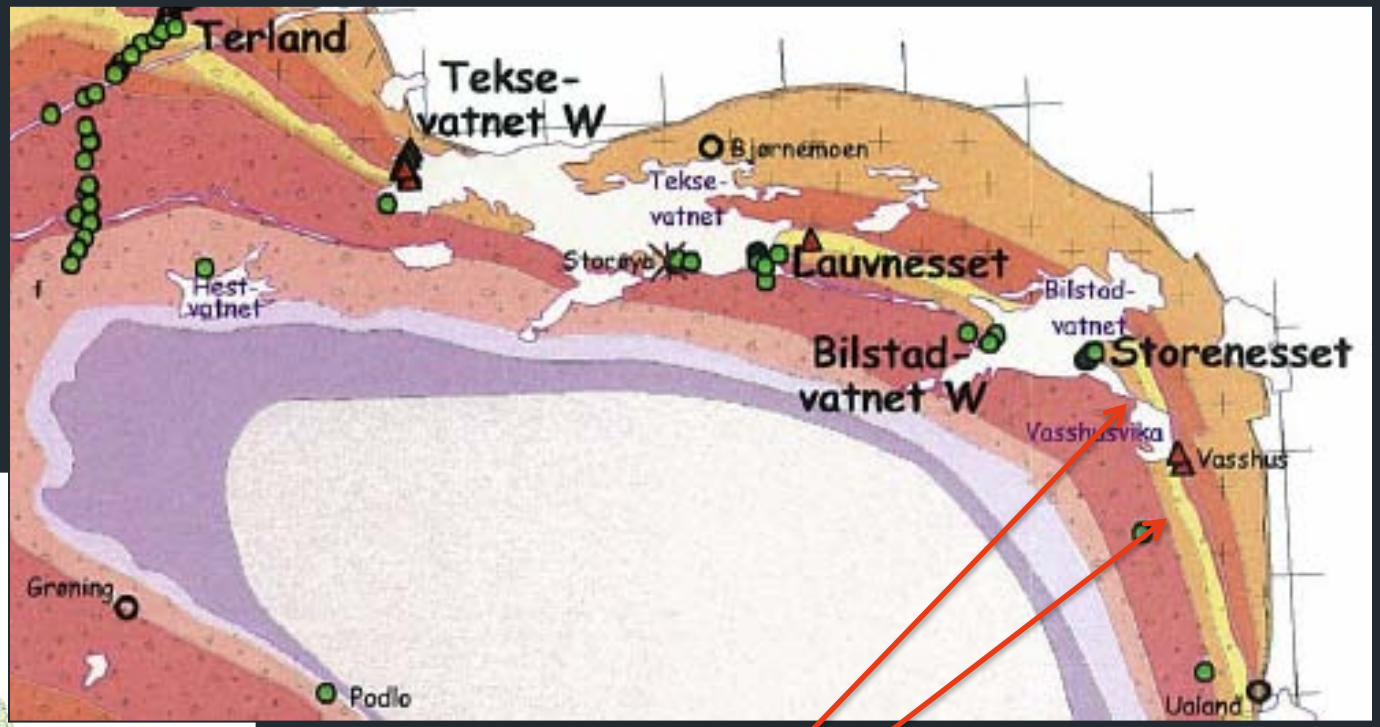
Apatite:	**8 %**
Ilmenite:	**15 %**
Magnetite:	**11 %**

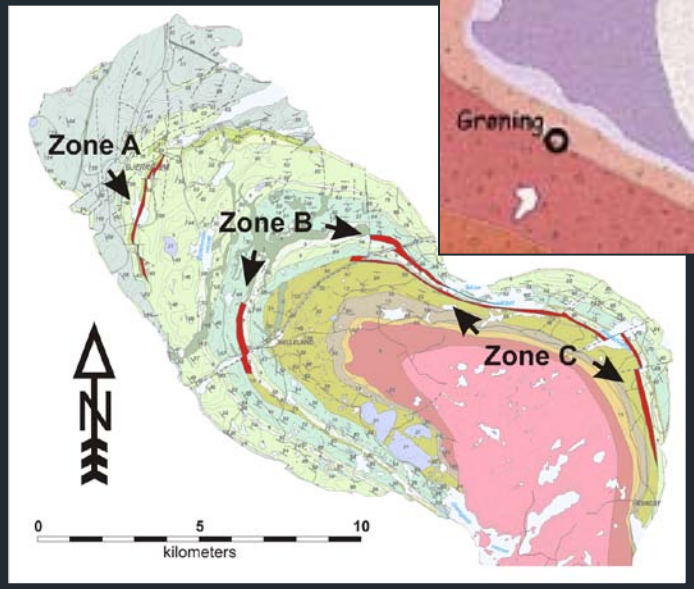
MgO (ilm.): 1,8 %

V_2O_3 (mt.): 0,91 %

NOT FULLY RESOLVED!!

AREA C: MCU IVe



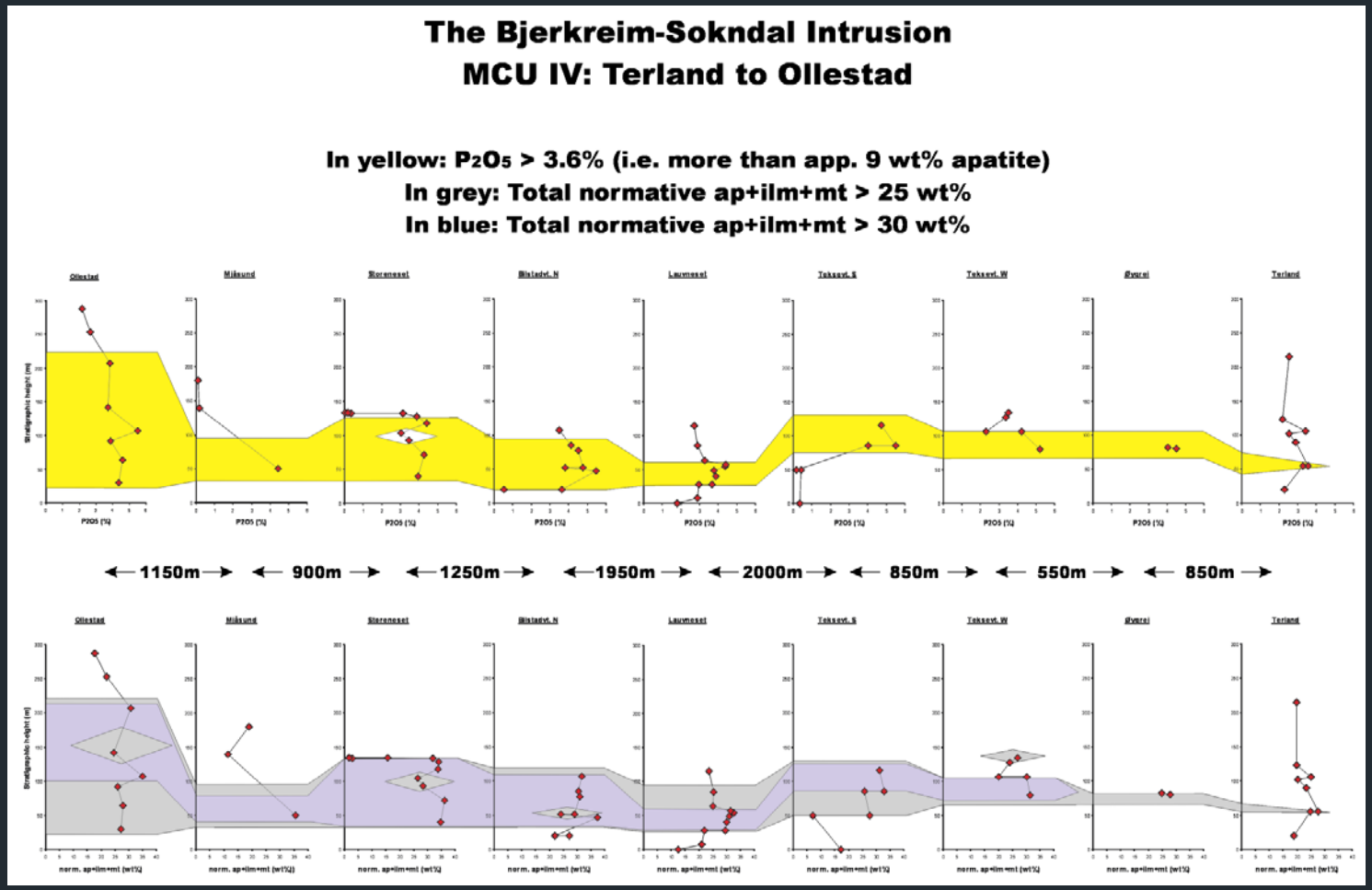


Successful drill holes

apatite-rich sequence in MCU IVe

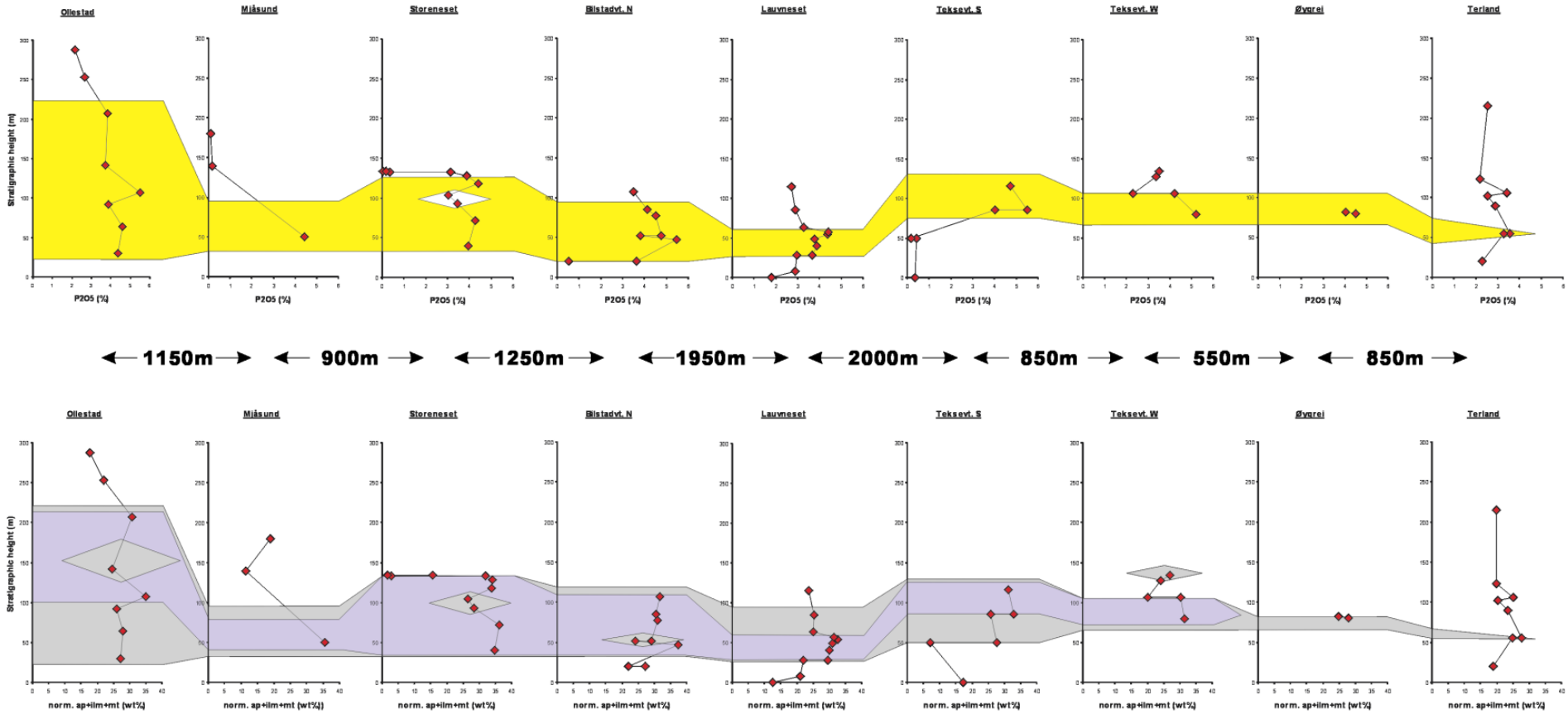
MCU IV apatite, ilmenite, magnetite

SOUTH ⟷ NORTH



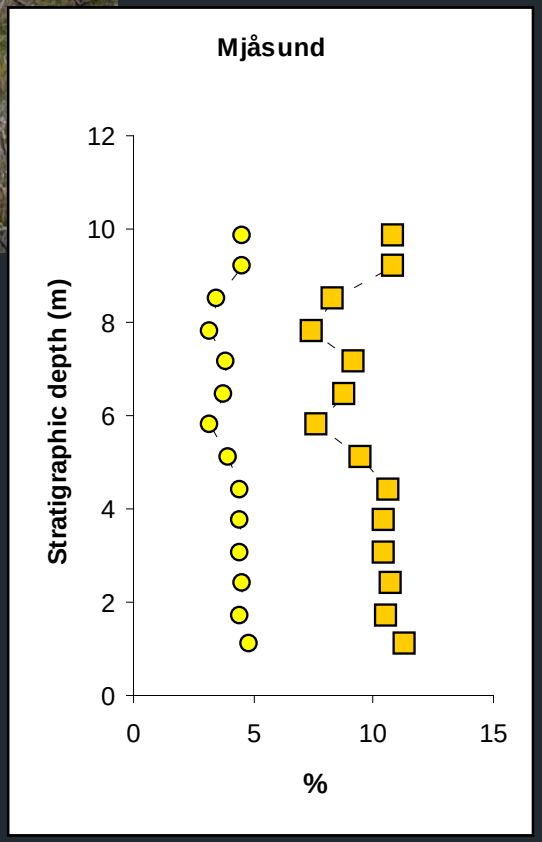
The Bjerkreim-Sokndal Intrusion
MCU IV: Terland to Ollestad

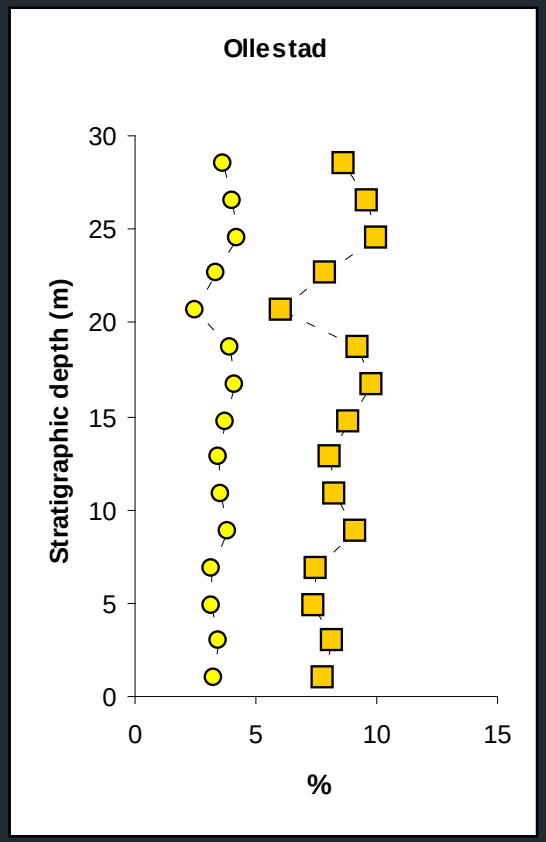
In yellow: P_2O_5 > 3.6% (i.e. more than app. 9 wt% apatite)
In grey: Total normative ap+ilm+mt > 25 wt%
In blue: Total normative ap+ilm+mt > 30 wt%

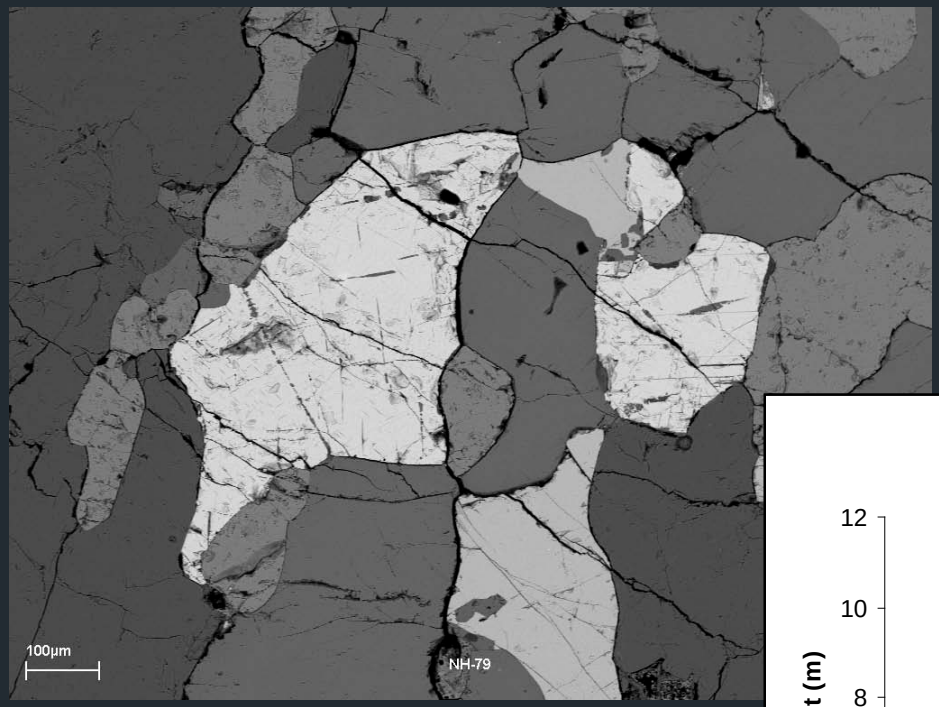


Successful drilling.
2 m core split
P_2O_5 and norm. ap.

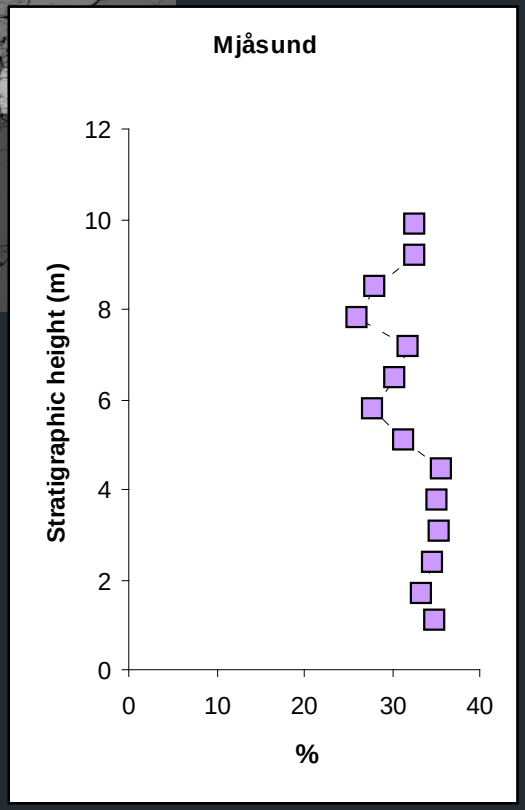
Mjåsund 5 m
consistently above
10 % apatite
note m-scale

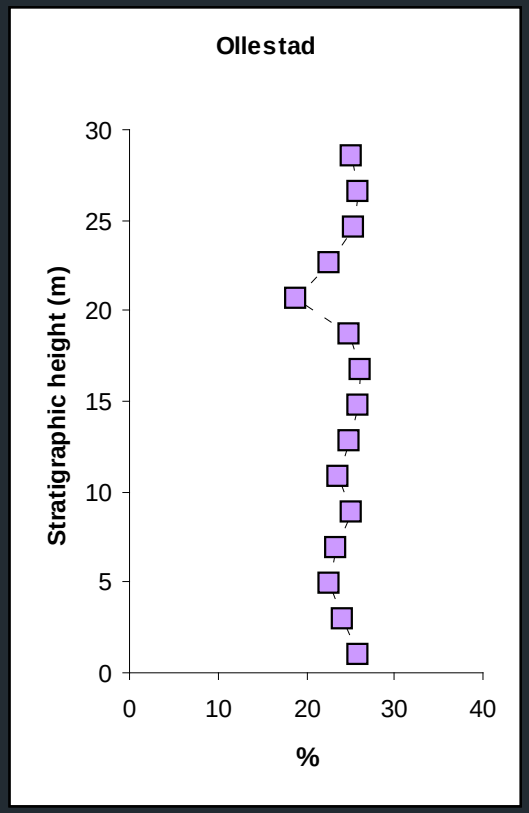






Successful drilling.
2 m core split
Total value minerals





Zone contacts not encountered for lateral correlation

AREA C, MCU IV:

Resource area : 30 – 90 m x 8500 m

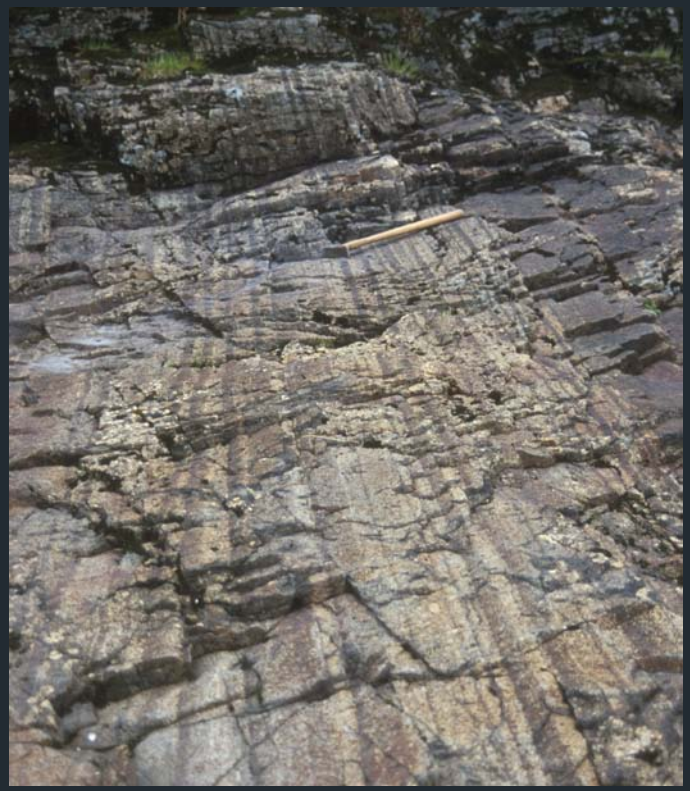
250.000 - 700.000 m^2

Estimated value mineral content :

Apatite:	**10 %**
Ilmenite:	**14 %**
Magnetite:	**8 %**

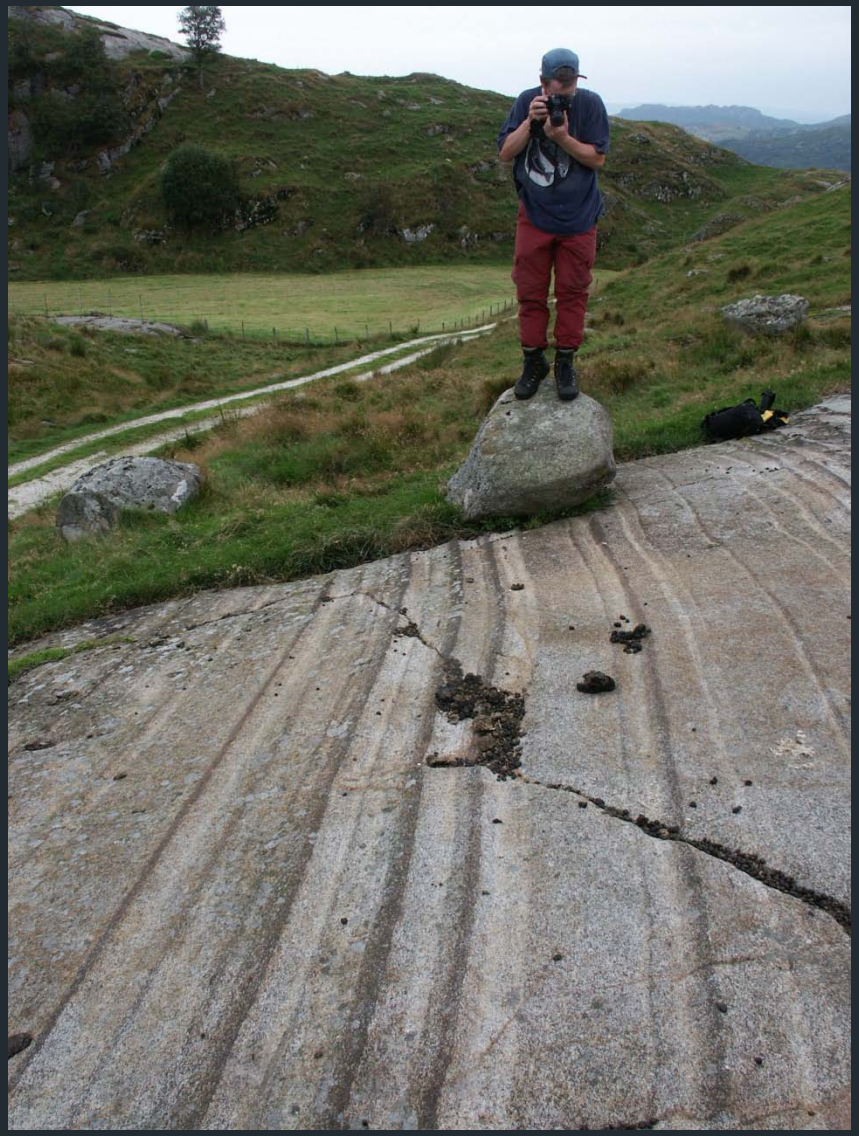
MgO (ilm.): 1,0 – 1,8 %

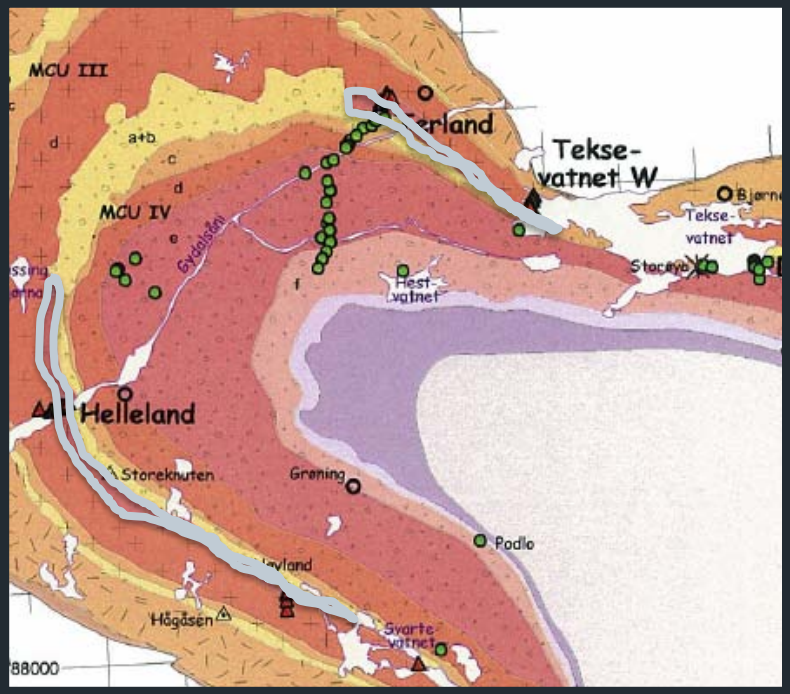
V_2O_3 (mt.): 0,90



Zone may possibly be constrained l/w to raise grades

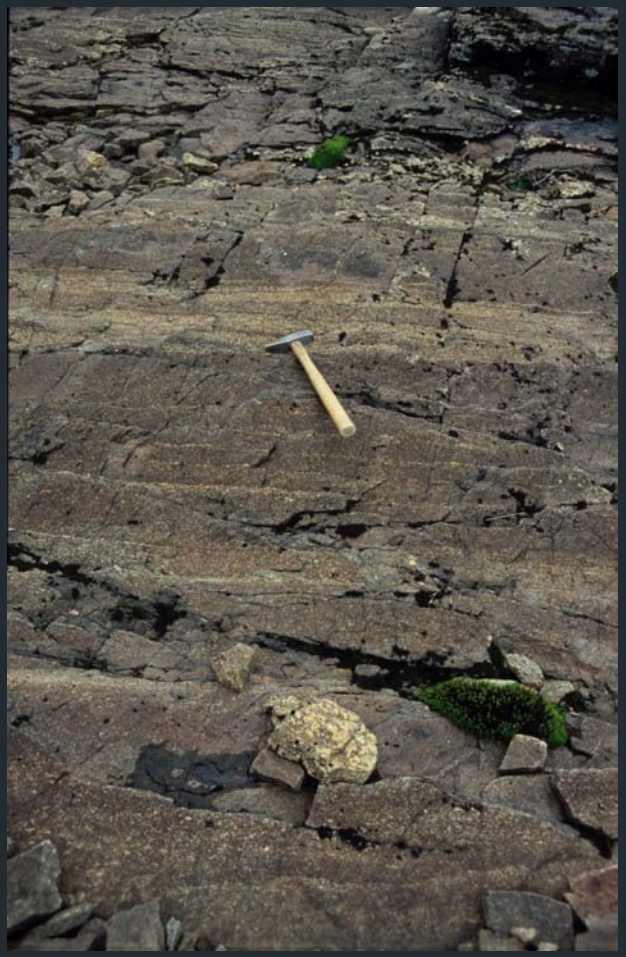
Modal layering, MCU IIIe

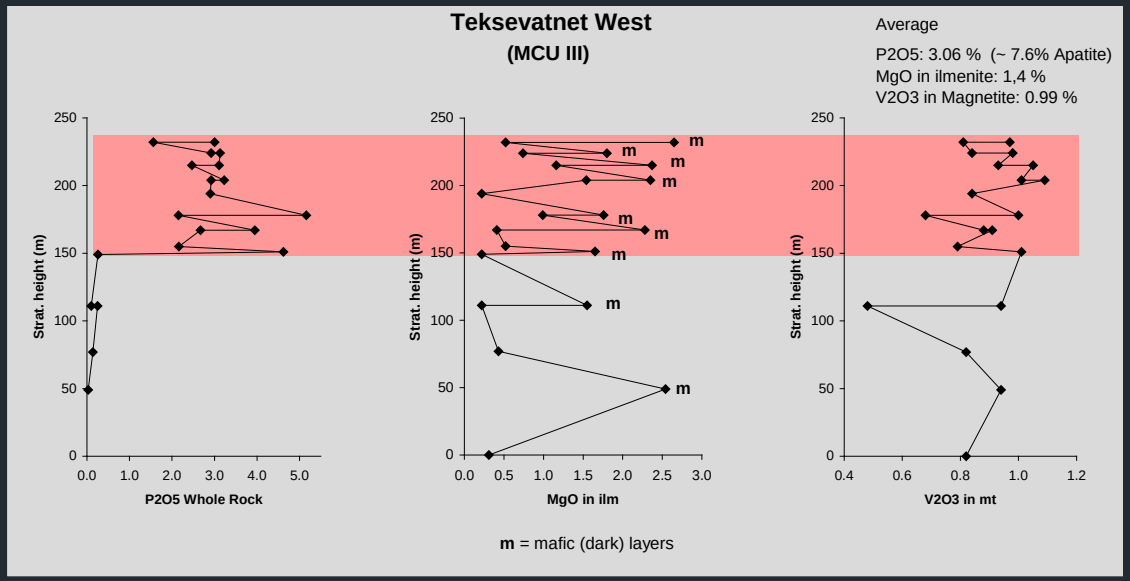




AREA B

MCU IIIe



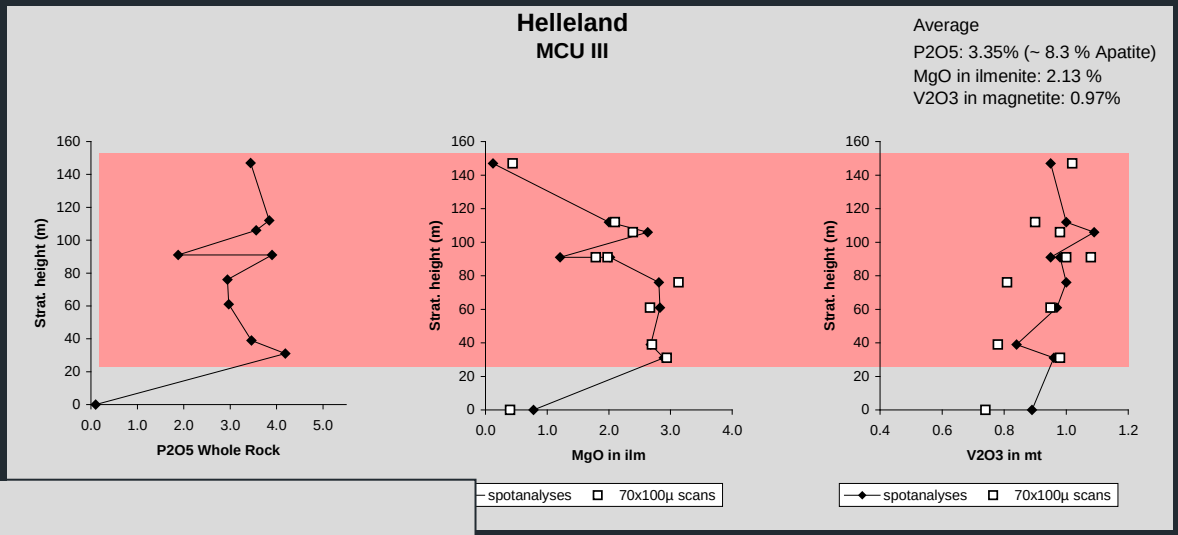


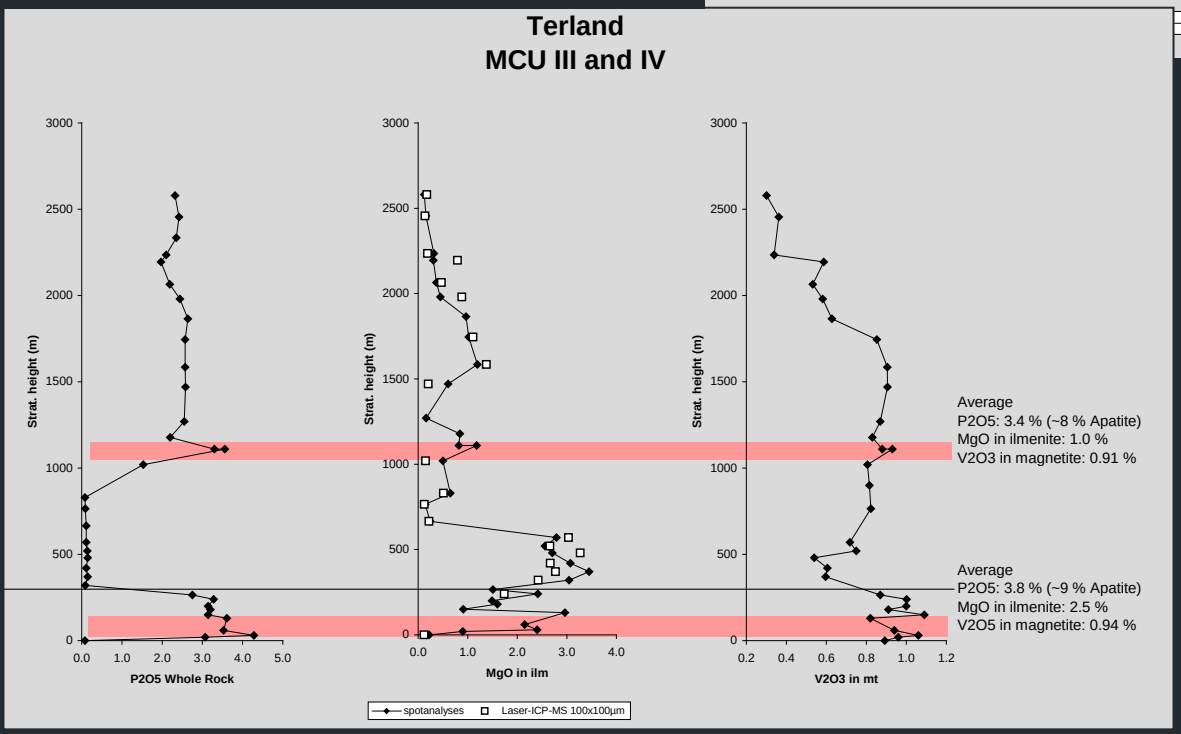
AREA B

MCU IIIe

Helleland

Terland





* Discontinuous
* Uncertain extent
* High max. P_2O_5
* Max at zone base
* Grades falling on intrusion flanks

A: **MCU IBe: 45x3000m @ 8.3 % ap, 15.2 % ilm, 10.6 % mt**

Poorly documented

B: **MCU IIIe: 100x3000m @ 7.8 % ap, 11.4 % ilm, 6.9 % mt**

Discontinuous, fairly uncertain extent

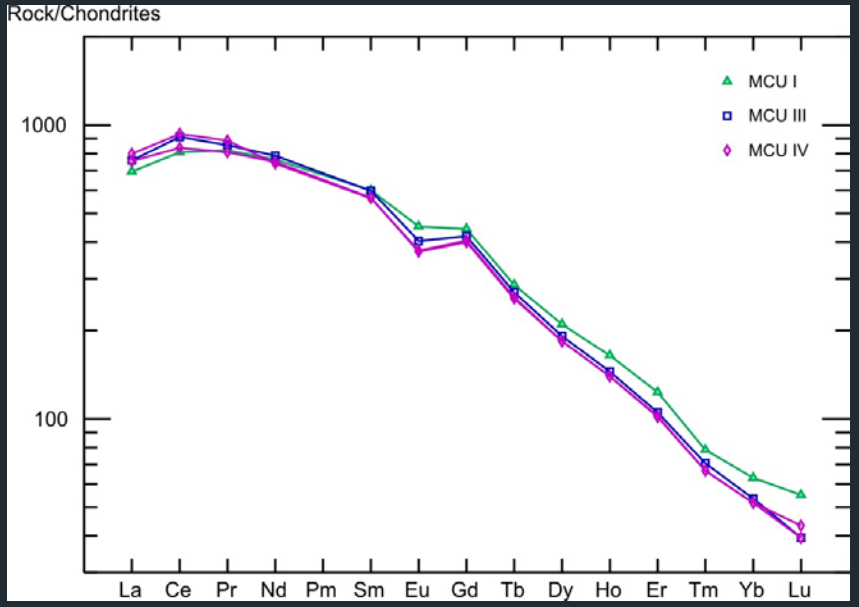
C: **MCU IVe: 70x8500m @ 10.2 % ap, 12.4 % ilm, 7.3 % mt**

Stratigraphic thickness and lateral persistency of high value zone unsufficiently constrained

All the high value zones are confined to the basal parts of the apatite-bearing sequences!!

Apatite in the BKSK

Investigated apatites are fluor-apatites with a Cl-content close to the detection limit by EDS-detection (500-900 ppm). The measured Cl/F ratios vary between 0.01 and 0.02



DEPOSIT	HOST ROCK	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Σ REE	Th
Misværdal	Coarse-grained pyroxenite	530,4	1910,1	237,5	933,4	213,8	50,4	152,9	16,0	65,1	9,3	18,3	1,9	10,0	1,2	4150,5	70,5
	Coarse-grained pyroxenite	737,3	2654,2	357,3	1394,0	309,5	73,7	215,4	23,4	94,3	13,8	26,2	2,7	14,3	1,7	5917,7	99,9
	Coarse-grained pyroxenite	989,4	2978,8	353,2	1340,5	283,3	65,5	194,8	20,4	80,2	11,4	21,2	2,2	11,3	1,3	6353,3	95,4
	Coarse-grained pyroxenite	745,1	2551,4	331,4	1294,2	271,5	62,5	182,3	19,1	76,2	11,2	21,0	2,2	11,9	1,5	5381,3	60,5
Bjerkreim-Sokndal Layered Intrusion	Apatite-Fe-Ti ore, Megacycle I	164,5	494,4	78,0	356,5	91,8	26,2	91,1	10,7	53,3	9,3	20,4	2,0	10,7	1,4	1410,3	1,6
	Apatite-Fe-Ti ore, Megacycle III	179,6	558,3	81,2	367,1	91,5	23,4	86,1	10,1	48,6	8,2	17,4	1,8	9,1	1,0	1483,5	2,4
	Apatite-Fe-Ti ore, Megacycle IV	178,6	512,0	76,8	349,9	86,7	21,5	82,2	9,6	46,7	7,9	16,9	1,7	8,8	1,0	1400,3	2,9
	Apatite-Fe-Ti ore, Megacycle IV	189,3	571,5	84,2	345,6	86,3	21,7	83,1	9,7	46,7	7,9	16,8	1,7	8,8	1,1	1474,4	6,7
Kodal	Monzonite, hanging wall	1286,7	2578,5	249,0	818,8	131,1	22,4	108,7	12,6	61,9	11,9	27,5	3,3	19,4	2,8	5334,6	36,6
	Patchy ore, hanging wall	1625,2	3693,4	374,4	1269,7	215,5	25,2	170,4	19,9	98,6	18,2	41,6	4,8	27,8	3,7	7588,4	51,8
	Ore zone, upper part	1601,2	4346,5	483,6	1690,7	301,3	49,9	223,9	27,5	138,7	24,7	58,3	6,7	38,0	4,7	8995,8	25,8
	Ore zone, central part	2233,2	5352,9	575,2	1910,9	323,3	58,0	235,9	28,8	140,9	24,9	58,5	6,6	36,1	4,5	10989,5	27,3
	Ore zone, lower part	1787,8	4126,4	474,4	1674,9	296,5	62,6	230,4	27,1	132,4	23,3	49,9	5,6	31,5	3,8	8926,6	30,4
	Patchy ore, footwall	2456,5	4521,9	462,1	1601,7	272,0	25,5	230,2	27,2	136,5	25,9	58,1	7,1	43,6	6,4	9874,8	70,7
	Monzonite, foot wall	2012,1	3760,9	377,5	1254,4	200,9	28,4	164,7	18,8	92,5	17,4	41,1	4,8	27,6	4,0	8005,1	57,7

Ilmenite and magnetite chemistry

ILMENITE	Stratigraphic height (m)	MgO	Al2O3	TiO2	V2O3	Cr2O3	MnO	FeO	Total
Sample: OLL_1.9	**1.87**	1.29	0.10	49.14	0.43	-0.01	0.23	49.00	100.18
Sample: OLL_5.85	**5.75**	1.28	0.20	49.19	0.42	0.00	0.23	48.05	99.37
Sample: OLL10.15	**9.98**	1.29	0.22	48.49	0.41	0.00	0.25	48.10	98.76
Sample: OLL_17.18	**16.89**	0.70	0.14	49.31	0.39	0.00	0.25	49.00	99.79
Sample: OLL_23.17	**22.78**	1.92	0.06	49.83	0.37	-0.02	0.25	48.74	101.15
Sample: OLL29.73	**29.23**	1.23	0.26	48.75	0.45	0.00	0.26	47.98	98.93
Sample: MJÅ 2.69	**0.91**	2.57	0.15	51.76	0.35	-0.01	0.23	44.92	99.97
Sample: MJÅ 6.28	**2.14**	1.98	0.12	49.96	0.50	-0.02	0.51	46.33	99.38
Sample: MJÅ 14.57	**4.95**	1.67	0.13	49.92	0.37	-0.02	0.24	46.29	98.60
Sample: MJÅ 19.54	**6.64**	2.42	0.14	50.50	0.40	0.02	0.22	44.57	98.27
Sample: MJÅ 24.63	**8.37**	2.00	0.20	49.43	0.44	-0.01	0.21	46.41	98.68
Sample: MJÅ 29.68	**10.09**	2.59	0.15	49.95	0.35	-0.01	0.23	44.88	98.14

MAGNETITE	Stratigraphic height (m)	MgO	Al2O3	TiO2	V2O3	Cr2O3	MnO	FeO	Total
Sample: OLL_1.9	**1.87**	0.11	0.69	0.08	0.89	0.03	0.00	91.52	93.32
Sample: OLL_5.85	**5.75**	0.13	0.66	0.04	0.97	0.03	-0.01	89.79	91.61
Sample: OLL10.15	**9.98**	0.20	0.72	0.20	0.89	0.01	0.00	89.93	91.95
Sample: OLL_17.18	**16.89**	0.17	0.66	0.16	0.92	0.03	-0.02	90.38	92.30
Sample: OLL_23.17	**22.78**	0.12	0.75	0.11	0.84	0.02	0.01	91.65	93.50
Sample: OLL29.73	**29.23**	0.05	0.78	0.04	0.92	0.04	-0.01	89.58	91.40
Sample: MJÅ 2.69	**0.91**	0.43	2.90	2.89	0.92	0.02	0.03	85.91	93.10
Sample: MJÅ 6.28	**2.14**	0.14	1.55	3.01	0.59	0.00	0.03	86.13	91.45
Sample: MJÅ 14.57	**4.95**	0.20	2.63	3.00	0.90	0.04	0.03	86.94	93.74
Sample: MJÅ 19.54	**6.64**	0.34	4.14	3.46	0.92	0.01	0.04	84.65	93.56
Sample: MJÅ 24.63	**8.37**	0.29	1.83	0.80	0.99	0.03	-0.02	87.00	90.92
Sample: MJÅ 29.68	**10.09**	0.36	2.17	1.86	0.98	0.02	0.01	87.64	93.04