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NORWEGIAN PEGMATITES I:
Tysfjord-Hamarøy, Evje-Iveland, Langesundsfjord

By: Axel Müller, Tomas Husdal, Øyvind Sunde, Henrik Friis, Tom Andersen, Tor Sigvald Johansen, Ronald Werner, Øivind Thoresen & Svein Olerud

GEOLOGICAL SOCIETY OF NORWAY

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'Iveland Wall' in Iveland showing partial melting of amphibolites and the related formation of pegmatites.

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Preface

This guide has been prepared for the geological excursions related to the 8th International Symposium on Granitic Pegmatites PEG2017 held at the University of Agder in Kristiansand, south Norway, from the 13th of June to the 15th of June 2017.
The guide contains detailed information about the pre-conference excursion (9th to 13th of June 2017) to the Tysfjord-Hamarøy pegmatite field in Nordland (chapter 1) and the post-conference excursion (16th to 19th of June 2017) to pegmatites of the Evje-Iveland (chapter 2) and Langesundsfjord (chapter 3) areas.
The series of International Symposia on Granitic Pegmatites (PEG) started in 2003, is biennial and collects geoscientists, mining and processing engineers, mineral and gemstone dealers from all over the world. The participants have one study subject in common: *Pegmatites*.
Pegmatite is defined as a very coarse-grained rock (with crystal sizes >2 cm) of magmatic origin. Pegmatites are economically important sources of a number of rare elements including lithium, caesium, rubidium, niobium, tantalum, beryllium, and Rare Earth Elements (REE), as well as the industrial minerals K-feldspar, Na-feldspar, quartz and mica. Niobium, beryllium and REE are classified as critical materials by the European Commission, meaning these are raw materials that are crucial to Europe's and the World's economy and essential for maintaining and improving the quality of life.
Pegmatite research, mining and processing has a 150-year long tradition in Norway and, in addition to the historically widespread mining of feldspar, quartz and mica, it also resulted in for example the establishment of the Porsgrund Porselænsfabrik AS in 1885 and of the high-purity quartz producer Norwegian Crystallites in 1996 (since 2011 The Quartz Corp).
The scientific study of Norwegian pegmatites started at the turn of the 19th and 20th century with the famous work of Waldemar C. Brøgger about the mineralogy of the Permian syenite pegmatites from Langesundsfjord (Brøgger 1890) and the Mesoproterozoic pegmatites in southern Norway (Brøgger 1906, 1922).
This field trip guide summarizes the current knowledge on pegmatites from the Tysfjord-Hamarøy, Evje-Iveland and Langesundsfjord areas and provides the reader with the latest results of their investigation.

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1. Pegmatites of the Tysfjord-Hamarøy area, northern Norway

Tomas Husdal, Axel Müller, Svein Olerud & Øivind Thoresen

Introduction

The pegmatites of the Tysfjord-Hamarøy area in Nordland, northern Norway, are famous mineral collecting sites like Hundholmen, Drag and Tennvatn and the raw material source of chemically very pure quartz mined currently by the Quartz Corp AS at Drag. The Tysfjord-Hamarøy pegmatite field comprises about 28 major pegmatite occurrences; 6 of these are visited during the PEG2017 excursion and described in more detail below. The pegmatites, which are typical NYF pegmatites with 'amazonite' and large fluorite masses, are hosted by and associated with the Tysfjord granites (1810-1660 Ma). Principally two pegmatite populations are distinguished in the area: (1) large, lenticular, deformed pegmatites and (2) relatively small, undeformed pegmatites rich in 'amazonite'. The granites and pegmatites of population (1) underwent amphibolite-facies deformation during Caledonian orogenesis about 430-410 Ma ago. Large, well-formed crystals make thalénite-(Y) from Hundholmen the best known mineral from the area, but also yttrofluorite and non-metamict gadolinite-(Y) are examples of minerals probably present in many collections worldwide. The Tysfjord pegmatites are the type localities of nine minerals: hundholmenite-(Y), fluorbritholite-(Y), atelisite-(Y), stetindite-(Ce), bastnäsite-(Nd), cayalsite-(Y), alnaperbøeite-(Ce), perbøeite-(Ce), and schlüterite-(Y), all first described during the last decade (Table 1.1). The Tysfjord-Hamarøy area is relatively remote; earlier collecting mainly based on occasional visits. Considering the number of localities, the long time span with mining activities (from 1906 until today) and the number of rare minerals found, scientific studies are scarce (e.g. Husdal 2008). The pegmatite mining history goes back to 1906 when feldspar mining started at the Hundholmen pegmatite.

Table 1.1. Type minerals from pegmatites of the Tysfjord-Hamarøy area, northern Norway.

Name	Formula	Reference
Hundholmenite-(Y)	$(Y,REE,Ca,Na)_{15}(Al,Fe^{3+})Ca_x(As^{3+})_{1-x}(Si,As^{5+})Si_6B_3(O,F)_{48}$	Raade et al. (2007)
Stetindite-(Ce)	$CeSiO_4$	Schlüter et al. (2009)
Fluorbritholite-(Y)	$(Y,Ca)_5(SiO_4)_3F$	Pekov et al. (2011)
Atelisite-(Y)	$Y_4Si_3O_8(OH)_8$	Malcherek et al. (2012)
Bastnäsite-(Nd)	$NdCO_3F$	Miyawaki et al. (2013)
Schlüterite-(Y)	$(Y,REE)_2AlSi_2O_7(OH)_2F$	Cooper et al. (2013)
Alnaperbøeite-(Ce)	$(CaCe_{2.5}Na_{0.5})Al_4(Si_2O_7)(SiO_4)_3O(OH)_2$	Bonazzi et al. (2014)
Perbøeite-(Ce)	$(CaCe_3)(Al_3Fe^{2+})(Si_2O_7)(SiO_4)_3O(OH)_2$	Bonazzi et al. (2014)
Cayalsite-(Y)	$CaY_6Al_2Si_4O_{18}F_6$	Malcherek et al. (2015)

The regional geology of Tysfjord-Hamarøy area

The geology of Tysfjord-Hamarøy area in northern county Nordland is dominated by Svecofennian basement of the ancient continent Baltica partially overlain by Caledonian nappe complexes. The basement is exposed in the tectonic window of Tysfjord where the Tysfjord pegmatite field is located (Fig. 1.1). The Svecofennian rocks of the Tysfjord window comprise predominantly weakly to strongly deformed Proterozoic Tysford granites. Some authors refer to them as Tysfjord granite gneiss due to the prominent foliation.
The Tysfjord granites belong regionally to the Trans-Scandinavian Igneous Belt (TIB), which comprises a giant elongated array of batholiths extending c. 1400 km along the Scandinavian Peninsula from south-easternmost Sweden to Troms in north-western Norway (Gorbatschev 1985; Högdahl et al. 2004; Fig. 1.2). The

TIB documents a more or less continuous and voluminous magmatic activity between 1850 to 1630 Ma, which developed between the Svecofennian (1920-1790 Ma) and Gothian orogenesis (1640-1520 Ma) (Lahtinen et al. 2008 and Bingen et al. 2008, respectively). The TIB is interpreted as a result of microcontinent-microcontinent and island-arc-microcontinent collisions at the margin of the Baltic continent (Högdahl et al. 2004). However, the interpretation is complicated by the presence of a large massif of anorthositic, mangeritic, charnockitic, and granitic (AMCG) rocks (Griffin et al. 1978) with ages between 1870 and 1790 Ma in the Lofoten-Island region (e.g. Corfu 2004). The TIB magmatism has been tentatively separated into two different episodes: TIB-1 group of 1810–1770 Ma and TIB-2 group of 1710–1660 (Skår 2002; Lathtinen et al. 2008) both occurring in the Tysfjord window (Romer et al. 1992). The TIB granite complexes comprise monzonitic, syenitic and peralkaline granitic differentiates, whereas trachytes (volcanic equivalent of syenite) and rhyolites occur in the volcanic complexes. The chemical compositions are commonly alkali-calcic and of the I and A types, or transitional between these two (Högdahl et al. 2004). A number of the TIB plutons are considered as high heat-production (HHP) granites because of their relative high U (~4 ppm) and Th (~10 ppm) contents (Wilson & Åkerblom 1980). Economic mineralizations are not known from the TIB plutons except the Høgtuva Be-REE-U-Sn-mineralisation and the pegmatites of the Tysfjord-Hamarøy area, which are mined for high-purity quartz since the late 1990's. The Høgtuva mineralisation is located in TIB-type granites of the Høgtuva window, 200 km SSW of Tysfjord, and comprises 350 000 t ore with 0.18 % Be (Lindahl & Grauch 1988).

At north and northwest Hamarøy the Tysfjord granites intruded into volcanic and sedimentary Svecofennian supracrustal rocks with ages of 2500-2100 Ma or 1910-1880 Ma (Karlsen 2000). North of Hamarøy, across the Ofotfjord, Archaean tonalitic to granitic rocks with local greenstone belt remnants occupy large parts of the island Hinnøy (Fig. 1.2). These Archean assemblages were intruded by plutons of the AMCG suite of the Lofoten-Vesterålen area which has a three-stage magmatic history beginning at 1870–1860 Ma with the emplacement of the Lødingen and Hopen plutons, followed by a dominant stage at 1800–1790 Ma that formed the bulk of the suite, and concluded by the emplacement of gabbro-hosted pegmatites, local rehydration and retrogression between 1790 and 1770 Ma (Corfu 2004).

The Caledonian nappe complexes were emplaced on the Baltic continent (today Scandinavia and Baltic region) during the Silurian–Devonian (430-390 Ma) closure of the Iapetus ocean and the subsequent collision of the continents Laurentia and Baltica. The nappe complexes consist of four allochthons (rock units which have been moved from their original site of formation): the Lower, Middle, Upper, and Uppermost Allochthons (Gee & Sturt 1985; Roberts & Gee 1985; Gee et al. 2008). The nappe complexes exposed in the Tysfjord area comprise parts of the Upper Allochthon (Köli nappe) and the Uppermost Allochthon (Helgeland and Röddingsfjell nappe complexes). The Köli nappe (upper part of the Upper Allochthon) is dominated by metamorphosed sedimentary and igneous rocks – mica schist, phyllite, greenstone - derived from the ancient Iapetus Ocean, including ophiolites and island arc complexes (Stephens 1988; Andréasson 1994; Grenne et al. 1999; Roberts 2003). The Uppermost Allochthon (Helgeland and Röddingsfjell nappe complexes) is generally interpreted to have formed in a continental margin setting with affinities to the Laurentian margin and comprises calc-silicate units, calcareous, pelitic, psammitic, and clastic metasedimentary rocks (see review in Roberts et al. 2007). The rocks underwent different grades of metamorphism from greenschist to high-grade amphibolite facies. The evolution of the Caledonian orogen was accompanied with different types and stages of mafic, intermediate and felsic magmatism (e.g. Stephens et al. 1985). There is a cluster of Caledonian granitic and granodioritic plutons in the Uppermost Allochthon south and northeast of Bodø which has not been studied in detail so far.

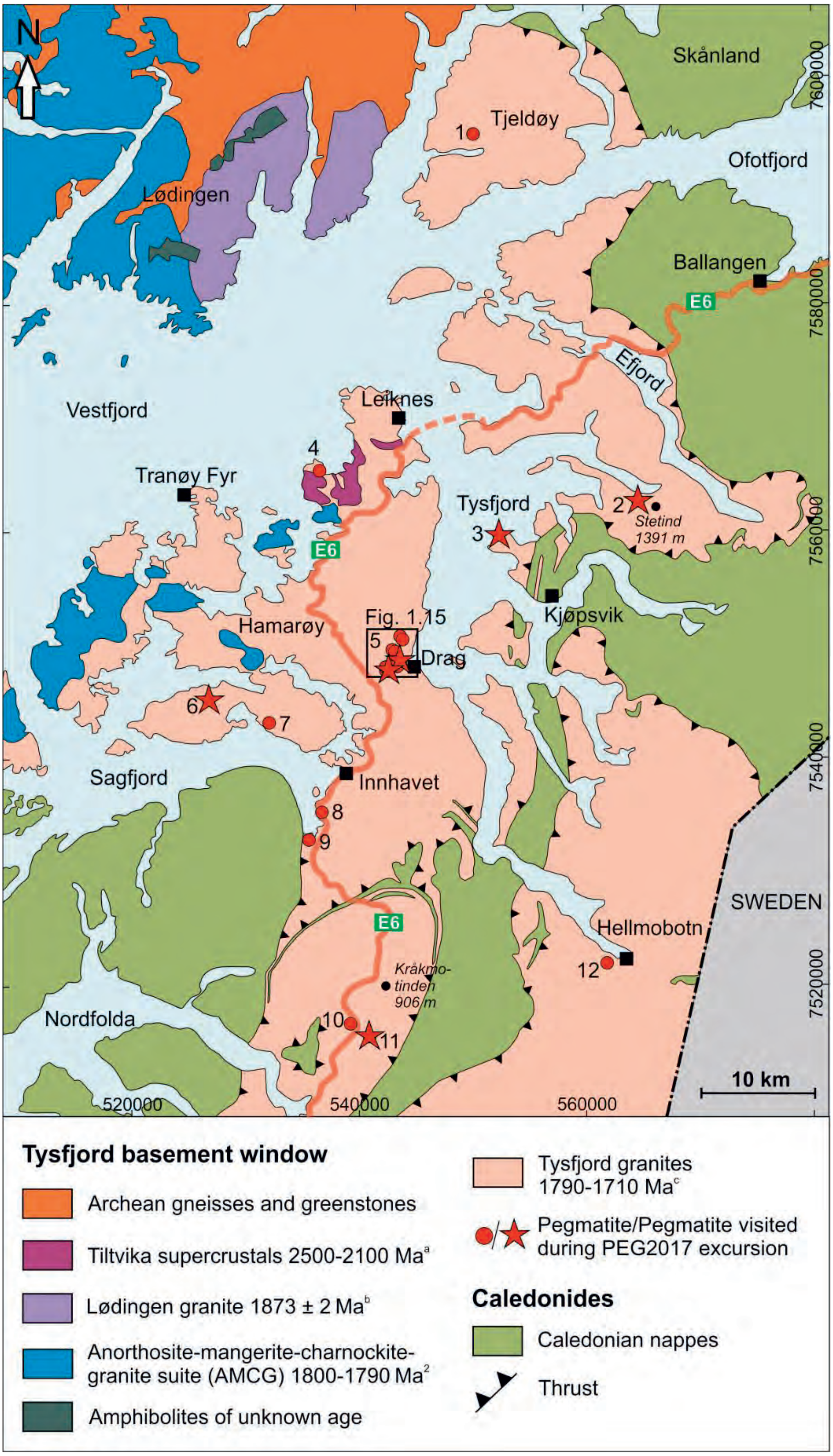


Fig. 1.1. Simplified geological map of the northern Tysfjord basement window with locations of pegmatites of the Tysfjord field and PEG2017 excursion stops. Pegmatites: 1 – Tjeldøy, 2 – Stetind, 3 – Hundholmen, 4 – Tiltvika, 5 – Drag pegmatite cluster, 6 – Håkonhals, 7 – Karlsøy, 8 – Lagmannsvik, 9 – Elveneset, 10 – Kråkmo, 11 – Tennvatn, 12 – Hellmobotn. Legend: a - Karlsen (2000), b – Corfu (2004), c – Romer et al. (1992).

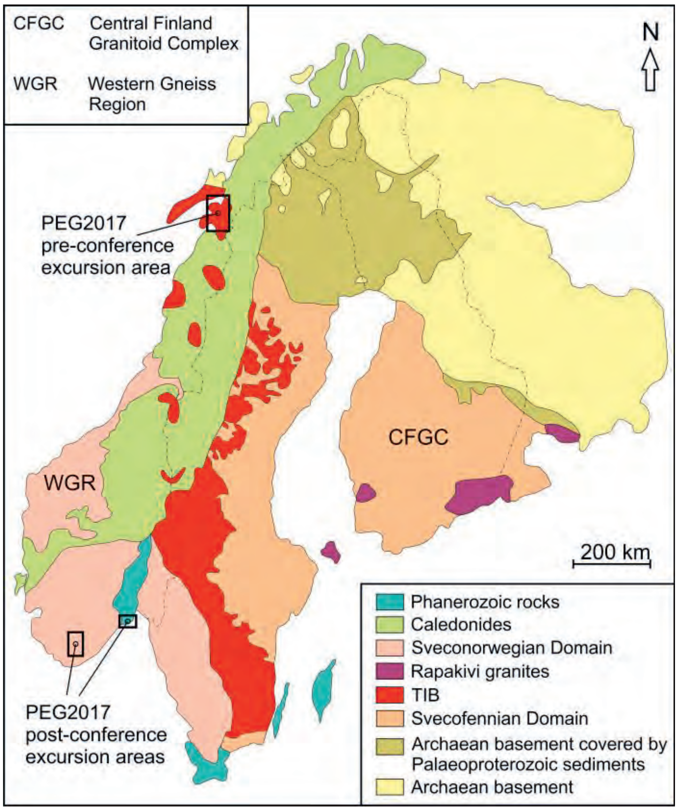


Fig. 1.2. Generalized geological map of Scandinavia showing the first-order geological subdivisions of the Baltic Shield and the extension of Trans-Scandinavian Igneous Belt (TIB) with the location of the excursion area shown in Figure 1.1 (square). From Högdahl et al. (2004).

The Tysfjord granites of the northern Tysfjord window

The Tysfjord granites cover an area of approximately 200 km^2, and are exposed in the tectonic window of Tysfjord which extends from Fauske in the south to Tjeldøya in the northern part of the Nordland County (Fig. 1.1). The Tysfjord granites are coarse-grained, foliated pale grey to pale red partly recrystallized gneissic granites with annite, Fe-rich "hastingsitic hornblende", quartz, K-feldpar, and oligoclase (Foslie 1941). Accessories are allanite, zircon, apatite, magnetite, fluorite, polycrase-(Y), titanite and thorianite (Müller et al. 2011).

Samples from the Efjord area provided a Rb-Sr whole-rock age of 1742 ± 46 Ma (Andresen & Tull 1986) whereas samples from the Hellemobotn have a bimodal U-Pb zircon age distribution of 1791 ± 10 Ma (TIB-1) and 1711 ± 26 Ma (TIB-2), respectively (Romer et al. 1992). The granite exhibits a distinct foliation, extending at least 2500 m down from the Caledonian cover/Tysfjord granite contact (Andresen & Tull 1986). The foliation has been attributed to the early stages of the Caledonian orogenesis, with amphibolite-facies conditions of 420 to 450°C and pressure between 2 and 3 kbar (Björklund 1989) peaking at c. 432 Ma (Northrup 1997).

The SiO_2-rich, subalkaline to alkaline, meta- to peraluminous Tysfjord granites of northern Tysfjord window are strongly enriched in REE (0.02 to 0.20 wt.% $REO+Y_2O_3$), Nb (mean 78 ppm), Rb (mean 269 ppm), Th (mean 56 ppm) and U (mean 15 ppm) (Romer et al. 1992; Müller et al. 2011) compared to average granite composition (Turekian & Wedepohl 1961) (Tables 1.2, 1.3). The TIB-2 granites have A-type (anorogenic) signatures with relative low $(Na_2O+K_2O)/CaO$ ratio, which classify them tectonically as within plate granites (Figs. 1.3, 1.4). The older TIB-1 granites and some of the less fractionated TIB-2 granites from Hellemobotn have I-type characteristics and were maybe formed in volcanic arc or collisional setting as suggested by Högdahl et al. (2004). The enrichment of REE, Nb, U, Th and F in the associated pegmatites supports their chemical relationship.

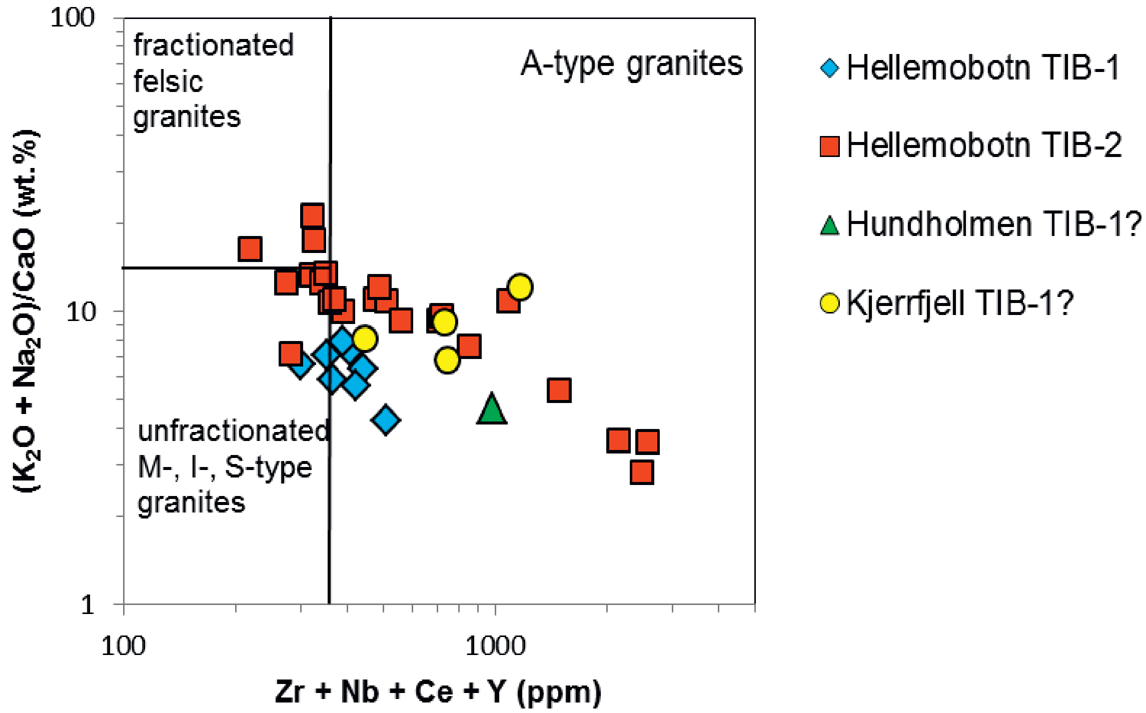


Fig. 1.3. A-type granite classification diagram illustrating that the majority of Tysfjord granites exposed in the northern Tysfjord window have A-type characteristics. Data are from Romer et al. (1992) and Müller et al. (2011).

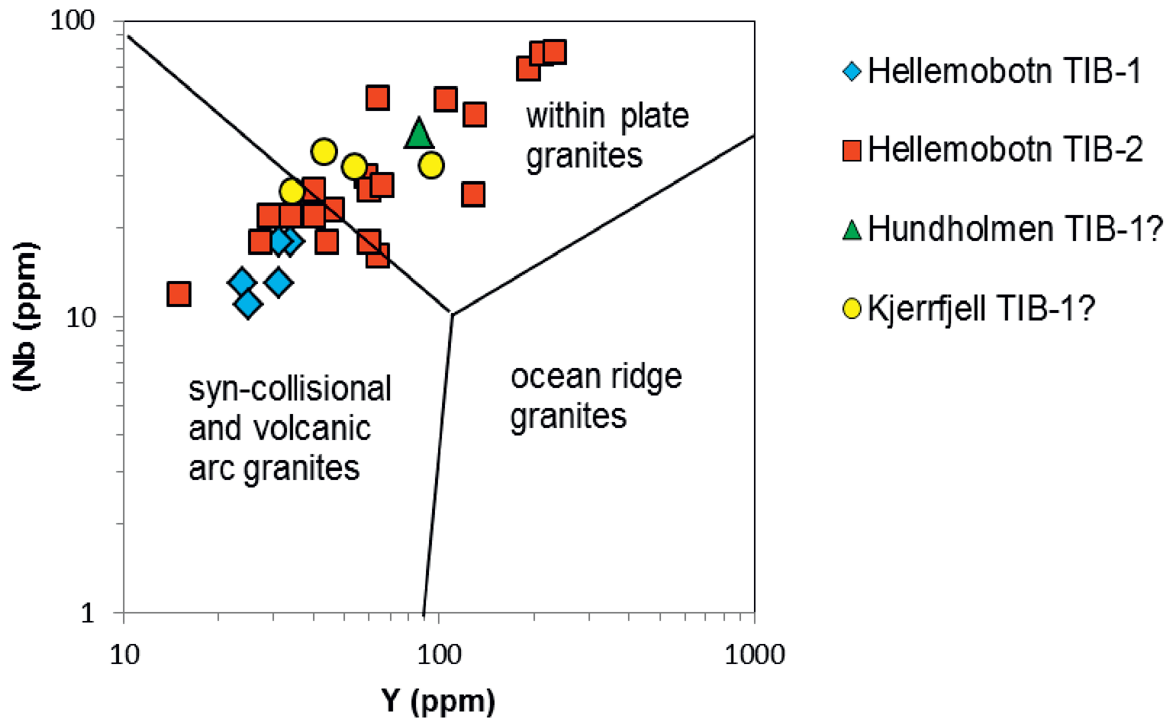


Fig. 1.4. Tectonic discrimination diagrams after Pearce et al. (1984) classifying the majority of the Tysfjord granites of the northern Tysfjord window as within plate granites. Data are from Romer et al. (1992) and Müller et al. (2011).

Table 1.2. Whole rock analyses of major elements of Tysfjord granites of the northern Tysfjord window. Analyses of samples starting with letters are from Romer et al. (1992) and those starting with “2…” from Müller et al. (2011).

Sample nr.	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**TiO_2**	**MgO**	**CaO**	**K_2O**	**Na_2O**	**P_2O_5**	**LOI**	**total**
Hundholmen – Tysfjord granite												
28091005	67.35	14.48	4.89	0.1	0.48	0.28	2.01	5.89	3.44	0.1	0.7	99.71
Kjerrfjellet – Tysfjord granites												
24091001	71.01	14.09	3.58	0.08	0.44	0.5	1.08	4.76	3.96	0.08	0.30	99.88
24091002	69.44	14.09	4.09	0.08	0.51	0.5	1.35	5.56	3.7	0.09	0.40	99.79
24091003	69.08	14.43	4.13	0.07	0.53	0.51	1.03	5.58	3.84	0.12	0.50	99.82
24091004	69.58	13.19	5.35	0.08	0.55	1.11	0.71	5.53	3.01	0.13	0.50	99.72
Hellemobotn - TIB-1 Tysfjord granites												
MH1-42	68.41	16.3	2.48	0.04	0.34	0.32	1.61	5.51	4.72	0.11	0.35	100.2
MH2-43	68.82	16.55	2.26	0.04	0.28	0.31	1.49	5.89	4.59	0.09	0.37	100.68
MH3-44	67.61	16.69	2.15	0.04	0.30	0.26	1.46	5.83	4.82	0.09	0.50	99.73
MH4-45	66.67	15.82	3.26	0.05	0.42	0.49	1.65	5.23	4.37	0.12	0.87	98.96
MH5-46	n.d.	16.43	2.25	0.04	0.28	0.29	1.56	5.54	4.75	0.08	0.51	100.7
25091001	69.29	14.77	3.42	0.06	0.41	0.43	1.2	5.42	4.05	0.07	0.70	99.81
25091002	69.39	13.51	4.92	0.09	0.55	0.65	1.47	4.33	3.84	0.1	0.80	99.69
25091003	68.86	12.61	6.43	0.11	0.76	0.72	1.75	3.89	3.53	0.15	0.80	99.61
Hellemobotn - TIB-2 Tysfjord granites												
KH50A-1	73.25	14.09	2.60	0.04	0.26	0.21	0.81	4.8	4.25	0.04	0.20	100.56
KH51-3**	72.02	15.06	3.01	0.05	0.32	0.25	1.06	5.98	3.87	0.06	0.22	101.89
KH52-4	73.66	14.12	2.02	0.03	0.19	0.08	0.86	5.62	3.8	0.03	0.18	100.58
KH55-7	72.86	14.22	2.11	0.03	0.28	0.46	0.87	5.64	3.78	0.06	0.31	100.62
KH56C-10	71.67	13.60	2.48	0.03	0.31	0.31	0.96	5.38	3.52	0.07	0.20	98.53
KH57A-11	75.37	13.11	1.73	0.03	0.15	0.09	0.44	5.66	3.62	0.02	0.19	100.41
KH58-13	79.55	11.76	1.12	0.02	0.07	<0.01	0.64	4.41	3.58	0.01	0.24	101.36
KH59-14	76.95	12.61	1.65	0.03	0.16	0.08	0.64	5.16	3.34	0.02	0.17	100.81
KH60-15**	74.74	12.60	1.81	0.03	0.18	0.15	0.7	4.86	3.64	0.03	0.17	98.9
KH61-16	75.97	11.88	1.88	0.03	0.18	0.12	0.64	4.72	3.26	0.02	0.23	98.94
KH62-17	70.14	14.36	3.10	0.05	0.36	0.73	1.24	5.47	3.98	0.06	0.26	99.76
KH63-18	66.61	13.09	8.17	0.14	0.99	0.77	2.07	4.08	3.41	0.15	0.38	99.87
GH1-33	74.63	13.63	2.03	0.03	0.23	0.24	0.86	4.96	3.67	0.04	0.21	100.52
GH2A-34	72.29	13.85	2.50	0.04	0.27	0.10	0.95	5.28	3.89	0.05	0.35	99.58
GH2B-35	78.30	12.73	0.28	0	0.03	<0.01	0.66	5.34	3.55	0.01	0.19	101.03
GH3-36	77.90	12.82	1.09	0.02	0.08	<0.01	0.54	5.09	3.71	0.02	0.18	101.37
GH4-37	67.49	17.44	2.03	0.03	0.5	0.95	1.01	4.66	6.36	0.11	0.47	101.04
GH5-39	64.39	13.25	8.84	0.13	1.14	1.08	2.56	3.81	3.43	0.19	0.38	99.18
GH6-40	70.09	12.84	5.22	0.1	0.63	0.51	1.49	4.88	3.16	0.12	0.30	99.33
GH6B-41	65.15	13.31	8.82	0.15	1.11	0.76	2.12	4.02	3.57	0.17	0.46	99.65
25091004	71.82	14.58	2.26	0.04	0.24	0.32	0.88	5.27	4.12	0.04	0.30	99.86
25091005	70.92	14.05	2.78	0.04	0.37	0.37	1.28	5.51	3.66	0.08	0.80	99.82
25091006	76.12	12.56	1.44	0.02	0.15	0.24	0.48	4.77	3.65	0.03	0.50	99.94
25091007	74.97	12.7	1.81	0.04	0.18	0.17	0.8	5.3	3.52	0.04	0.40	99.93

Table 1.3. Whole rock analyses of trace elements of Tysfjord granites of the northern Tysfjord window. Analyses of samples starting with letters are from Romer et al. (1992) and those starting with "2…" from Müller et al. (2011).

Sample nr.	Ba	La	Sr	Y	Zr	Nb	Rb	Ce	Sm	Hf	Ta	Th	U
Hundholmen – Tysfjord granite													
28091005	1047	76	173	87	665	42	251	186	16	18	2	21	7
Kjerrfjellet – Tysfjord granites													
24091001	518	10	102	34	357	26	184	29	4	9	1	14	3
24091002	625	103	117	54	441	32	229	218	11	12	2	40	7
24091003	576	8	107	43	626	36	229	26	5	18	2	30	4
24091004	522	187	96	94	632	33	262	411	27	16	1	18	8
Hellemobotn - TIB-1 Tysfjord granites													
MH1-42	788	98	197	34	209	18	194	180	10	7	1	31	7
MH2-43	854	73	203	24	185	13	201	130	5	7	1	24	3
MH3-44	884	90	200	25	213	11	190	160	6	7	1	28	3
MH4-45	751	80	192	31	157	18	206	160	7	8	1	26	4
MH5-46	751	56	192	31	157	13	206	98	6	6	1	23	5
25091001	246	161	81	51	443	30	292	332	15	12	2	91	20
25091002	190	322	78	93	684	42	261	640	26	19	2	122	29
25091003	166	399	63	118	910	60	299	791	32	26	4	138	33
Hellemobotn - TIB-2 Tysfjord granites													
KH50A-1	294	35	87	46	332	23	317	86	5.6	16	4	82	17
KH51-3**	443	150	64	59	329	30	214	290	17	14	3	58	9
KH52-4	288	120	61	44	202	18	244	210	12	7		60	12
KH55-7	706	97	172	15	252	12	173	230	8	8		29	3
KH56C-10	348	130	76	60	260	27	265	210	12	10	3	53	10
KH57A-11	107	53	27	40	177	22	370	85	6	9	2	52	10
KH58-13	5	28	6	64	123	16	266	72	4	7		56	22
KH59-14	85	53	38	27	165	18	281	110	5	6	1	46	11
KH60-15**	79	130	38	60	180	18	262	230	13	8	2	70	20
KH61-16	71	52	34	29	190	22	262	99	5	9	2	67	10
KH62-17	244	210	67	66	391	28	258	370	18	16	2	69	11
KH63-18	191	585	60	191	939	69	323	940	47	34	6	206	42
GH1-33	295	39	75	40	211	27	299	110	4	11	5	59	15
GH2A-34	140	140	49	128	296	26	340	270	16	13	5	68	24
GH2B-35	94	20	44	64	172	55	269	59	5	14	5	27	29
GH3-36	13	17	18	34	114	22	280	50		7	3	58	13
GH4-37	237	210	40	105	514	54	184	410	21	19	6	67	10
GH5-39	235	677	91	211	1200	78	213	1000	60	45	6	218	45
GH6-40	208	410	60	130	655	48	257	650	33	26	4	110	26
GH6B-41	193	722	57	232	1100	79	332	1150	57	43	8	249	53
25091004	229	122	70	38	311	22	288	259	12	10	1	70	18
25091005	756	69	154	24	383	19	230	162	8	10	1	23	4
25091006	137	27	90	29	185	24	270	72	3	7.4	1	63	14
25091007	186	61	49	37	210	22	304	133	7	7.3	2	58	16

The Tysfjord-Hamarøy pegmatites

The Tysfjord-Hamarøy pegmatites are classical NYF pegmatites relatively rich in F and genetically related to the A-type Tysfjord granites. Main accessory minerals of these pegmatites are allanite-(Ce), fergusonite-(Y), columbite-(Fe), beryl, various sulfides and fluorite. Mining of Tysfjord-Hamarøy pegmatites started in Hundholmen in 1906 and in different pegmatites in the Drag area in 1907, and continued in these and additional occurrences in Tysfjord and Hamarøy continually or temporarily until around 1970. Most pegmatites were mined for feldspar, some for quartz and minor fluorite (Hundholmen). The Tennvatn pegmatite was during a short period in the 1960s exploited for 'amazonite' for the use as semi-precious stone. Mining started again in 1996 at Nedre Øyvollen and in 2006 at Håkonhals for the production of high-purity quartz (quartz with <50 ppm contaminating elements) and for occasional gravel production at Jennyhaugen. The Nedre Øyvollen and Håkonhals pegmatites, and most of the other Tysfjord-Hamarøy pegmatites, contain quartz which has very low concentration of trace elements. Compared with quartz from other pegmatites worldwide, the Tysfjord-Hamarøy pegmatite quartz is one of the purest in the world (Fig. 1.5).

However, just in the last 10 years 9 new minerals have been described (Table 1.1). The total number of 157 identified minerals (Table 1.4) from the pegmatites makes the Tysfjord-Hamarøy pegmatite field one of the areas in Norway richest in different mineral species.

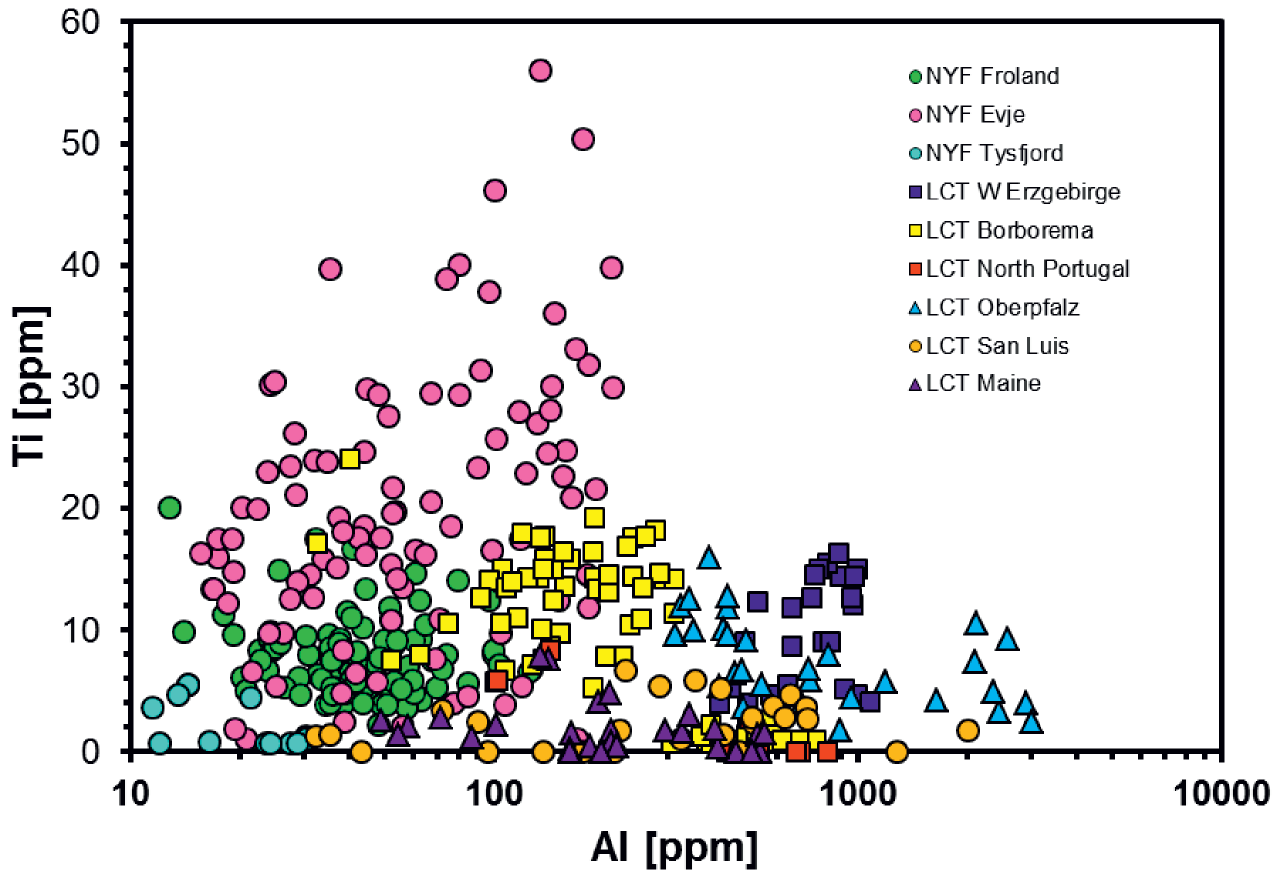


Fig. 1.5. Concentrations of Al and Ti in pegmatite quartz from Tysfjord (bright blue dots) and other pegmatite fields. Aluminium and Ti are generally the most common trace elements in quartz and, thus, an indicator of the chemical quartz quality. Quartz from Tysfjord has the lowest Ti and Al concentrations compared to quartz from other pegmatite localities. Data from Müller et al. (2013, 2015) and Müller unpublished.

Table 1.4. Minerals found in the Tysfjord-Hamarøy pegmatites. TL – type locality.

Mineral name	Mineral name	Mineral name	Mineral name
Adamsite-(Y)	Chabazite-Na	Ixiolite	Rutile
Albite	Chalcopyrite	Kainosite-(Y)	Samarskite-(Y)
Allanite-(Ce)	Chamosite	Kamphaugite-(Y)	Scheelite
Allanite-(Y)	Chernovite-(Y)	Kasolite	**Schlüterite-(Y) (TL)**
Almandine	Chrysocolla	Keiviite-(Y)	Schröckingerite
Alnaperbøeite-(Ce) (TL)	Coffinite	Keiviite-(Yb)	Schorl
Aluminocerite-(Ce)	Columbite-(Fe)	Kozoite-(Nd)	Scorodite
Anatase	Columbite-(Mn)	Kuliokite-(Y)	Siderite
Anglesite	Cosalite	Laumontite	Spessartine
Annite	Covellite	Lokkaite-(Y)	Sphalerite
Arsenocrandallite	Cryptomelane	Luinaite-(OH)	**Stetindite-(Ce) (TL)**
Arsenoflorencite-(Ce)	Dolomite	Löllingite	Stibiocolumbite
Arsenopyrite	Epidote	Magnesiorowlandite-(Y)	Stibiotantalite
Asbecasite	Euxenite-(Y)	Magnetite	Stilbite-Ca
Atelisite-(Y) (TL)	Ferberite	Mikrocline	Sulphur
Babingtonite	Fergusonite-(Y)	Mikrolite	Svabite
Bastnäsite-(Ce)	Fluocerite-(Ce)	Milarite	Synchysite-(Ce)
Bastnäsite-(Nd) (TL)	Fluorapatite	Mimetite	Synchysite-(Y)
Bavenite	**Fluorbritholite-(Y) (TL)**	Molybdenite	Tantalite-(Fe)
Bergslagite	Fluorcalciobritholite	Monazite-(Ce)	Tantalite-(Mn)
Bertrandite	Fluorite	Montmorillonite	Tapiolite
Beryl	Fluor-schorl	Muscovite	Tengerite-(Y)
Betpakdalite-CaCa	Gadolinite-(Y)	Nuffieldite	Tennantite
Beudantite	Galenite	Opal	Thalénite-(Y)
Bismoclite	Gasparite-(Ce)	Parisite-(Ce)	Thorite
Bismuth	Gypsum	**Perbøeite-(Ce) (TL)**	Titanite
Bismuthinite	Goethite	Petscheckite	Topaz
Bismutite	Graphite	Pharmacosiderite	Törnebohmite-(Ce)
Boltwoodite	Greenockite	Phenakite	Uraninite
Britholite-(Y)	Halloysite	Philipsbornite	Uranophane
Brookite	Hellandite-(Y)	Phosgenite	Uranophane-β
Calcioancylite-(Ce)	Hematite	Polycrase-(Y)	Vyuntspakhkite-(Y)
Calcioancylite-(Nd)	Heulandite-Ca	Pumpellyite	Wulfenite
Calcite	Hingganite-(Y)	Pyrite	Xenotime-(Y)
Cassiterite	Hisingerite	*Pyroxene*	Xenotime-(Yb)
Cayalsite-(Y) (TL)	*Hornblende*	Pyrophanite	Yttrialite-(Y)
Cerianite-(Ce)	**Hundholmenite-(Y) (TL)**	Pyrrhotite	Zircon
Cerussite	Hydrocerussite	Quartz	
Chabazite-Ca	Iimoriite-(Y)	*Roméite*	
Chabazite-K	Ilmenite	Rowlandite-(Y)	

Husdal (2008) distinguishes two types of pegmatites within Tysfjord-Hamarøy field:

1) Large (up to 1 km; Håkonhals) lenticular bodies consisting of mainly microcline, quartz and annite, with subordinate muscovite, plagioclase and fluorite. These older type 1 pegmatites have diffuse and transitional borders against the Tysfjord granites and are internally deformed probably during Caledonian times (Fig. 1.6). These pegmatites represent the latest crystallization stages of the Tysfjord granites (TIB-1) having U-Pb columbite ages of c. 1772 Ma (Tiltvika) and c. 1755 Ma (Hundholmen; Rosing-Schow unpublished). Accessory minerals are rich in REE, F, Nb, Ti, Ta, As, Th, U and Be. Masses of yttrofluorite with a thin (~1 mm), dark reaction zone of mainly allanite-(Ce) at the contact against quartz and feldspar are characteristic for these pegmatites.
2) Small but chemically highly evolved pegmatites rich in green microcline (‘amazonite’), quartz and platy albite (‘cleavelandite’), with common fluor-schorl (up to 30 cm). Only three pegmatites, Hellemobotn, Tennvatn and Tjeldøya, belong to

this group. The bodies have sharp boundaries, and are discordant to the foliation of the Tysfjord granites. A xenotime-(Y) from Tennvatn was dated to 370 Ma (Emma Rehnström, personal communication 2006), thus confirming the post-tectonic (post-Caledonian) appearance. The pegmatites are rich in cavities (up to around 10 cm), and lack deformation textures. Replacement units of 'cleavelandite' make significant volumes of the pegmatite bodies, and late fluids have deposited a number of rare minerals with Pb, Bi, REE, As, F, Nb, Be, U, Th and Sb.

Type 1 pegmatites underwent strong, ductile deformation resulting in recrystallization and re-texturing of the primary mineralogy and zoning. Thus, the classical zoning of pegmatites – border, wall, intermediate and core zones - is almost lacking. The contacts of the pegmatites against the Tysfjord granites are diffuse and transitional. The contact zone – here called transitional zone – is generally formed by fine-grained leucocratic aplite up to 3 m wide. Characteristic are agglomerates of annite flakes which are strongly aligned parallel to the contact marking the foliation. The transitional zone graduates into large, euhedral masses of recrystallized K-feldspar, plagioclase and quartz representing presumably the intermediate zone prior to deformation. The dimension of the monomineralic masses of quartz and K-feldspar increases towards the pegmatite core whereas the amount of plagioclase decreases. Some pegmatites have one, e.g. Nedre Øyvollen, or several large quartz cores (Håkonhals).
Major minerals are quartz, K-feldspar, plagioclase and annite. Main accessories are allanite-(Ce), fergusonite-(Y), columbite-(Fe), beryl, various sulfides (pyrite, pyrrhotite, arsenopyrite) and fluorite, particularly an Y-rich variety, yttrofluorite, with abundant inclusions of various REE-minerals (Husdal 2008). Sverdrup (1968) determined 6.5 and 14.0 wt.% Y_2O_3 in yttrofluorite from Hundholmen and Nedre Øyvollen, respectively.

Yttrofluorite
Masses of fluorite with some REE (mostly around 3 atom% Y and Ln) described as the now discredited mineral "yttrofluorite" by Vogt (1911) are found in several localities, and seem to be rather a rule than an exception in the formation of the pegmatites of type 1. These masses cut earlier textures; reaction rims of REE-silicates together with inclusions of rounded quartz grains and large partly dissolved skeletal feldspars are indicators of a late deposition replacing primary minerals. Experimental work demonstrating the partitioning of REE between immiscible silicate and fluoride melts indicates a strong REE-affinity for the latter (Veksler et al. 2005). Yttrofluorite probably formed from such REE-rich fluoride melts/fluids.

Fig. 1.6. Folation-(sub-)parallel upper contact of an apophyse of the Jennyhaugen pegmatite. The contact of the Tysfjord granite to the pegmatite is diffuse grading into an aplitic transional zone (homogeneous, bright greyish rock). The core of the apohyse consists of megacrystic, slightly pinkish K-feldspar and massive, dark grey quartz. Field of view is about 2 m.

Yttrofluorite occurs as masses reaching several meters (the large mass from Hundholmen described by Vogt (1911) was 4 m long and 1.75 m wide). It is colourless to pale yellow/yellowish brown to pale red and the contact against quartz and feldspar is defined by a dark reaction zone of mainly allanite-(Ce). The border zone is normally very thin (less than 1 mm) but can locally be better developed (up to several dm in Hundholmen). Yttrofluorite in direct contact with quartz or feldspar (without the allanite-rim) is rare if present at all.
Individual masses display at least some zoning when it comes to type of inclusions (Fig. 1.7), typically with allanite-(Ce), britholite-(Y)/fluorbritholite-(Y) and thalénite-(Y) being most abundant in the outer zones, and cavities (with the more exotic phases) becoming more common in the central parts.

Included minerals are for most of the occurrences randomly oriented. Some of the material from Hundholmen does however indicate deformation; hundholmenite-(Y) and subparallel prisms of allanite-(Ce) are concentrated in bands, giving the masses a gneiss-like texture. Some hundholmenite-(Y) occurs as large (more than 2 cm) rounded, slightly elongated grains in a groundmass of yttrofluorite and fine-grained anhedral hundholmenite-(Y), and folds and sigmodal textures give ideas of recrystallization during movement.

The mineral content of yttrofluorite varies strongly between localities and even between different masses within the same locality (see Table 1.5). Some examples to illustrate this:

- Two main types of yttrofluorite occur in Hundholmen, both in rather large amounts. **Type 1** (the one described by Vogt (1911)) has rather few included minerals (scattered grains of allanite-(Ce) and britholite-(Y)), but occasionally has a well-developed border zone with abundant allanite-(Ce), gadolinite-(Y), fergusonite-(Y), xenotime-(Y) and thalénite-(Y). **Type 2** is very rich in hundholmenite-(Y), but contains no other minerals than rare fergusonite-(Y) and perbøeite-(Ce). Bastnäsite-(Ce), the most common inclusion in all the other yttrofluorites, does not occur in yttrofluorite from Hundholmen.
- At Håkonhals a certain type of yttrofluorite contains only monazite-(Ce) as inclusions. Phosphates in general are hardly found in other occurrences, and then restricted to xenotime-(Y) or very late fluorapatite along cracks.
- Gadolinite-(Y) is a common mineral in yttrofluorite from most occurrences, particularly in the border zones, but is completely absent from the otherwise very mineral rich Stetind pegmatite.

Other aggregates probably related to yttrofluorite are rounded, brown masses of bastnäsite-(Ce) and fluocerite-(Ce) rimmed by black allanite-(Ce) occurring both in association with yttrofluorite (Fig. 1.7) but also isolated and even in pegmatites without yttrofluorite. They are typically zoned with massive basnäsite-(Ce) forming an outer zone and a core of platy bastnäsite-(Ce) in a groundmass of fluocerite-(Ce).

The typical yttrofluorite has not been found in the type 2 pegmatites, but pale green, massive, translucent fluorite occurs in 'cleavelandite' from the Tennvatn pegmatite. Occasionally parts of these masses turn opaque and porous with inclusions of REE minerals (hingganite-(Y), chernovite-(Y) and a metamict (Mn,Fe)-Y-(Sb,As)-(Nb,Ti) oxide (Raade & Husdal 2010).

A total number of 51 mineral species have been indentified in yttrofluorite (Table 1.5). The majority are REE-minerals, with the REE-silicates strongly represented. The minerals are spatially related to four certain structural domains within the yttrofluorite masses: (1) Minerals associated with the allanite-(Ce) rims, (2) an- to subhedral mineral grains embedded in yttrofluorite, (3) minerals found as euhedral crystals in small cavities, and (4) post-secondary minerals along cracks in and around yttrofluorite. Some minerals are represented in several of the domains.

The large diversity of rare minerals found in the pegmatites of the Tysfjord granite is partially a result of deformation-related recrystallization (type 1 pegmatites) and element mobilisation and partially due to late pneumatolytic/hydrothermal activity (type 1 and 2 pegmatites). A large number of species are found only in yttrofluorite or in the type 2 Tennvatn pegmatite: of the 157 different minerals found, 32 occur exclusively in association with yttrofluorite, and 24 only in Tennvatn. The total numbers of species are 51 for yttrofluorite and 57 for Tennvatn, with only 14 in common. Thus, 94 different species have been identified either in yttrofluorite or from Tennvatn. Considering the relatively small volumes these two modes of occurrence represent, this is rather remarkable.

REE-minerals are strongly represented in the area. As many as 50 different minerals containing REE as a major constituent (dominating structural sites) have been identified. The majority of these occur in yttrofluorite. Another important element is As with 16 As-dominated minerals. Characteristic elements of other Norwegian granite pegmatites, like Li (Ågskardet, Tørdal) and Sc (Tørdal, Evje/Iveland), are apparently absent, and apart from small amounts of monazite-(Ce), xenotime-(Y), xenotime-(Yb) and apatite-(CaF), phosphates have not been found.

Table 1.5. Minerals found in selected yttrofluorite masses related to type 1 pegmatites according to Husdal (2008). B – minerals of the border zone, X – minerals within massive yttrofluorite, C – minerals in cavities within massive yttrofluorite, S - secondary minerals in cracks within massive yttrofluorite. The number of letters of each type reflects the rarity, i.e. X - rare, XX - uncommon to common and XXX - abundant. *See text for explanation of Hundholmen 1 and Hundholmen 2.

Mineral	**Stetind**	***Hundholmen 1**	***Hundholmen 2**	**Øvre Lapplægeret**	**Lagmannsvik**	**Håkonhals**
Adamsite-(Y)		S	SS			
Allanite-(Ce)	BBB	BBB	BBB	BBB	BBB	BBB
Allanite-(Y)	B					
Alnaperbøeite-(Ce)	XX					
Annite				CC		
Apatite-(CaF)					S	
Arsenopyrite	X			X		
Atelisite-(Y)	S(?)					
Bastnäsite-(Ce)	XXXCCC			XXXCCC	XXX	XX
Bastnäsite-(Nd)	C					
Britholite-(Y)	?	XXX		BBBXX		
Calcioancylite-(Ce)	C		SS			
Calcioancylite-(Nd)	C					
Cayalsite-(Y)	C			CX		
Chabazite-Ca	C					
Fergusonite-(Y)		BB	X			
Fluorbritholite-(Y)					BBB	
Fluorcalciobritholite						
Gadolinite-(Y)		BBB			BBB	
Hematite	CCC					
Hundholmenite-(Y)	XXC		XXX	XC	XX	
Iimoriite-(Y)				XC		
Aluminocerite-(Ce)					XX	
Kainosite-(Y)	S			CCSS	SS	SS
Kamphaugite-(Y)			S			
Keiviite-(Y)	C					
Keiviite-(Yb)	C					
Kozoite-(Nd)	C					
Kuliokite-(Y)	C					
Magnesiorowlandite-(Y)	C					
Molybdenite		B	B		B	
Monazite-(Ce)					X	XX
Muscovite				C		
Perbøeite-(Ce)	XX	X				
Pyrite					S	
Quartz	C		S			
Rowlandite-(Y)	XC			X		
Schlüterite-(Y)	CCS					
Stetindite-(Ce)	C					
Synchysite-(Ce)				C		
Synchysite-(Nd)				C		
Synchysite-(Y)	CCC	CC		CCSS		
Tengerite-(Y)		SS	SS			
Thalénite-(Y)	BXXCC	BBBXX		XX	XX	
Thorite	XX					XXX
Törnebohmite-(Ce)	XXC					
Uranophane-β	S					
Vyuntspakhkite-(Y)	CC			C		
Xenotime-(Y)	S	BB				
Yttrialite-(Y)	XX					
Zircon	X					XXX

Fig. 1.7. Typical yttrofluorite rimmed by black allanite-(Ce), Hundholmen. Yttrofluorite is typically colourless to pale yellow/yellowish brown to pale red as in the upper part of the specimen. The greenish miscolouring in the lower part of the specimen is caused by algae. The specimen is 14 cm in length. Photo by Øivind Thoresen.

Field locations

Locality 1.1: Hundholmen pegmatite

Highlights

- Deformed NYF pegmatite being the type locality for hundholmenite-(Y) and perbøeite-(Ce).
- Very good crystals of thalénite-(Y) (Plate 1.1E and 1.2F).
- Easy accessible mine dump material in the tidal zone of the Tysfjord.

Coordinates EU89-UTM Zone 33V 552619E/ 7559838N

Directions and Access

Take the ferry from Drag to Kjøpsvik. Take left 100 m after leaving the ferry, then follow the road for 8.5 km. The mine is an abondand quarry opened for mineral collectors but filled with seawater (Fig. 1.8). The site is on private land. The exposures are relatively fresh and there is plenty material at the dumps along the shoreline of the Tysfjord. In summer the mine can be crowded by mosquitoes, thus, make use of suitable insect repellents if necessary. The dump is placed in the tidal zone and is accessible only during low tide.

Distance to walk: 0.1 km
Elevation changes: 5 m
Excursion time: 2 hours
Conservation status: None

Fig. 1.8. The abandoned Hundholmen mine in the foreground filled with seawater and used as harbour today. The mining dump is along the shoreline behind the mine. In the background is the Tysfjord, the Hatten Mt. on the left, the Skarbergfloget Mt. on the right and the Lofoten in the distant background.

Pegmatite structure

The Hundholmen pegmatite forms a c. 100 m long and 60 m wide, NE-SW striking lens-shaped body (Fig. 1.9). Most recent U-Pb columbite dating revealed a crystallization age of 1755±5 Ma (Rosing-Schow unpublished). The host rock is grey, medium- to coarse-grained 'biotite'-amphibole-bearing Tysfjord granite with common allanite-(Ce) and titanite (Vogt 1922). The strike of the pegmatite body is parallel to the foliation of the Tysfjord granite. Due to the Caledonian amphibolite-facies deformation the boundaries between host rock and pegmatite and between pegmatite-internal zones are unsharp and gradual. Close to the pegmatite contact the Tysfjord granite shows an increasing degree of foliation and becomes almost mylonitic. The pegmatite consists of a fine-grained, 'biotite'-rich, up to 20 m wide margin (wall zone) with foliated aplitic texture with strongly elongated and aligned aggregates of recrystallized 'biotite' (cm to m in size). The aplitic facies grades into a blocky zone dominated by massive pink K-feldspar. Meter-sized masses of yttrofluorite occur in the blocky zone. The deformation caused the partial remobilization and recrystallization of the yttrofluorite masses. The pegmatite core (up to 40 m in diameter), which has been largely exploited, consists of massive quartz. Due to ductile deformation, crystal faces of primary pegmatite minerals are rarely preserved. The findings of euhedral quartz crystal (up to 20 cm in size; Fig. 1.10A), albite, muscovite and fluorite indicate that open cavities (at least 50 cm in diameter) occurred in the pegmatite core of the pegmatite despite the generally strong deformation. The Hundholmen pegmatite was mined from 1906 until the 1970s for feldspar, some quartz and fluorite. The mine was 50 to 60 m deep and is today filled with seawater and serves as boat harbour.

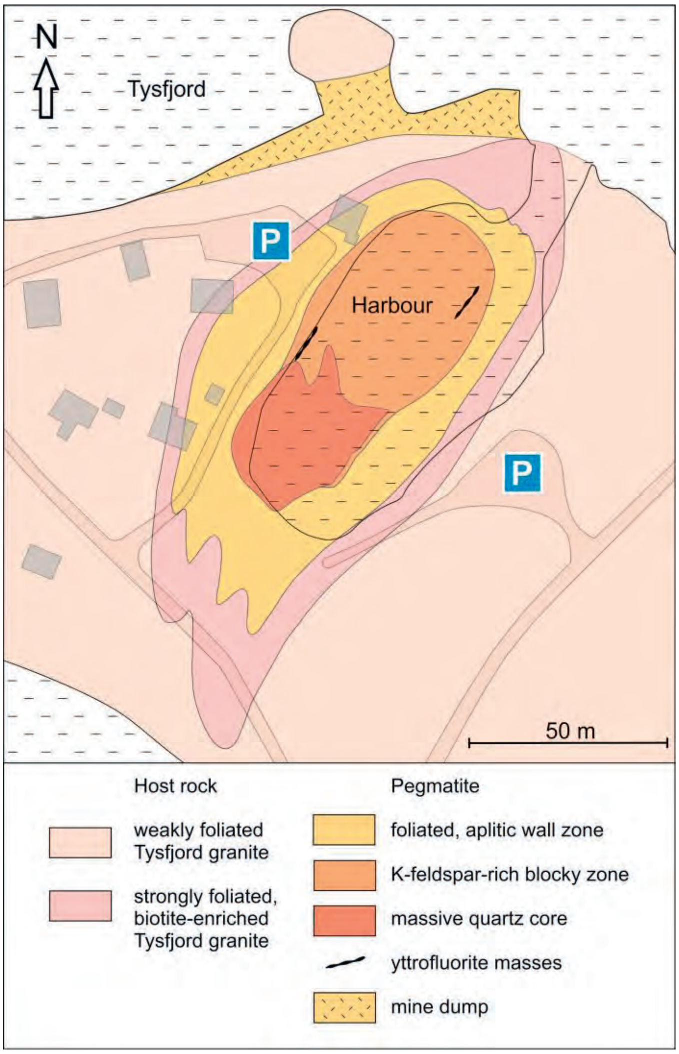


Figure 1.9. Geological map of the Hundholmen pegmatite. Modified from Foslie (1941).

Mineralogy

Hundholmen is a good collecting spot with 59 different mineral species (Table 1.6) and large amounts of interesting material. Most of the material from the mine dump was used as filling material when the road to Kjøpsvik was constructed. However, there is still plenty of dump material accessible but it is located in the tidal zone. The permanent exposure to seawater causes a thin organic cover on the rocks (apart from some seaweed and barnacles).

Major minerals are quartz, K-feldspar, and 'biotite', and minor plagioclase. 'Biotite' has siderophyllite composition with 1.47 wt.% F and 0.27 wt.% Li_2O. Yttrofluorite is the most common accessory mineral and samples of yttrofluorite associated with gadolinite-(Y), xenotime-(Y), fergusonite-(Y), britholite-(Y) and thalénite-(Y) are abundant. Hundholmenite-(Y) and adamsite-(Y) are also possible to find with some luck (Figs. 1.10B, C). Because of the great diversity of minerals found at Hundholmen only the most interesting material is described here.

Yttrofluorite is quite abundant in different parts of the dump, and must have occurred in large amounts in the pegmatite. Vogt (1911) describes a mass sized 4 x 1.75 m, and smaller aggregates can still be found in the quarry wall. There are two completely different types of yttrofluorite: (1) Coarse-grained aggregates (individual grains to some cm, Fig. 1.7), colourless to faintly green. The central parts of these aggregates contain only scattered grains of allanite-(Ce) and britholite-(Y), while the border zone is occasionally well developed and several decimeters thick with allanite-(Ce), euhedral thalénite-(Y) to 5 cm, xenotime-(Y), gadolinite-(Y) and fergusonite-(Y). (2) Granular aggregates with grain size around 1 to 3 mm, with abundant hundholmenite-(Y) (up to around 50 vol % of the aggregates). Some aggregates show two generations of hundholmenite-(Y) – large (up to 2 cm) irregular masses in a more finegrained groundmass of hundholmenite-(Y) and yttrofluorite (Fig. 1.10B). Both types are cut by cracks with secondary REE carbonates: lokkaite-(Y), tengerite-(Y), synchysite-(Y), calcioancylite-(Ce), kamphaugite-(Y) and adamsite-(Y) (Fig. 1.10C), the latter formed from a reaction with saline water intruding the cracks either in situ (the pegmatite is located close to the fjord) or post mining on the dump. Adamsite-(Y) is the youngest mineral in these cracks.

Parisite from Hundholmen was mentioned by Vogt (1922), and is found as prismatic crystals to 8 cm (Eldjarn 1978). Recent examinations of similar material show the greyish cores of such crystals to be Ce-dominated, while the brown outer zones are Y-dominated. Both zones give synchysite patterns, and are synchysite-(Ce) and synchysite-(Y). Associated minerals are bertrandite, calcioancylite-(Ce), chabazite-K, chabazite-Na, columbite-(Fe), hingganite-(Y), monazite-(Ce) and xenotime-(Y), all as microcrystals.

Table 1.6. Minerals found in the Hundholmen pegmatite.

Mineral	Comments	Rarity (X = rare, XXX= common)
Adamsite-(Y)	Colourless microcrystals in cracks in yttrofluorite. Formed from a reaction between yttrofluorite and seawater intruding along cracks, either in situ or post mining on the dump. Associated with, and younger than, calcioancylite-(Ce) and kamphaugite-(Y) (Fig. 1.10C)	XX
Albite	Rockforming. Also as colourless crystals to some cm in cavities.	XXX
Allanite-(Ce)	Black prismatic, several dm in size. Also as main constituent of border zones around yttrofluorite (Fig. 1.11).	XXX
Allanite-(Y)	Black massive with yttrian epidote. Up to 5.94 wt% ThO_2.	X
Anatase	Microcrystals in cavities, with rutile.	X
Annite/siderophyllite	Rockforming.	XXX
Arsenopyrite	Rare, as small masses and crystals in association with fergusonite-(Y). Partly altered to brownish crusts of secondary arsenates.	X
Bastnäsite-(Ce)	In aggregates with fluocerite-(Ce).	X
Bertrandite	Microcrystals in cavities in feldspar, with hingganite-(Y) and columbite-(Fe).	X
Beryl	Yellow – green massive.	X
Beudantite	Secondary after arsenopyrite	X
Boltwoodite	Yellow crust around uraninite.	X
Britholite-(Y)	Pink grains in yttrofluorite.	XX
Calcioancylite-(Ce)	Yellow to pink aggregates on synchysite-(Y) (Fig. 1.10D) and in cracks in yttrofluorite.	X
Calcite	White in cavities in feldspar.	X
Cerianite-(Ce)	Small inclusions with fluocerite-(Ce).	X
Chabazite-K	Colourless crystals in cavities in microcline.	X
Chabazite-Na	Colourless crystals in cavities in microcline.	X
Chalcopyrite	Metallic grains.	X
Chamosite	Late mineral in cavities with luinaite-(OH) and schorl. No Mg detected (SEM-EDS) (Fig. 1.10D)	X
Clinochlore	-	X
Coffinite	Found in thin sections, associated with uraninite	X
Columbite-(Fe)	Black massive, microcrystals.	X
Dolomite	White massive	X
Epidote	Massive with allanite-(Y). Yttrian.	X
Euxenite-(Y)	-	X
Fergusonite-(Y)	Dark brown massive, microcrystals.	XX
Fluocerite-(Ce)	Brown rounded aggregates.	X
Fluorapatite	In thin sections, associated with allanite-(Y). Rimmed by britholite-(Y).	X
Fluorite	Large masses, both beige yttrofluorite and a colourless to pale green type without REE.	XXX
Gadolinite-(Y)	Dark green crystals and grains, in border zone of yttrofluorite.	XX
Galena	In cavities in feldspar. Altered to secondary Pb-minerals (wulfenite, cerussite(?) and angelsite (?)).	X
Gypsum	White secondary on allanite-(Ce).	X
Hingganite-(Y)	Pale brown microcrystals in cavities, with bertrandite and columbite-(Fe).	X
Hundholmenite-(Y)	Brown massive in yttrofluorite. Type locality (Fig. 1.10B).	XX
Kamphaugite-(Y)	Colourless, globular crusts in cracks in yttrofluorite.	X
Laumontite	Late, in cracks.	X
Lokkaite-(Y)	White, radiating in cracks in yttrofluorite.	X
Luinaite-(OH)	A 10 cm aggregate in a cavity in feldspar. With schorl.	X
Magnetite	Metallic, grey massive.	X
Microcline	Rock-forming.	XXX
Molybdenite	Scattered flakes.	X
Monazite-(Ce)	Brownish grey massive and microcrystals in cavities.	X
Montmorillonite	-	X
Muscovite	Rockforming.	XXX
Parisite-(Ce)	Known from literature only. Probably intergrown with synchysite-(Y).	X

Table 1.6. Continued

Mineral	Comments	Rarity (X = rare, XXX= common)
Perbøeite-(Ce)	Greenish grey crystals in hundholmenite-rich yttrofluorite. Only one sample found. Type locality.	X
Pyrite	-	XX
Quartz	Rock forming. Also dm-sized well-formed crystals.	XXX
Rutile	Microcrystals in cavities.	X
Schorl	With luinaite-(OH), as a 10 cm black aggregate in a cavity in feldspar.	X
Stilbite	Filling cracks in feldspar.	X
Synchysite-(Ce)	Zones in crystals of synchysite-(Y).	X
Synchysite-(Y)	Brown prismatic up to 8 cm, and as microcrystals in small cavities in type 1 yttrofluorite (Fig. 1.10D)	XX
Tengerite-(Y)	White, secondary in cracks. Hard to tell from other secondary REE-carbonates.	X
Thalénite-(Y)	Pink, well-formed crystals in yttrofluorite. Up to at least 5 cm (Plates 1.1 and 1.2).	XX
Thorite	Brown to yellow massive.	X
Törnebohmite-(Ce)	Inclusions in fluocerite-(Ce).	X
Uraninite	Black cubes in material with allanite-(Y). Often surrounded by yellow boltwoodite.	X
Wulfenite	Small, brown crystals on galena.	X
Xenotime-(Y)	Microcrystals in cavities and in border zone of yttrofluorite.	XX
Zircon	-	X

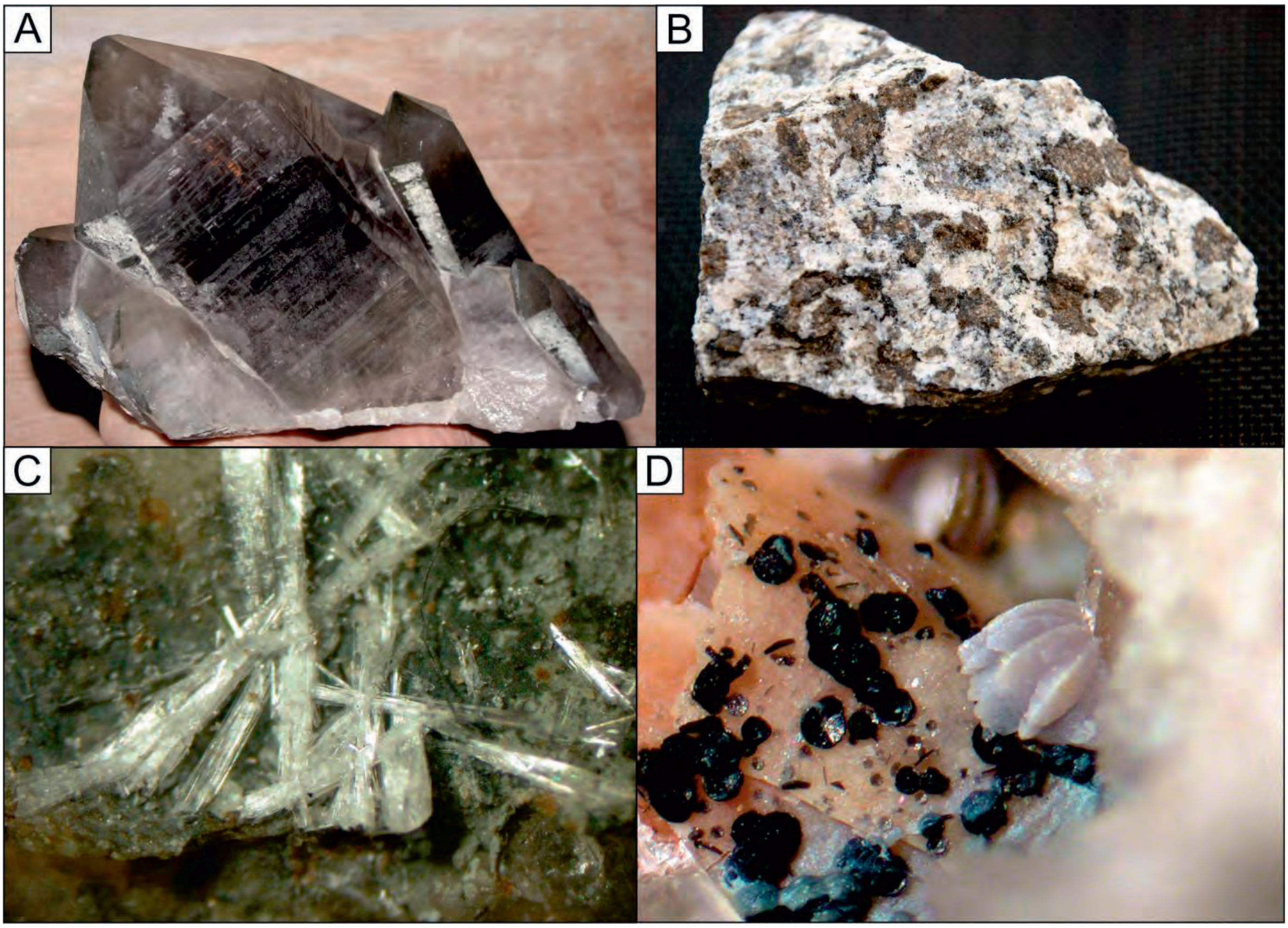


Fig. 1.10. Photographs of minerals from the Hundholmen pegmatite. A – Large quartz crystal from a cavity. The crystal is 20 cm in size. B – Brown hundholmenite-(Y) in yttrofluorite. The specimen is 5 cm across. C – Adamsite-(Y). Field of view is 2 mm. D – Pink calcioancylite-(Ce) and black chamosite on synchysite-(Y). Field of view is 2 mm.

Fig. 1.11. 50-cm large, partially boudinaged allanite-(Ce) crystal embedded in quartz and surrounded by two large sheet-like biotite aggregates. NE wall of the mine (accessible by boat only).

Locality 1.2: Stetind pegmatite

Highlights

- Deformed NYF pegmatite with highly evolved yttrofluorite with many rare minerals
- Type locality for 7 minerals

Coordinates EU89-UTM Zone 33V 564499E/ 7563037N

Directions and Access

Follow Road 827 for 18 km from Kjøpsvik, to the parking just before the Stetind Tunnel. Continue to walk along the road towards the tunnel for 100 m, then turn right and follow the walking path (partially paved with quartz and feldspar gravel) for 500 m. This site is on private land and the landowner has to be asked for permission to collect. The exposures are relatively fresh and there is plenty of material on the dumps and some inside the quarry. Be aware of loose boulders. In summer the mine can be crowded by mosquitoes, thus, make use of suitable insect repellents if necessary.

Distance to walk: 500
Elevation changes: 90 m
Excursion time: 2 hours
Conservation status: None

Pegmatite structure

The Stetind pegmatite forms a 80-m long, NNW-SSE striking, vertical lens-shaped body up to 15 m wide (Fig. 1.12). The body strikes parallel to the foliation of the Tysfjord granite host. Due to the intense deformation the primary zoning of the pegmatite is only rudimentarily preserved. The aplitic, foliated wall zone is about 1- 2 m wide and grades into a blocky core zone dominated by massive K-feldspar. In the core several meter-sized lenses of massive yttrofluorite occur. The pegmatite was mined for quartz in the 1960s.

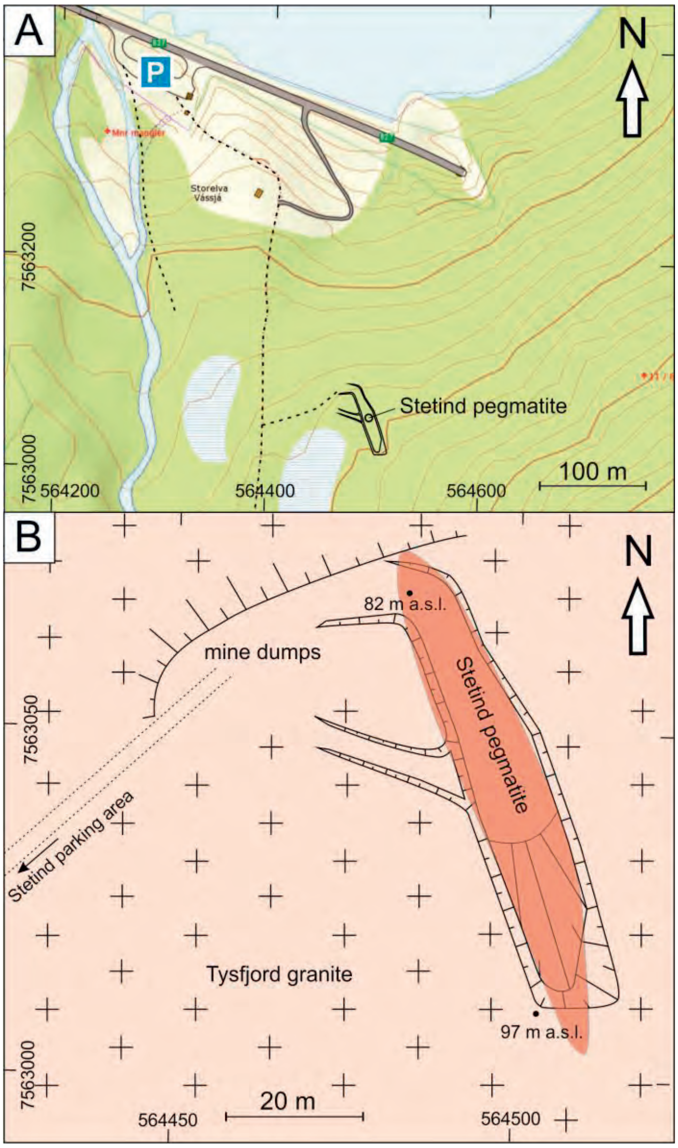


Fig. 1.12. A – Access map of the Stetind pegmatite. B – Geological map of the Stetind pegmatite.

Mineralogy

Major minerals are K-feldspar, quartz, plagioclase and ‘biotite’ and minor muscovite. Latter is mostly found along fractures in K-feldspar. K-feldspar dominates of plagioclase; in fact plagioclase makes a small proportion of the pegmatite, probably less than 10 vol.%. The trace element composition of K-feldspar is quite variable (Table 1.7). Due to deformation sheet-like megacrystals of ‘biotite’ are smeared out and recrystallized. All large feldspars show elongated lens-shaped or boudinaged forms and crystal faces are hardly preserved. Accessory minerals found at Stetind are listed in Table 1.8. The yttrofluorite from Stetind occurs as a number of lenticular masses along a narrow zone which can be traced for 10 m. It is highly evolved, and has, in addition to the “common” minerals of the less evolved types (allanite-(Ce), bastnäsite-(Ce), thalénite-(Y), britholite-(Y) and hundholmenite-(Y)) central zones with numerous small cavities hosting microcrystals of many rare and even unique REE-minerals (Stetind is the only locality for stetindite-(Ce), schlüterite-(Y) and atelisite-(Y)). Yttrofluorite from Stetind is highly differentiated, with mineral content differing between individual masses, between zones in each mass and even between individual cavities some mm apart. A 4 cm large sample has more than 20 different species. A certain part of the material had highly oxidizing conditions in the cavities, forming Ce^{4+} (and stetindite-(Ce)), making Nd the dominant trivalent LREE available for calcioancylite-(Nd), kozoite-(Nd), bastnäsite-(Nd) and Nd-dominant törnebohmite. No minerals with Be nor Nb have been found in the yttrofluorite from Stetind. Accessory minerals for the rest of the pegmatite are limited to massive, bluish beryl, columbite-(Fe), microlite, fergusonite-(Y) and tetrahedrite.

Table 1.7. Composition of feldspars from Tysfjord pegmatites. Bulk XRF analyses. Data from Müller, unpublished.

	Stetind	**Stetind**	**Jennyhaugen**	**Jennyhaugen**	**Tennvatn**	**Tennvatn**
	Kfs south	Kfs north	pink Kfs	albite	amazonite	'cleavelandite'
sample #	08081504	08081505	08081517	08081518	08081531	08081532
Major elements (wt.%)						
SiO_2	65.1	67.6	65.8	68	64.9	68.3
Al_2O_3	18.7	19.8	18.7	19.6	18.5	19.6
Fe_2O_3	0.096	0.079	0.136	0.103	0.068	0.082
TiO_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
CaO	0.147	0.998	0.144	0.306	0.026	0.095
Na_2O	2.83	9.37	3.59	11.1	2.22	11.5
K_2O	12.2	2.18	11.3	0.454	13.2	0.149
MnO	<0.01	<0.01	0.011	<0.01	<0.01	<0.01
P_2O_5	<0.01	0.011	<0.01	<0.01	<0.01	<0.01
LOI	0.135	0.11	0.135	0.1	0.115	0.109
Sum	99.2	100	99.7	99.5	99	99.8
An	0.7	4.9	0.7	1.5	0.1	0.5
Ab	25.9	82.5	32.3	96.0	20.3	98.7
Or	73.4	12.6	67.0	2.6	79.5	0.8
Trace elements (ppm)						
Ba	401	81	16	11	29	<10
Cs	<10	<10	<10	<10	93	<10
Ga	29.6	69.5	38.1	71.9	93.6	177
Pb	82.2	43.1	78	16.8	1550	388
Rb	618	87.8	955	29.5	1580	<5
Sr	79.2	61.1	12.6	26.1	<5	14.8
Ta	<5	<5	<5	<5	<5	<5
Y	<3	<3	9.4	<3	<3	<3

Table 1.8. Minerals found in the Stetind pegmatite. Bold = type locality

Mineral	**Comments**	**Rarity (X = rare, XXX = common)**
Albite	Rock-forming.	XXX
Allanite-(Ce)	Always present as rims around yttrofluorite.	XXX
Allanite-(Y)	Found in one sample, brown massive with allanite-(Ce).	X
Alnaperbøeite-(Ce)	Not uncommon, forming greenish grey prismatic crystals to some mm. Visually indistinguishable from alnaperbøeite-(Ce).	XX
Annite	Rock-forming.	XXX
Atelisite-(Y)	Colourless to pale brown, very small crystals in cavities in an altered type of yttrofluorite, associated with kainosite-(Y) and calcioancylite-(Nd). Fig. 1.14A.	X
Bastnäsite-(Ce)	Common as yellowish brown platy inclusions and as platy crystals in the cavities.	XXX
Bastnäsite-(Nd)	Some bastnäsite-(Ce), and particularly if associated with stetindite-(Ce), have thin, Nd-dominated outer zones.	X
Beryl	Bluish massive.	X
Britholite-(Y)	Pink, rounded grains in the outer parts of the masses.	X
Calcioancylite-(Ce)	These three minerals form both pink, dipyramidal crystals to 1 mm (Fig. 1.13D) and smaller, rounded crystals in cavities. They are visually indistinguishable apart from those associated with atelisite-(Y) which are calcioancylite-(Nd) with La-dominant cores.	X
Calcioancylite-(Nd)		X
Kozoite-(Nd)		X

Table 1.8. Continued.

Mineral	**Comments**	**Rarity (X = rare, XXX = common)**
Cayalsite-(Y)	Pink prismatic crystals in cavities. Two intergrown polytypes: cayalsite-(Y)-1O and cayalsite-(Y)-1M. Type locality.	X
Chabazite-Ca	Colourless, blocky crystals in cavities.	X
Columbite-(Fe)	Black massive, with microlite group.	X
Fergusonite-(Y)	Dark brown massive.	X
Fluorite	Large masses of yttrofluorite. No “normal” fluorite has been found.	XXX
Hematite	Common as aggregates of tabular crystals.	XX
Hundholmenite-(Y)	Locally common as slightly rounded, brown, translucent crystals to 7 mm, associated with bastnäsite-(Ce), thalénite-(Y) and törnebohmite-(Ce). Also as pale brown, transparent to translucent, tabular crystals to 1 mm in cavities. The triangular shape of these crystals makes them easy recognizable. Observed forms are prominent pedions and two less developed pyramid**s**. Multiple contact twinning (with angles of approximately 60°/120° between the individuals) is sometimes developed (Fig. 1.14B).	XX
Kainosite-(Y)	Fine-grained alteration product after yttrofluorite.	X
Keiviite-(Y)	Keiviite-(Y) from Stetind forms white translucent prisms to some mm with square cross sections in cavities in yttrofluorite (Fig. 1.13B). The faces are normally rough and dull with striations in the length direction, and in rare cases smooth and transparent. Terminations are poorly defined, and seem to consist of parallel growth of smaller needles. Smaller prisms (to 0.1 mm) do often grow randomly on the surfaces of the largest crystals. Most of the chemically checked (SEM-EDS) crystals show Y-dominance, but a single specimen with a somewhat different appearance (the prisms have a triangular cross section and grow in a radiating aggregate) gives Yb-dominance – keiviite-(Yb).	X
Keiviite-(Yb)		X
Kuliokite-(Y)	Pale grey grains. colorless to pale pink tabular to bladed crystals to 1 mm in cavities. The shape of the crystals can be described as slightly distorted rectangular plates (the corners are truncated). The normal angle between some of the edges helps distinguishing kuliokite-(Y) from other minerals of platy habit, like synchysite-(Y) and the frequent bastnäsite-(Ce). Fan-shaped aggregates are often formed, and sometimes the mineral is found completely filling the cavity, appearing as pink lamellar anhedral masses.	X
Magnesiorowlandite-(Y)	Very rare, as pale grey grains.	X
Microcline	Rock-forming.	XXX
Microlite Group	Yellow with columbite-(Fe).	X
Muscovite	Rock-forming.	XXX
Perbøeite-(Ce)	Not uncommon, forming greenish grey prismatic crystals to some mm. Visually indistinguishable trom alnaperbøeite-(Ce).	XX
Quartz	Rock-forming. Also as small crystals in cavities in yttrofluorite.	XXX
Rowlandite-(Y)	from Stetind is non-metamict, and gives a well-defined XRD-pattern. It occurs rather rare as greenish grey, transparent, subhedral crystals to 2 mm in massive yttrofluorite, and as tabular crystals in cavities, often covered by hematite.	X
Schlüterite-(Y)	Fan-shaped aggregates of pink to white needles.	X
Stetindite-(Ce)	Pale yellow, prismatic crystals often in fan-shaped aggregates. Square cross section (Fig. 1.13C).	X
Synchysite-(Y)	Very common, forming crusts of small, white tabular crystals in cavities or along cracks.	XXX
Tetrahedrite	Small masses in feldspar.	X
Thalénite-(Y)	Quite common – seems to have formed during the entire crystallization sequence of the yttrofluorite, and occurs both as pink, blocky crystals in the cavities (two generations) and as grains and rounded crystals in the massive fluorite and even in the surrounding quartz.	XX
Thorite	Brown to yellow masses associated with yttrialite-(Y), or euhedral reddish brown crystals (tetragonal prisms terminated by a dipyramid) to 1 mm embedded in yttrofluorite.	X

Table 1.8. Continued.

Mineral	**Comments**	**Rarity (X = rare, XXX = common)**
Törnebohmite-(Ce)	Rather common in parts of the material from Stetind, where it forms prismatic to bladed brown, rarer pink, greenish or blue, crystals to 2 mm. The rhombus-like cross section and a striation along the length direction are often helpful in distinguishing törnebohmite-(Ce) from confusable minerals like bastnäsite-(Ce) and hundholmenite-(Y). Törnebohmite-(Ce) has also been found in cavities, as well-formed prismatic crystals to 1 mm with rectangular cross sections (Fig. 1.14C). Some of these are very Nd-rich and even Nd-dominated.	X
Uraninite	Black massive.	X
Uranophane-β	Yellow, fibrous along cracks and in cavities.	X
Vyuntspakhkite-(Y)	In cavities as prismatic to bladed crystals with oblique terminations. Most crystals are transparent with pale pink interiors and characteristic purple outer zones (Fig. 1.13A)	XX
Yttrialite-(Y)	Always metamict, identification based on the chemical composition (Y-Th-silicate) and the characteristic XRD-pattern after annealing at 1000°C for 24 hours. It is found as dark brown masses to around 1 cm in yttrofluorite. Most of the masses occur along zones or cracks, and is associated with zircon, thalénite-(Y) and törnebohmite-(Ce), but isolated masses can be found in massive yttrofluorite. In very rare cases crystals to 1 cm have been developed. The crystals are incomplete with dull faces, and seem to have low symmetry.	X
Zircon	Brown to grey massive, often along the border zone, but also embedded in ytttrofluorite.	X

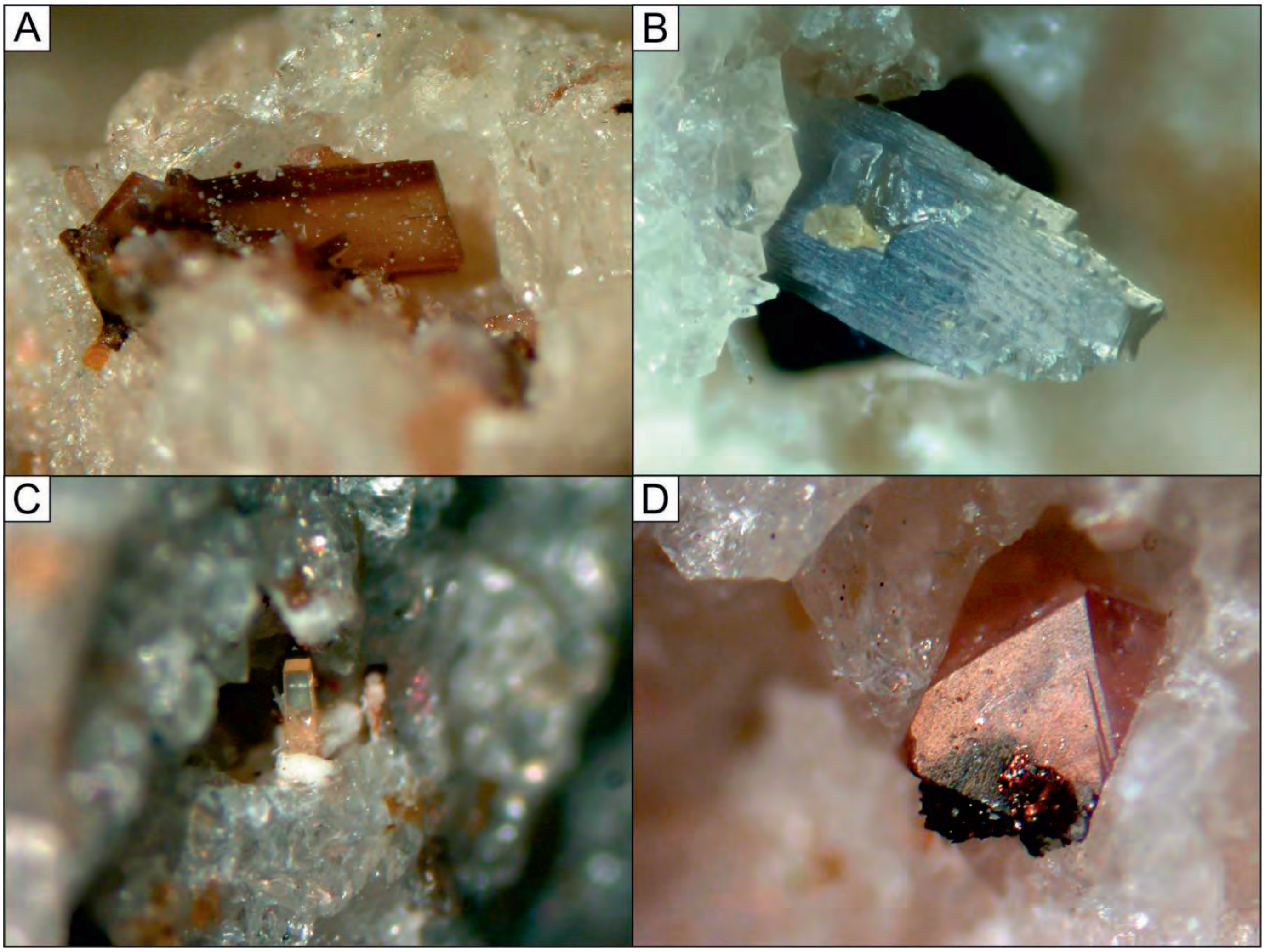


Fig. 1.13. Microphotographs of accessory minerals from the Stetind pegmatite. A - Vyuntspakhkite-(Y). The crystal is 1 mm in length. B - Keiviite-(Y). The crystal is 0.6 mm in length. Photo by O.T. Ljøstad. C - Stetindite-(Ce). The crystal is 0.3 mm in length. D - Calcioancylite-(Nd) or kozoite-(Nd). The crystal is 1 mm in size.

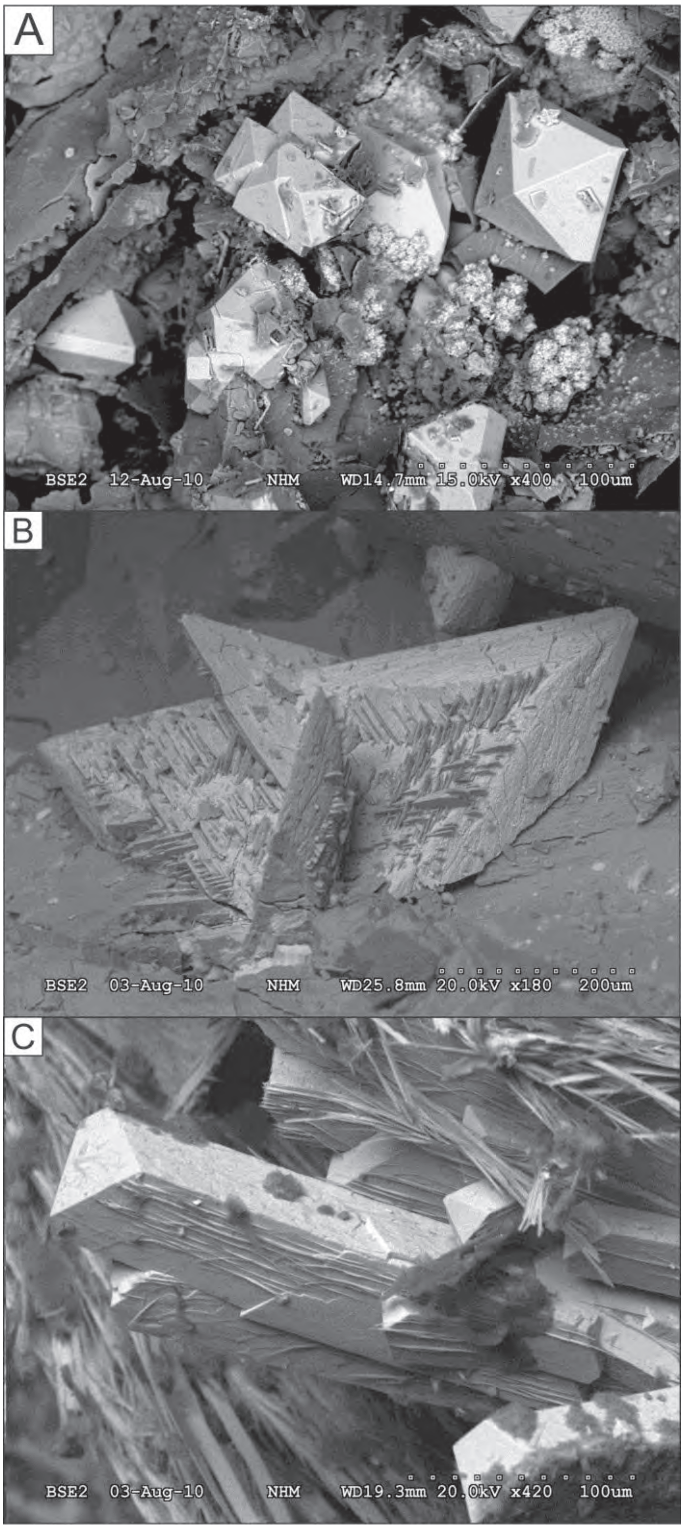


Fig. 1.14. BSE images of minerals from Stetind. A - Atelisite-(Y). B - Twinned hundholmenite-(Y). C - Fibrous schlüterite-(Y) on törnebohmite-(Ce).

Locality 1.3: Jennyhaugen pegmatite

Highlights

- Deformed NYF pegmatite freshly exposed with the entire width of the pegmatite in an active gravel quarry
- 'Amazonite' with tantalite-(Mn) and microlite group minerals

Coordinates EU89-UTM Zone 33V 543313E/7548208N

Directions and Access

Drive road 827 towards the ferry port on Drag, turn left at the major crossroad in the village center (by the grocery store), follow the road for 1.8 km, then turn left and continue for 500 m on the dirt road (Fig. 1.15). Park by the boom barrier, and walk 100 m into the mine. The Jennyhaugen mine is an active quarry producing gravel and landowner must be asked for permission to enter the mine. The exposures are very fresh and there is some material at the dumps, in particular 'amazonite'. In summer the mine can be crowded by mosquitoes, thus, make use of suitable insect repellents if necessary.

Distance to walk: 0.1 km
Elevation changes: 0 m
Excursion time: 1 hour
Conservation status: None

Pegmatite structure

The Jennyhaugen pegmatite is situated in the centre of the Drag pegmatite cluster and forms a large, NE-SW striking, lens-shaped body which is up to 40 m wide and at least 200 m long (Fig. 1.16). It is possible that the abandoned mines at Store Grønnhola and Nedre Kvartsen were located in the same body (Fig. 1.15). The pegmatite is currently exposed across its entire width in the Jennyhaugen gravel quarry. The strike of the body is parallel to the foliation of the Tysfjord granite host. Close to the vertical contacts the foliation of Tysfjord granite is more distinctly developed, having almost mylonitic texture. The border to the host rock is gradual. The up to 5 m wide wall zone is foliated and felsic aplitic with smeared out and recrystallized 'biotite' as foliation markers (Fig. 1.17). The wall zone grades into a blocky core zone dominated by massive quartz and bright pinkish K-feldspar (Fig. 1.18). In the upper part of the core zone the K-feldspar becomes more withish and greenish ('amazonitic'). The quartz masses are elongated and parallel to the general strike of the pegmatite.

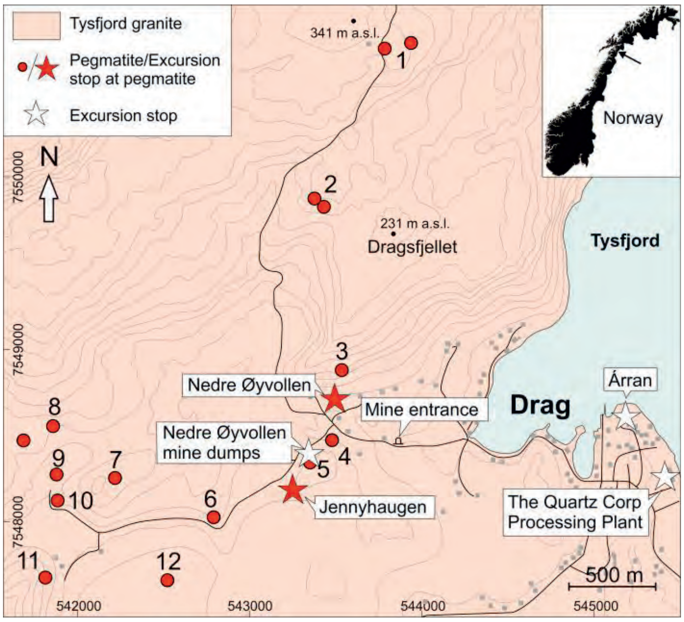


Fig. 1.15. Simplified geological map with the locations of pegmatites in the vicinity of the Drag village. The inset shows the location of the area within Norway. Abandoned pegmatite mines: 1 – Fjellgruva, 2 – Nekkateltet, 3 – Øvre Øyvollen, 4 – Store Grønnhola, 5 – Nedre Kvartsen, 6 – Littbakkgruva, 7 – Svenskgruva, 8 – Treldebakkgruva, 9 – Øvre Lapplægeret, 10 – Nedre Lapplægeret, 11 – Bennygruva, 12 – Erlinggruva. Note that the map does not cover all pegmatite occurrences of the Drag pegmatite cluster. During the PEG2017 excursion the Sami multi-activity center Árran will be visited. The center includes a museum about Sami culture, language, history and ethnicity, a library, a Sami kindergarten and conference facilities.

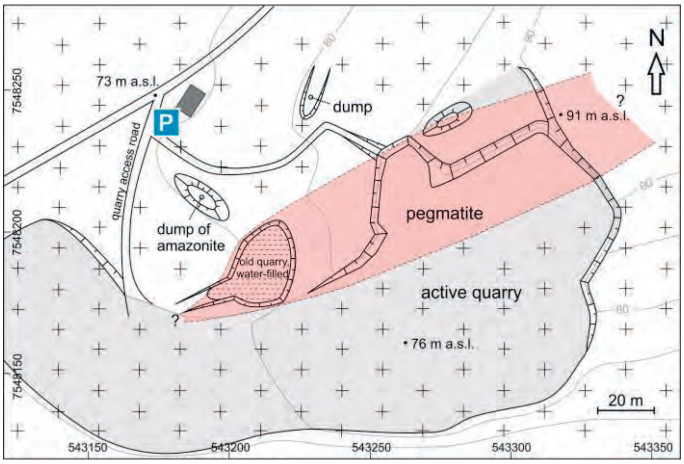


Fig. 1.16. Geological map of the Jennyhaugen pegmatite (pink) hosted by the Tysfjord granite. The greyish area corresponds to the extension of the gravel quarry (status 2016).

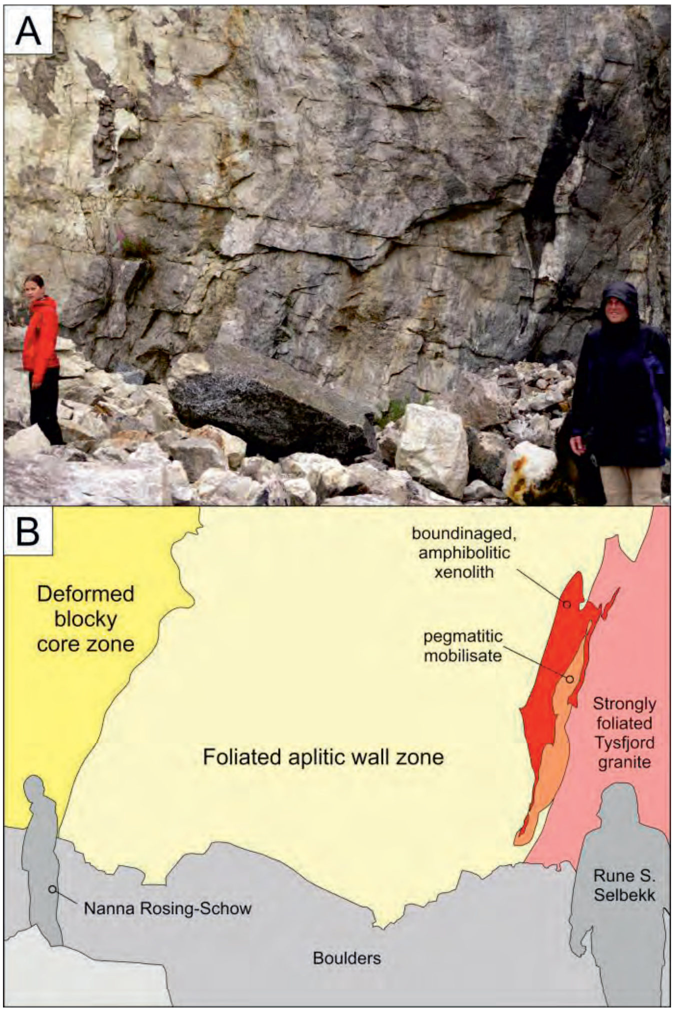


Fig. 1.17. A – ENE Wall of the Jennyhaugen quarry exposing the transitional contact of the pegmatite to the Tysfjord granite (to the right). B – Scheme illustrating the lithological borders of pegmatite and Tysfjord granite facies shown in (A).

Mineralogy

The Jennyhaugen pegmatite is poor in mineral species compared to other Tysfjord pegmatites, probably due to the lack of available dump material. There's an old dump close to the parking (Fig. 1.16) with massive, pale green 'amazonite' with inclusions of beryl, microlite and tantalite-(Mn). The rest of the dumps from the original mining has been crushed to gravel. The old mine wall (prior to recent workings) had some areas with massive allanite-(Ce), monazite-(Ce), zircon and traces of yttrofluorite with almost no inclusions. Three smaller quarries nearby probably mined the same pegmatite, in one of them arsenopyrite and/or löllingite with secondary pharmacosiderite and scorodite was found. Native bismuth was also found in this material.

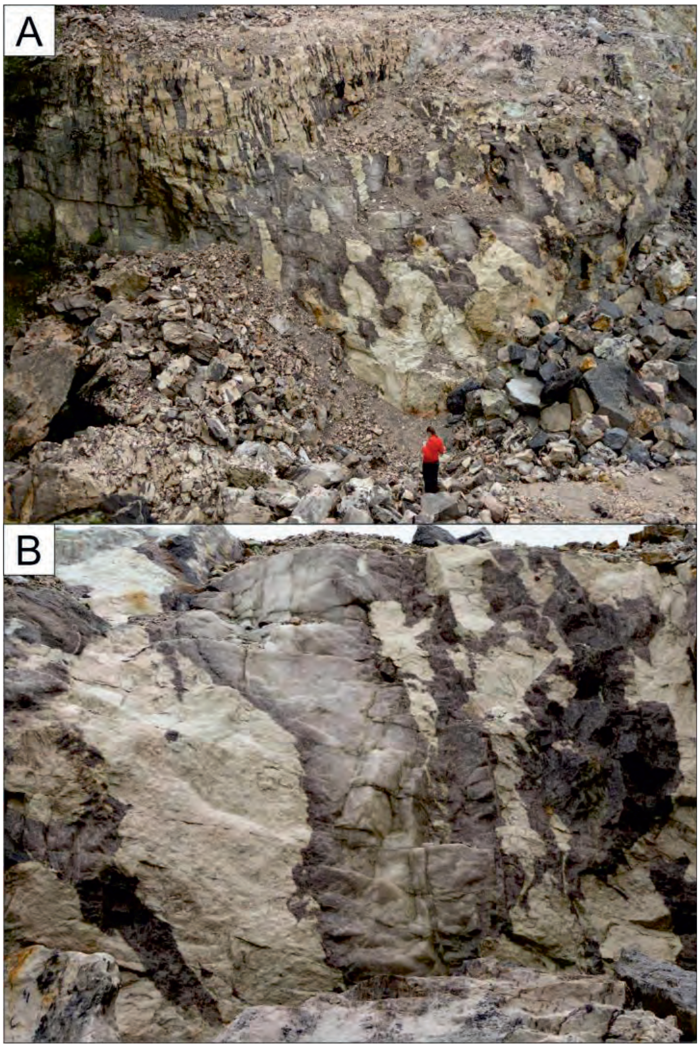


Fig. 1.18. A – View of the core zone of the Jennyhaugen pegmatite. B – Detail of the core zone with aligned quartz and K-feldspar masses. Field of view is 5 m.

Locality 1.4: Tennvatn pegmatite

Highlights

- 'Amazonite'-rich NYF pegmatite with many rare minerals in numerous small cavities, like asbecasite and gasparite-(Ce)
- Nice samples of fluor-schorl in combination with 'amazonite' (Plate 1.1D)

Coordinates EU89-UTM Zone 33V 541290E/ 7516080N

Directions and Access

Follow E6 northwards from Fauske for 87 km. There's a small parking lot on the left side on the road just before the border between Sørfold and Hamarøy (Fig. 1.19). From there walk eastward for about 1 km, up to the ridge, and follow the ridge southeastward for another 1 km. Take right by some small ponds, and walk down to the right. It's not easy to find the correct way, but there's a faint path leading to the pegmatite. The pegmatite is in the middle of a steep mountain wall. Move around carefully and watch the people below you. People with fear of heights should not go to the site. This site is on private land, ask the landowner for permission to collect. The exposures are relatively fresh and there is some material at the dumps. In summer the mine can be crowded by mosquitoes, thus, make use of suitable insect repellents if necessary.

Distance to walk: 2 km
Elevation changes: 200 m
Excursion time: 4 hours
Conservation status: None

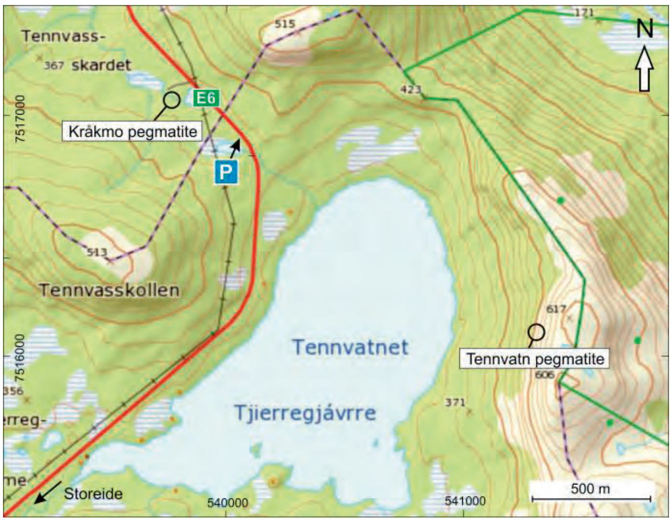


Fig. 1.19. Access map of the Tennvatn pegmatite.

Pegmatite structure

The Tennvatn pegmatite represents the type locality of *type 2 pegmatites* of the Tysfjord-Hamarøy pegmatite field (see chapter *The Tysfjord-Hamarøy pegmatites*) with spectacular textures of large euhedral 'amazonite' and schorl crystals surrounded by radiating 'cleavelandite' and greyish to colourless quartz. The pegmatite forms a relative small, 25 m long, irregular body with sharp boundaries to the Tysfjord granite (Fig. 1.20). It is chemically highly evolved, rich in 'amazonite', quartz and 'cleavelandite', with common fluor-schorl (up to 30 cm) (Fig. 1.21). In contrast to type 1 pegmatites, the Tennvatn pegmatite is undeformed and shows a classical internal zoning. The zoning comprises an up to 5 cm wide granitic border zone (only partially developed along the upper contact), a coarse-grained wall zone already dominated by 'amazonite' megacrysts, blocky intermediate zone and and core zone with massive quartz and large 'amazonite' crystals up to 1 m. The zoning is 'overprinted' by 'cleavelandite' replacement zones comprising about 25 vol% of the pegmatite. The replacement zones are rich in cavities (up to 10 cm) and late fluids have deposited a number of rare minerals in the replacement zone with Pb, Bi, REE, As, F, Nb, Be, U, Th and Sb. A xenotime-(Y) from Tennvatn was dated to 370 Ma (Emma Rehnström, personal communication 2006), thus confirming the post-tectonic (post-Caledonian) appearance.

Mineralogy

Major minerals are 'amazonite', quartz, albite (var. 'cleavelandite'), 'biotite', muscovite and tourmaline. Compositions of feldspars are given in Table 1.7. The tourmalines have schorl composition (Table 1.12). Beside the main minerals the Tennvatn pegmatite hosts a large number of unusual mineral species (Table 1.10, Fig. 1.22, Plates 1.1 and 1.2), mainly found in four different settings:

1) Rare species associated with masses of galena and cosalite. Primary minerals are in addition nuffieldite and greenockite; secondary minerals include anglesite, cerussite, hydrocerussite, phosgenite, bismutite, mimetite, bismoclite, wulfenite and covellite and some blue and green Cu-minerals. None of these form well-formed crystals larger than a few mm. The only exception must be the rare cases with needles of cosalite partly altered to yellow bismutite as inclusions in crystals of smoky quartz to 5 cm (Plate 1.2B). Only the needles in direct contact with cracks or with

the surface of the crystals are altered, indicating that the quartz was deposited after galena and cosalite, but before the formation of the secondary minerals.

2) Rare species in cavities in 'cleavelandite' replacement zones. Large amounts of porous 'cleavelandite' occur in the quarry, but only certain parts contain rare minerals. Fluorite and columbite-(Mn) are good indicators of rare and interesting species. Columbite-(Mn) forms black, euhedral crystals to 2 cm in the cavities, fluorite is found as pale green masses up to several cm across, or as modified cubes in cavities. Other minerals found here are svabite (Fig. 1.22B), stibiocolumbite (Fig. 1.22C), bergslagite (Fig. 1.22D), roméite, gasparite-(Ce), monazite-(Ce), hingganite-(Y), cassiterite, philipsbornite, chernovite-(Y), arsenocrandallite, hematite, spessartine and clinochlore.

3) Rare species in cavities in 'amazonite'-rich zones, associated with asbecasite. Asbecasite, first reported by Ellingsen et al. (1995), has been found in two limited parts of the quarry, as poorly defined yellow translucent masses to 4 cm in size (Fig. 1.22A). A closer inspection of the material shows that the masses in fact consist of intergrown plates to some cm. A small number of well-formed crystals to 1 cm have been found. The surfaces of the crystals have dissolution textures, and crystallographically oriented cavities are often found within the crystals. Asbecasite is an early formed mineral, and secondarily altered into chernovite-(Y) (well-formed dipyramids and at least two generations of white to pale brown, massive crusts), rare hingganite-(Y) (small, yellow prisms) and titanite (dusty, red coatings). A reddish brown, massive mineral in one of the oriented dissolution cavities is a Fe-Ti-As-mineral, possibly fetiasite. SEM-EDS analysis of asbecasite from Tennvatn gives a "normal" chemistry, with major Si, Ca, Ti, As and minor Fe, Y and Sb (Alf Olav Larsen, pers. comm. 1990); the Y-content is insufficient to form the Y-rich breakdown products. It seems like asbecasite reacted with an Y-rich fluid, forming the secondary minerals. This fluid is probably related to or identical with the F-rich fluid forming the minerals in 'cleavelandite' – an Y- and F-rich fluid analogous with the yttrofluorite-forming fluids in the type 1 pegmatites of the area?

4) In cavities in quartz and microcline in a very limited area of the pegmatite. Almost all hingganite-(Y) and stibiocolumbite found come from these cavities. Other minerals are xenotime-(Y), chernovite-(Y), apatite-(CaF), magnetite and pyrophanite, and parts of these cavities are filled with phyllosilicates.

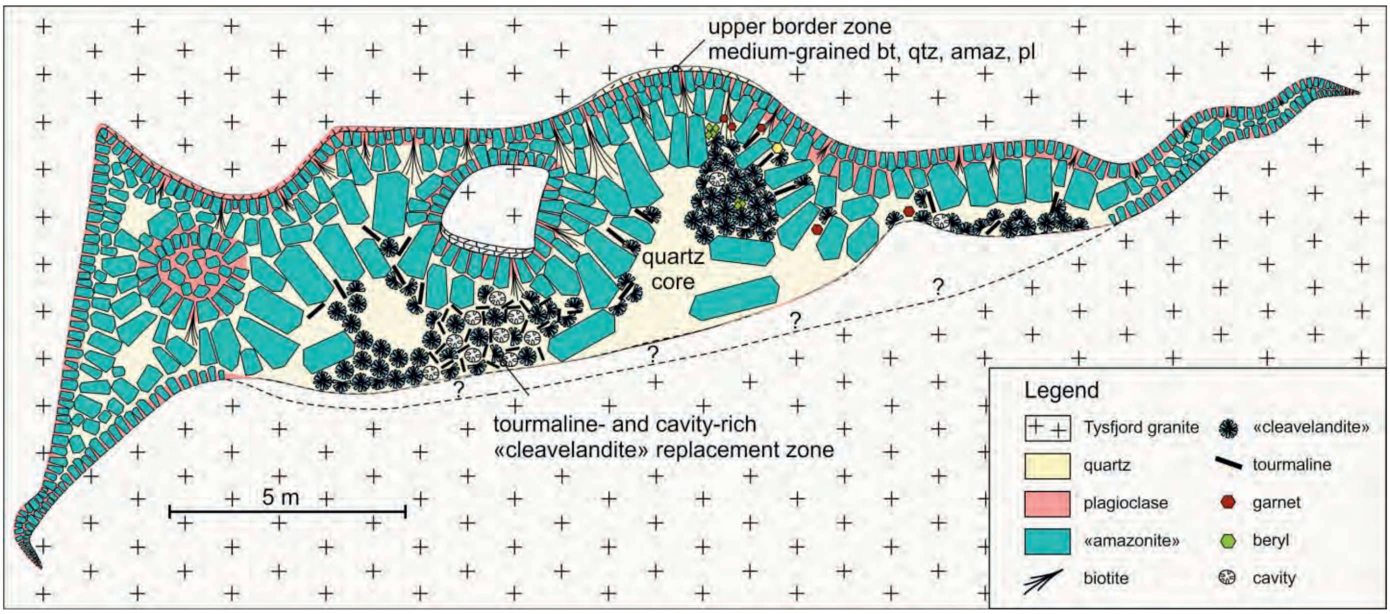


Fig. 1.20. Simplified structure of the Tennvatn pegmatite.

Table 1.9. Composition of tourmaline from Tennvatn according to Larsen et al. (1999).

SiO_2	33.3
Al_2O_3	28.2
FeO	20.2
TiO_2	0.7
MgO	0.1
CaO	0.1
Na_2O	2.6
K_2O	0.1
MnO	0.4
ZnO	0.2
Sum	85.9

T - Si	5.90
Al	0.10
Z - Al	5.89
Mg	0.11
Y - Ti	0.09
Al	-
Fe	2.89
Mg	0.03
Mn	0.06
Zn	0.03
X - Ca	0.02
Na	0.89
K	0.02

Table 1.10. Minerals found in the Tennvatn pegmatite.

Mineral	**Comments**	**Rarity (X = rare, XXX = common)**
Albite	Rock forming. As *cleavelanite*.	XXX
Allanite-(Ce)	In the border zone, black massive.	X
Almandine	Red massive.	XX
Anglesite	Secondary around galena. Microcrystals.	XX
Annite	Rock forming.	XXX
Arsenocrandallite	Very rare, white fibrous or powdery. In ‘cleavelandite’.	X
Asbecasite	Yellow corroded masses and crystals in cavities in ‘amazonite’. (Fig. 1.22A, Plate 1.2A)	XX
Bastnäsite-(Ce)	Very rare, alteration product after monazite-(Ce)	X
Bergslagite	Yellow microcrystals in ‘cleavelandite’. Si-rich (empirical formula $^{Ca1}Ca_{1.00}{}^{Ca2}Ca_{0.068}(Be_{0.94}Si_{0.06})(As_{0.774}Si_{0.226})O_4[(OH)_{0.97}O_{0.03}]$ (Raade et al. 2006) (Fig. 1.22D)	X
Beryl	Yellow massive	X
Bismoclite	Powdery pseudomorphs in aggregates of galena and cosalite.	X
Bismutite	Yellow, secondary after cosalite and other Bi-sulphosalts.	XX
Calcioancylite-(Ce)	Very rare, intergrown with gasparite-(Ce) as red inclusions in granular aggregates of hingganite-(Y).	X
Calcite	-	X
Cassiterite	Brown crystals in ‘cleavelandite’	X
Cerussite	Colourless crystals, secondary around galena	X
Chernovite-(Y)	Not uncommon in different parageneses: i.e. bipyramidal crystals in porous fluorite, crusts around corroded asbecasite.	XX
Clinochlore	In cavities associated with hingganite-(Y) and fluorapatite.	XX
Columbite-(Mn)	Black to dark brown crystals in ‘cleavelandite’	X
Cosalite	Metallic, fibrous aggregates and prisms with galena.	XX
Covellite	Crusts of minute flakes, secondary on cosalite	X
Fergusonite-(Y)	Dark brown massive	X
Fluorapatite	Pink, tabular crystals to some cm with hingganite-(Y)	X
Fluorite	Green massive and crystals in ‘cleavelandite’. Sometimes with inclusions of REE minerals.	XX
Fluor-schorl	Very common as black prisms to 30 cm.	XXX

Table 1.10. Continued.

Mineral	Comments	Rarity (X = rare, XXX = common)
Galena	Massive with cosalite and other Bi sulphosalts. Displays octahedral cleavage with exsolution lamellae of an unidentified Pb-Bi-S-phase along the planes.	XX
Gasparite-(Ce)	In a very limited number of samples as pale reddish brown to green crystals and masses forming crusts on partly decomposed monazite-(Ce). Gasparite-(Ce) from Tennvatn is without detectable P, and has variable REE content (one sample has Nd dominance).	X
Greenockite	Red, transparent grains and small, irregular masses in aggregates of galena and cosalite. Contains some Zn.	X
Hematite	Very common as microcrystals in cavities in 'amazonite'.	XXX
Heulandite-Ca	Colourless crystals in cavities in 'amazonite'.	X
Hingganite-(Y)	Found in a number of different settings, mainly as yellow, transparent, prismatic crystals to 7 mm in cavities in a very limited part of the pegmatite. Also in cavities in fluorite, as a secondary phase around asbecasite and as massive, granular aggregates to several cm in 'cleavelandite'. Displays variable Ca- and Fe-content.	XX
Hydrocerussite	A single sample, massive around corroded galena	X
Kasolite	Small, yellow aggregates with secondary Pb- and Bi-minerals	X
Löllingite	Grey crystals and masses in matrix, with brown, secondary arsenates (pharmacosiderite and others)	X
Magnetite	Euhedral in cavities associated with hingganite-(Y).	X
Microcline	Rock forming. 'Amazonite'.	XXX
Mimetite	Secondary around galena and cosalite	X
Monazite-(Ce)	Brown crystals and masses in 'cleavelandite'	X
Muscovite		XX
Nuffieldite	Prismatic crystals associated with galena and cosalite	X
Pharmacosiderite	Brown crusts around löllingite.	X
Philipsbornite	Yellow microcrystals in 'cleavelandite'	X
Phosgenite	Secondary around galena and cosalite	X
Pyrochlore	-	X
Pyrophanite	Black, platy crystals with hingganite-(Y)	X
Quartz	Rock forming. Occasionally well-formed in cavities, a few with inclusions of cosalite and other species	XXX
Roméite Group	Brown, powdery masses and crusts in 'cleavelandite'	X
Schorl	With fluor-schorl in a zoned crystal (decreasing F from core to rim) (Kolitsch et al. 2013).	X (?)
Spessartine	Pale red massive with clinochlore in 'cleavelandite'	X
Stibiocolumbite	Yellow brown needle-like crystals in fans or random aggregates usually on pyrophanite. Associates are hingganite-(Y), chernovite-(Y), apatite-(CaF) and columbite-(Mn). (Fig. 1.22C)	X
Stilbite-Ca	White aggregates, late in cavities in 'amazonite'	X
Sulphur	Secondary around galena	X
Svabite	White prismatic in cavities in cleavelandite (Fig. 1.22B)	X
Thorite	Brown massive in 'cleavelandite', partly altered to a yellow substance rich in Th and As.	XX
Titanite	Pale red grains in the border zone. Secondary after abecasite.	X
Wulfenite	Secondary around galena.	X
Xenotime-(Y)	Pale yellowish brown, transparent crystals associated with hingganite-(Y).	X
Zircon	Brown aggregates in 'cleavelandite'.	XX

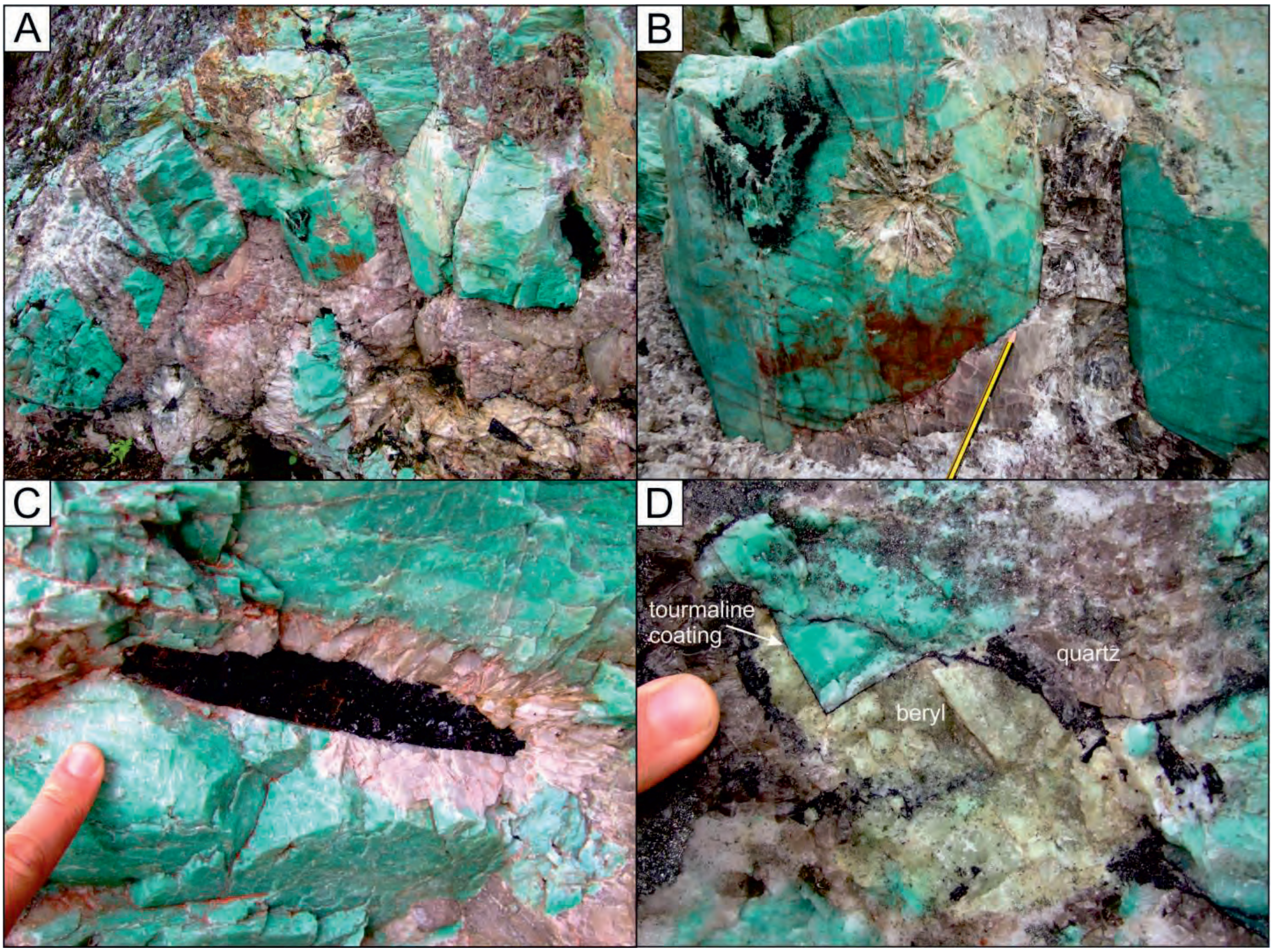


Fig. 1.21. Photographs of minerals from Tennvatn. A – Euhdral ‘amazonite’ crystals up to 50 cm in size embedded in quartz. Field of view is 2 m. B – Detail of (A) showing a large ‘amazonite’ partially coated with black tourmaline and with a ‘cleavelandite’ sun. C – Large tourmaline with a corona of ‘cleavelandite’ in ‘amazonite’. D - Anhedral, yellowish beryl surrounded by ‘amazonite’ and quartz. The ‘amazonite’ is coated with black tourmaline.

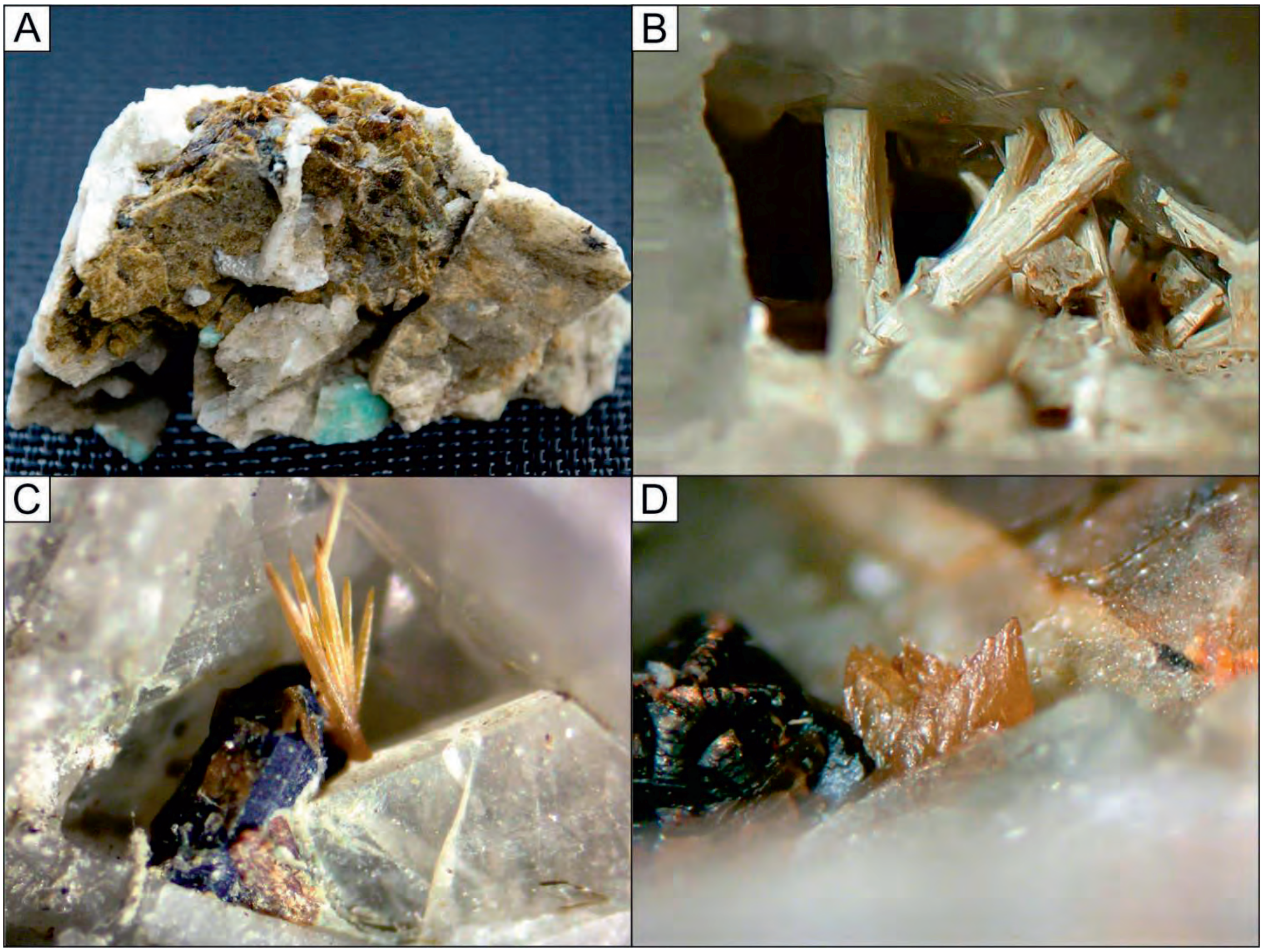


Fig. 1.22. Photographs of accessory minerals from Tennvatn. A – Asbecasite. The specimen is 5 cm across. B - Svabite in a micro cavity in 'cleavelandite'. Field of view is 4 mm. C - Stibiocolumbite on columbite-(Mn). Field of view is 2 mm. D - Bergslagite and hematite. Field of view is 2 mm.

Locality 1.5: The Quartz Corp plant at Drag - processing of high-purity quartz

Highlights

- Processing og high-purity quartz mined, among others, from the Nedre Øyvollen and Håkonhals pegmatites

Coordinates EU89-UTM Zone 33V 545443E/7548307N

Directions and Access

Being at the major crossroad at the village center of Drag turn E and follow National Road 682 for 300 m (Fig. 1.15). The entrance to the Quartz Corp processing plant is on the north side of the road (left). Visting address: Hamnbakken, Drag. http://www.thequartzcorp.com/en/

Distance to walk: 0 m
Elevation changes: 0 m
Excursion time: 1 hour

The Quartz Corp (TQC) is one of two big players in the high purity quartz market serving the solar-, semiconductor- and lighting industries. The processed high purity quartz powder is mainly used as raw material for crucibles, optical fibers, tubes, rods, lenses, "quartz glass" parts, etc. An example of one quartz product processed at Drag is given in Table 1.11.
The Nedre Øyvollen quartz mine and the processing plant at Drag were opened in 1987 (Fig. 1.23), but experienced quickly problems to produce quartz

qualities that the market would buy. Therefore, it ended in several shotdowns and bankruptcies in the first years. In 1996 the Norwegian family owned mining company Hustadkalk, bought the plant and mining rights and formed the company Norwegian Crystallites. After a few problematic years in the latest 1990s, Norwegian Crystallites developed good quartz products based on the Nedre Øyvollen mine and the Håkonhals mine. The simple geology of Nedre Øyvollen is; a zoned pegmatite with a minable quartz core surrounded by a coarse grained mixed pegmatite hosted by the Tysfjord granite. The Håkonhals deposit is an elongated zoned pegmatite with a flat lying, lens-like quartz core, surrounded by a mixed pegmatite dominated by K-feldspar. Håkonhals has a higher degree of deformation than Nedre Øyvollen resulting in different quartz chemistries.

Some differences between the two deposits were discovered; the trace element content of Al, Ti, Li and other elements and the fluid inclusion inventory of quartz are different. These differences resulted in products with different applications from the two deposits. The quartz processed from the Nedre Øyvollen mine, were mainly used for glass in halogen lamps, and used in semiconductor memory chips. The quartz from Håkonhals gave a slightly better quality for halogen lamps, and was also used as material for crucibles in solar industry.

From 2005 and on Norwegian Crystallites wanted to develop cleaner products that could match the fast growing solar industry. The best raw material available for the solar and semiconductor applications showed to be the raw material found in the coarse-grained granite called alaskite of Spruce Pine in North Carolina, USA. Norwegian Crystallites first bought a partly cleaned quartz concentrate from a feldspar producer in Spruce Pine. This cooperation developed into the joint venture; The Quartz Corp from 2011 and on. TQC is now owned 50/50 by the industrial mineral company Imerys and Norsk Mineral, a Norwegian family owned company.

Today the main product of TQC, Drag is high purity quartz sand and powder based on quartz from the alaskite in Spruce Pine, but processed at Drag. In Spruce Pine TQC produce feldspar and mica in addition to quartz for further cleaning at Drag. The Drag company still make products based on quartz from Nedre Øyvollen mine, while Håkonhals mine has been closed since 2016.

The processing plant. After grinding and sizing many mineral separation steps are necessary to obtain the high standard quartz concentrate: several magnetic separation steps, several floatation steps, various acid washing steps and washing steps as well as high temperature treatment. TQC has today more than 160 employees; half of them are employed in the mineral processing plant at Drag.

Table 1.11. Trace element concentrations (in ppm) of processed quartz from the Nedre Øyvollen pegmatite (Drag NC1) compared with processed quartz from Spruce Pine alaskites, North Carolina, USA (Iota STD) and with the average of natural quartz (average of c. 2500 LA-ICP-MS data of natural quartz worldwide; Müller et al. (2012b) and unpublished data. Iota STD is one of the purest quartz sands currently produced from natural quartz. n.p. – not provided.

	Li	**B**	**Mn**	**Na**	**Al**	**P**	**K**	**Ca**	**Ti**	**Fe**
Drag NC1 Tysfjord	4.00	<0.40	0.01	2.70	26.0	n.p.	0.70	0.6	4.0	0.50
Iota STD Spruce Pine	0.90	0.08	<0.05	0.90	16.2	0.10	0.60	0.5	1.3	0.20
Average natural quartz	7.73	1.40	0.25	11.10	72.6	2.96	9.74	10.2	15.6	4.62

Fig. 1.23. The Quartz Corp processing plant at Drag seen from the Tysfjord.

Locality 1.6: Nedre Øyvollen Pegmatite – abandoned quarry, active underground mine and mine dumps

Highlights

- NYF-pegmatite with large core consisting of quartz with unusual low trace element content
- Type locality for perbøeite-(Ce)

Pegmatite currently mined for high-purity quartz

Coordinates EU89-UTM Zone 33V 543483E/7548669N (abandoned quarry) ; 543920E/7548441N (entrance active mine), 543346E/7548397N (mine dumps)

Directions and Access

Drive National Road 827 towards the ferry port at Drag, turn left at the major crossroad in the village center just before the ferry port (by the grocery store), and follow the road for 1.8 km (you pass the entrance to the underground mine right hand at 1.2 km; Fig. 1.15). Take right at the crossroad and park by the red building (543510E/7548630N). Walk 100 m uphill (north) following the tractor track. The quarry is to the left of the track, but can be difficult to see due to dense vegetation. The quarry, which is about 40 m deep with vertical walls, is fenced and for access permission the Quartz Corp has to be asked. Some remains of old dumps from the feldspar mining time around the mine are on private land and the landowner has to be asked for permission to collect. Recent dumps from the quartz mining area are spread in the area but mainly found along the road up to Jennyhaugen. The PEG2017 excursion will stop at one of these dumps (543346E/7548397N; (Fig. 1.15). In summer the area can be crowded by mosquitoes, thus, make use of suitable insect repellents if necessary.

Distance to walk: 50 m
Elevation changes: 0 m
Excursion time: 2 hours
Conservation status: None

Pegmatite structure

The Nedre Øyvollen pegmatite is part of the Drag pegmatite cluster which comprises at least 17 pegmatite bodies in the vicinity of the village of Drag (Fig. 1.15). The Nedre Øyvollen pegmatite has a vertical, cigar-shaped quartz core enclosed by a wall zone consisting of plagioclase, K-feldspar and mica. The top of the pegmatite consisted of a plagioclase-rich cupola which has been mined in a quarry (Neumann 1952). The body is about 60 m in horizontal section and approximately 120 m in vertical section (Fig. 1.24). The pegmatite is less deformed than, for example, the Jennyhaugen body. The contact to the Tysfjord granite is relative sharp and the pegmatite grades within a few dm into the wall zone comprising megacrystic K-feldspar, plagioclase, quartz and huge, fen-like clusters of bent 'biotite' sheets (up to 10 m in size). The feldspar megacrysts exhibit lens-shaped, boudinaged habit due to shearing. The plagioclase boudings are commonly enveloped by 'biotite' sheets. Close to biotite plagioclase contains masses of sulphides up to 0.5 m in size or the sulphides are aligned parallel to the plagioclase-biotite contact. The majority of the pegmatite body is occupied by an enormous, massive quartz core which is up to 80 m in vertical section. The occurrence of primary fluorite masses (up to 2 m in size) within the marginal part of the quartz core is a characteristic feature of the pegmatite. Local miners tell stories of large cavities with crystals of quartz and fluorite.

Mining of feldspar in the Drag area started in 1907. The Nedre Øyvollen pegmatite was discovered during construction of a mine railway in 1909 and in the same year the mining of the pegmatite started in an open pit. Feldspar mining continued, with interruptions, until the 1930s. The total feldspar production was about 12,000 tons, resulting in a 40-m deep open pit. The deposit was drilled in 1975 and 1979 by NGU and about 175,000 tons of massive quartz were proven below the open pit (Åmli & Lund 1979). Mining of quartz, underground, started in 1987 and continued, with interruptions, until Norwegian Crystallites AS overtook the mine in 1996. During underground mining a second large quartz body immediately SE of the main body was discovered (Fig. 1.24). Since then the pegmatitic quartz has been the major source of the high-purity quartz produced by Norwegian Crystallites AS; since 2011 the Quartz Corp (Table 1.11). The Nedre Øyvollen pegmatite is one of the few deposits in the world from which high-purity quartz has been produced for more than a decade. The large, massive quartz body, the large crystal size and the homogeneous chemistry with very low trace element concentrations have made it a highly economic, world-class high-purity quartz deposit.

Fig. 1.24. Simplified cross section of the Nedre Øyvollen pegmatite (red – quartz core; yellow – wall zone) and mine tunnels. The NW quartz core is currently mined. With permission of the Quartz Corp.

Mineralogy

Major minerals are quartz, K-feldspar, plagioclase, and ‘biotite’. Due to difficult access for collectors little is known about the accessory minerals. The plagioclase in the pegmatite is usually An_{10}, but in contact with the fluorite is much more basic, An_{30}. Fluorite is very common. There seems to be two generations of fluorite: (1) primary white to colourless fluorite forming large homogeneous masses and (2) yellowis-pinkish yttrofluorite masses with allanite-(Ce) margins and common inclusions. Mineralogically most interesting is the second fluorite generation. Yttrofluorite with törnebohmite-(Ce), zircon, perbøeite-(Ce), bastnäsite-(Ce) and britholite-(Y) was found as loose samples on the floor of the old quarry. However, the white to colourless massive fluorite found at the mine dump NE of the Jennyhaugen quarry (33V 543346E/7548397N; Fig. 1.15) is free of inclusions but exhibits a strong thermoluminescence. Some fluocerite-(Ce) was however found on the dumps some years ago. This locality will be visited during the PEG2017 excursion. Occasionally large amounts of massive sulphides (pyrite, pyrrhotite, sphalerite, galena, chalcopyrite, arsenopyrite) appear also on the dumps.

Locality 1.7: Håkonhals pegmatite

Highlights

- Large, strongly deformed NYF pegmatite with fresh exposures
- Occurrence of petscheckite and xenotime-(Yb), two very rare minerals
- Nice samples with massive phenakite and blue/green beryl

Coordinates EU89-UTM Zone 33V 527376E/ 7545507N

Directions and Access

Follow National Road 662 westward from Innhavet for about 15 km passing the village of Karlsøy (Fig. 1.25). Turn left into the dirt road shortly before the small Froneset boat harbour. At the beginning of the dirt road is gate. The landsowner or the Quartz Corp has to be asked to get the key. Follow the dirt road uphill for about 3 km to the quarry. The quarry is at an altitude of about 300 m a.s.l. The first part the dirt road is quite steep and winding and after the winter season the road can be in bad condition. This mine is on private land and the landowner has to be asked for permission to collect. The exposures are relatively fresh and there is plenty material at the dumps. In summer the mine can be crowded by mosquitoes, thus, make use of suitable insect repellents if necessary.

Distance to walk: 0 km (however the mine is large)
Elevation changes: 0 m
Excursion time: 2 hours
Conservation status: None

Pegmatite structure

The Håkonhals quarry is a relative large open pit (150x150 m) which was mined until 2016 for quartz. The quarry is situated in the eastern part of a 400 m long (E-W) and up to 200 wide flat pegmatite lens with a thickness of up to 25 m. The pegmatite is strongly ductile deformed and the contacts to the Tysfjord granite are relatively sharp but strongly mylonitized (Figs. 1.26, 1.27). Due to intense deformation the internal structure of the pegmatite is only rudimentary preserved. Quartz, which reacted most rigid during deformation, forms large lens-shaped masses embedded in recrystallized feldspar and smeared out biotite sheets (Fig. 1.28). Large accessory minerals, like beryl and allanite-(Ce) are boudinaged and form textures unusual for these minerals.

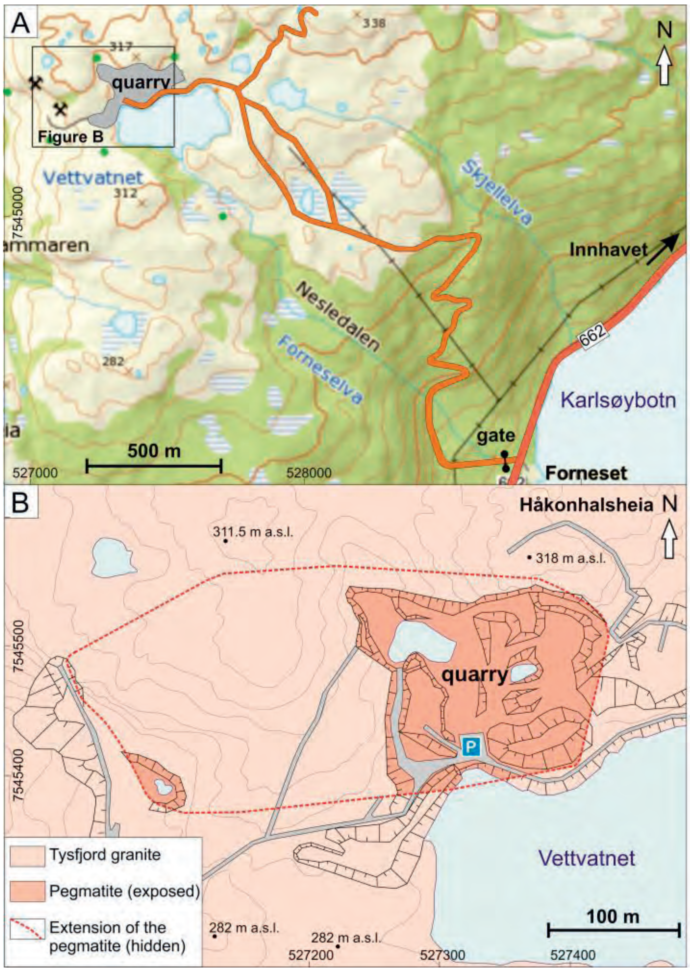


Fig. 1.25. A - Access map of the Håkonhals quarry. B – Geological map of the Håkonhals mining area. With permission of the Quartz Corp.

Fig. 1.26. North wall of the Håkonhals mine exposing massive K-feldspar (pinkish) with some vein-like quartz masses (grey). In the upper part of the wall the contact to the mylonitized Tysfjord granite can be seen.

Mineralogy

Major minerals are K-feldspar, plagioclase, quartz, and 'biotite' of siderophyllite composition. Despite the large size of the pegmatite, it contains rather few interesting minerals. Accessory and major minerals found at Håkonhals are listed in Table 1.12. The rarest is xenotime-(Yb), forming small colourless crystals on the surface of massive zircon. There are two types of yttrofluorite, one with only monazite-(Ce) as inclusions, the other type with no cavities and only thorite, gadolinite, monazite-(Y), bastnäsite-(Ce), allanite-(Ce) and kainosite-(Y) as accessory minerals. There is also a very dark violet to black fluorite (not analysed), with inclusions of zircon, uraninite, thorite and uranophane/uranophane-β (Fig. 1.29B).

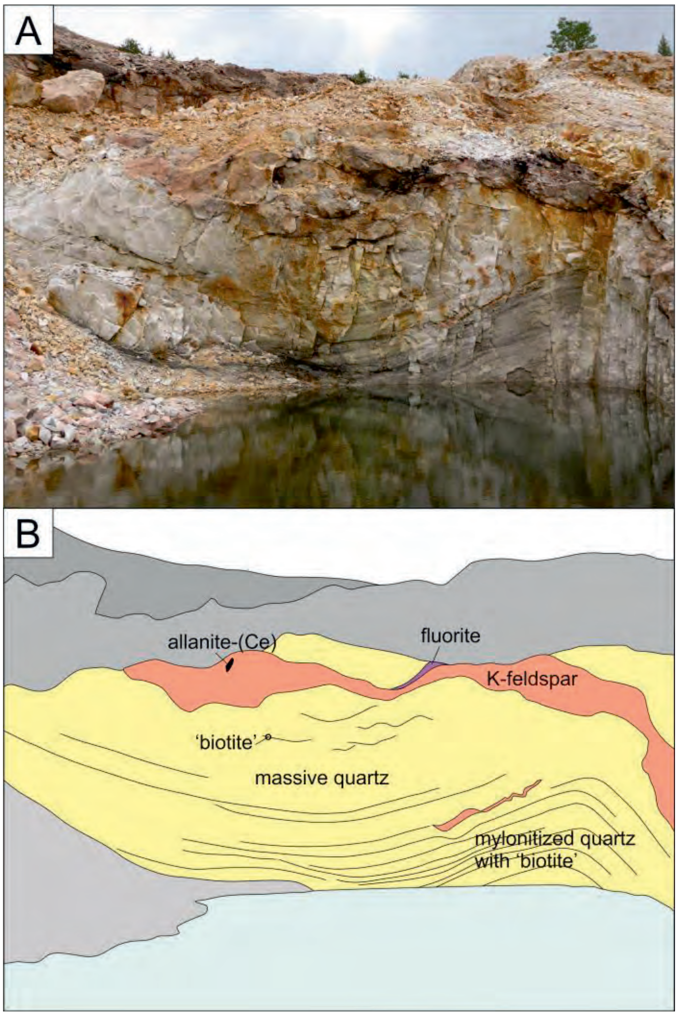


Fig. 1.27. A - Section of the internal part of the Håkonhals pegmatite showing boudinaged megacrystic K-feldspar embedded in massive quartz. Towards the bottom of the wall the 'biotite' content in quartz increases and becomes increasingly mylonitized quartz. Field of view is c. 8 m. B - Scheme illustrating the structures and mineralogy shown in (A).

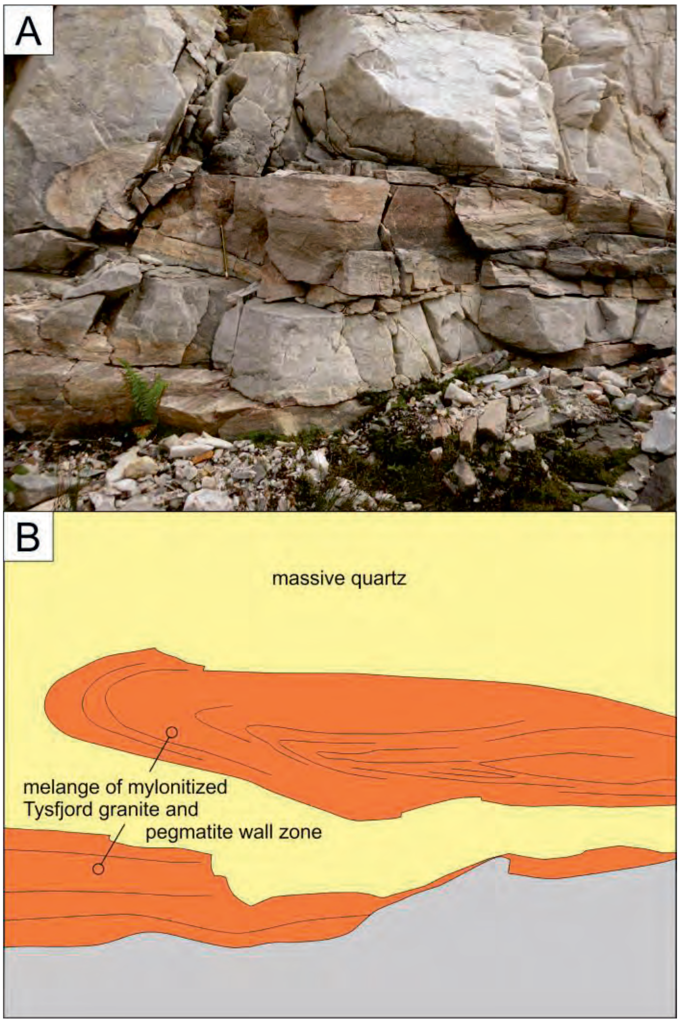


Fig. 1.28. A - Section of the lower contact of the Håkonhals pegmatite showing massive quartz (white) with a melange of mylotinized and isoclinally folded Tysford granite and pegmatite wall zone (pinkish). The lower mylonite at the bottom of the wall corresponds to the lower contact of the pegmatite and Tysfjord granite. The field of view is 3 m. B - Scheme highlighting the structures shown in (A).

Phenakite occurs as colourless masses to 10 cm, surrounded by blue and green beryl when in contact with microcline. Sigmoidal lenses of beryl with cores of phenakite indicate alteration during movement (Fig 1.29A).

Petscheckite, samarskite-(Y), allanite-(Ce), ilmenorutile and magnetite occur as black masses and subhedral crystals, while xenotime-(Y), chabazite-Ca and stilbite-Ca form microcrystals in cavities in microcline. Molybdenite is also rather common.

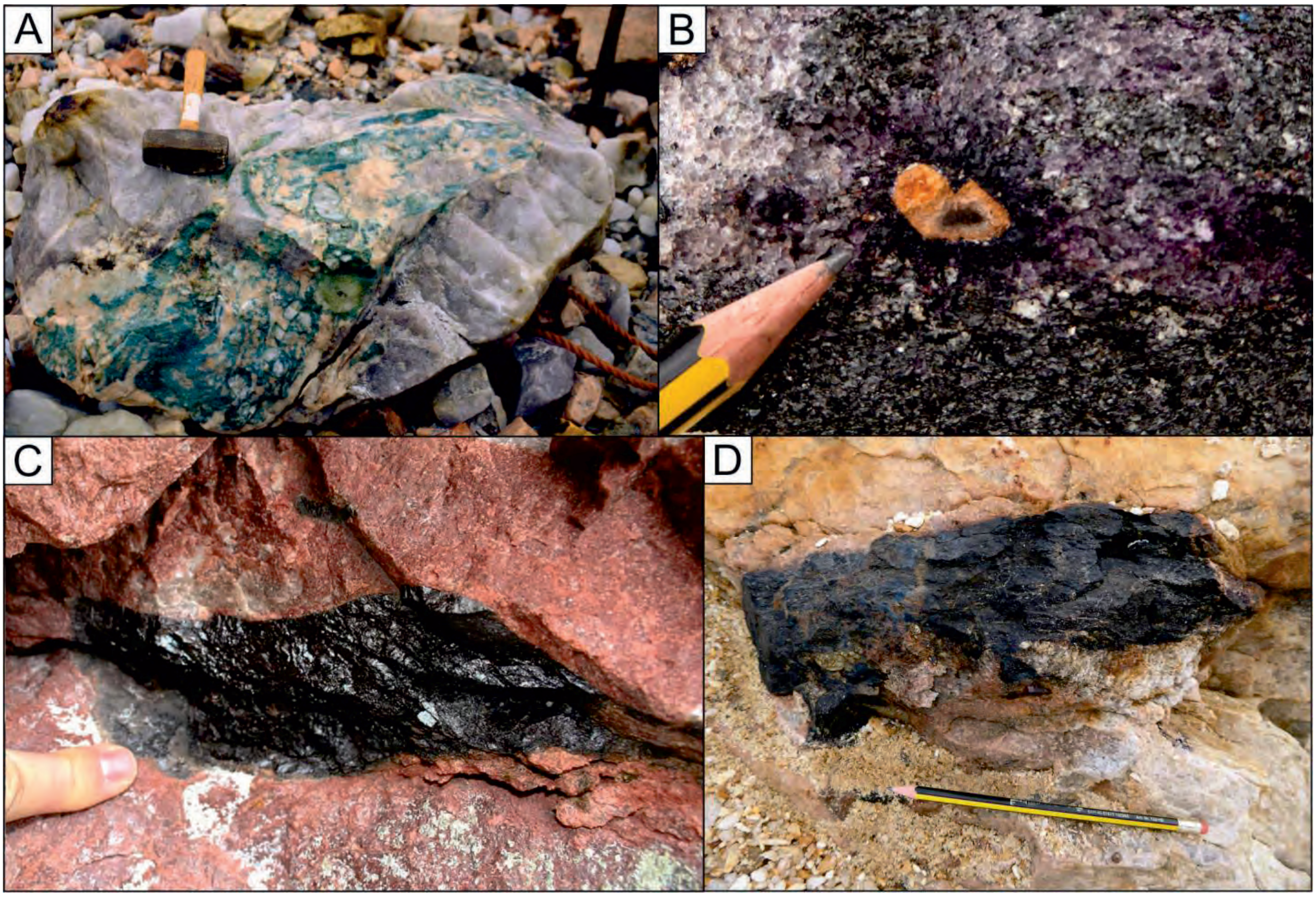


Fig. 1.29. Photographs of minerals from the Håkonhals pegmatite. A - Boulder with boudinaged bluish beryl with white phenakite embedded in quartz. B – Thorite altered to orangite along margins. The crystal is embedded in fine-grained quartz, fluorite and 'biotite'. C – Massive petscheckite in K-feldspar. Photo by K.E. Larsen. D – Large allanite-(Ce) crystal in K-feldspar.

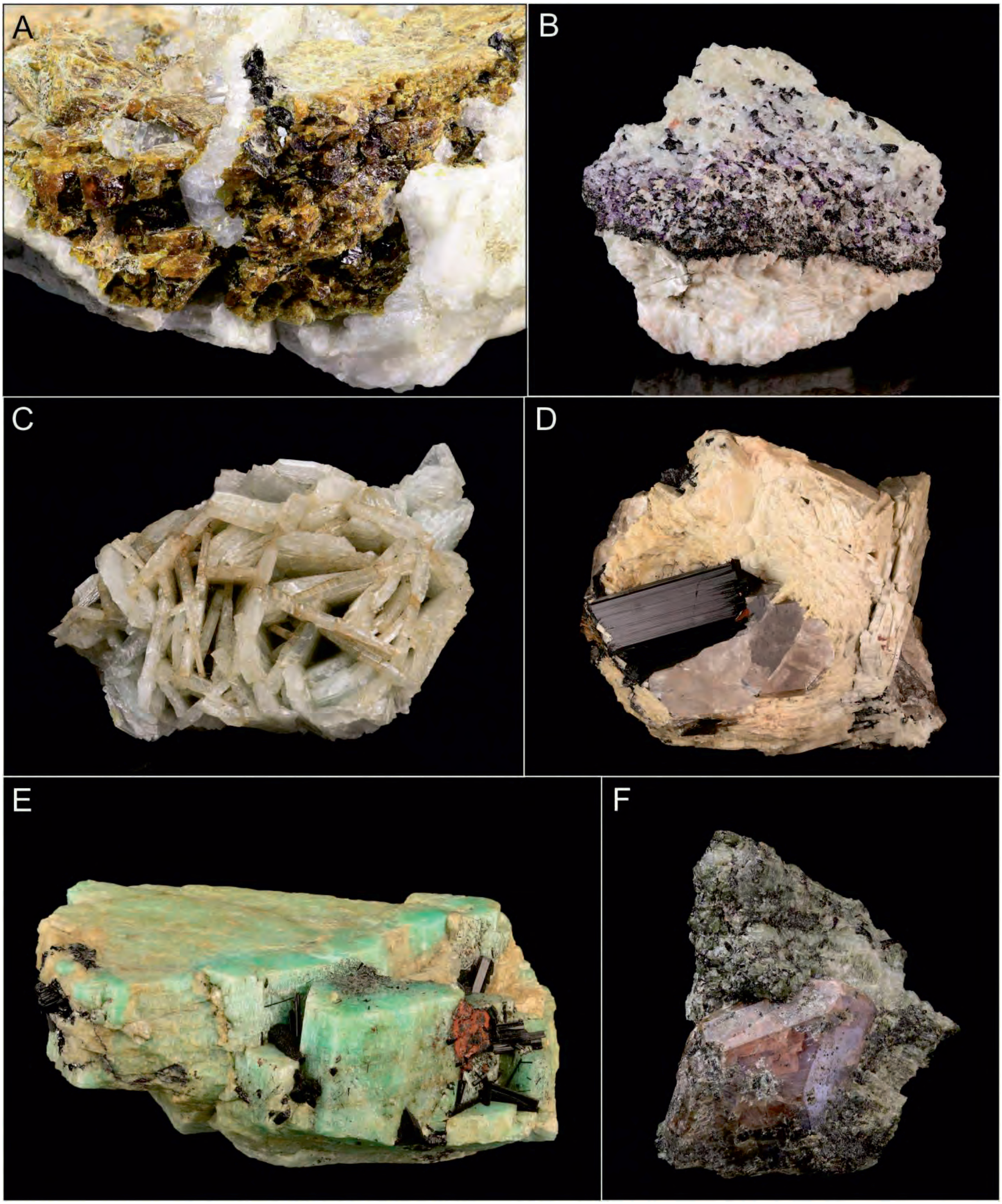
Table 1.12. Minerals identified in the Håkonhals pegmatite. Modified from Mindat (2017).

Mineral name	**Mineral name**	**Mineral name**
Albite	Magnetite	Stilbite-(Ca)
Allanite-(Ce)	Microcline	Thorite
Bastnäsite-(Ce)	Molydenite	Titanite
Beryl	Monazite-(Ce)	Uranophane
Chabazite-(Ce)	Opal	Uranophane-β
Fluorite (var. Yttrofluorite)	Petscheckite	Xenotime-(Y)
Bertrandite	Phenakite	Xenotime-(Yb)
Gadolinite-(Y)	Quartz	Zircon
Ilmenite	Rutile (var. Ilmenorutile)	
Kainosite-(Y)	Samarskite-(Y)	

Plate 1.1. Photographs of minerals from pegmatites of the Tysfjord-Hamarøy area. A – 'Amazonite' from Tennvatn. The crystal is 5.6 cm in size. Collection of Astrid Haugen. Photo by Øivind Thoresen. B - Quartz with inclusion of cosalite and bismutite from Tennvatn. The crystal is 4 cm in size. Collection of Tomas Husdal. Photo by Øivind Thoresen. C – Unknown metamict mineral from Tennvatn. The crystal is 4.5 cm in size. Collection of Astrid Haugen. Photo by Egil Hollund. D – Fluor-schorl, 'amazonite' and hematite from Tennvatn. The specimen is 8 cm across. Collection of Astrid Haugen. Photo by Egil Hollund. E – Thalénite-(Y) from Hundholmen. The crystal is 1.5 cm in size. Collection of Astrid Haugen. Photo by Egil Hollund. F – Fluor-schorl from Tennvatn. The crystal is 2.5 cm in size. Collection of Tomas Husdal. Photo by Øivind Thoresen.


A
B
C
D
E
F

Plate 1.2. Photographs of minerals from pegmatites of the Tysfjord-Hamarøy area. All photographs by Øivind Thoresen. A - Asbecasite from Tennvatn. Field of view is 4 cm. Collection of Tomas Husdal. B – Border zone of yttrofluorite mass (upper part) with black allanite-(Ce) rim from Øvre Lapplægeret. The specimen is 4 cm across. Collection of Tomas Husdal. C – 'Cleavelandite' from Tennvatn. The specimen is 6 cm across. Collection of Astrid Haugen. D – 'Fluorschorl' on quartz and 'cleavelandite from Tennvatn. The specimen is 1.2 cm across. Collection of Øivind Thoresen. E – 'Fluorschorl' and hematite on 'amazonite' from Tennvatn. The specimen is 7 cm across. Collection of Astrid Haugen. F – Thalénite-(Y) from Hundholmen. The crystal is 2.4 cm in size. Collection of Tomas Husdal.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2. Sveconorwegian pegmatites of the Evje-Iveland area, South Norway

Axel Müller, Henrik Friis, Tor Sigvald Johansen, Ronald Werner & Øivind Thoresen

Introduction

The granitic pegmatites of the Evje-Iveland area in Setesdalen, south Norway, and their minerals have attracted much attention since feldspar mining started at the end of the nineteenth century. A number of rare, until then unknown minerals were found during mining (Brøgger 1906, 1922). Two of them, thortveitite and davidite-(Ce), were identified and described for the first time (Schetelig 1911; Neumann & Sverdrup 1960). Scientists and mineral collectors who were fascinated by the large amount and size of rare pegmatite minerals found in the area soon became frequent guests in the feldspar mines. The local landowners and farmers, who ran the mines, as well as local merchants, eventually realized that the sale of these rare minerals gave good extra income. The trade of minerals took place both through local retailers and professional sales-men who had access to the worldwide market. It did not take long before the minerals of the Evje-Iveland pegmatites were found in museums and private collections worldwide.

The first pegmatite mine in the Evje-Iveland area was opened in 1884 for the extraction of quartz used as a flux for the melting of nickel ore from the Flåt mine located northwest of Evje. The opening of the railway Setesdalsbanen between Kristiansand harbour and Evje in 1895 finally initiated the mining of feldspar for the European ceramic industry which at that time was growing rapidly. The feldspar production in Evje-Iveland peaked in the 1920s when about 50 pegmatite mines were in operation. Since then, production has declined continuously and today only two small mines produce about 50 tons of high-quality feldspar for the production of artificial teeth.

The first mention of Evje-Iveland pegmatites is found in "Resultater af en mineralogisk Reise i Tellemarken 1844" by Scheerer (1845). Scheerer was a German chemist and mineralogist who travelled in 1844 through southern Norway. At the beginning of the twentieth century mineralogists and geologists of the University of Christiania (Oslo) eventually became aware of the scientific importance of the pegmatites through numerous findings of unknown and rare minerals during feldspar mining. In 1903 and 1905 professor W. C. Brøgger sent his students and colleagues P. Schei, C. Hornemann and J. Schetelig to Evje-Iveland to study the pegmatites. In 1906 Brøgger published "Die Mineralien der südnorwegischen Granitpegmatitgänge" (Brøgger 1906) which is the first scientific publication about the minerals of south Norwegian pegmatites including minerals from Evje-Iveland. The second volume was published in 1922 (Brøgger et al. 1922). A good understanding of the mineralogy and genesis of the Evje-Iveland pegmatites was achieved 20-30 years later when comprehensive scientific work of T.F.W. Barth and H. Bjørlykke was published (Andersen 1926, 1931; Barth 1931, 1947; Bjørlykke 1930, 1935).

The Evje-Iveland granitic pegmatite field lies within the Setesdal pegmatite district belonging to the Late-Proterozoic Sveconorwegian pegmatite province (Fig. 2.1). The Sveconorwegian pegmatite province is part of the Sveconorwegian (Grenvillian) orogeny (1.2–0.9 Ga) and covers most of southern Norway and parts of southwestern Sweden. It includes the pegmatite districts of Hardanger, Mandal, Setesdal, Bamble, Nissedal, Buskerud, and Østfold-Halland (from west to east; Müller et al. 2015; for definitions of pegmatite province, districts and fields see Černý 1982). The province hosts more than 5000 major pegmatite bodies and represents one of the largest pegmatite clusters in the world. The pegmatites were mined for feldspar, quartz, white mica, Sc, Be and U from the 1860s until today, and are famous for their rare metal mineralization including REE, Be, Sc, REE and Ta-Nb (Brøgger 1906; Bjørlykke 1937). Most of these pegmatites show a NYF-type affinity. They are not related to parental granites, from which they could derive by melt fractionation. Instead, they occur in areas of high-grade metamorphism and are interpreted as the product of partial melting of preferably amphibolite sources, local melt segregation and accumulation (Müller et al. 2017a).

The Sveconorwegian orogen is divided into five main lithotectonic domains (Andersen et al., 2004), from east to west, the Eastern Segment, Idefjorden Terrane, Kongsberg Sector, Bamble Sector and Rogaland-Hardangervidda-Telemark Sector (Fig. 2.1). These domains are separated by roughly N-S-trending crustal scale deformation zones of Sveconorwegian age. Each domain is characterized by distinct Pre-Sveconorwegian as well as Sveconorwegian evolution, including timing and style of crustal growth, deformation, metamorphism and magmatism (review in Bingen et al. 2008a). The Sveconorwegian orogeny resulted in widespread high-grade metamorphism, partial melting and deformation of the Fennoscandian crust. The orogeny can be divided into several phases, namely the Arendal (1140-1080 Ma), Agder (1050-980 Ma), Falkenberg (980-970 Ma), and Dalane (970-900 Ma) phases (Bingen et al. 2006, 2008a). The Evje-Iveland field is hosted in the westernmost Rogaland-

Hardangervidda-Telemark Sector, mainly affected by the Agder and Dalane phases.

In the orogenic context, there are three genetic groups of Sveconorwegian pegmatites: (1) rare-element pegmatites related to HP-HT high-grade metamorphism associated with the assembly of the Sveconorwegian orogen; (2) rare-element pegmatites related to post-orogenic extension with local LP-HT granulites; and (3) rare-element pegmatites related to granite magmatism during post-orogenic extension (Müller et al. 2017a). As there are several collisional events, rare-element pegmatites related to compressional tectonic events formed during several periods, whereas rare-element pegmatites related to post-collisional extension by and large formed – independent of their mode of formation – during one single period. The pegmatite formation comprises principally four periods restricted to certain lithotectono domains: (I) 1094-1060 Ma in the Bamble Sector, (II) 1041-1030 Ma in the Idefjord Terrane, (III) 992-984 Ma in the Idefjord Terrane and Rogaland-Hardangervidda-Telemark Sector, and (IV) 922-901 Ma in the Rogaland-Hardangervidda-Telemark and Bamble Sectors (Müller et al. 2017a). The observed relationships between pegmatite formation and regional high-grade metamorphism reveal that the majority of Sveconorwegian pegmatites are formed by anatexis as a result of either crustal stacking during different stages of continental/terrane collision (HP metamorphism) (periods I to III) or mafic magma underplating (HT metamorphism) during orogenic extension (period IV). In several provinces that have been affected both by early HP metamorphism during continental collision and by late HT metamorphism during crustal extension, there may occur several generations of pegmatites that are widely separated in time. The excursion area of the Evje-Iveland pegmatite field belongs to genetic group (2) and to the temporal group (IV).

The Evje-Iveland pegmatite field

The Evje-Iveland pegmatite field trends N-S; it is some 30 km long, up to 10 km wide, and consists of more than 400 large (>1,000 m^3) pegmatite bodies. The pegmatites are hosted mainly by banded amphibole gneisses (1459 ± 8 Ma Vånne banded gneiss), gabbroic amphibolites of the Iveland-Gautestad mafic intrusion (1285 ± 8 to 1271 ± 12 Ma), and by the Flåt-Mykleås metadiorite (1034 ± 2 Ma; Pedersen et al. 2009). These high-density units cause a strong positive Bouguer anomaly below the pegmatite field, indicating that there is no hidden granite body at depth which could be the source of the pegmatite melts (Gellein 2007). A gadolinite U/Pb date from an unspecified pegmatite from the Evje-Iveland field yields an age of 910 ± 14 Ma (Scherer et al. 2001) and a monazite-(Ce) from another unspecified pegmatite gives a $^{206}Pb/^{238}U$ age of 906 ± 9 Ma (Seydoux-Guillaume et al. 2012). Most recent $^{207}Pb/^{206}Pb$ ages of columbite-(Fe) from Mølland (900.7±1.81 Ma) and Steli (910.2±7.11 Ma) confirm the late-orogenic formation of the Evje-Iveland pegmatites (Müller et al. 2017a). Thus, the emplacement of the Evje-Iveland pegmatites classified regionally as period-IV pegmatites (901-922 Ma; see introduction) formed at the end of a period of voluminous late orogenic Hornblende-Biotite Granite (HBG) magmatism peaking at ca. 930 Ma (e.g., Bingen et al. 2011; Vander Auwera et al. 2011). It is the only pegmatite-forming period of the Sveconorwegian orogeny coeval to (late-) orogenic magmatism. The magmatism is related to late Sveconorwegian orogenic extension (Dalane phase). The magmatism was accompanied by a low-pressure, high- to ultrahigh temperature metamorphic event at c. 930 to 920 Ma. The large-scale heat source for this metamorphism and extensive magmatism, which is unique to the Rogaland-Hardangervidda-Telemark sector (Bingen et al. 2008b), was large-scale and long-lasting mafic underplating according to Hansen et al. (1996), Andersen et al. (2007b) and Vander Auwera et al. (2011). The underplating is evident, apart from the formation of the Rogaland Igneous Complex (RIC) some 100 km west of Evje-Iveland (Schärer et al. 1996; Vander Auwera et al. 2011), for example, from the juvenile nature of the 918-Ma-old Tørdal granite and the presence of distinct, mantle-derived components in the other HBG granites (Andersen et al. 2002a, b, 2007a, b). Underplating caused partial melting in the lower to middle crust which can be observed today, for example, at the so-called Iveland wall exposed in the centre of the Iveland village (excursion locality 2.3). Estimated coeval (930–920 Ma) low-pressure high-temperature metamorphic conditions recorded in gneisses some 10 km east of the RIC were ca. 760°C and 5.5 kbars (Möller et al. 2002; Möller 2003; Westphal et al. 2003; Bingen et al. 2008a, b; Drüppel et al. 2013). A regional-scale titanite U/Pb age cluster (12 samples) defines the timing of cooling through ca. 610°C at 918 ± 2 Ma (Bingen & van Breemen 1998). A hornblende $^{40}Ar/^{39}Ar$ plateau age in six samples yields a cluster at 871 ± 10 Ma (Bingen et al. 1998). Together, the titanite and hornblende data point toward a slow and very late regional cooling between ca. 610° and 500°C in southwestern Telemark. Given these constraints, the interpolated pressure-temperature conditions during

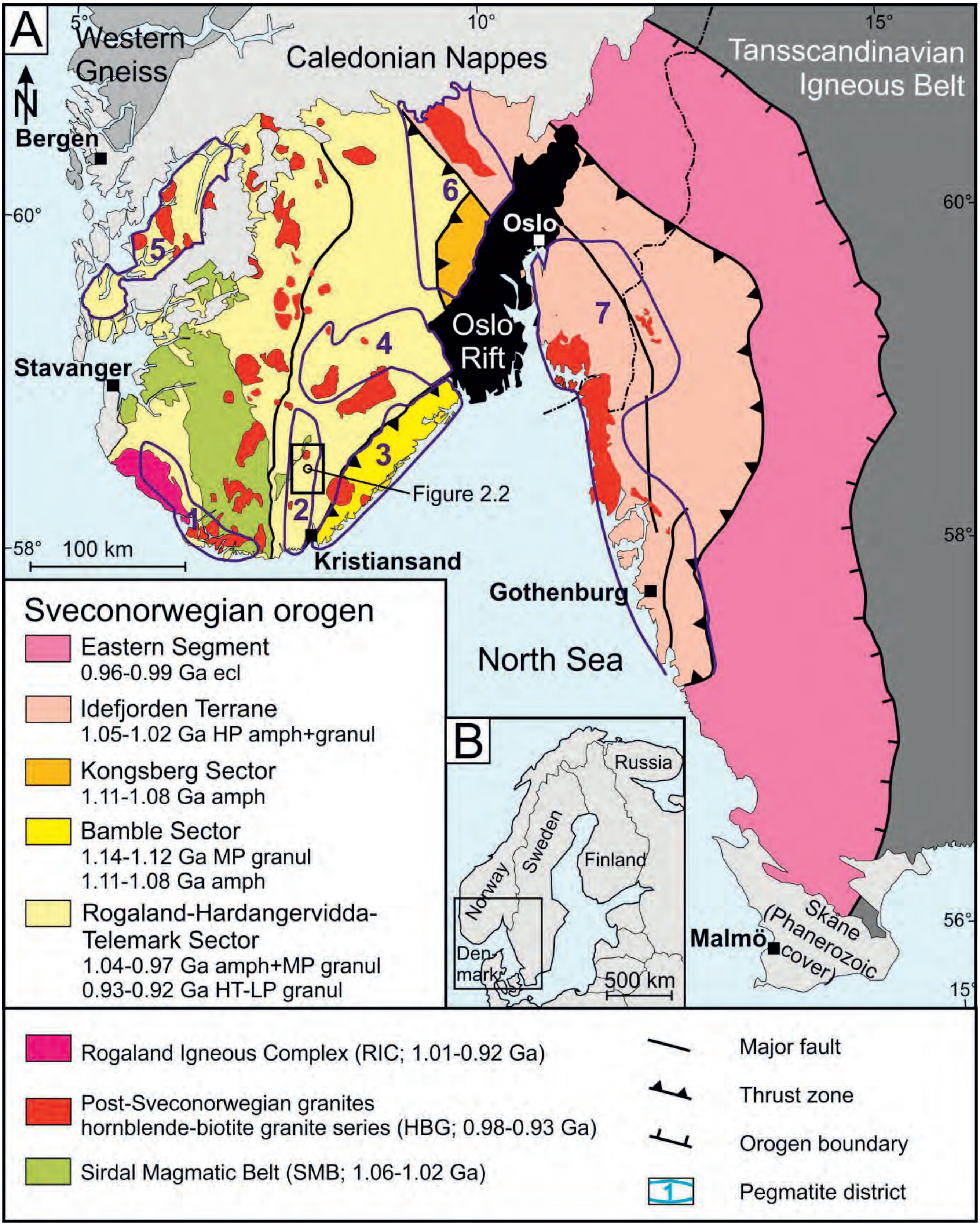


Fig. 2.1. A – Simplified map of southern Norway and southwestern Sweden showing the domains and segments of the Sveconorwegian orogen (coloured areas), major faults and thrust zones, orogenic magmatism and pegmatite districts. The pegmatite districts (areas framed with solid blue lines) include 1 = Mandal, 2 = Setesdal, 3 = Bamble, 4 = Nissedal, 5 = Hardanger, 6 = Buskerud, and 7 = Østfold-Halland. Metamorphic grades of the Sveconorwegian orogeny as given in the explanation: amph – amphibolite facies, ecl – eclogite facies, granul – granulite facies. B – Inset showing the location of map A at the southern tip of Scandinavia. Modified from Müller et al. (2015).

emplacement of the Evje-Iveland pegmatites were close to 600° to 550°C at 4 to 5 kbars. The pegmatites are spatially associated with the Høvringsvatnet granite intrusion, located at the northeastern margin of the field (Fig. 2.2). However, zircon U/Pb dating demonstrates that the Høvringsvatnet pluton formed between 983 ± 4 and 980 ± 4 Ma and is, therefore, genetically unrelated to the pegmatites (Snook 2014).

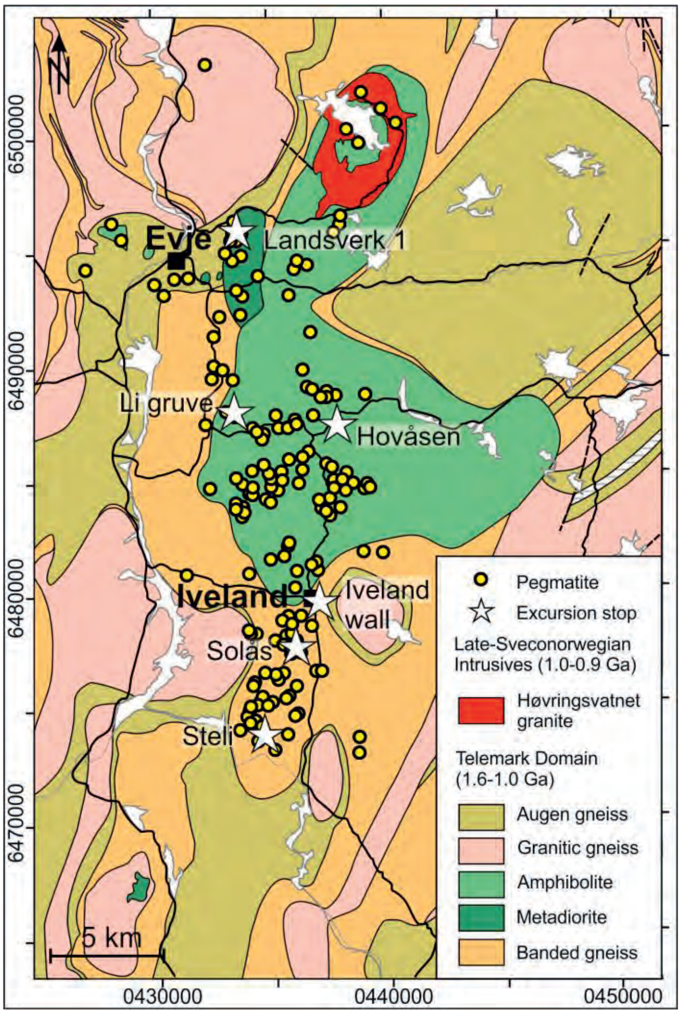


Fig. 2.2. Simplified geologic map of the Evje-Iveland area with the locations of pegmatites and excursion localities (stars).

According to the scheme of Černý & Ercit (2005), the Evje-Iveland pegmatites are classified as rare element REE and muscovite rare element REE pegmatites consisting of K-feldspar, plagioclase, quartz, 'biotite' (siderophyllite and Mg siderophyllite), and muscovite (Fe muscovite), with minor magnetite and garnet. In addition, they contain about 120 accessory mineral species, the most common are garnet of the almandine-spessartine series, magnetite, monazite-(Ce), allanite-(Ce), beryl, columbite-tantalite group minerals, aeschynite-(Y), euxenite-(Y), fergusonite-(Y), gadolinite-(Y), polycrase-(Y), xenotime-(Y), and zircon (Table 2.1).

As a consequence of their chemical NYF signature and their relative low fractionation degree, the Evje-Iveland pegmatites contain a total number of identified mineral species (about 130) comparatively low relative to LCT pegmatites. However, the Evje-Iveland pegmatites are famous for: (1) the occurrence of Sc minerals and Sc-enriched mica, garnet and beryl; (2) the enormous size of some accessory minerals, e.g. beryl, gadolinite-(Y), monazite-(Ce), and columbite group minerals; and (3) the occurrence of 'cleavelandite' replacement zones with LCT characteristics defining some of the Evje-Iveland pegmatites as mixed NYF-LCT pegmatites.

The pegmatites are known for the discovery of the first Sc mineral later named thortveitite and described by Schetelig (1911). Thortveitite, davidite-(Ce) and originally tombarthite-(Y) have their type localities in Evje-Iveland. However, the mineral tombarthite-(Y) has been discredited most recently by the IMA (Friis 2016). The first description of the primary mineral of Sc, thortveitite $Sc_2Si_2O_7$, came from the Evje-Iveland localities Knipane (Thortveitittgruve) and Landsverk 3 (Schetelig 1911). Since then there has been a certain interest in the geochemistry of Sc in this "Sveconorwegian Scandium Province" which includes also the Tørdal pegmatite field (Juve & Bergstøl 1997; Segalstad & Raade 2003). Goldschmidt (1934) suggested that Sc forming the thortveitite could not have come from the pegmatite magma, but rather from the amphibolite-rich host rocks because granitic rocks in general have much less Sc than mafic rocks. Goldschmidt (1934) found that Sc had been supplied to the pegmatite, by depleting the amphibolite wall-rock next to the pegmatite. Oftedal (1943) reported Sc contents of 50 to 150 ppm in amphibole in amphibolite from Evje-Iveland. According to Oftedal (1943) Sc contents in 'biotite' are 50 to 1,000 ppm and in muscovite 5 to 1,000 ppm. Stokkeland (2016) detected up to 1,040 ppm Sc in 'biotite' and up to 1,240 ppm Sc in garnet. In an attempt to investigate the possibility of using beryl from Evje-Iveland as a Sc ore, Neumann (1961) analysed 57 samples of beryl from this area, showing 10 to 1,000 ppm Sc. Davidite-(Ce) from Evje-Iveland contains 200 to 500 ppm Sc and ilmenite shows Sc contents of 30 to 1,000 ppm. Beside the Sc enrichment, the amount and size of some of the accessory minerals found in Evje-Iveland is astonishing. Rosenquist (1947) reported the finding of several gigantic beryl crystals at the Hovåsen mine, the largest weighing about 3 tons. Large columbite-(Mn) crystals have been found also at Hovåsen weighing up to 55 kg. Of specific interest is the high abundance and size of gadolinite-(Y) crystals (e.g. Revheim 2004). Already Schetelig reported in Brøgger et al. (1922) that in in 1906, 400 kg of gadolinite-(Y) were mined at a feldspar mine at Frikstad. In terms of tonnage the Evje-Iveland pegmatite field is presumably the area with the highest abundance of gadolinite-(Y) in the world (Pedersen et al. 2007).

The Evje-Iveland pegmatites are well zoned, consisting of a granitic wall facies, a megacrystic intermediate zone and core zone with feldspar megacrysts embedded in massive quartz. The pegmatites have NYF-type characteristics (Černý 1991) but are generally poor in F. Some of the pegmatites (about 10%) exhibit late pegmatitic (metasomatic), REE-depleted replacement zones comprising ‘cleavelandite’ (platy albite), quartz and muscovite and minor topaz, columbite group minerals, fluorite, garnet, beryl, and tourmaline. The mineral assemblage of the replacement zones has lithium-cesium-tantalum (LCT) family characteristics (Černý 1991) and hence these pegmatites are considered as mixed NYF-LCT pegmatites. At the northern margin of the field, in the Landsverk area, four of the exposed pegmatites are brecciated and partially replaced by hydrothermal quartz, formed from fluids of largely meteoric origin (Snook 2014). This event overprinted (brecciated) the primary zoning of the pegmatites and a new assemblage of quartz-microcline-epidote-stilpnomelane-pyrite-calcite-fluorite crystallized in open cavities. The mineralogy of the Evje-Iveland pegmatites has been described by Andersen (1931), Barth (1931, 1947) and Bjørlykke (1934, 1937). More recent studies were carried out by Frigstad (1999), Larsen (2002), Larsen et al. (2000, 2004), Müller et al. (2012a, 2015), and Snook (2014).

The studies by Larsen (2000, 2004), Snook (2014) and Müller (2015) are the outcome of national prospection campaigns for high-purity quartz, related to inceasing demand for silicon for the photovoltaic and semiconductor industry. High-purity quartz, which is defined to contain less than 50 ppm of contaminating elements (Harben 2002), is rare in nature. These studies were the first of their kind applying laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for the exploration of high-purity quartz. The studies revealed that the quartz from Evje-Iveland pegmatites is relatively low in Al (<200 ppm) but rich in Ti (up to 57 ppm) and, thus, the quartz does not fulfil the industrial high-purity requirements (Fig. 2.3). Compared with the quartz chemistry of other pegmatite fields, the Evje-Iveland quartz is richest in Ti indicating a high Ti activity in the pegmatite melt and high crystallization temperature (Huang & Audétat 2012).

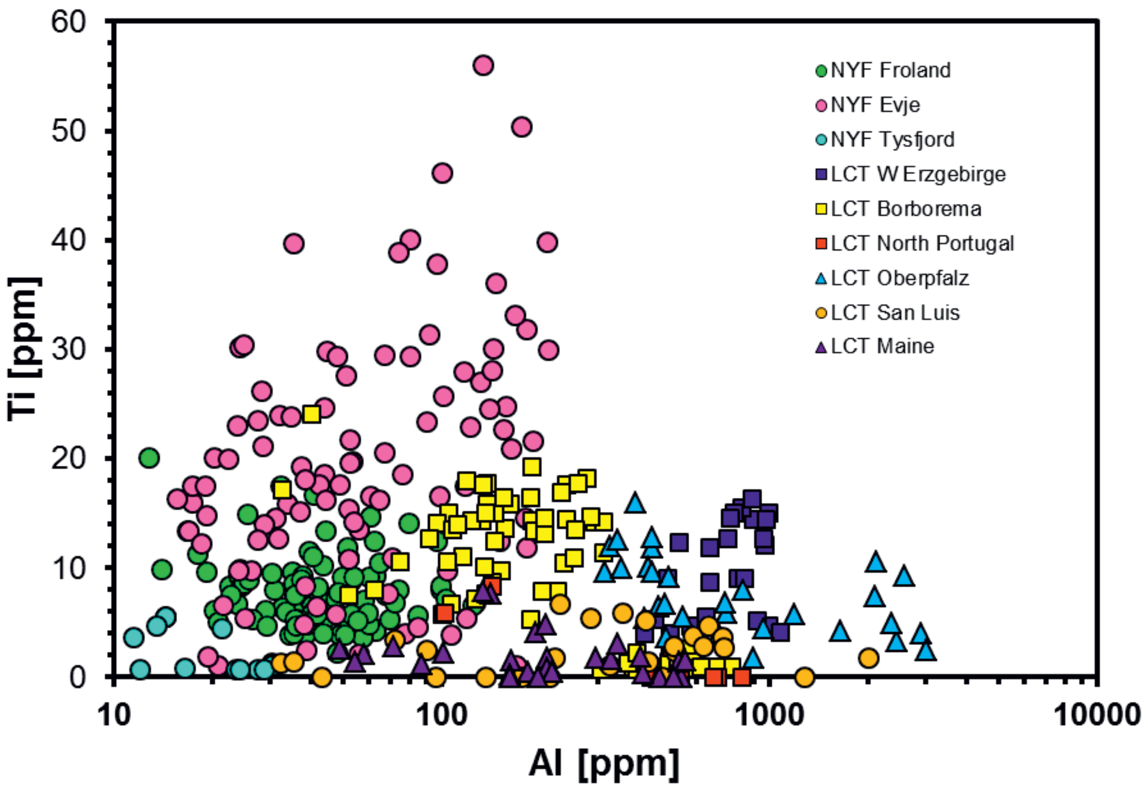


Fig. 2.3. Concentrations of Al and Ti in pegmatite quartz from Evje-Iveland (pinkish dots) and other pegmatite fields. Aluminium and Ti are generally the most common trace elements in quartz and, thus, an indicator of the chemical quartz quality. Quartz from Evje-Iveland has the highest average Ti content compared to quartz from other pegmatite localities. Data from Müller et al. (2013, 2015) and Müller unpublished.

Table 2.1. List of minerals found in Sveconorwegian Evje-Iveland pegmatites. Modified from Mindat (2017). TL – type locality.

Mineral name	**Mineral name**	**Mineral name**
Aeschynite-(Y)	Diaspore	Prehnite
Albite	Elbaite	Pumpellyite-(Fe^{3+})
Allanite-(Ce)	Epidote	Pyrite
Almandine	Euclase	Pyrochlore Group
‘Amazonite’	Euxenite-(Y)	Pyrophanite
Analcime	Fergusonite-(Y)	Pyrrhotite
Anatase	Fersmite	Quartz
Ancylite-(Ce)	Fluocerite-(Ce)	Rhabdophane-(Ce)
Annite	Fluorapatite	Rozenite
‘Apatite’	Fluorapophyllite-(K)	Rutile
Arsenopyrite	Fluorite	Samarskite-(Y)
Bastnäsite-(Ce)	Fourmarierite	’Scheteligite’
Bavenite	Gadolinite-(Y)	Schoepite
Bertrandite	Gahnite	Schorl
Beryl (aquamarine, heliodor)	Galena	Schröckingerite
'Biotite' (Siderophyllite)	Goethite	Siderite
Bismite	Gypsum	Siderophyllite
Bismuth	Hellandite-(Y)	Sillimanite
Bismuthinite	Hematite	Spessartine
Bismutite	Heulandite-Ca	Sphalerite
Bityite	'Hornblende'	Stilbite-Ca
Calcioancylite-(Ce)	Hydroxycalciomicrolite	Stilpnomelane
Calcite	Ilmenite	Tantalite-(Fe)
Carnotite	Kainosite-(Y)	Tantalite-(Mn)
Cerianite-(Ce)	Kamphaugite-(Y)	Tengerite-(Y)
Chabazite-Ca	Keiviite-(Y)	Thorianite
Chalcocite	Lanthanite-(Nd)	Thorite
Chalcopyrite	Laumontite	**Thortveitite (TL)**
Chamosite	Liandratite	Titanite
‘Chlorite Group’	Magnetite	Topaz
Chrysoberyl	Malachite	Törnebohmite-(Ce)
Churchite-(Y)	Microcline	Triplite
‘Cleavelandite’	Microlite Group	Tveitite-(Y)
Clinochlore	Milarite	Uraninite
Clinozoisite	Molybdenite	Uranophane
Coffinite	Monazite-(Ce)	Vandendriesscheite
Columbite-(Fe)	Montmorillonite	Xenotime-(Y)
Columbite-(Mn)	Muscovite (Fe muscovite)	Yttrialite-(Y)
Corundum	Opal	Yttrotantalite-(Y)
Covellite	Orthoclase	'Zeolite Group'
Cuprite	Phenakite	Zircon
Davidite-(Ce) (TL)	Polycrase-(Y)	

Field locations

Locality 2.1: Agder Naturmuseum and botanical garden, Kristiansand (ice breaker location)

Highlights

One of the oldest museums of Norway displaying minerals, rocks, plants and animals, and artifacts

Coordinates EU89-UTM Zone 32V 441346E/6446831N

Directions and Access

The Agder Naturmuseum and botanical garden is situated in the district Gimlemoen of Kristiansand, c. 2 km NE of the city centre (Gimleveien 23, Gimle Gård, 4630 Kristiansand). The parking place is east of the botanical garden. The museum can be easily reached from downtown by walking northeast along the County Road 471 (Drønnings gate). After crossing the river Otra turn northwest into the Torridalsveien (left) and after 800 m into the Gimleveien (right). There a number of public bus routes going from downtown to Gimlemoen (busses nr. 17, 18, 19, 22, 23, A1, M1, M2, M3; http://www.akt.no/english/). Go off station Oddemarka, enter Gimleveien and walk 500 m westward. The Agder Naturmuseum and botanical garden is on the right (northern) side of the road.

Distance to walk: 0.5 km (from nearest bus station)
Elevation changes: 0 m

The history of Agder Naturmuseum and botanical garden, formerly Kristiansand Museum, dates back to 1828 making it one of the oldest museums in Norway (Fig. 2.4). Originally it was a part of Kristiansand Cathedral School. This lasted until 1917, when the municipality took over the ownership. Although the museum had a mineral collection from the beginning, changes of location, improper storing conditions and lack of qualified personnel to curate the collection, have led to the loss of valuable specimens. Conditions improved in 1975 when the museum board decided that the museum should have a geological department. In 1976 the geologist Ole Fridtjof Frigstad was employed as head of the department on a part-time basis. He did a great effort to restore the collection and also add new samples, mainly from the Agder district. The geological collections have been on the current location since 1965, but it wasn't until 1990 that the Museum became open to the public. In 1994 Kristiansand Museum was renamed Agder Naturmuseum and botanical garden. An important event in the history of the museum will occur in 2017 as it will be merged with the University of Agder.

Fig. 2.4. The Agder Naturmuseum and botanical garden in Kristiansand. With permission Agder Naturmuseum.

The Agder Naturmuseum has six different collections of minerals, rocks and fossils. These are the mineral collection (worldwide), the petrological collection (worldwide), the Agder collection (rocks from the Agder region), the "mine" collection (minerals and rocks from mines in Norway), the fossil collection (worldwide) and the quaternary collection (quaternary fossils worldwide but mainly from Agder). The total number of objects exceeds 9,800, with the mineral collection comprising about 4,000 specimens. Among the highlights in the collections are historical samples of type minerals from Agder, e.g. datolite and babingtonite from Arendal. These samples may not be very impressive in appearance, but they are nearly irreplaceable. The oldest samples in the mineral collection date back to the 18th century. As Agder Naturmuseum is a small museum with a moderate budget the capacity to acquire large samples of striking beauty is limited. However, some fine specimens are in the possession of the museum, among notable Norwegian samples can be mentioned gold from Bømlo, silver from Kongsberg, zircon from Seiland, ilmenite from Froland, etc.

The municipality of Kristiansand has several mineral occurrences of various type and origin, some of which were of economic importance in the past. In the Ålefjær – Kjevik area manganese ore (pyrolusite and manganite) of hydrothermal origin were mined at various periods between 1896 and 1919 (Berg et al. 2016). Total production was 144 tons. Marble formed during Sveconorwegian orogeny (1.2-0.9 Ga) was mined at Sødal, Bakken, Hagen and other places near Kristiansand in the period from 1826 to 1975. Minor sub-economic skarn deposits are associated with the marble. Findings of collector quality of e.g. vesuvianite were made there. Near Hagen, at a skerry in the river Otra, a silver-bearing calcite vein was discovered in 1920 and 15 kg of silver was taken out during six weeks this year (Rosenlund 1922). The Kristiansand Nickel Company (Kristiansand Nikkelverk) was the entrepreneur. This company was founded in 1910 and changed name to Falconbridge Nickel Company when Canadians overtook the ownership in 1929. It soon became a very important enterprise for the region and is still today, with 500 employees. Today it is named Glencore and has a yearly production capacity of 92,000 tons of nickel, 39,000 tons of copper, 4,700 tons of cobalt, 115,000 tons of sulphuric acid, and some gold, platinum and palladium. The matte is not supplied by local mines anymore, but historically the Flåt mine in Evje delivered matte (Industrimuseum 2017). Here, exploitation of pentlandite-bearing pyrrhotite and chalcopyrite started in 1872. A melting plant was built in Evje in 1873, where the nickel and copper ore was transformed into matte. It was transported to Kristiansand after the ore refinery was built in 1910. With some interruptions the Flåt mine was active until 1946.

Pegmatite mining, i.e. feldspar, had also some impact in the local industrial history. The richest feldspar occurrences were in Aust-Agder, particularly in the Evje-Iveland area. In Vest-Agder, around Kristiansand, pegmatites had less importance, although minor occurrences are widespread in the region. The oldest feldspar and quartz mine in Norway was at Narestø near Arendal, Aust-Agder, an area which was more famous for its iron mines. In 1792 the pegmatite mining was started by a woman named Nikoline Jørgensen who in her first shipment exported 69 barrels of feldspar to the Royal Porcelain Factory in Copenhagen. Her enterprise dominated the feldspar market in the Agder region until 1829.

The Randesund area east of the Kristiansand town centre, where up to 12 feldspar quarries were in operation from 1876 to 1930, was the most important area with the Søm quarry being the largest. The host rock of the pegmatites at Randesund is amphibolite. The presence of beryl is characteristic for the Kristiansand pegmatites, and some large crystals (up to 50 cm) have been found in the Randesund area, e.g. Søm and Strømme. At the location Hånes the beryl is partially altered to bavenite. Other feldspar quarries in the Randesund area were Korsvik, Rona, Torsvik, and Grovig near Hånes. South of the town centre there were quarries at Møvik, Fossevik and on the Flekkerøy island. The feldspar was sorted into three grades of purity, transported to the harbour of Kristiansand and then shipped to the European mainland, mainly Germany and Denmark, for production of porcelain. The feldspar that was mined during the early period was microcline, but later on also albite for the manufacture of artificial teeth. In contrast to other pegmatite mining districts in the Sveconorwegian orogeny, quartz and mica were not mined in the Kristiansand area. The silicon metal factory at Fiskå in Kristiansand received its quartz from the Evje-Iveland area. However, beside feldspar beryl was collected from the Kristiansand pegmatites and sold by some of the workers for an extra income. Other notable minerals found in Kristiansand pegmatites are garnet (almandine), titanite, hematite, magnetite, fluorite, columbite-(Fe), monazite-(Ce), gadolinite, molybdenite and bismuthinite.

Locality 2.2: Steli pegmatite

Highlights

Simple zoned pegmatite with NYF affinity famous for collector-quality almandine, monazite-(Ce) and columbite-(Fe) specimens

Coordinates EU89-UTM Zone 32V 434394E/6474268N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Ivelandsveien/Kilefjorden Camping (County Road 403 Ivelandsveien) and travel east towards Iveland for 8 km to the junction in the centre of the Iveland village and turn right here continuing on the Road 403 (Ivelandsveien) for another 6 km southward. In the village Bakken turn right following the sign “Øyna” and the dirt road (Øynaveien) westward for 2 km. The excursion bus stops at the junction where the dirt road to the Steli mine branches off (UTM Zone 32V 434578E/6474358N). From the bus stop follow for 250 m the gravel road to the mine (Fig. 2.5). The Steli mine is a relatively large abandoned quarry opened for mineral collectors. This site is on private land, and 100 NOK has to be paid to the landowner when taking samples (there is a payment box at the mine entrance). The exposures are relatively fresh and there is plenty material within and around the mine.

Distance to walk: 0.2 km
Elevation changes: 25 m
Excursion time: 1 ½ hour
Conservation status: None

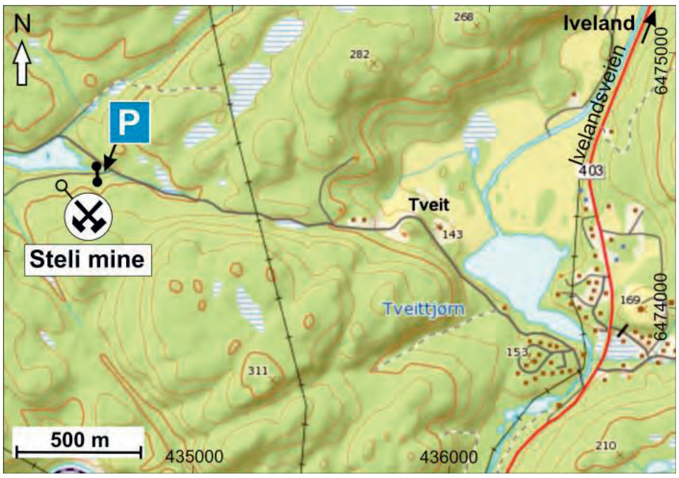


Fig. 2.5. Access map for the Steli mine.

Pegmatite zoning and host rocks

The Steli pegmatite is one of the southernmost feldspar quarries of the Evje-Iveland pegmatite field (Fig. 2.2), and it is a quite large quarry for this area. The tabular, tongue-shaped pegmatite extending 90 m in E-W direction and 30 m in N-S direction plunges towards S (Fig. 2.6). Characteristical for Steli is the dominance of plagioclase over K-feldspar and the massive quartz core. The host rocks are garnet-bearing banded gneisses partially migmatitic. At the south side of the mine a metagabbro body is exposed. It is not known when feldspar mining started here, but mining activity is recorded as early as 1911. In addition to feldspar, quartz and muscovite have been produced from Steli until the 1970s.

The pegmatite shows a distinct sub-vertical zoning (currently exposed in the western part of the quarry), with upper and lower border zone of granitic texture (0.5 cm crystals), which is up to 0.3 m thick (Fig. 2.7). The lower border zone exhibits a layered structure of alternating smaller and coarser-grained granitic bands. The upper border zone grades into the coarser 0.5 m-thick wall zone containing subhedral plagioclase (45%), quartz (50%), ‘biotite’ (5%) and accessory magnetite. The intermediate zone consists of massive plagioclase graphically intergrown with quartz and characteristic radiating sheets of ‘biotite’ up to 80 cm in size. A few euhedral K-feldspar megacrysts (up to 80 cm) are embedded in the plagioclase matrix. The core is composed of massive quartz containing radiating muscovite sheets up to 1 m in diameter and some euhedral K-feldspar megacrysts (up to 1m). Towards the centre of the core the radiating muscovite splays change into massive muscovite booklets.

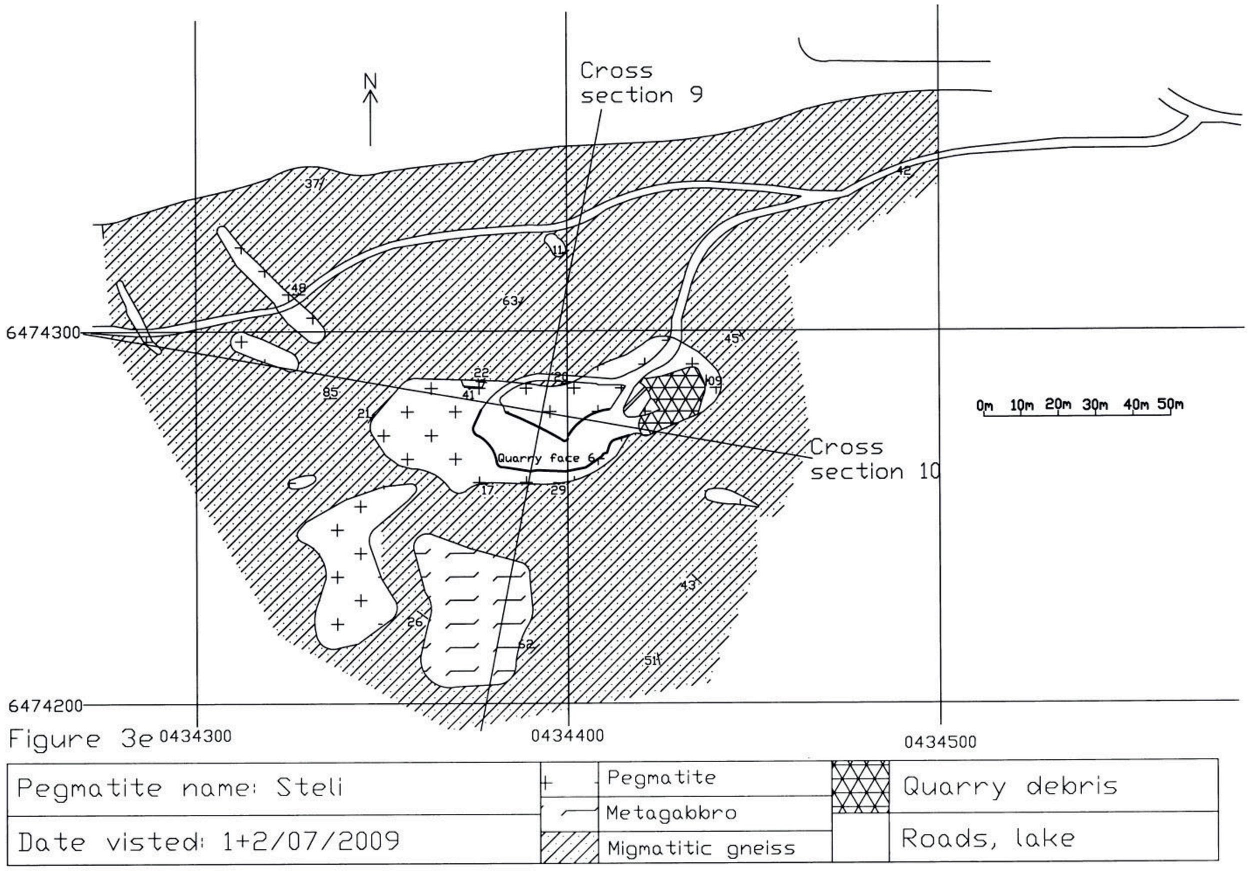


Fig. 2.6. Geological map of the Steli pegmatite by Uren (2010). The visiting site corresponds to the location of the quarry debris.

Mineralogy

The main minerals comprise K-feldspar, plagioclase, quartz, ‘biotite’ and Fe muscovite. Accessory minerals are given in Table 2.2. Compared to other Evje-Iveland pegmatites, Steli is distinctively richer in plagioclase and a high muscovite/’biotite’ ratio. ‘Biotite’ has Mg siderophyllite to siderophyllite composition (Fig. 2.8). Plagioclase composition corresponds to albite with $An_{06}Ab_{92}Or_{02}$. Garnet and magnetite are the most abundant accessories. Y-rich minerals are much rarer than in many other pegmatites in the area. Muscovite may occur as pseudohexagonal crystals up to 30 cm in diameter and form commonly as radiating sheet clusters (wall zone) or massive booklets (core). The radiating muscovite sheets host the diversity of accessory minerals, most commonly garnet, columbite-(Fe), and monazite-(Ce). The chemistry of quartz shows a distinct zoning within in the pegmatite body (Fig. 2.9). Quartz of the core is more enriched in Al and Ge and depleted in Ti compared to quartz of the wall and border zones. The zoning reflects the progressing differentiation of the pegmatite melt during crystallization towards the core of the pegmatite.

Table 2.2. Minerals identified in the Steli pegmatite. Modified from Mindat (2017).

Mineral name	Mineral name
Albite	Magnetite
Allanite-(Ce)	Microcline
Almandine	Monazite-(Ce)
Bertrandite	Muscovite (Fe muscovite)
Beryl	Pyrite
'Biotite' (Siderophyllite)	Quartz
Bityite	Rutile (var. Ilmenorutile)
Bismuthinite	Samarskite-(Y)
‘Chlorite group’	Siderophyllite
Columbite-(Fe)	Xenotime-(Y)
Euxenite-(Y)	Zircon (var. Alvite)

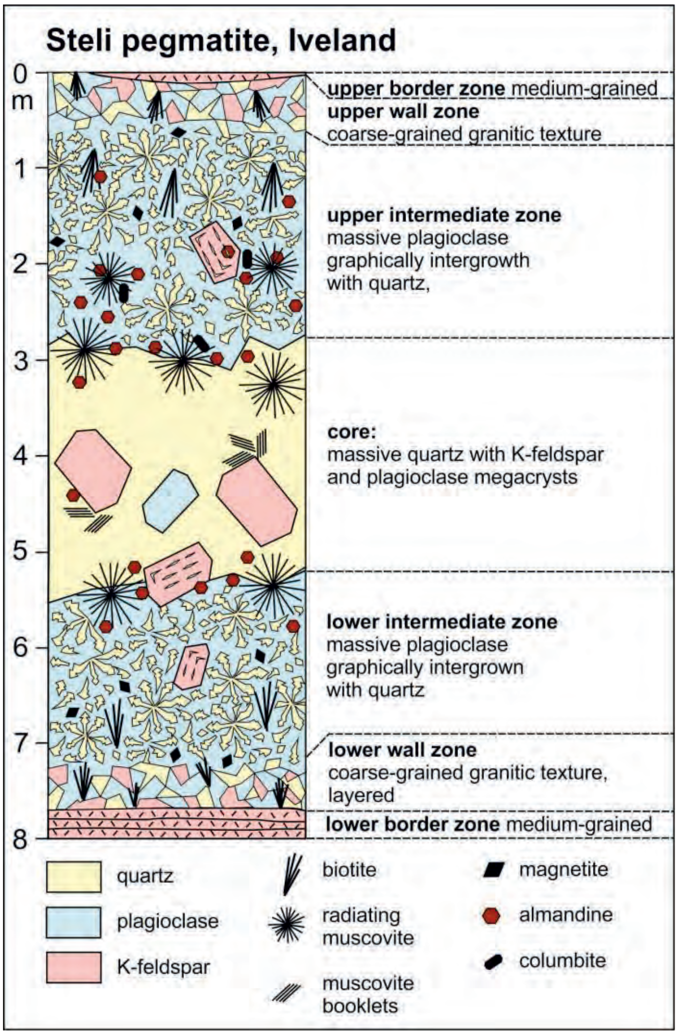


Fig. 2.7. Schematic zoning of the Steli pegmatite.

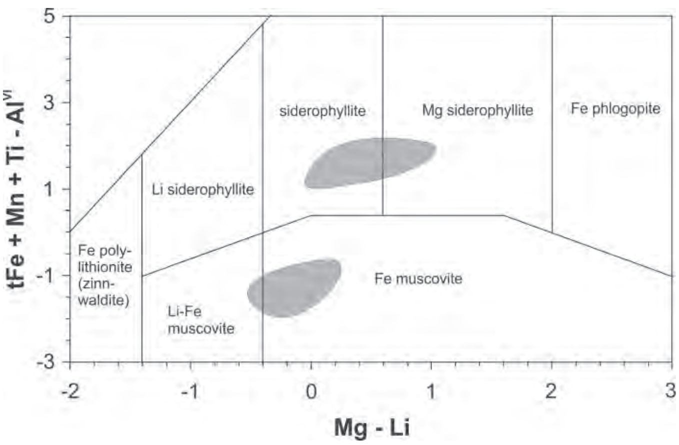


Fig. 2.8. Compositions of micas from Evje-Iveland pegmatites plotted in the classification diagram of Tischendorf et al. (2001). 'Biotite' comprise Mg siderophyllite and siderophyllite compositions and muscovites predominantly Fe muscovite compositions. Data from Rosing-Schow et al. (2017).

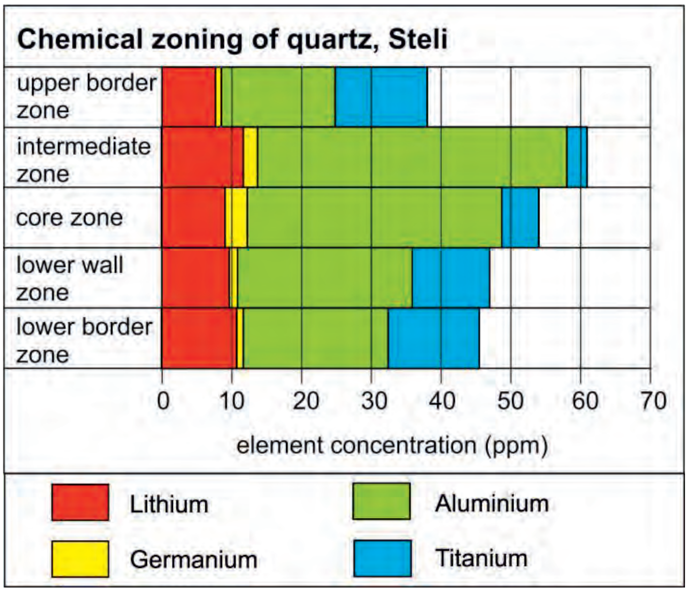


Fig. 2.9. Graph showing the distribution of Li, Ge, Al and Ti in quartz from different zones of the Steli pegmatite. From Müller et al. (2015).

Bjørlykke (1935) reported up to 6 m long microcline crystals with well-developed crystal faces from Steli, which occurred in massive white quartz from the deeper, eastern part of the mine (now buried). Furthermore, he described well-formed beryl crystals up to 1 m in length and with a diameter of 15 cm. Pieces of smaller beryl crystals may still be found on the dumps. According to Bjørlykke (1935) some of the beryl crystals were altered to a dark mass in which small white translucent crystals of bertrandite were imbedded. Samarskite-(Y) was found as anhedral masses with a diameter up to 15 cm. Columbite-(Fe) occurred in well-developed crystals reaching a weight of 2 to 3 kg. Well-shaped columbite-(Fe) crystals up to 10 cm have been reported for very recent findings.

The locality is a well-known collecting site for high-quality garnet specimens. Garnets from Steli have the composition of the almandine-spessartine series with dominating almandine component. The garnets from Steli are the most Fe-rich garnets compared to garnets from other Evje-Iveland pegmatites (Fig. 2.10). Considering the observed overall fractionation-induced trend characterized by the increase in MnO/(MnO + FeO) of garnet, the Steli pegmatite is one of the least fractionated pegmatites of the Evje-Iveland area.

Garnets, which can be up to 5 cm in size, occur in three different assemblages: (1) Up to 5 cm wide veins within and between K-feldspar megacrysts. These veins are composed of subhedral to euhedral brownish red garnets and form well crystallized clusters of crystals. However, these garnets have a lot of microfractures and disintegrate into garnet sand, when opening the veins;

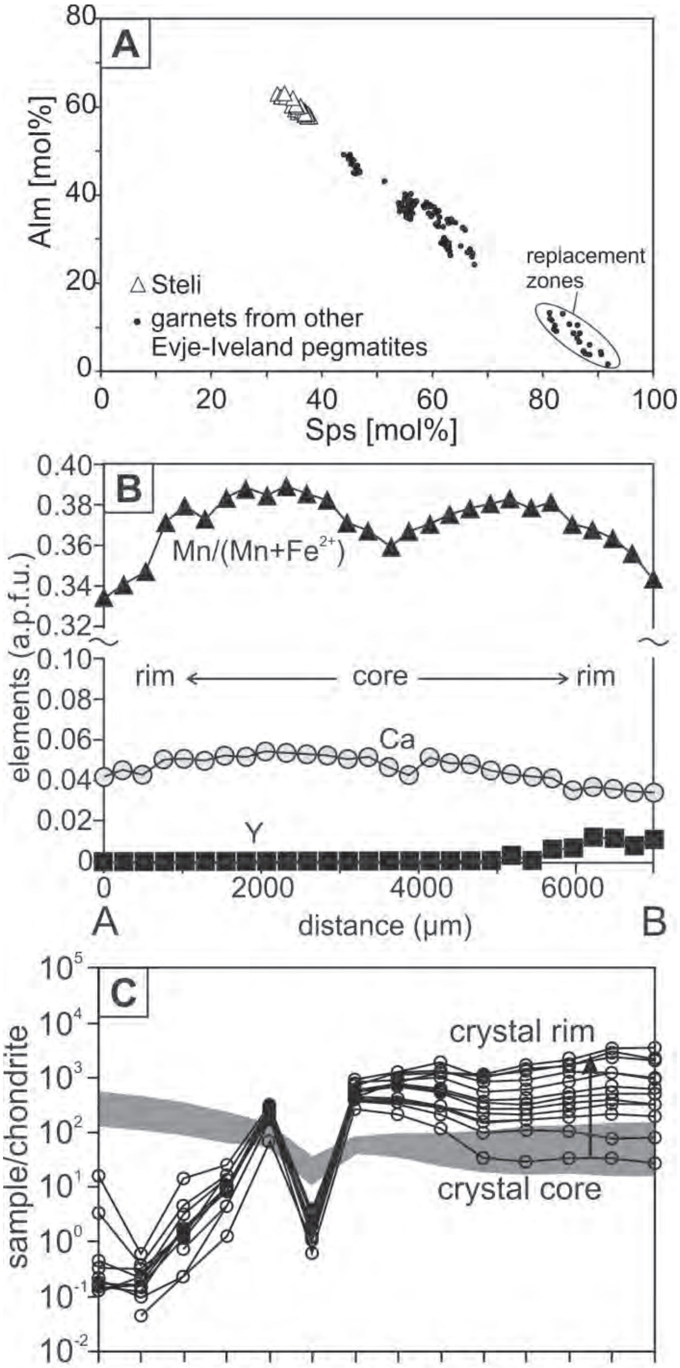


Fig. 2.10. Chemistry of garnets from the Steli pegmatite. A - Spessartine (Sps) versus almandine (Alm) component plot. See text for explanation. B - Profile of the Ca and Y content in atoms per formula unit (apfu) and the $Mn/(Mn + Fe^{2+})$ value of garnet from Steli. The analyses were performed with electron microprobe. For explanation see text C - Chondrite-normalized REE pattern of garnet. The grey-shaded REE pattern is the bulk composition of the wall zone of the pegmatite, representing roughly the bulk composition of the pegmatite. Analyses were performed with LA-ICP-MS. Data from Müller et al. (2012a) and Müller unpublished.

(2) Isolated or small groups of garnet crystals embedded within or between quartz or feldspar crystals. The best formed crystals found are hosted in massive quartz. These crystals occur relative close to the radiating muscovite sheets; (3) Crystals wedged between muscovite sheets. These garnets are flattened (Fig. 2.11). Some specimens are no more than a couple of millimeters thick, but 4 to 5 cm in diameter. Smaller crystals of this type may be transparent and have a nice orange-red colour.

In backscattered electron imaging all garnet types appear homogeneous. Micro-inclusions of Ta-poor, Sc-bearing columbite-(Fe) (5–40 µm), associated niobian rutile (10–60 µm), rutile (5–20 µm) and muscovite (20–100 µm) are rare and occur only in the crystal cores. Some of the columbite-(Fe) inclusions are porous and marginally overgrown by euxenite-(Y) (Fig. 3C). The pyrope, grossular and andradite components are less than 5 mol.%. Other components containing Ti, Cr and V are mostly negligible, and concentrations of TiO_2, Cr_2O_3 and V_2O_5 are <0.4, <0.02 and <0.02 wt.%, respectively. The Steli garnet has the lowest Y content compared to other Evje-Iveland garnets (mean 0.05 wt.% Y_2O_3, Müller et al. 2012a). Concentrations are slightly enriched at the outermost margin (0.25 wt.% Y_2O_3). The chondrite-normalized pattern of garnet is strongly HREE- enriched, with increasing normalized abundance from La to Lu (Fig. 2.10C). The pattern shows a distinct negative Eu anomaly due to preferential partitioning of Eu into plagioclase.

Monazite-(Ce) occurs commonly in the radiating muscovite stars. The crystals are usually up to 1 cm in size (in a few cases up to 3 cm) with well-developed crystal faces and golden brown colour. The large monazite crystals are often altered to secondary minerals, which have not been described. Columbite-(Fe) is found predominantly between or close to radiating muscovite sheets. Compositions of the Steli columbites-(Fe) are plotted in Figure 2.12. Compared to other columbite group minerals from Evje-Iveland, Fe and Nb contents are high, indicating a relative low fractionation degree of the Steli pegmatite melts. This is in accordance with the primitive garnet chemistry. In addition to monazite-(Ce) and columbite-(Fe) rare, small specimen of xenotime-(Y) and zircon has been found in the mica splays. The local mineral collector Andreas Corneliussen identified whitish, millimeter-sized mass of bityite at Steli, probably an alteration product of beryl. Bityite is one of the very few Li-minerals found in Evje-Iveland pegmatites.

Table 2.3. Average compositions of garnets from Evje-Iveland pegmatites determined by EPMA. Data from 1 - Müller et al. (2012a), 2 – Stokkeland (2016), 3 - Müller et al. (2017b). IZ – Intermediate zone, REZ – Reaction zone, RPZ – Replacement zone.

	Steli[1]	**Li gruve[1]**	**Slobrekka[1]**	**Hovåsen[1]**	**Solås[1]**		**Solås[2]**	**Birkeland 4[3]**	**Skipeland[3]**	**Topazbrudd[3]**
	IZ	IZ	IZ	IZ	REZ	REZ	RPZ	RPZ	RPZ	RPZ
	n=28	n=28	n=30	n=25	core (n=6)	rim (n=19)	n=4	n=15	n=31	n=26
EPMA analsyes (wt.%)										
SiO_2	35.69	36.21	35.45	35.40	35.28	36.48	35.1	35.11	34.93	34.73
TiO_2	0.07	0.18	0.09	0.16	0.21	0.02	0.04	0.13	0.03	0.07
Al_2O_3	20.23	20.25	20.32	20.03	20.17	20.56	20.3	20.08	20.67	20.52
Na_2O	0.00	0.02	0.10	0.03	0.07	0.03	<0.01	0.05	0.00	0.00
CaO	0.52	0.53	0.47	0.33	0.59	0.46	0.62	0.64	0.82	0.91
FeO	26.87	22.48	17.62	15.32	17.70	17.66	3.8	14.13	5.86	8.04
MnO	15.00	19.80	23.84	26.39	23.05	24.95	40.0	28.52	37.24	35.02
MgO	0.59	0.75	0.29	0.58	0.46	0.37	<0.01	0.05	<0.01	<0.01
Sc_2O_3	0.01	0.05	0.00	0.04	0.10	0.01	<0.01	<0.01	<0.01	<0.01
Y_2O_3	0.05	0.21	2.31	0.89	1.95	0.59	0.05	0.73	0.12	0.19
Dy_2O_3	0.00	0.00	0.06	0.02	0.06	<0.01	<0.01	<0.01	<0.01	<0.01
Er_2O_3	0.10	0.10	0.17	0.08	0.19	0.03	<0.01	<0.00	<0.01	<0.01
Yb_2O_3	0.00	0.02	0.20	0.09	0.88	0.10	<0.01	0.04	<0.01	0.12
Total	98.59	100.63	100.93	99.38	100.67	101.19	99.97	99.48	99.68	99.68
cation proportions (12 O)										
Si	2.967	2.967	2.931	2.947	2.936	2.976	2.98	2.923	2.890	2.881
IVAl	0.033	0.033	0.069	0.053	0.064	0.024	0.02	0.077	0.110	0.119
Total Z(3)	3.000	3.000	3.000	3.000	3.000	3.000	3.00	3.000	3.000	3.000
VI Al	1.949	1.922	1.911	1.912	1.915	1.953	1.90	1.893	1.904	1.887
Ti	0.004	0.011	0.005	0.010	0.013	0.001	0.00	0.008	0.002	0.004
Sc	0.001	0.003	0.000	0.003	0.007	0.001	0.00	0.000	0.000	0.000
Zr	0.000	0.000	0.000	0.000	0.001	0.000	0.00	0.000	0.000	0.000
V	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.000	0.000
Fe^{3+}	0.074	0.079	0.061	0.081	0.038	0.046	0.06	0.143	0.197	0.216
Fe^{2+}	0.000	0.000	0.023	0.007	0.025	0.002	0.00	0.000	0.000	0.000
Total Y(2)	2.028	2.016	2.000	2.015	2.000	2.004	1.96	2.044	2.103	2.107
Fe^{2+}	1.794	1.460	1.136	0.978	1.168	1.156	0.05	0.841	0.209	0.342
Mn^{2+}	1.057	1.373	1.670	1.861	1.625	1.724	2.79	2.012	2.610	2.365
Mg	0.073	0.092	0.035	0.072	0.057	0.045	0.00	0.006	0.000	0.000
Ca	0.046	0.047	0.041	0.030	0.052	0.040	0.00	0.057	0.073	0.081
Na	0.001	0.004	0.016	0.005	0.012	0.005	0.06	0.008	0.000	0.096
Y	0.002	0.009	0.102	0.039	0.086	0.026	0.00	0.032	0.005	0.008
Total X(3)	2.972	2.984	3.000	2.985	3.000	2.996	2.90	2.956	2.897	2.893
end members (mol%)										
Yttrogarnet	0.06	0.30	2.29	1.16	2.13	0.73	0.10	1.07	0.18	0.28
Schorlomite-Al	0.20	0.55	0.00	0.23	0.00	0.02	0.00	0.41	0.09	0.21
Spessartine	35.22	45.76	55.67	62.02	54.14	57.47	92.99	67.05	86.99	82.02
Pyrope	2.42	3.06	1.17	2.40	1.89	1.50	0.00	0.20	0.00	0.00
Almandine	59.63	46.98	36.42	30.03	37.58	37.92	0.60	26.34	6.96	11.41
Grossular	0.10	0.00	0.00	0.01	0.00	0.03	0.00	0.00	1.09	0.65
Andradite	1.17	0.80	0.83	0.27	0.21	1.16	1.70	1.50	1.25	1.83
Skiagite	0.17	1.68	1.43	2.50	1.26	0.62	0.88	1.71	0.00	0.00

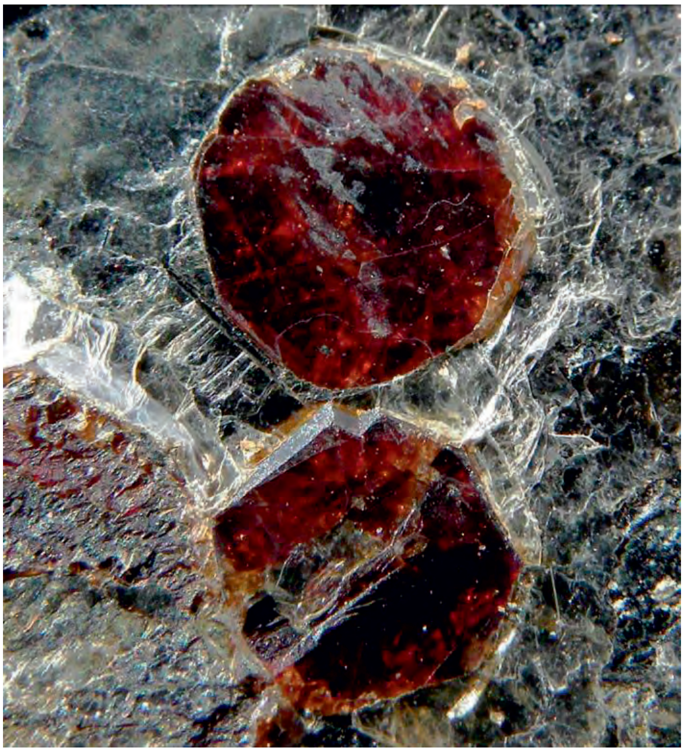


Fig. 2.11. Platy garnet embedded in muscovite sheets. Field of view is 3 cm. Photo by Olav Revheim published on MinDat (2017).

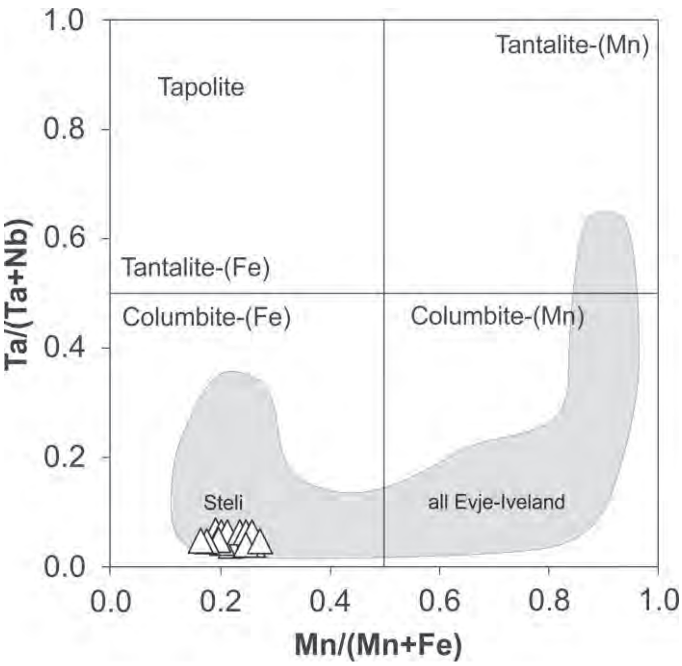


Fig. 2.12. Quadrilateral classification diagram of columbite-group minerals according to Černý (1989) showing the variation in Mn-Fe and Ta-Nb ratios of columbites-(Fe) from Steli compared with other columbite group minerals from Evje-Iveland (grey shaded area). Concentrations were determined with EPMA. Data from Lund (2016) and Müller et al. (2017a, 2017b).

Locality 2.3: Iveland Wall

Highlights

Road cut showing partial melting (anatexis) of amphibolites and the related formation of pegmatites

Coordinates EU89-UTM Zone 32V 436770E/ 6479749N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Ivelandsveien/Kilefjorden Camping (County Road 403 Ivelandsveien) and travel east towards Iveland for 8 km to the junction in the centre of the Iveland village and turn left and turn left again after 50 m into the parking place of the Centre Building Åkle. The Iveland Wall is the road cut across the road.

Distance to walk: 0 km
Elevation changes: 0 m
Excursion time: ½ hour
Conservation status: None

At the junction of Ivelandsveien and Frikstadveien in the centre of Iveland a spectacular road cut has been exposed in 2009 (Fig. 2.13). The exposed cross-section, which is c. 25 m long and up to 6 m high, shows the three most typical rocks of the Evje-Iveland area: (1) the banded amphibole gneiss (1459 ± 8 Ma Vånne banded gneiss), (2) massive, dark green, gabbroic amphibolite of the Iveland-Gautestad mafic intrusion (1285 ± 8 to 1271 ± 12 Ma) and (3) coarse-grained pegmatites. The protoliths of the banded gneiss were sediments deposited about 1.46 Ga. At about 1280 Ma the sediments were intruded by gabbroic melt of the Iveland-Gautestad mafic suite. During the Sveconorwegian orogeny the rocks of the Evje-Iveland area, being part of the Rogaland-Hardangervidda-Telemark Sector, were multiple metamorphosed. The first metamorphic event comprises amphibolite to medium-pressure granulite conditions between 1035 and 970 Ma, called M1 stage and the second event high-temperature-low-pressure amphibolite to granulite facies conditions between 930 to 920 Ma (e.g. Bingen et al. 2008b). The M2 stage took place at the end of a period of voluminous late orogenic magmatism during Sveconorwegian dilatation and relaxation. The grade and structures observed in the Iveland Wall correspond to the M2 stage. Applying PT estimates for M2 in southwestern Telemark by Bingen & van Breemen (1998) and Bingen et al. (1998), the interpolated pressure-temperature conditions during emplacement of the Evje-Iveland pegmatites (924 to 896 Ma) were close to 600° to 550°C at 4 to 5 kbars (corresponding to depths of 13.2 to 16.5 km).

The banded gneisses show migmatitic textures with leucocratic schlieren (neosomes; partially pegmatitic) flowing preferentially parallel to the ductile folded foliation and collect in larger, irregular batches of coarse-grained to megacrystic pegmatites. Almost all types of migmatite structures, like diktyonitic, schollen, phlebitis, stromatic, surreitic, schlieren and folded structures (Mehnert 1968) can be observed in the wall. Pegmatites in the northern part (left) of the wall are unzoned and contain euhedral magnetite (up to 4 cm) as major mafic mineral. In addition a single, 3-cm large rutile crystal is exposed. In the southern part (right) the pegmatites show simple zoning with granitic to blocky wall zone and quartz core. The major mafic mineral is 'biotite', indicating increasing water content in the melt compared to the magnetite-bearing pegmatites. There is a gradual transition between both pegmatite types. The Iveland Wall is a unique exposure were the differentiation of the anatectic-formed Evje-Iveland pegmatites can be observed in meter-scale.

The heat responsible for this M2 stage metamorphism and the widespread and voluminous late orogenic magmatism in the Telemark lithotectonic domain can be explained by large-scale and long-lasting mafic underplating generating high heat flows (Hansen et al. 1996; Andersen et al. 2002b; Vander Auwera et al. 2011). The underplating of the lower crust east of the Evje-Iveland area is evident from the emplacement of juvenile, mantle-derived material, such as the 940 Ma Tovdal granite, and from the presence of distinct, mantle-derived components in the other granites (Andersen et al. 2002a, b). In the area of Evje-Iveland the underplating caused melting of the amphibolites and banded gneisses. Field observations and geochemical modeling by Snook (2014) indicate that the pegmatites formed by 15 to 30% partial melting of Iveland-Gautestad amphibolites. Figure 2.14 shows the modelling result for the rocks of the Iveland Wall performed by Snook (2014). The REE composition of pegmatites exposed in the Iveland Wall ('Target') is achieved with 30% melting (approximately that observed in the wall) of the amphibolite gneiss ('Source').

The estimated quartz crystallization temperature of Evje-Iveland pegmatites (613° ± 70°C; Müller et al. (2015), which represents the minimum temperature of partial melting, is in the range of fluid-present partial melting of crustal rocks (650°–700°C; e.g., Brown & Korhonen 2009). However, the estimated regional temperature (600° to 550°C) in southwest Telemark is slightly below the fluid-present partial melting temperature. That might be due to the fact that precise PT estimates for the M2 stage are missing for the Evje-Iveland area. It is concluded that the Evje-Iveland pegmatites formed due to anatexis of metamorphosed intermediate and mafic rocks (amphibolites) of the Iveland-Gautestad intrusion (Müller et al. 2015). The water-rich pegmatite melts were probably too viscous to coalesce into large granitic intrusions and/or the subhorizontal compressive stress regime did not allow for large-scale melt segregation, coalescence, and transport.

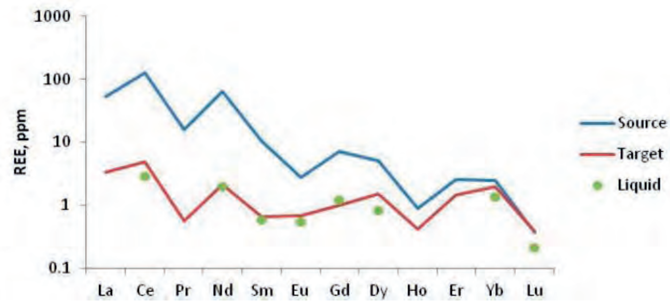


Figure 2.14. Geochemical modelling for batch partial melting of amphibolite gneiss of the Iveland Wall to produce the bulk composition of the pegmatites exposed at the same locality (Snook 2014). The green dots correspond to the modelled REE concentrations in the 'Liquid' (pegmatite melt) with 30% melting of the gneiss. The observed ('Target') and modelled ('Liquid') REE patterns are in good agreement implying that the amphibolite gneisses are most likely the source of the pegmatite melts.

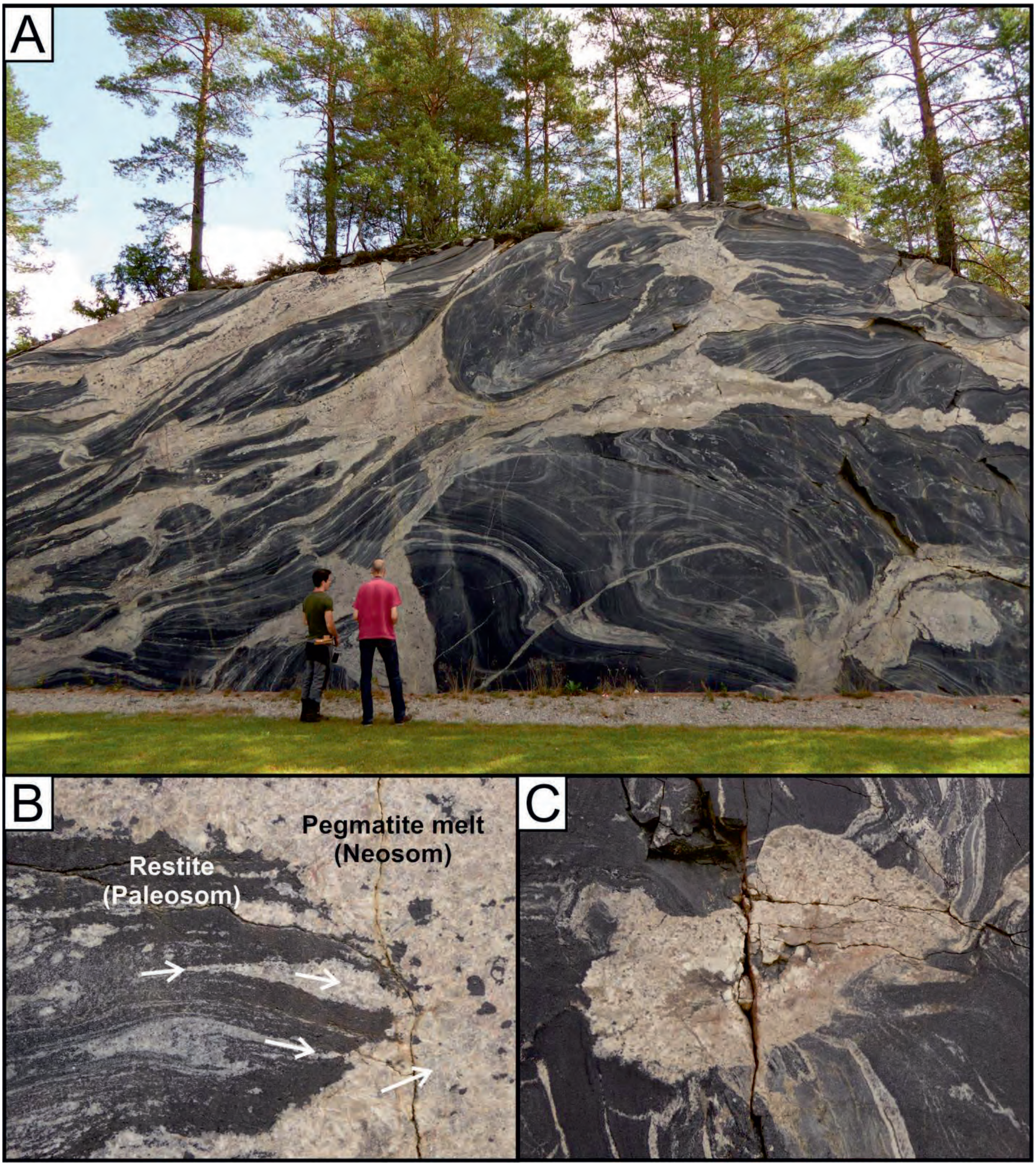


Fig. 2.13. A - Road cut in Iveland called "Iveland wall" (Evje-Iveland pegmatite field) representing a snapshot of anatectic melting of amphibolites (Iveland-Gautestad amphibolites) and the formation of leucocratic pegmatite melt (neosome). B – Detail of the road cut exposing the relationship between restite and expelled leucogratic pegmatite melt. C – Detail of the road cut showing a zoned pegmatite with graphic wall zone, coarse-grained intermediate zone, and quartz core. From Müller et al. (2017a).

Locality 2.4: Mineral collection of the Iveland municipality

Highlights

The finest exhibition of minerals from Evje-Iveland pegmatites

Coordinates EU89-UTM Zone 32V 436762E/ 6479830N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Ivelandsveien/Kilefjorden Camping (County Road 403 Ivelandsveien) and travel east towards Iveland for 8 km to the junction in the center of the Iveland village and turn left and turn left again after 50 m into the parking place of the Centre Building Åkle. The exhibition of the mineral collection of the Iveland municipality is in the ground floor of Centre Building Åkle. The exhibition is opened Monday to Friday 09.00-20.00 and Saturday 09.00-18.00.

Distance to walk: 0 km
Elevation changes: 0 m
Excursion time: ½ hour

In 1971 the council of the Iveland municipality voted for buying the mineral collection of the local miner and amateur geologist Olaf Landsverk (1887-1966) (Fig. 2.15). Olaf Landsverk is known as one of the first and greatest mineral collectors in southern Norway. He was often visited by collectors and geologists from all over the world exchanging minerals and knowledge. He had a collection of about 500 specimens of more than 200 different minerals from Evje-Iveland and other Norwegian and international localities. His collection and knowledge made him a central figure amongst other collectors and geologists both in Norway and abroad. Landsverk received H.M. the Kings Gold Medal in 1960 for his lifework in geology in Iveland. The purchase of his collection was the start of the mineral collection of the Iveland municipality, which since then has continuously developed and extended and contains today only minerals from the Evje-Iveland area. From 1972 until today Kjell Gunnufsen, geological consultant of the Iveland municipality, has been responsible for maintenance, preparation and acquisition of new minerals for the collection. Thanks to the interest for the municipality's mining history and geology, both the municipality administration and local politicians have always been positive in supporting and financing the collection and related exhibition. The main objective to improve of the collection has been to remove specimen from foreign and other Norwegian localities and replace them by local minerals of highest possible quality and mineralogical and scientific interest. The Iveland municipality supported the collection work with half a million Norwegian Kroner over the years and about 60 persons have contributed with donations.

Today the collection comprises 808 local specimens. Highlights of the collection are a large block with several beryl crystals, the largest being 70 cm long, several thortveitite crystals up to 25 cm in length, a 17-kg heliodor, a euhedral spessartine 7.5x6 cm in size, gadolinite-(Y) 10x6 cm from the Landsverk area, a 2-kg mass of davitite-(Ce), a group of aeschynite-(Y) crystals 10x20 cm from Mølland, a group of monazite crystals with crystal sizes of up to 2.5 cm, etc. (Fig. 2.16). From 1987 to 2015 part of the collection was exhibited in the community house of Iveland. In March 2015 a new exhibition, the result of cooperation with the Setesdalsmuseet, was opened in the neighbouring Centre Building Åkle. Beside the minerals, the exhibition also provides some information about the local mining history. An information booklet in four languages (Norwegian, German, English, Dutch) is available in the exhibition area.

Fig. 2.15. The local miner and mineral collector Olaf Landsverk (1887-1966). His collection of minerals from Evje-Iveland pegmatites was the start and is still the base of the mineral collection of the Iveland municipality.

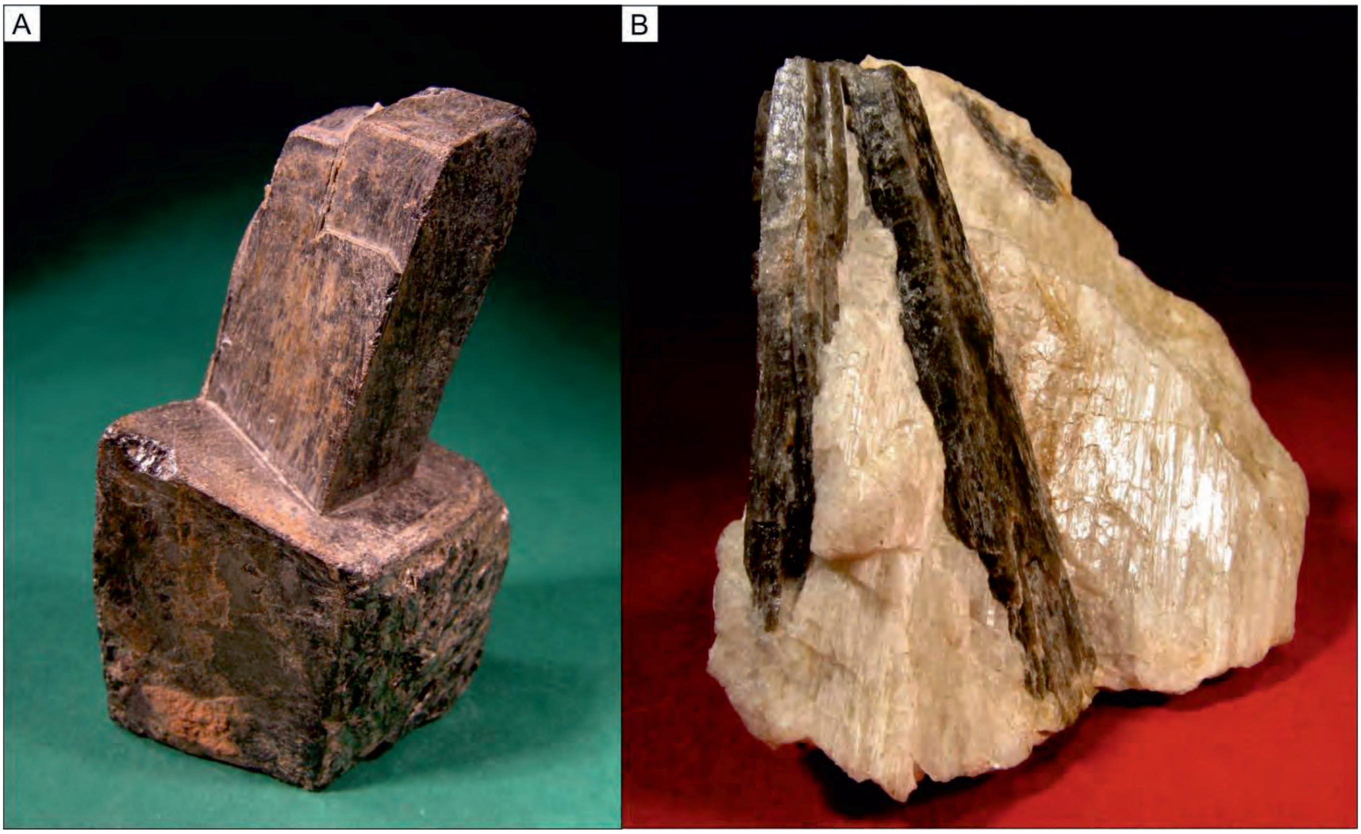


Fig. 2.16. Minerals of the Iveland municipality collection. A – Aeschynite-(Y) crystal (6.5 cm) from Mølland. The specimen is part of the original Olaf Landsverk collection. Photo by Kjell Gunnusen and Ronald Werner. B – Thortveitite crystals on plagioclase from the Tuftane mine at Frikstad. The length of the longer crystals is 6 cm. Photo by Kjell Gunnusen and Ronald Werner.

Locality 2.5: Solås pegmatite

Highlights

Mixed NYF-LCT pegmatite of the rare element class with ‘amazonite’ and ‘cleavelandite’ replacement zone exposed in a 4-m high wall

Coordinates EU89-UTM Zone 32V 437086E/6483790N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Ivelandsveien/Kilefjorden Camping (County Road 403) and travel east towards Iveland for 8 km to the junction in the centre of the Iveland village. Turn left here into the Road 291 (Frikstadveien) and drive for 4 km northward. The excursion bus has to stop at the junction where the dirt road to the Solås farm branches off (UTM Zone 32V 437352E/6483784N). A small parking lot for two passenger cars is located on the left side of the dirt road after 300 m. From the bus stop walk for 400 m along the dirt road and then turn to the right into the tractor track which leads after 150 m to the Solås mine (Fig. 2.17). The Solås mine is a small abandoned quarry open for mineral collectors. The site is on private land and an entrance fee of 100 NOK should be paid when taking samples (there is a payment box at the mine entrance). The exposures are relatively fresh and there is plenty material at the dumps in front of the wall and around the mine.

Distance to walk: 0.6 km
Elevation changes: 30 m
Excursion time: 1 ½ hour
Conservation status: None

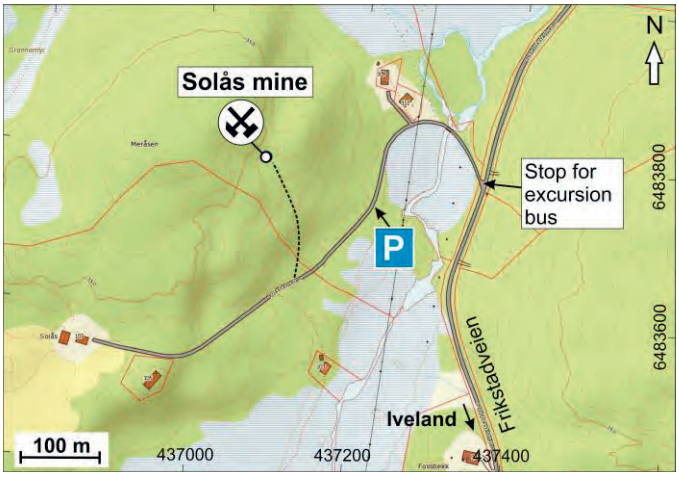


Fig. 2.17. Access map for the Solås mine.

Pegmatite zoning and host rocks

The Solås pegmatite comprises an up to 5 m thick, sub-horizontal sheet with a lateral extension of at least 300 m (Fig. 2.18). Southwest of the mine the sheet branches into two apophyses. The country rock is banded amphibole gneiss (Vånne banded gneiss; 1459 ± 8 Ma), which is partially migmatitic. The contact between the pegmatite and gneiss is relatively sharp.

The pegmatite shows a vertical zoning, consisting of a fine-grained granitic upper border zone (<5 cm), a coarse-grained granitic upper wall zone with 'biotite' as mafic mineral, a megacrystic intermediate zone dominated by graphic K-feldspar and 'biotite', a core zone with massive quartz and feldspar and muscovite booklets, a lower intermediate zone dominated by graphic plagioclase, allanite-(Ce) and spessartine, and a lower wall zone made of plagioclase with accessory magnetite and polycrase-(Y) (Fig. 2.19). The bulk pegmatite has NYF-type characteristics but is poor in F. The vertical structural zoning appears symmetrically; however, the mineralogical and chemical zoning is asymmetric. 'Biotite' (water-bearing Fe-phase) and K-feldspar are enriched in the upper wall and intermediate zone, whereas magnetite (water-free Fe-phase) and plagioclase are enriched in the lower wall and intermediate zone. The zoning indicates an internal fractionation of the pegmatite melt and, thus, the crystallization was presumably relatively slow.

This primary zoning is overprinted by late pegmatitic (metasomatic), REE-depleted replacement zones consisting of 'cleavelandite' (platy albite), quartz and muscovite and minor topaz, spessartine, columbite and microlite group minerals, fluorite, garnet, beryl, and black tourmaline. The replacement zone has a reaction aureole ("metasomatic zone" according to Frigstad 1968) characterized by 'amazonite' and colour-zoned almandine-spessartine with the dark red brown core and orange margin (Frigstad 1968; Müller et al. 2012a).

The scheme in Figure 2.19 illustrates the zoning of the Solås pegmatite with the location of replacement zone and the surrounding reaction zone as exposed in 2012. The replacement zone has a chemical and mineralogical LCT signature (Černý 1991) and hence these pegmatites are considered as mixed NYF-LCT pegmatites (Müller et al. 2012a). In contrast to "normal" LCT pegmatites, the replacement zones in Evje-Iveland are enriched in Cs and Ta but very poor in Li.

About 10 % of the c. 400 pegmatites in Evje-Iveland display such replacement zones. In general pegmatites with replacement zones seem to be erratically distributed over the entire Evje-Iveland pegmatite field. However, a cluster of these pegmatites occurs in the Birkeland area (centre of the pegmatite field), from where the largest replacement zones of up to 100 m^3 have been described (Frigstad 1968). The replacement zones are volumetrically small, 2 to 100 m^3 compared to the average size of the Evje-Iveland pegmatites which is about 15,000 m^3 (Müller et al. 2015). The replacement zones usually occur at the bottom of the core zone but can also extend into external parts of the pegmatite body.

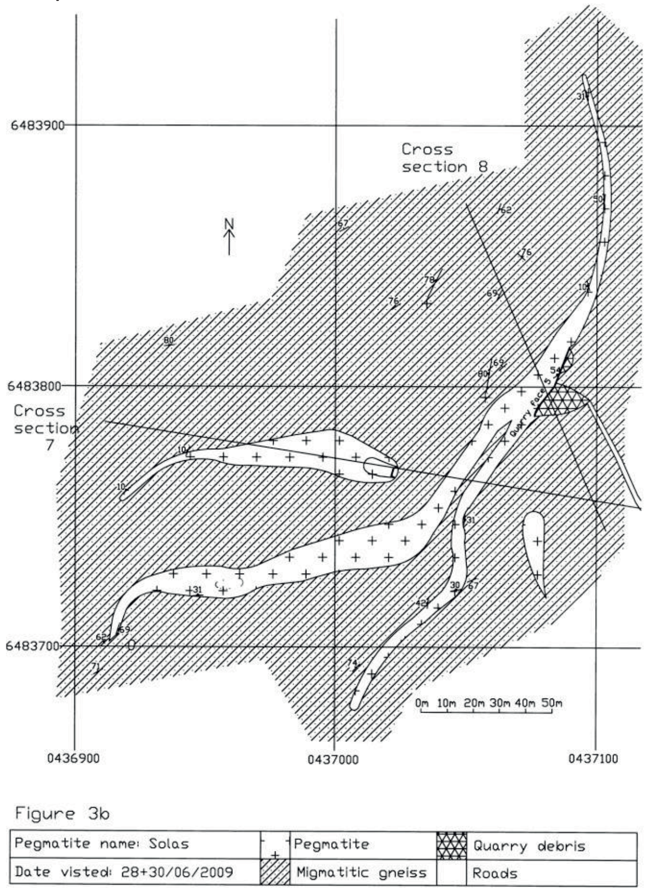


Fig. 2.18. Geological map of the Solås pegmatite by Uren (2010). The visiting site corresponds to the location of the quarry debris.

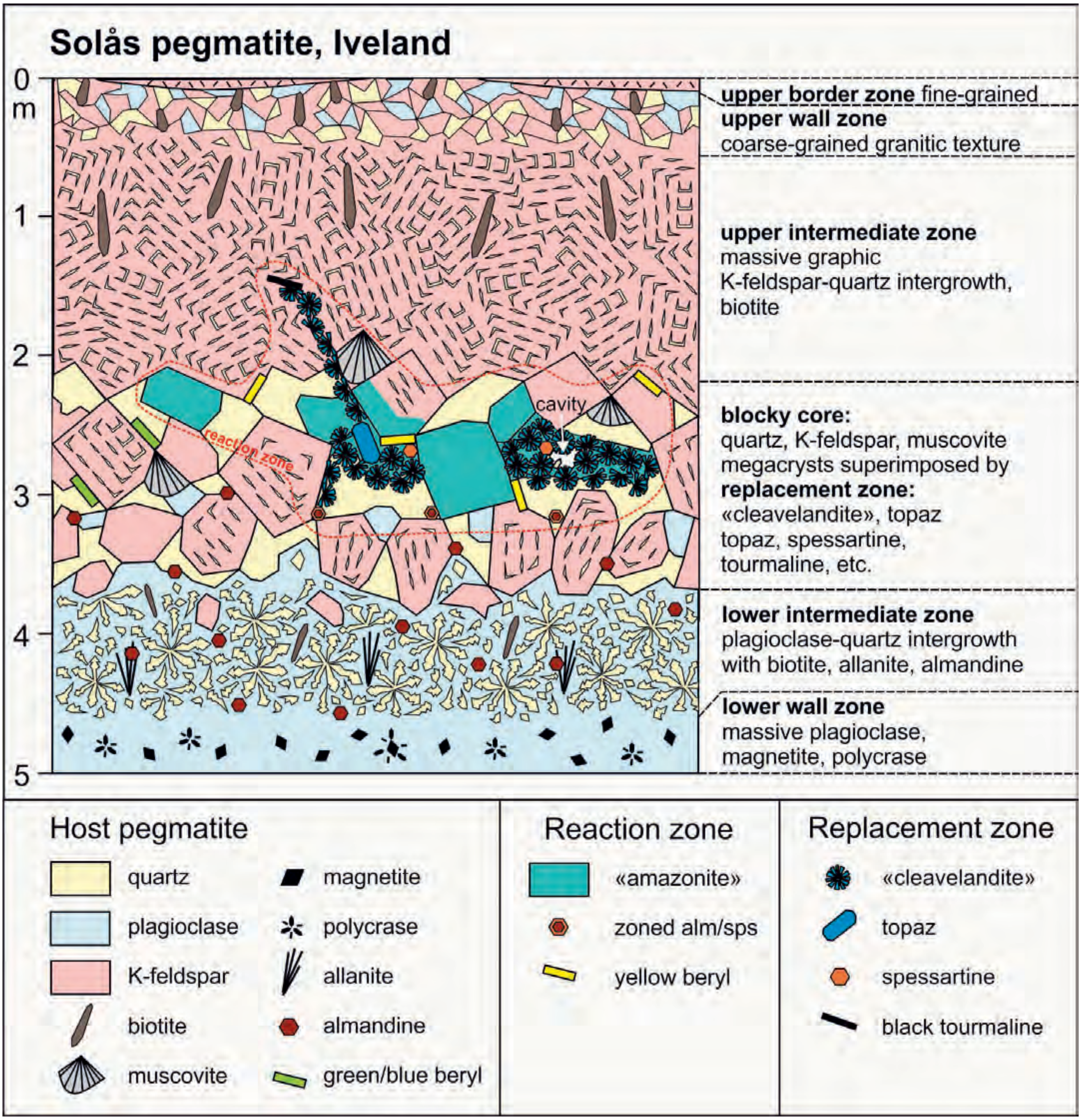


Fig. 2.19. Simplified zoning of the Solås pegmatite. From Müller et al. (2017b).

Mineralogy

The primary pegmatite assemblage comprises the major minerals quartz, K-feldspar, plagioclase, 'biotite' and muscovite. Most common accessory minerals are spessartine, magnetite, ilmenite, allanite-(Ce), monazite-(Ce), polycrase-(Y), and beryl in various colours. The complete list of minerals is given in Table 2.4. 'Biotite' has Mg siderophyllite to siderophyllite composition. The Li_2O content of Fe muscovite varies between 0.1 and 0.4 wt.% and F between 0.1 and 0.5 wt.% (Rosing-Schow et al. 2017). Scandium concentrations are up to 354 ppm in muscovite and up to 182 ppm in siderophyllite. Pink K-feldspar has high Ba (mean 3240 ppm) and Sr (mean 634 ppm) and low Cs (30 ppm) and Rb (401 ppm) (Table 2.5). Magnetite forms large (up to 6 cm) dipyramidal crystals in the lower wall zone. They are intergrown with and surrounded by platy polycrase-(Y) crystals up to 1 cm in size. Allanite-(Ce) occurs as aggregates of fan-like arranged, needle-like crystals in the lower intermediate zone (Fig. 2.20). The fans are intergrown with euhedral, dark red-brown garnet (up to 4 cm in size). Kjell Gunnufsen reports a euhedral, 30-cm long allanite-(Ce) crystal with a dimater of 2 to 3 cm. The allanite-(Ce) was surrounded by several polycrase-(Y) crystals up to 3 cm in size. Beryl is relative common at Solås. The crystals which are commonly subhedral to anhedral are greenish to bluish and up to 40 cm in length. Some of the aquamarines have gemmy domains which have been used for manufacturing of faceted stones. Beryl from Solås contains in average 223 ppm Li and 591 ppm Cs which is relatively low compared to beryl from other Evje-Iveland pegmatites (Fig. 2.21). Thus, beryl is beside muscovite the major carrier of Li.

Table 2.4. Minerals identified in the Solås pegmatite. Modified from Mindat (2017).

Mineral name	Mineral name	Mineral name
Albite (var. 'Cleavelandite')	Euxenite-(Y)	Pyrochlore Group
Allanite-(Ce)	Fergusonite-(Y)	Pyrophanite
Almandine	Fersmite	Pyrrhotite
'Amazonite'	Fluorite	Quartz
'Apatite'	Gadolinite-(Y)	Samarskite-(Y)
Bastnäsite-(Ce)	Gahnite	Siderophyllite
Bertrandite	Hellandite-(Y)	Spessartine
Beryl (var. aquamarine, heliodor)	Ilmenite	Tantalite-(Fe)
'Biotite' (Siderophyllite)	Magnetite	Tantalite-(Mn)
Bismutite	Microcline	Topaz
Calcioancylite-(Ce)	Microlite Group	'Tourmaline'
'Cleavelandite'	Monazite-(Ce)	Xenotime-(Y)
Columbite-(Fe)	Muscovite (Fe muscovite)	Yttrotantalite-(Y)
Epidote	Polycrase-(Y)	Zircon

Table 2.5. Average composition of feldspars from Solås. Bulk XRF analyses. Data from Müller, unpublished. n = number of analyses.

	pink K-feldspar	transitional pink K-feldspar/ 'amazonite'	'amazonite'	'cleavelandite'
	n=4	n=3	n=3	n=3
major elements (wt.%)				
SiO_2	64.61	65.37	64.77	68.26
Al_2O_3	18.60	18.46	18.36	19.32
Fe_2O_3	0.08	0.04	0.04	0.02
TiO_2	<0.01	<0.01	<0.01	<0.01
MgO	<0.04	<0.04	<0.04	<0.04
CaO	0.07	0.03	<0.01	0.10
Na_2O	2.63	3.43	1.97	12.05
K_2O	12.86	11.84	13.58	0.33
MnO	<0.01	<0.01	<0.01	<0.01
P_2O_5	0.02	0.02	0.03	0.02
LOI	0.40	0.44	0.68	0.35
Sum	99.30	99.57	99.41	100.65
An	0.3	0.1	0.1	0.4
Ab	23.7	30.5	18.1	97.8
Or	76.0	69.3	81.9	1.8
trace elements (ppm)				
Ba	3240	50	21	<10
Cs	30	266	1416	22
Ga	16	49	66	87
Pb	101	151	123	46
Rb	401	3182	7530	76
Sr	634	7	9	3
Ta	1	0	0	9
Y	2	5	26	2

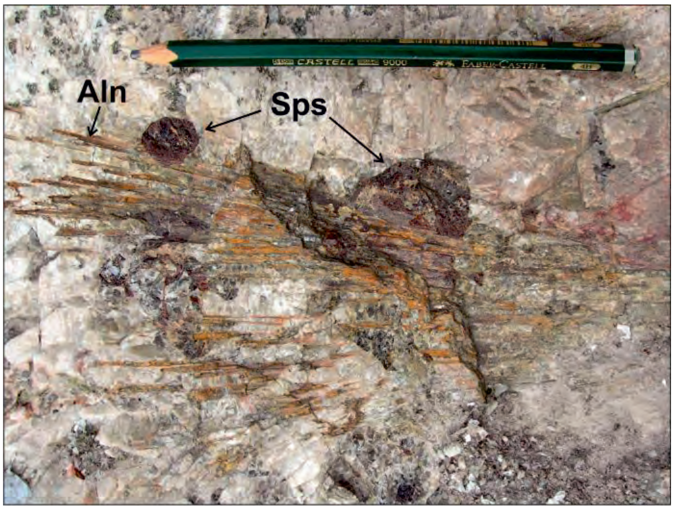


Fig. 2.20. B. Euhedral crystals of spessartine (Sps) intergrown with altered needles of allanite-(Ce) (Aln) in the intermediate zone of the Slobrekka pegmatite. The appearance of allanite-(Ce) at Solås is very similar. From Müller et al. (2012a).

The major constituents of the *replacement zone* are 'cleavelandite', greenish and pinkish muscovite, topaz, fluorite, spessartine and quartz, and accessory columbite and microlite group minerals, black tourmaline, monazite-(Ce), zircon, and 'apatite' (Frigstad 1968, 1999). This mineral paragenesis is very different from the mineralogy of the host pegmatite.

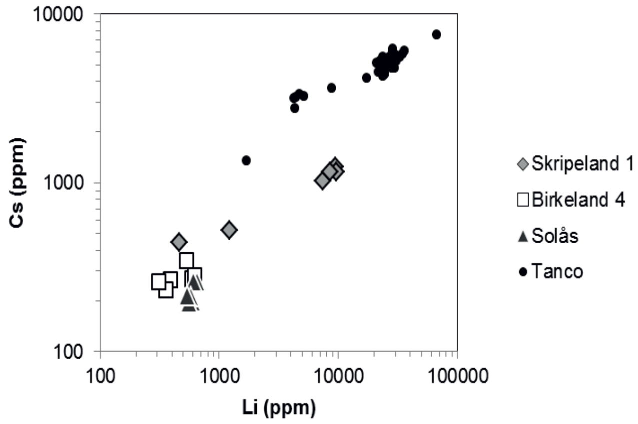


Fig. 2.21. Plot of Li and Cs concentrations in beryl from different Evje-Iveland pegmatites (Solås, Skripeland 1, Birkeland 4) and compared with beryl data from the Tanco LCT pegmatite, Manitoba, Canada (Černý 1977). Evje-Iveland data from Müller et al. (2017b).

Chemical differences are enrichments in Na, Ta, Mn, F, and B and depletions in REE, Ti, Fe of the replacement zones. Modal compositions determined on the base of image analyses (distribution of topaz and fluorite) revealed a minimum content of at least 4 wt.% F of the replacement zone (Müller et al. 2017b).

'Cleavelandite' forms characteristic spheroidal aggregates of platy crystals (up to 10 cm in size) or interleaved fans penetrating, replacing and superimposing minerals of consolidated parts of the pegmatite body. Veinlets of fine-grained, sugary albite extend from the coarse-grained 'cleavelandite' into neighbouring 'amazonite' and pinkish K-feldspar as well. Occasionally, star-like 'cleavelandite' aggregates occur isolated in K-feldspar megacrysts in some distance from the replacement zone. 'Cleavelandite' has an almost pure albite composition and contains high Ga (mean 87 ppm) and Ta (mean 9 ppm), and low Sr, Rb, Ba and Cs (Table 2.5). At Solås topaz occurs as large (3 to 30 cm) white to pale yellow, anhedral to subhedral crystals (Figure 2.22). The crystals are partially intergrown with 'cleavelandite' and are covered by small, pinkish, Mn-rich micas. The largest topaz found in Evje-Iveland pegmatites weighs about 80 kg.

Green and violet fluorite occurs as anhedral masses between 'cleavelandite' plates or in micro cavities. Spessartine is red brown to orange in colour and forms irregular masses up to 5 cm in size between 'cleavelandite' plates. Gemmy, etched orange spessartine crystals have been found in an open cavity (50 cm in size) (Fig. 2.23) within 'cleavelandite' masses together with smoky crystal quartz, and 2-3 kg of massive fluorite. The orange garnet from Solås has a spessartine component up to 93 % (Stokkeland 2016) (Table 2.3; Fig. 2.24). Due to the peralkaline nature of the replacement zone quartz precipitated only during the final stage of the replacement zone evolution mostly as fillings in micro cavities or euhedral crystals (up to 12 cm) in pockets.

Fig. 2.22. Large topaz crystal with remnants of 'cleavelandite' from the replacement zone of the Solås pegmatite.

Columbite group minerals from the replacement zone of Solås have the most diverse and most evolved chemistry compared to other Evje-Iveland localities (Fig. 2.25). The data plot in the columbite-(Fe) and tantalite-(Mn) fields imitating two chemical trends: (1) the "beryl type" trend and (2) the "complex lepidolite type" trend according to Černý (1989). Tantalite-(Mn) forms small millimetric crystals embedded in a matrix of fine-grained 'cleavelandite' and green fluorite (Lund 2016), whereas columbite-(Fe) crystals are up to 8 cm in size and occur together with coarse, platy 'cleavelandite'. According to Černý (1989) the "complex lepidolite type" trend is typically for columbite group minerals occurring in complex zoned LCT pegmatites. The occurrence of tantalite-(Mn) at Solås seems to be in conflict with the overall NYF affinity of the Evje-Iveland pegmatites; however, it confirms the mineralogical LCT type characteristics of the described replacement zones. Euhedral crystals of microlite group minerals up to 1 cm in size were found in between 'cleavelandite' plates. These crystals are very rare.

A 15x40 cm large cavity was discovered in the replacement zone under blasting in the 1980's (Kjell Gunnufsen, personal communication). It is the only larger cavity reported from Solås. The walls of the cavity were plastered 'cleavelandite' masses and smoky crystal quartz (up to 12 cm) and filled with etched spessartine crystals, green fluorite masses (2-3 kg). The quartz crystals are rich in micro inclusions, including needle-like black tourmaline, muscovite "trees" and a number of unidentified needle-like minerals with metallic lustre (Kjell Gunnufsen, personal communication). In addition to the large cavity several small cavities (~5 cm) were found. Some of these small cavities contained needle-like schorl decorated with tiny, euhedral muscovite flakes.

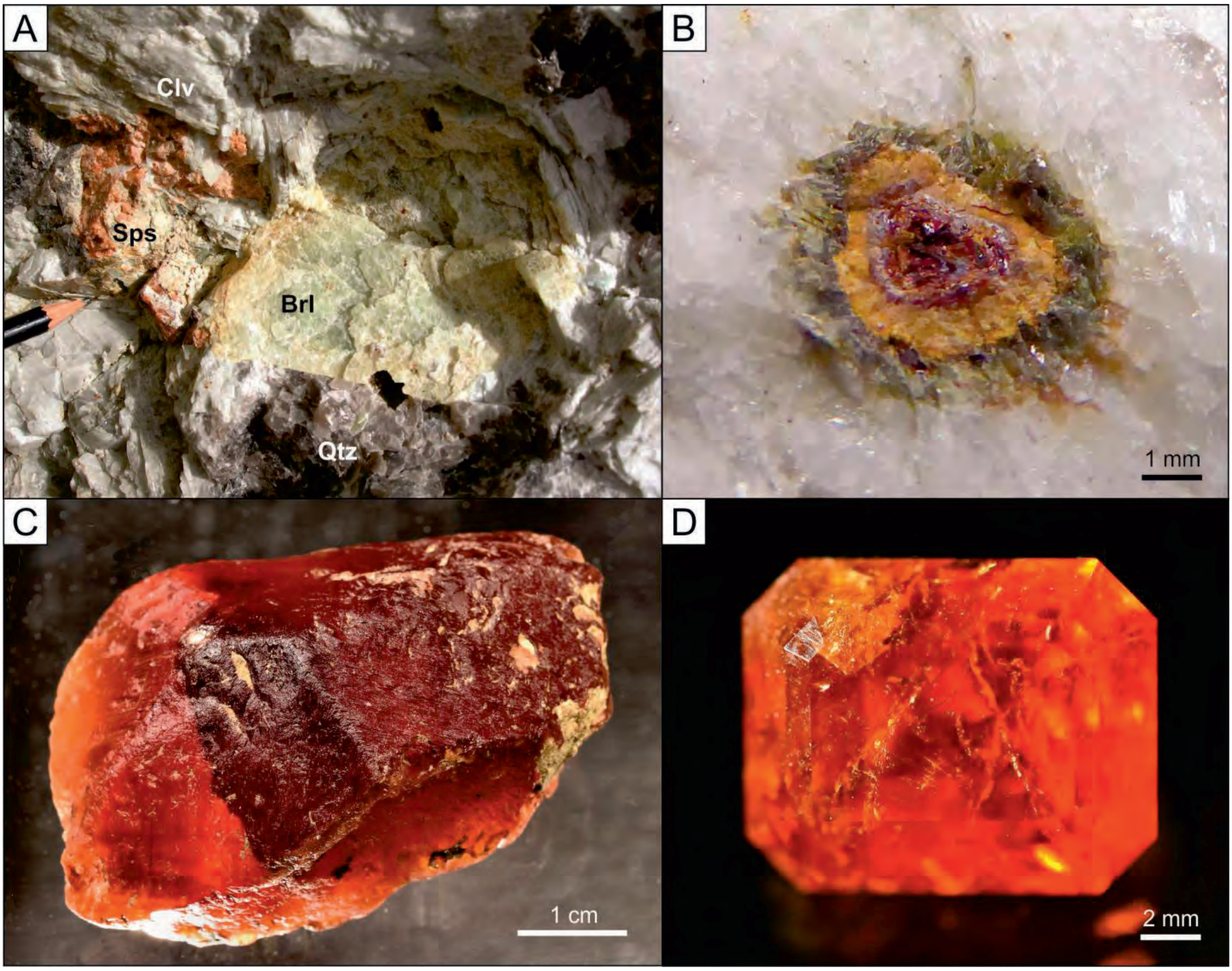


Fig. 2.23. A – Irregular mass of orange spessartine (Sps) surrounded by beryl (Brl), 'cleavelandite' (Clv) and quartz (Qtz) in the replacement zone of the Solås pegmatite. From Müller et al. (2012a). B – Zoned garnet with almandine core and yellowish orange spessartine margin surrounded by green muscovite from the reaction zone at Solås. From Müller et al. (2017b). C – Etched spessartine crystal from a cavity at Birkeland, supposedly Røykkvartsbrudd. Similar spessartine crystals were found at Solås. Photo by Ronald Werner. D – Faceted spessartine from the Birkeland area, supposedly Røykkvartsbrudd. Photo by Ronald Werner.

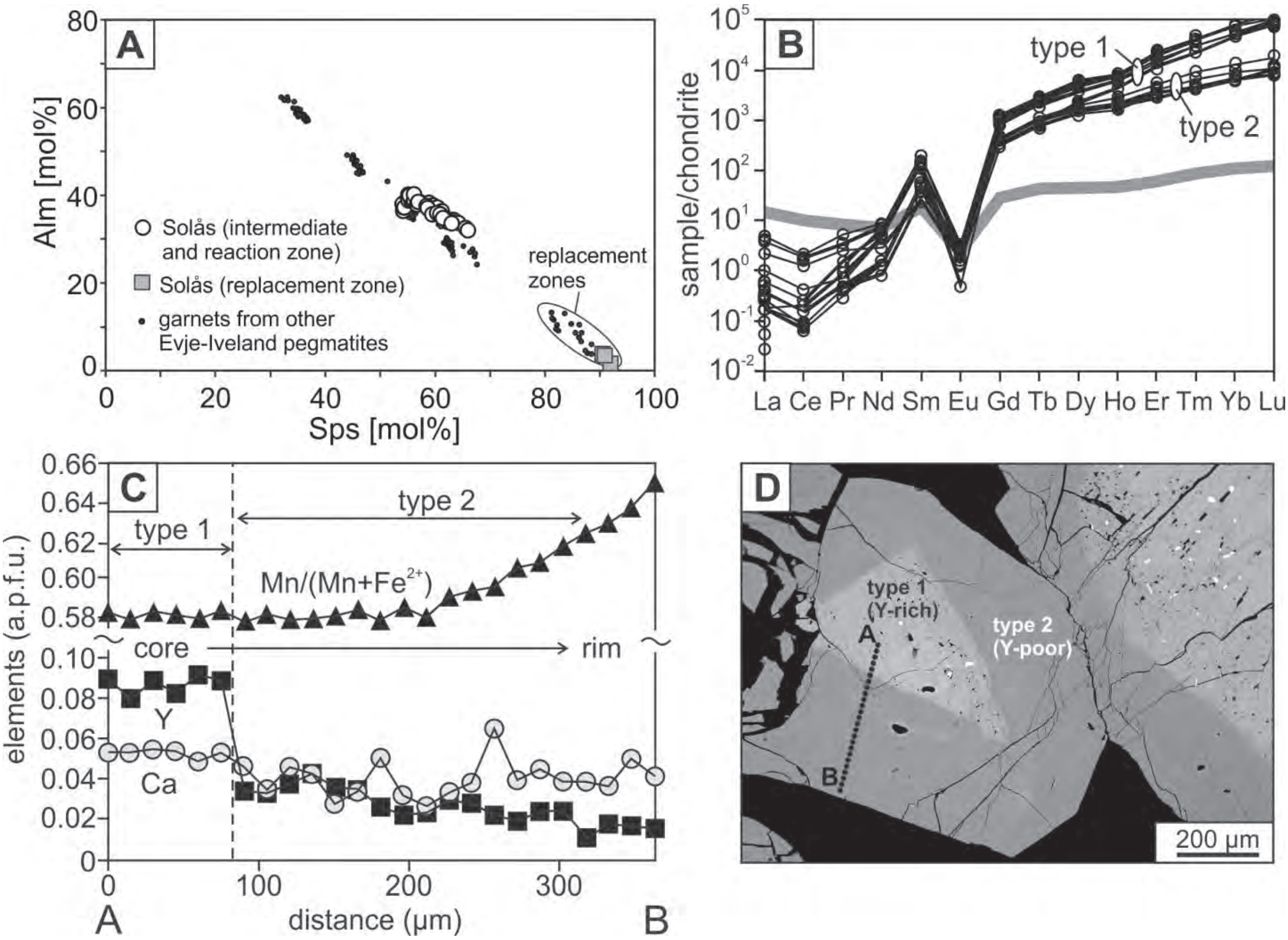


Fig. 2.24. Chemistry of zoned garnet from the reaction zone of the Solås pegmatite (similar garnet type as shown in Figure 2.23). A - Spessartine (Sps) versus almandine (Alm) component plot. The major chemistry of the garnet indicates relative high differentiation degree of the pegmatite melts (compared to Steli and Li gruve). B - Chondrite-normalized REE pattern of Solås garnet from the reaction zone. The grey-shaded REE pattern is the bulk composition of the wall zone, representing roughly the bulk composition of the pegmatite. The garnet analyses were performed with LA-ICP-MS. C - Profile of the Ca and Y content in atoms per formula unit (apfu) and the Mn/(Mn + Fe^{2+}) value of garnet from Solås (intermediate and reaction zone). The analyses were performed with electron microprobe. D – Backscattered electron image of spessartine from the reaction zone of the Solås pegmatite showing a bright grey, Y-rich core (type 1) with a dark grey, Y-poor overgrowth (type 2). The black dots correspond to the analytical profile shown in (C). The Y-rich type 1 crystal has been etched before the overgrowth. The white spots are micro inclusions of gadolinite-(Y), ‘yttrofluorite’, and microlite group minerals. Data from Müller et al. (2012a), Stokkeland (2016) and Müller et al. (2017b).

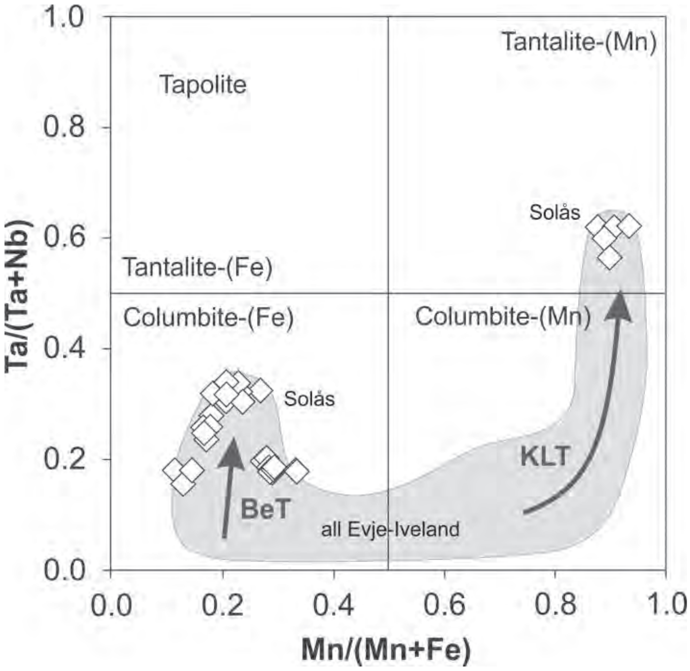


Fig. 2.25. Quadrilateral classification diagram of columbite-group minerals according to Černý (1989) showing the variation in Mn-Fe and Ta-Nb ratios of columbite group minerals (three different crystals) from Solås compared with data from other Evje-Iveland pegmatites (grey shaded area). Concentrations were determined with EPMA. BeT – beryl type trend, KLT – complex lepidolite type trend according to Černý (1989). Data from Lund (2016) and Müller et al. (2017a, 2017b).

Zircon is more common in the replacement zones than in the host pegmatite. It forms cauliferous aggregates of needle-like crystals commonly intergrowth with ‘cleavelandite’ whereas zircon in the host pegmatite has short-prismatic habitus. Monazite-(Ce) forms yellow brown anhedral crystals with low Th content which is different to high-Th monazite-(Ce) found in the host pegmatite (Frigstad 1968). Apatite is very rare and occurs as whitish to bluish anhedral masses between ‘cleavelandite’ plates or filling micro fractures in spessartine and beryl. An aggregate of spherically arranged, black tourmaline needles about 10 cm in size was exposed in 2009. In general, the chemistry of tourmaline from Evje-Iveland replacement zones is unknown. Frigstad (1968) describes small tourmalines (up to 5 mm) of different colours from different replacement zones in Evje-Iveland and one analysis gave elbaite composition. Frigstad (1968) described also bismutite from Solås and interpreted it as an alteration product of bismuthinite belonging to the primary pegmatite assemblage. However, Bi-bearing minerals are a common constitute of the Evje-Iveland replacement zones (Müller et al. 2017b).

The *reaction zone* (aureole), which surrounds the replacement zone and was named “metasomatic zone” by Frigstad (1968), is characterized macroscopically by the occurrence of ‘amazonite’ (up to 1 m in size), colour-zoned garnets and yellow to white beryl. ‘Amazonite’ does not belong to the replacement zone assemblage but is - in Evje-Iveland pegmatites - always spatially associated with it. ‘Amazonite’ itself does not replace other minerals and has commonly euhedral habit. The greenish colour of the Evje-Iveland ‘amazonite’ is less intense than the colour of ‘amazonite’ from classical occurrences, such as Pikes Peak in Colorado, USA, or Western Keivy Massif at the Kola Peninsula, Russia. Intra-crystal transitions from pinkish to greenish colour can be observed in K-feldspar megacrysts at Solås. ‘Amazonite’ has high Rb (mean 7530 ppm) and Cs (mean 1416 ppm) and low Sr and Ba (Table 2.5) (Müller et al. 2017b). The highest Cs value in ‘amazonite’ from Solås detected by Müller et al. (2017b) is 2004 ppm. Frigstad (1968) analysed up to 3000 ppm Cs in ‘amazonite’ from other Evje-Iveland localities. Interestingly, the Pb content, which is supposed to be responsible for the green colour of ‘amazonite’, is similar to pink K-feldspar. The plot in Figure 2.26 reveals a gradual chemical transition from pink K-feldspar to ‘amazonite’. Interestingly, Cs concentrations of the Evje-Iveland ‘amazonites’ are in the same range as K-feldspars from the strongly Li-Cs-enriched Tanco pegmatite in Manitoba, Canada. The Tanco pegmatite is considered as the classical LCT pegmatite (Černý et al. 1985). Thus, the ‘amazonites’ from Evje-Iveland have a chemical LCT signature although they are hosted by pegmatites belonging to the NYF family considering the ‘primary’ (non-replacement-zone-related) mineralogy.

Colour-zoned spessartine with a dark red brown core and orange margin, which was first described (Frigstad 1968; Fig. 2.23B), is a typical indicator of the reaction zone. The zoning is caused by sudden decrease of the Y content combined with a smooth increase of the Fe/(Fe+Mn) ratio (Figs. 2.23C,D). The ‘primary’ Y-rich garnets seem to be partially replaced by Y-poor garnet overgrowths. Yellow and white beryl is also an indicator of the reaction zone. In the replacement zone beryl is commonly altered to and replaced by chlorite, bertrandite and other minerals. Beryl of greenish to bluish colour is a common constituent of the host pegmatite (Frigstad 1968).

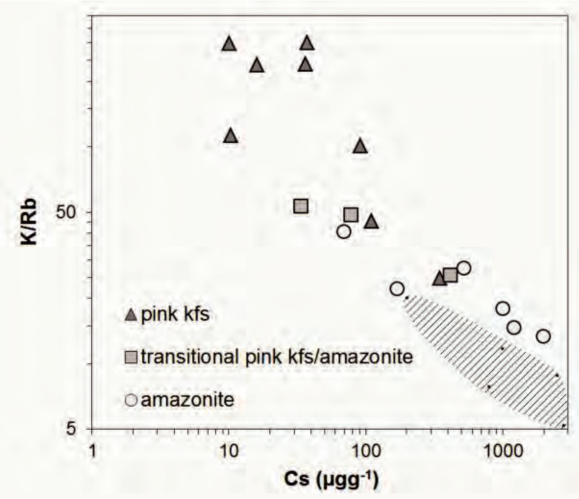


Fig. 2.26. Caesium versus K/Rb plot of pink K-feldspar and 'amazonite' from Evje-Iveland pegmatites. The hatched area corresponds to K-feldspar composition of the Tanco pegmatite in Manitoba, Canada (Černý et al. 1985). Evje-Iveland data from Müller et al. (2017b).

Locality 2.6: Beryllen Mineral Senter

Highlights

Mineral store selling minerals from Evje-Iveland pegmatites and other Norwegian and international localities

Coordinates EU89-UTM Zone 32V 428114E/ 6475282N

Directions and Access

The Beryllen Mineral Senter next to the National Road 9 in the village center of Kile with the Kilefjorden lake to the east. The parking lot is next to the store.

Distance to walk: 0 km
Elevation changes: 0 m
Excursion time: 1 hour

The mineral store 'Beryllen Mineral Senter' is located in the village centre of Kile next to the National Road 9 (Beryllen 2017) (Fig. 2.27A). The store is run by Arild Omestad. Arild is a representant of the last generation of miners of Evje-Iveland pegmatites. He started working as a miner for Theodor Gautestad in 1966 in the Beinmyra pegmatite mine. In this mining season a number of fine beryl, monazite-(Ce), euxenite-(Y), and columbite-(Fe) specimens were found by Arild and one of the monazite-(Ce) is exhibited in the Fennefoss Geomuseum in Evje. The Beinmyra mine became later on famous for findings of large beryl crystals weighting up to 1.65 ton. In 1967, when Arild was 16 years old, he bought a tractor, compressor and drilling equipment, started his own business and leased 6 pegmatite mines (e.g. Granatgruve, Kongsbergruve, Slobrekka, Høyland, Håverstad) for exploitation of quartz and feldspar. From 1970 on he worked for several local construction and mining companies. Between 1998 and 2002 Arild worked occasionally in his sparetime in the Brattekleiv mine at Lauvland and Storsynken mine at Knipane for mineralogical interest. The Brattekleivgruve was rich in beryl, monazite-(Ce) and columbite-(Fe)/columbite-(Mn) (Fig. 2.27B). At Storsynken, Arild found plenty of titanite, epidote, monazite-(Ce), xenotime-(Y), bluish 'apatite'and large clusters of pyrite crystals (c. 100 kg) after pumping 2500 m^3 of water out of the mine (Fig. 2.27C). A number of these minerals are exhibited at the Iveland municipality museum and Fennefoss Geomuseum in Evje. In 2002 he got the licence to rework the mine dumps at Slobrekka and found numerous fine gadolinite-(Y) crystals. Arild always had the dream to have his own mineral shop. The dream became true in 2002, when he got the opportunity to rent the building of the former Hægeland railway station. Since then Arild is running his mineral shop which is open every day during summer and on weekends during the winter season. Unfortunately, his lease contract for the former railway station will run out at the end of 2017 and by then the last local mineral shop will have closed down.

The wooden building hosting the store was the Hægeland railway station of the Setesdalbanen designed by Paul Due and built in 1895 (Fig. 2.27D). The Setesdalbanen was a railway between Kristiansand and Byglandsfjord in southern Norway, 78 km long, which opened in 1896. Beside passengers the railway transported timber, nickel and feldspar from Evje and other places to the Kristiansand harbor. The nickel ore was mined in the Flåt mine next to the Landsverk 1 pegmatite and processed in the Fennefoss smelter in Evje. The railway was closed in 1962.

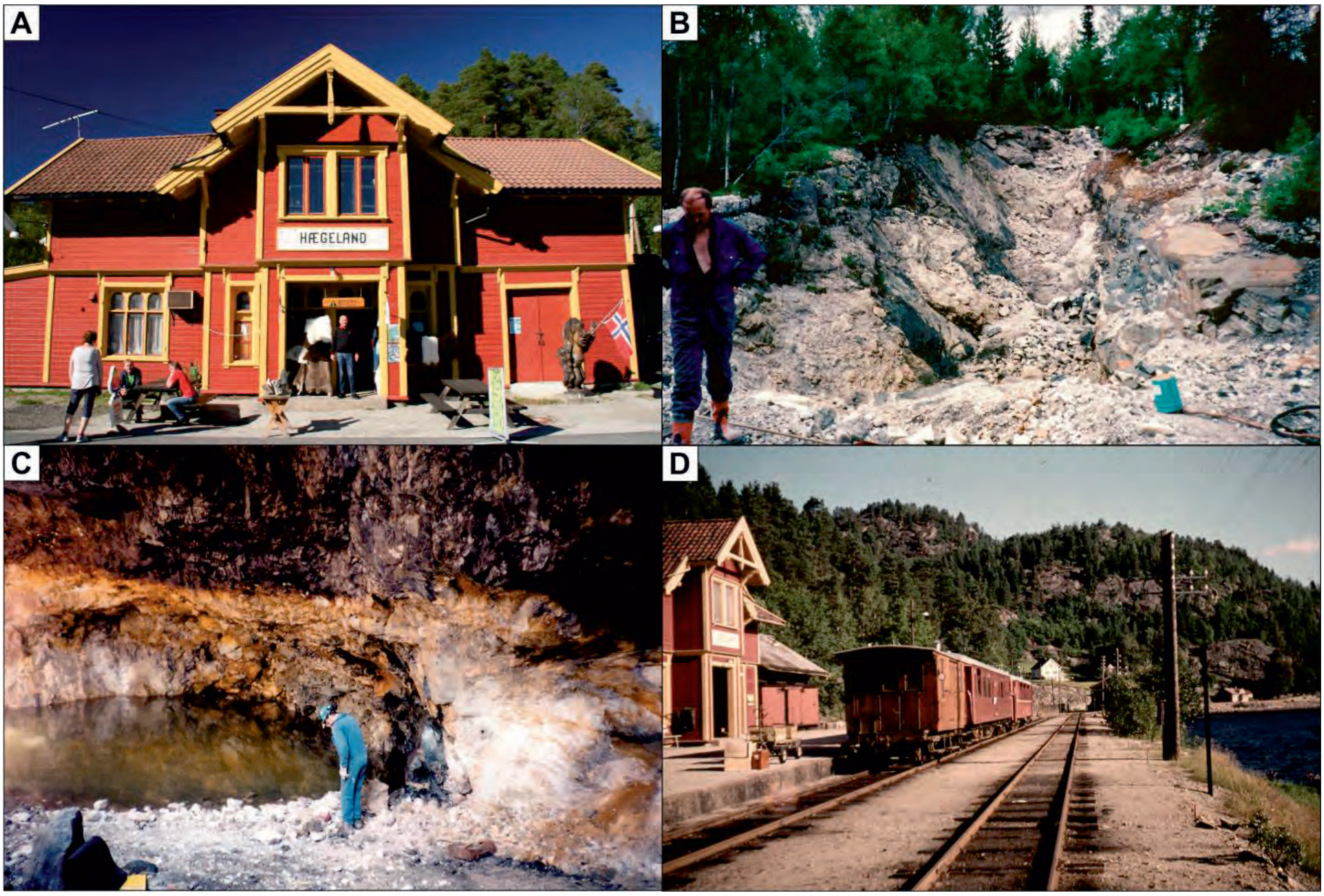


Fig. 2.27. A - Beryllen Mineral Senter in the building of the former Hægeland railway station in 2015. Arild Omestad is standing in the entrance. B - Arild Omestad at the Brattekleiv mine in 2000. C - Arild Omestad in the gallery of the Storsynken mine in 2001 after water had been pumped out. The original water level can be recognized at the mine face. D - Hægeland railway station in 1960. Today the railway is replaced by the National Road 9. Photo by Svend Jørgensen. Source: Norsk Jernbanemuseum (2017).

Locality 2.7: Hovåsen pegmatite

Highlights

Chemically evolved NYF pegmatite containing large beryl and columbite-(Fe) crystals and is unusually rich in xenotime-(Y)

Coordinates EU89-UTM Zone 32V 437957E/ 6487440N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Ivelandsveien/Kilefjorden Camping (County Road 403) and travel east towards Iveland for 8 km to the junction in the centre of the Iveland village. Turn left here into the Road 291 (Frikstadveien) and drive 8 km northward. At the junction Road 291/Road 292 turn right (eastward) and continue 700 m. Park at the parking lot on the left side of the road next to the Hovåsen farm (UTM Zone 32V 437408E/ 6487280N) (Fig. 2.28). Walk 300 m eastward along the Road 292 (Engeslandsveien) and then turn right into a little used tractor track. The track leads directly to the mine after 500 m. The Hovåsen mine is a disused mine partially under hanging walls. Hard hats have to be used. To enter the mine, permission is needed from the mine owner. The exposures are relatively fresh and there is plenty material at the dumps on the southern slope of the mine. The slope is very steep so be very careful when moving around.

Distance to walk: 0.8 km
Elevation changes: 30 m
Excursion time: 2 hours
Conservation status: None

Fig. 2.28. Access map for the Hovåsen mine.

Pegmatite zoning and host rocks

The lens-shaped pegmatite body of Hovåsen, historically also called Eptevann 4 (Bjørlykke 1935), extends 120 m in WNW-ESE direction and in its central part, where the mine is located, it is up to 10 m thick (Fig. 2.29). The body plunges towards NNE and is hosted by dark, massive amphibolite (metanorite) of the Iveland-Gautestad mafic intrusion (1285 ± 8 to 1271 ± 12 Ma). Immediately NE and W of the pegmatite, coarse-grained metagabbro is outcropping. At the WNW end of the pegmatite, near the mine cabin and workshop, magmatic mingling textures of the metanorite and metagabbro are exposed. In addition the pegmatite cuts an up to 2 m wide, NNW-SEE-striking metamonzonite dyke. At the pegmatite contact the amphibolite is altered to "biotitite" (up to 0.5 m away from the contact) due to reaction with escaping water of the crystallizing pegmatite. The foliation of the amphibolite ('biotitite') is smoothly bent and curved into the contact zone indicating ductile deformation conditions during pegmatite emplacement. The vertical pegmatite zoning described in the following is exposed in the major mine in the central part of the body (Fig. 2.30). The pegmatite displays a 5-cm wide, medium-grained, 'biotite'-rich granitic border zone that grades into a 0.5-m wide wall zone consisting of coarse-grained quartz, plagioclase and 'biotite' intergrowths. The wall zone contains accessory magnetite up to 2 cm in size.

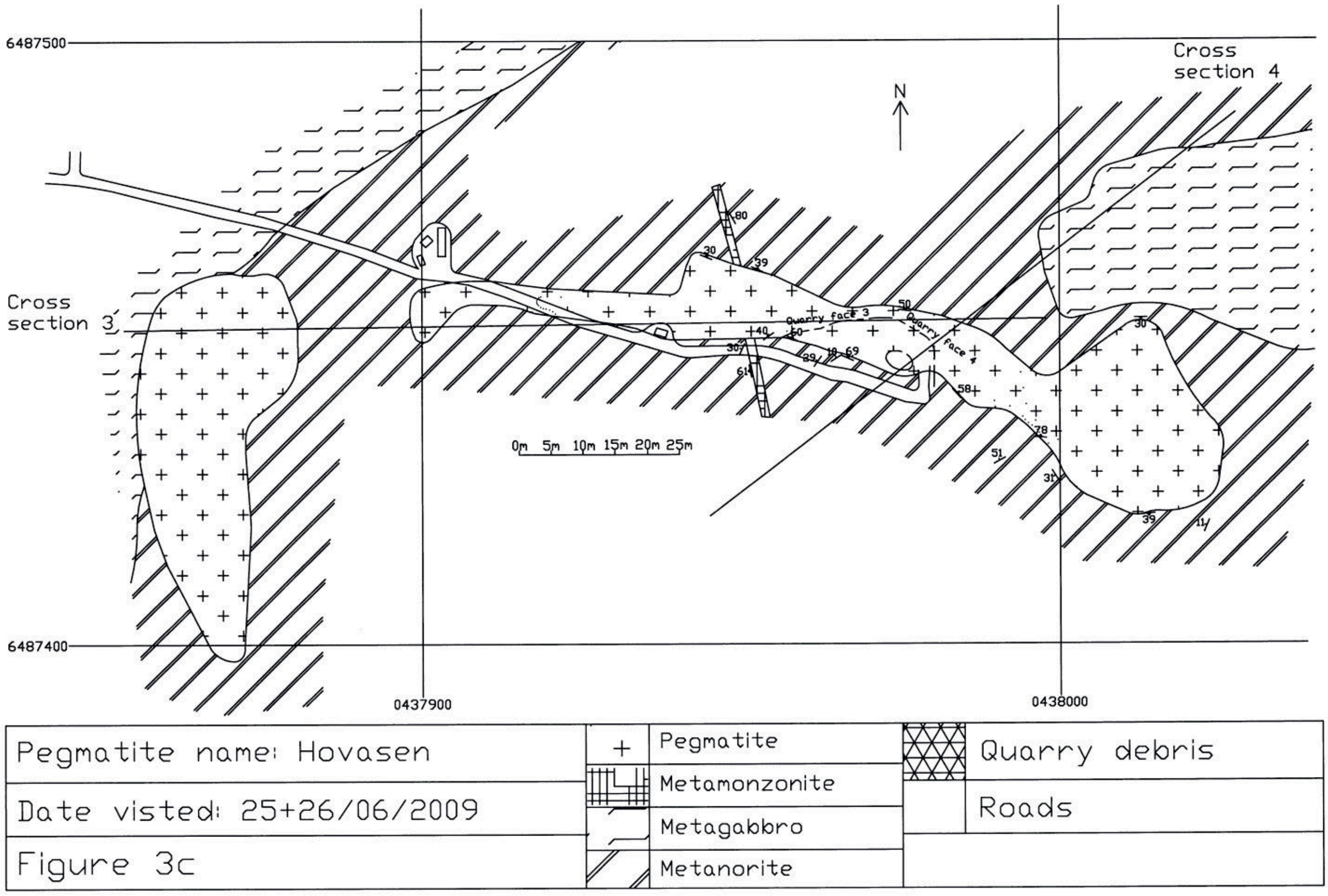


Fig. 2.29. Geological map of the Hovåsen pegmatite by Uren (2010). The visiting site corresponds to the location of the quarry debris.

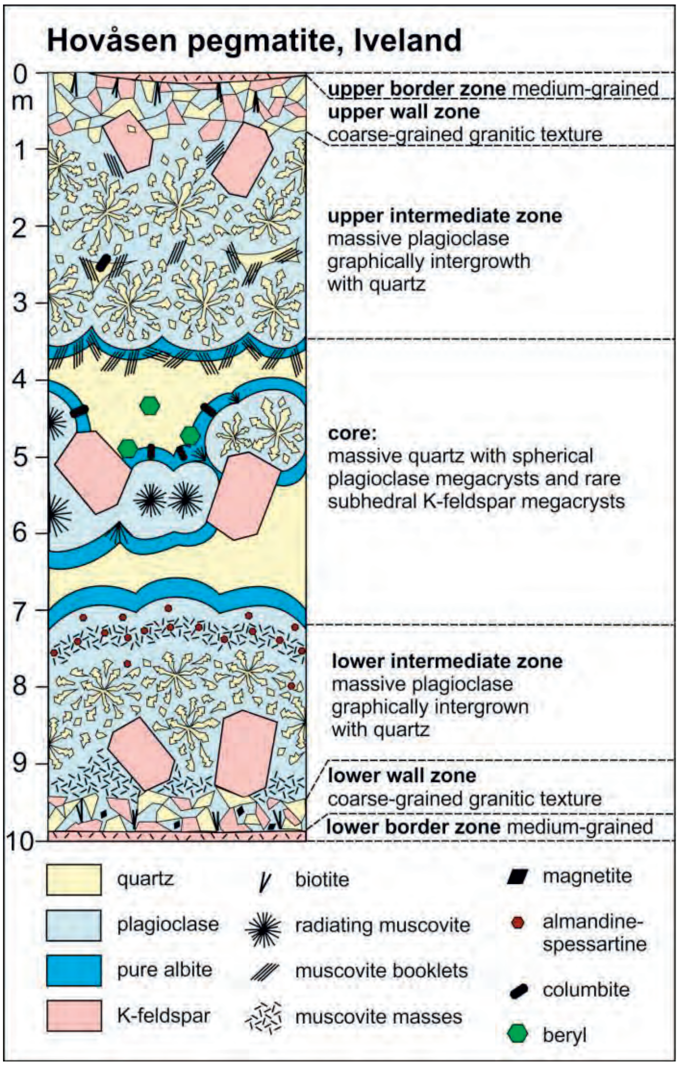


Fig. 2.30. Simplified zoning of the Hovåsen pegmatite.

The wall zone grades into the 'biotite'-free and muscovite-rich intermediate zone dominated by massive plagioclase and quartz containing euhedral K-feldspar megacrysts. Some of the feldspar megacrysts are completely altered to large muscovite masses. The blocky core zone consists predominantly of spherical plagioclase megacrysts (about 2 m in size), subhedral K-feldspar megacrysts and huge quartz masses up to 15 m^3. The quartz masses show smoky rims (up to 20 cm) where they are in contact with K-feldspar megacrysts. The spherical, whitish plagioclase megacrysts often display up to 20 cm wide albite overgrowths. Albite also encapsulates the large beryl crystals (up to 15 cm in diameter) occurring in the core zone (Fig. 2.31). Aggregates (up to several meters in size) of muscovite (2 cm crystals) and massive albite are variably associated with columbite-(Mn) crystals weighing up to several tens of kilograms. Locally, fractures and small cavities (<3 cm) are filled with fine muscovite, drusy quartz and clear albite crystals, respectively. In the lower transitional intermediate –core zone lines of garnets occur in the apical part of spherical plagioclase megacrysts. Thirty meters west of the major mine (=major pegmatite core) is a second, smaller core zone exposed. The occurrence of two or more spatially separated core zones within one pegmatite body is a common feature of the Evje-Iveland pegmatites.

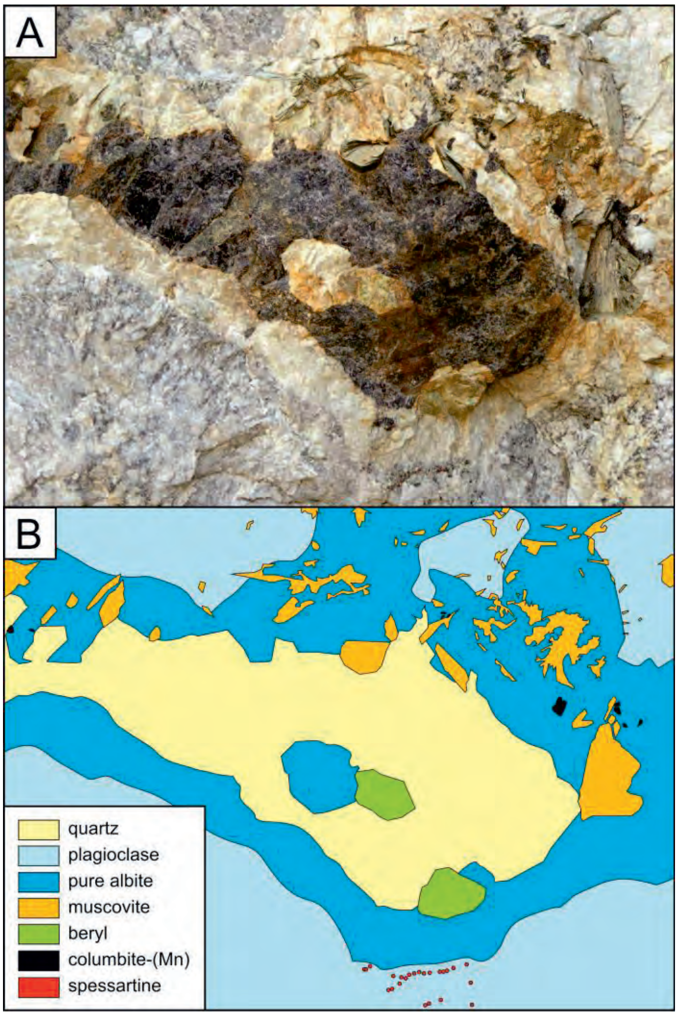


Fig. 2.31. A - Typical mineral assemblage of the core zone of the Hovåsen pegmatite. Field of view is about 1.5 m. B – Drawing illustrating the distribution of minerals shown in (A).

Mineralogy

The main minerals of the Hovåsen pegmatite comprise K-feldspar, plagioclase, quartz, 'biotite' and Fe muscovite. The pegmatite is particularly rich in plagioclase and muscovite. Muscovite occurs as large masses in the lower intermediate zone, as megacrystic booklets (40 cm in length) in the upper intermediate zone and as radiating crystals in the core zone. 'Biotite' has Mg siderophyllite to siderophyllite composition. Characteristic for the pegmatite, are up to 20 cm wide, massive overgrowths of yellowish albite on spherical, whitish plagioclase megacrysts. A second, younger albite generation occurs in micro cavities (5-10 cm) as transparent, euhedral crystal clusters. The individual crystals are up to 2 cm in size. Despite the richness in albite no 'cleavelandite' and, therewith, no replacement zones are developed at Hovåsen. Garnet, magnetite, columbite-(Mn), beryl, monazite and xenotime are the most common accessories.

Bjørlykke (1934) reported that a huge beryl crystal weighing about 1 ton was mined in 1933. In 1947-1948 several large beryl crystals with a diameter of up to 1.1 m and 3.5 m in length were found here (Rosenquist 1947). The largest crystal, probably the largest found in Norway, weighed almost 3 tons. In these years 13 tons of beryl, the total mass of 5 crystals, were mined at Hovåsen. The crystals were crushed and sold for 4 NOK/kg to Poland (Pedersen et al. 2007). Today several large, greenish beryl crystals up to 15 cm in diameter are exposed in the core zone of the pegmatite.

Fig. 2.32. A 55-kg columbite-(Mn) crystal from Hovåsen exhibited (until 2016) in the stairway of the Natural History Museum of Oslo, nr. 41323. Size: 35 x 33 x 19 cm.

Table 2.6. Composition of feldspars from Hovåsen. Bulk XRF analyses. Data from Müller, unpublished.

	K-feldspar megcryst	Core of plagioclase megacryst	Margin of plagioclase megacryst	Albite rim on plagioclase megacryst	Transparent albite crystals from cavities
Major elements (wt.%)					
SiO_2	66.7	65.0	67.6	68.2	66.5
Al_2O_3	18.8	20.4	19.6	19.7	18.8
Fe_2O_3	0.05	0.06	0.10	0.06	0.04
TiO_2	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	<0.04	<0.04	<0.04	<0.04	<0.04
CaO	0.05	1.61	0.89	0.43	0.20
Na_2O	3.97	11.1	11.4	12.4	12.3
K_2O	11.3	0.68	0.57	0.12	0.11
MnO	<0.01	0.01	0.02	<0.01	0.02
P_2O_5	0.03	0.01	0.02	0.03	0.02
LOI	0.02	0.23	0.17	0.17	0.22
Sum	100.98	99.15	100.42	101.17	98.26
An	0.3	7.1	4.0	1.9	0.9
Ab	34.7	89.3	92.9	97.5	98.5
Or	65.0	3.6	3.1	0.6	0.6
Trace elements (ppm)					
Ba	54	<10	<10	<10	<10
Cs	216	36	11	<10	<10
Ga	52	45	44	50	62
Pb	136	103	71	40	31
Rb	7550	168	63	7	16
Sr	25	46	4	4	5
Ta	<4	<4	<4	<4	29
Y	80	10	4	2	3

Beside beryl, the mine is famous for its numerous findings of large, well-shaped columbite-(Mn) crystals weighing up to 55 kg (Figs. 2.32, 2.33). Columbite-(Mn) occurs in association with megacrystic muscovite and massive albite in the upper intermediate zone and in the core. Already in 1906 the Natural History Museum of Oslo bought several large columbite-(Mn) crystals from Hovåsen. In 1975 Ola P. Tveit, the owner of the Hovåsen mine at that time, found several crystals weighing 72 kg combined. The largest crystal, 55 kg, he sold to the museum for 800 NOK. Analyses of three different columbite-(Mn) crystals revealed a consistent columbite-(Mn) composition (Fig. 2.34). Historical records of columbite-(Fe) are not supported by modern analyses.

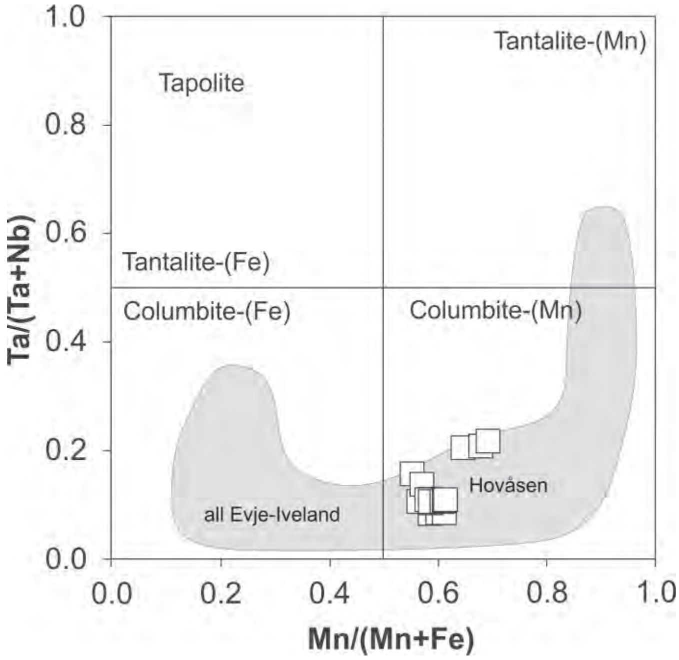


Fig. 2.34. Quadrilateral classification diagram of columbite-group minerals according to Černý (1989) showing the chemical variation of columbites-(Mn) from Hovåsen compared with other columbite group minerals from Evje-Iveland (grey shaded area). Concentrations were determined with EPMA. Data from Lund (2016) and Müller et al. (2017a, 2017b).

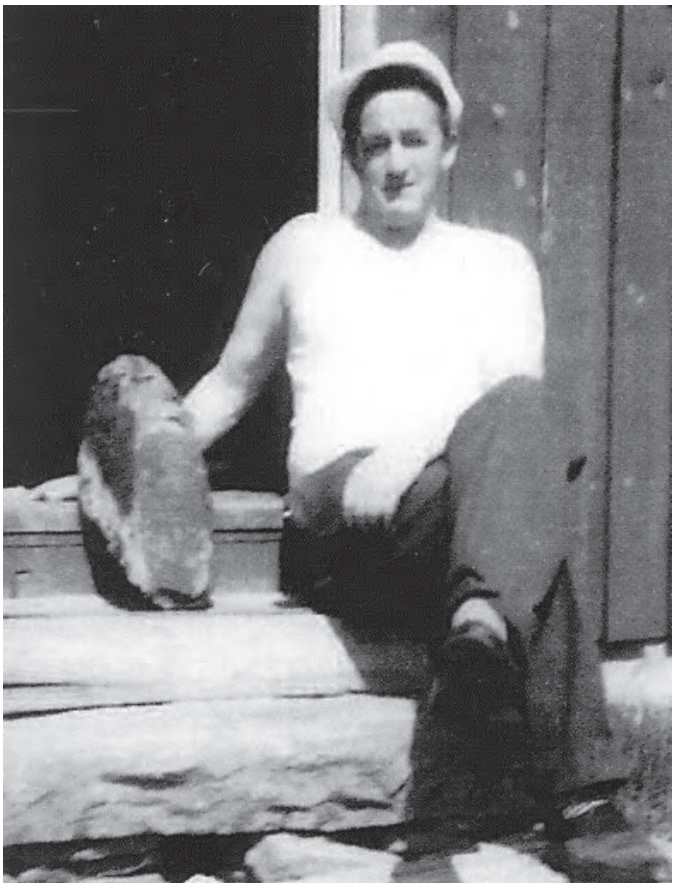


Fig. 2.33. Knut Nateland in 1960s with a columbite-(Mn)? crystal most likely from Hovåsen. Photo from Pedersen et al. (2007).

The reddish brown, euhedral to subhedral garnet crystals are up to 4 cm in size and have spessartine composition (Fig. 2.35A). The garnets occur predominantly as individual crystals or aligned parallel to the shape of spherical plagioclase megacrysts in the lower intermediate zone close to the core zone. Occasionally the garnets are associated with needle-like, radiating allanite-(Ce) crystals. The individual crystals show in some cases dendritic garnet-quartz overgrowths. In BSE images, the core of garnet crystals is homogeneous with a marginal darker overgrowth. The grey-shade change towards the crystal margin is due to drop in the Y concentration, where the high Y content of the core (1.15 wt.% Y_2O_3) decreases to 0.06 wt.% Y_2O_3 at the crystal margin (Fig. 2.35B). Micro inclusions in garnet comprise euhedral grains of monazite-(Ce) and metamict zircon (5–120 µm). Anhedral inclusions of xenotime-(Y) (10–60 µm) occur along open cracks. The chondrite-normalized REE patterns of Hovåsen garnets are LREE-depleted and HREE-enriched compared to the bulk pegmatite composition (Fig. 2.35C). The pattern shows a distinct negative Eu anomaly due to preferential partitioning of Eu into plagioclase. The Eu anomaly is less distinct in the flat bulk-pegmatite REE patterns, indicating that fractionation of some plagioclase occurred prior to garnet crystallization and that plagioclase continued to crystallize during garnet formation. Garnet crystals from Hovåsen are relatively rich in Sc (mean >700 ppm) and highest in U (about 2 ppm) compared to other garnets from Evje-Iveland.

Xenotime-(Y) is a rather common accessory mineral at Hovåsen. It occurs as groups of several intergrown, dark brown, dipyramidal crystals up to 3 cm in size associated with megacrystic muscovite or along fracture-like features in plagioclase. Allanite-(Ce) forms radiating clusters of needle-like crystals up to 20 cm in length. The crystals occur preferentially in the lower intermediate zone. Bertrandite is an alteration product of beryl and forms small, transparent crystals up to 4 mm in length. Bismuthinite is very rare and forms elongated, up to several cm long crystals with fibrous texture. Strand (1953) described euclase from a beryl pseudomorph found at Hovåsen. The 3 to 4 mm large, clear euclase crystals occurred in matrix of muscovite aggregates and subhedral bertrandite crystals.

The high abundance of albite and muscovite, the high spessartine component in the garnets and the wealth of columbite-(Mn) define the Hovåsen pegmatite as one of the chemically most evolved pegmatites of the Evje-Iveland area. Considering the high differentiation degree it is rather surprising that no ‘cleavelandite’ replacement zones are developed at Hovåsen. This may be due to the lack of fluorine in the Hovåsen pegmatite melt.

Table 2.7. Minerals identified in the Hovåsen pegmatite. Modified from Mindat (2017).

Mineral name	Mineral name
Albite	Microcline
Allanite-(Ce)	Monazite-(Ce)
Bertrandite	Muscovite (Fe muscovite)
Beryl	Quartz
'Biotite' (Siderophyllite)	Siderophyllite
Bismuthinite	Spessartine
Columbite-(Mn)	Xenotime-(Y)
Euclase	Zircon

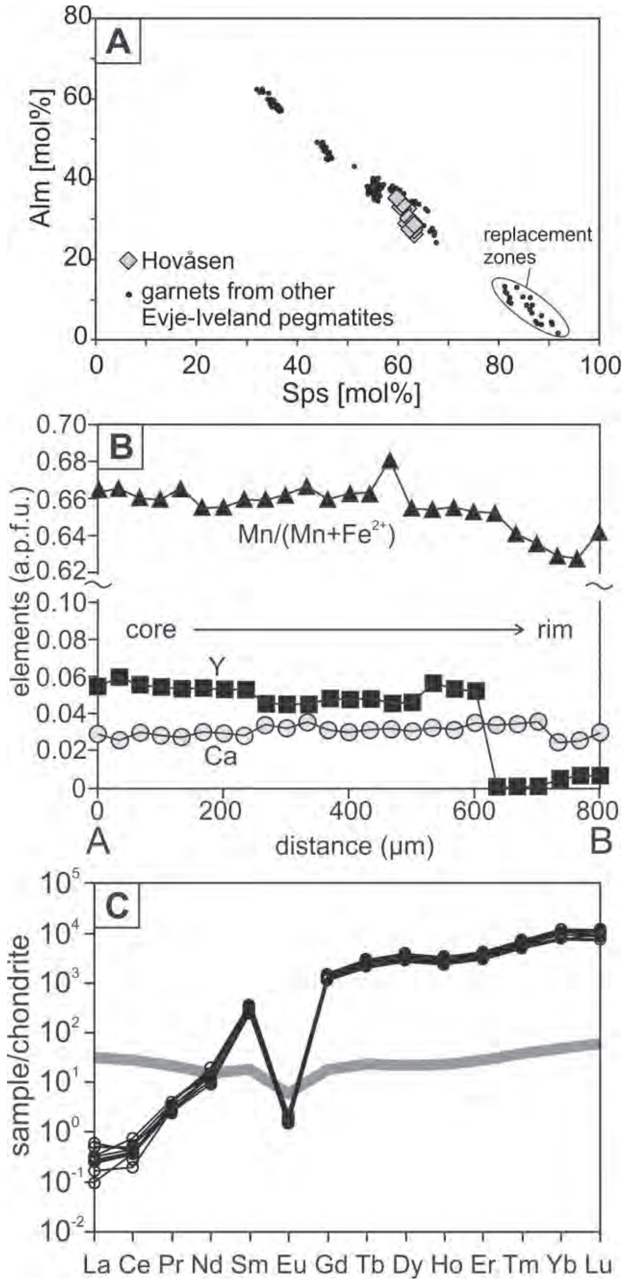


Fig. 2.35. Chemistry of garnet from the Hovåsen pegmatite. A - Spessartine (Sps) versus almandine (Alm) component plot illustrating the general trend of increasing MnO/(MnO + FeO) values with increasing fractionation of Evje-Iveland pegmatites. Garnets from Hovåsen have a relatively evolved composition, actually the most evolved composition of garnets un-related to replacement zones. B - Profile of the Ca and Y content in atoms per formula unit (apfu) and the Mn/(Mn + Fe^{2+}) value of garnet from Hovåsen. The analyses were performed with electron microprobe. For explanation see text. C - Chondrite-normalized REE pattern of garnet. The grey-shaded REE pattern is the bulk composition of the wall zone of the pegmatite, representing roughly the bulk composition of the pegmatite. Analyses were performed with LA-ICP-MS. Data from Müller et al. (2012a) and Müller et al. (2017b).

Locality 2.8: Li Gruve

Highlights

Largest exposed pegmatite (and mine) of the Evje-Iveland area with large-scale layered structures (line rocks)

Coordinates EU89-UTM Zone 32V 433145E/ 6488074N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Vånnevegen 500 m north of Moi. Follow the road eastward for 7 km to junction Vånnevegen/ Lauvlandsvegen and continue northward for c. 1.8 km on Lauvlandsvegen. Turn right (east) into dirt road that leads to the Li gruve after 1 km (Fig. 2.36). There is a gate after 20 m and permission is required from the landowner Hans Kalleberg. The gravel road is in good condition but in parts relative steep (100 m climb over a distance of 1 km). Park the car at the northern entrance area of the mine next to the workshop. The Li gruve is a large pegmatite mine with high vertical walls (up to 25 m) and underground workings. Wear hard hat and torch if you enter the underground area. No hammering in the underground part.

Distance to walk: 0.2 km
Elevation changes: 10 m
Excursion time: 2 hours
Conservation status: None

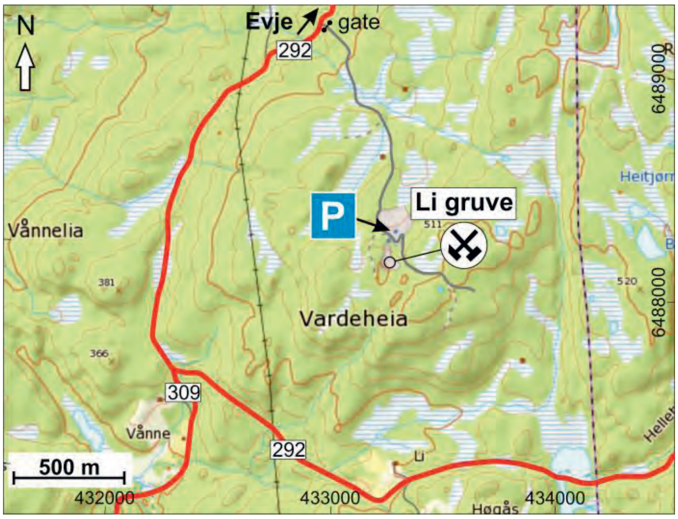


Fig. 2.36. Access map for the Li gruve.

Pegmatite zoning and host rocks

The Li gruve is a feldspar mine hosted in the largest exposed pegmatite of the Evje-Iveland field. The mine is temporarily active extracting about 10 to 50 t of high-quality K-feldspar annually for the production of artificial teeth. The raw material, hand-sorted, fist-sized lumps, is exported to Germany. Chemically it is a primitive (almost barren) rare-element pegmatite of the monazite and euxenite subtype with NYF affinity. Although the pegmatite only contains a few mineral species, the mine exposes some spectacular, large-scale layered structures (line rocks) and enormous sizes of feldspar and 'biotite' crystals. Emplaced in metanorite of the Iveland-Gautestad mafic intrusion (1285 ± 8 to 1271 ± 12 Ma) and banded gneisses, the Li gruve pegmatite forms an approximately 1 km long, sheet-like body striking NW-SE (Fig. 2.37). The body varies in thickness from a few meters to 25 m, and dips at a shallow angle towards SW. At the upper contact, there is an up to 10 cm wide medium-grained granitic border facies, which grades into wall zone (up to 2 m wide) of coarse granitic texture with plagioclase, K-feldspar and 'biotite'. Crystal sizes in the wall zone can reach 0.5 m. The sharp lower contact of the upper wall zone to the intermediate zone is marked by a line of megacrystic, fan-like 'biotite' sheets (up to 1 m in length) pointing towards the pegmatite centres forming unidirectional solidification textures (USTs) (Figs. 2.38, 2.39). The larger 'biotite' sheets are bent. The 'biotite'-rich layer (0.5- 1 m in thickness) is followed by a layer of pinkish K-feldspar megacrysts (0.3 to 1 m in length) with interstitial plagioclase. These 'biotite'-rich and K-feldspar-rich UST-layers alternate several times forming a layered line rock, in this case the intermediate zone. The last line at the contact to the core zone is 'biotite'-rich with fan-like 'biotite' up to 4 m in length. The core zone comprises of up to 8 m long, whitish subhedral K-feldspar crystals embedded in massive quartz. The lower intermediate zone consists also of line rock but with several differences compared to the upper intermediate zone: (1) the layers are thinner (3 to 30 cm) but higher in number; (2) within some layers the crystals grow in two opposite directions (not only in one direction as in the upper intermediate zone); (3) garnet, which is absent in the upper intermediate zone, is common and strongly enriched in some layers forming garnet-rich bands (Fig. 2.40). The lower contact is not exposed. The vertical structural zoning appears symmetrical; however, the mineralogical and chemical zoning is asymmetric in respect to 'biotite'/garnet and K-feldspar/plagioclase ratios. 'Biotite' and K-feldspar are enriched in the upper wall and intermediate zone, whereas garnet and plagioclase are enriched in the lower wall and intermediate zone. The asymmetrical zoning implies a relative low undercooling (if at all) and slow cooling rate.

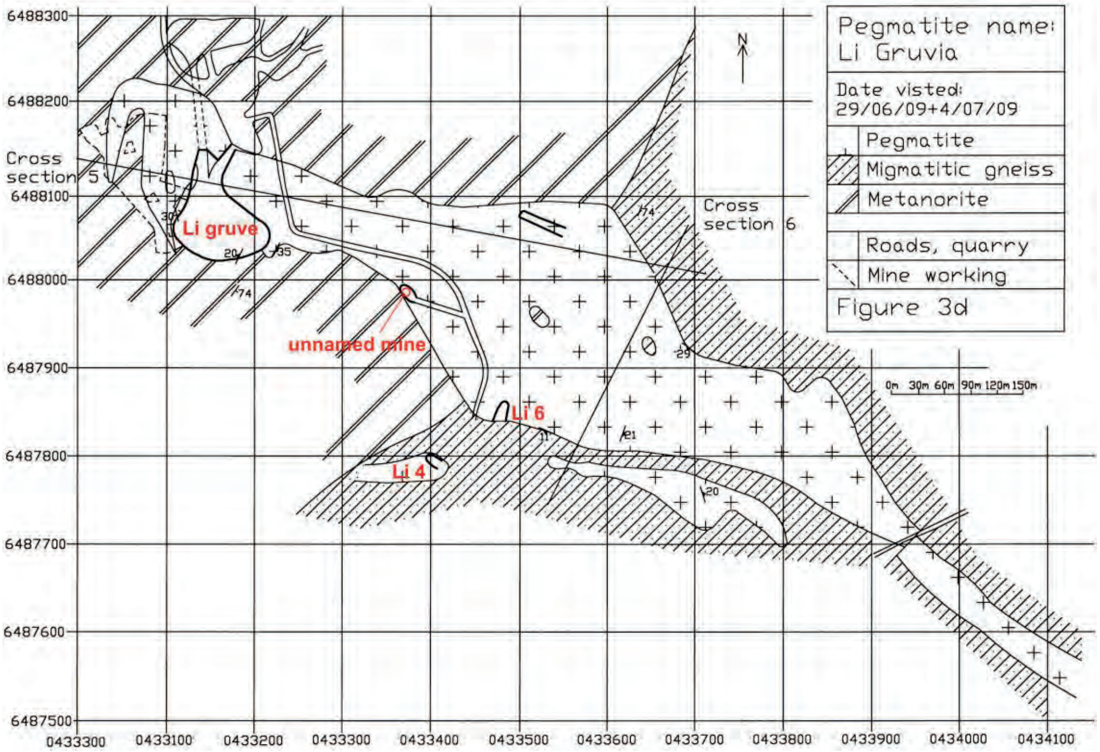


Fig. 2.37. Geological map of the Li gruve pegmatite by Uren (2010). The mine is located at the NW end of the pegmatite body.

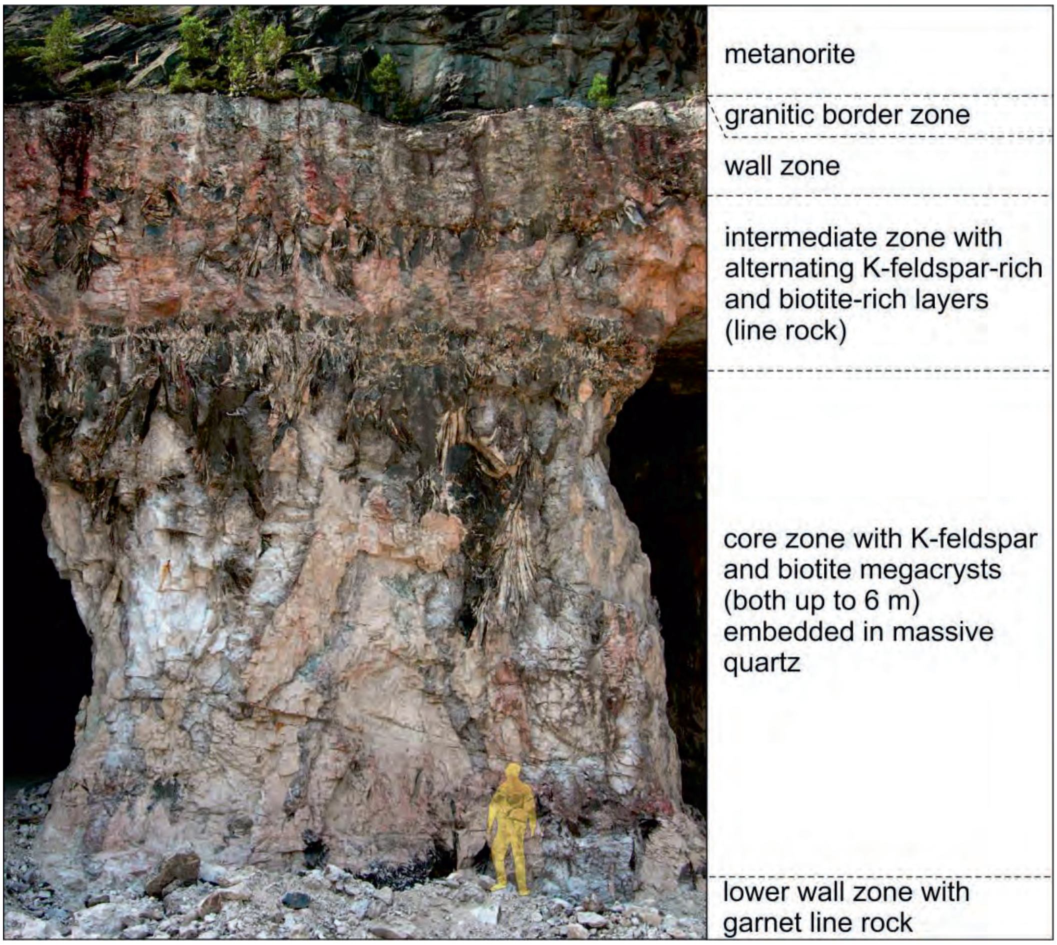


Fig. 2.38. Pillar at the entrance of the underground mine showing an almost complete section of the Li gruve pegmatite (border zone and part of the lower wall zone are not exposed). The “yellow person” is for scale.

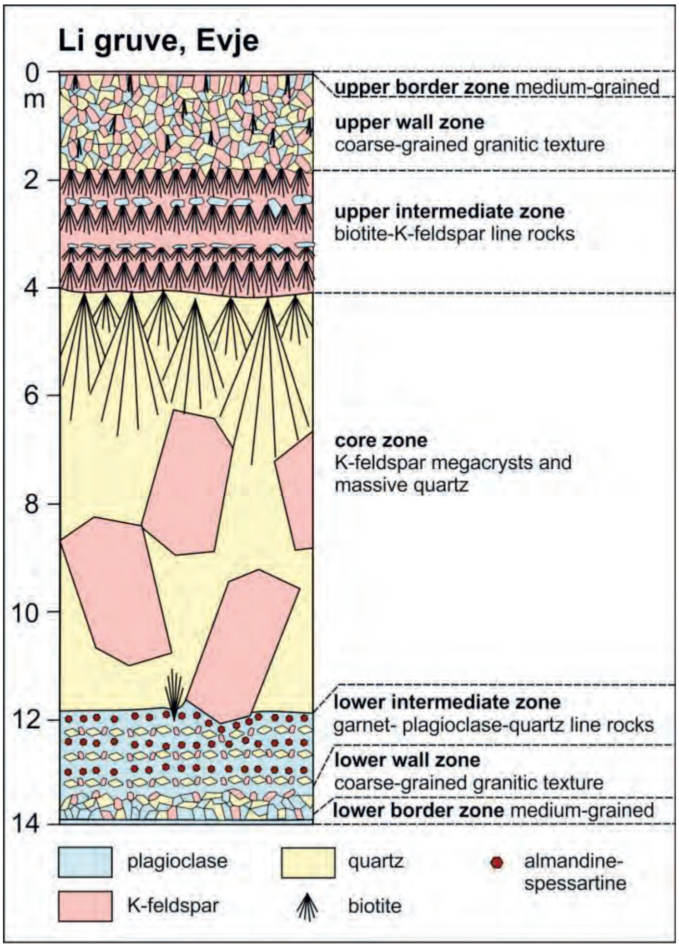


Fig. 2.39. Simplified zoning of the Li gruve pegmatite.

Mineralogy

Despite its large size the Li gruve pegmatite is rather poor in mineral species. The major minerals comprise K-feldspar, plagioclase, quartz and 'biotite'. 'Biotite' has Mg siderophyllite to siderophyllite composition. Muscovite is rare. The most common accessory mineral is garnet occurring as isometric crystals up to 4 cm in size in the lower intermediate zone. The almandine component slightly prevails over the spessartine component (Fig. 2.41A). Concentrations of TiO_2, Cr_2O_3 and V_2O_5 are <0.4, <0.02 and <0.02 wt.%, respectively. Across individual crystals, the Mn/(Mn + Fe) value and Y content decreases continuously from core to rim (Fig. 2.41B). The chondrite-normalized REE patterns are depleted in LREE and enriched in HREE compared to the pegmatite bulk composition (Fig. 2.41C). The patterns show a distinct negative Eu anomaly due to preferential partitioning of Eu into plagioclase. Garnets from the Li gruve are relatively rich in Sc (mean 490 ppm; n =30). Euxenite-(Y) up to 1 cm in size occurs between 'biotite' sheets.

Andreas Corneliussen, a local mineral collector, reported a 'cleavelandite' replacement zone associated with approximately 5 m^3 of "good-quality" 'amazonite'. The replacement zone was situated in the lower core zone in the most southern part of the underground mine. According to Corneliussen the 'amazonite' had the second best quality in terms of colour of the Evje-Iveland area, after Landsverk 1. The replacement zone was very small considering the size of the entire pegmatite body and there exists no mineralogical record of the unit.

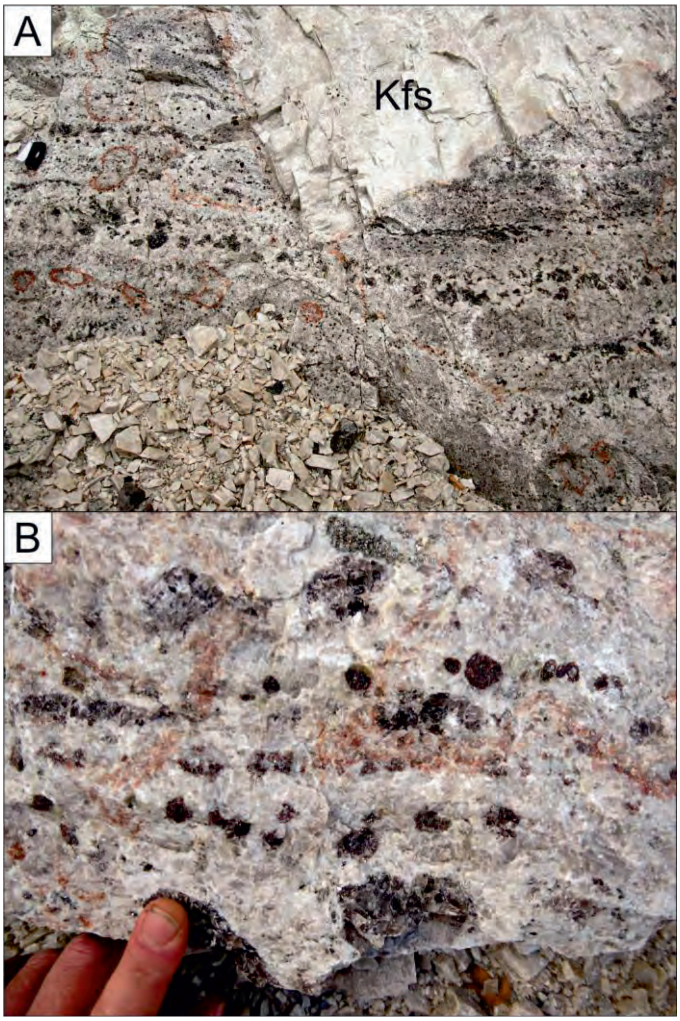


Fig. 2.40. A - Line rock with alternating garnet-rich, feldspar-rich and quartz-rich layers at the base of the Li gruve pegmatite (photo from Müller et al. 2012a). A huge K-feldspar megacryst (Kfs) seems to push away the layers implying a simultaneous formation of the megacryst and line rock. Field of view is about 1 m. B – Detail of the garnet line rock showing two layers of aligned garnet crystals (up to 2 cm) embedded in fine-grained granitic mass alternating with coarse-grained, quartz-rich layers.

On the SE slope of the Liheia, about 300 to 400 m SW of the mine there are three small quarries, Li 4, Li 6, and an unnamed locality (Fig. 2.37). These mines are probably situated in the same pegmatite body as the Li gruve. In the northern wall of the unnamed locality an enormous large 'biotite' sheet about 10 m^2 in size is exposed. Today the mine is filled with water. Li 6 contains a large 'cleavelandite' replacement zone rich in yellow beryl which partially altered to bertrandite+chlorite group minerals. In the wall of Li 4, similar line rocks as in the Li gruve, but at a smaller scale are exposed.

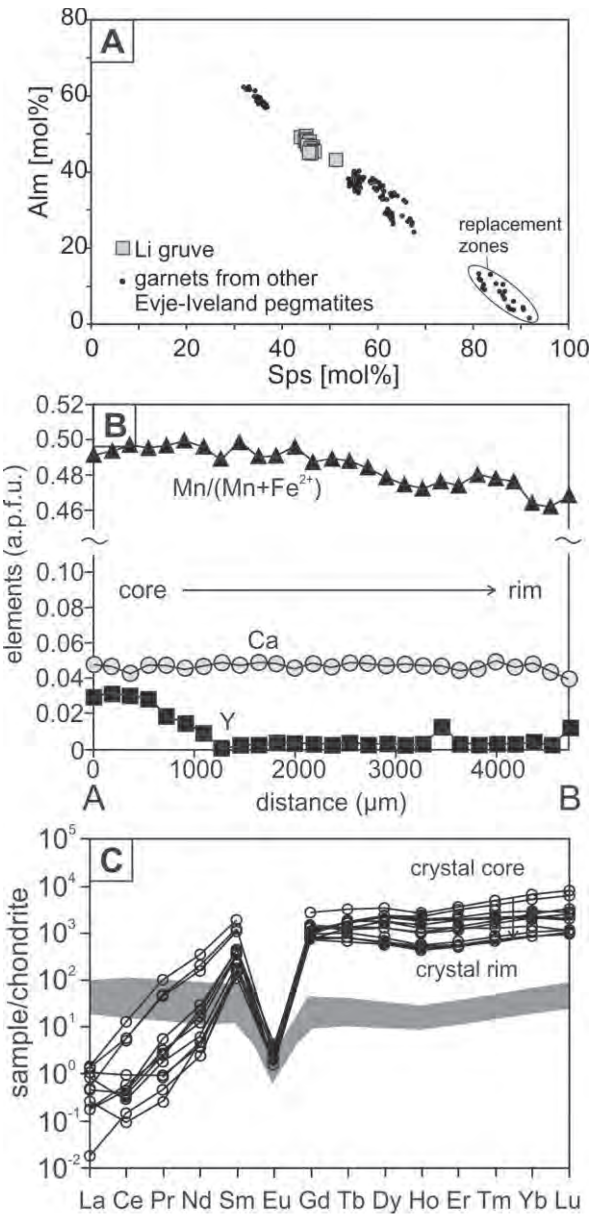


Fig. 2.41. Chemistry of garnet from the Li gruve. A - Spessartine (Sps) versus almandine (Alm) component plot illustrating the general trend of increasing MnO/(MnO + FeO) values with increasing fractionation of Evje-Iveland pegmatites. Garnets from Li gruve have moderately evolved composition. B - Profile of the Ca and Y content in atoms per formula unit (apfu) and the Mn/(Mn + Fe^{2+}) value of garnet from Li gruve. The analyses were performed with electron microprobe. For explanation see text. C - Chondrite-normalized REE pattern of garnet. The grey-shaded REE pattern is the bulk composition of the wall zone, representing roughly the bulk composition of the pegmatite. Analyses were performed with LA-ICP-MS. Data from Müller et al. (2012a) and Müller unpublished.

Table 2.8. Minerals identified in the Li gruve pegmatite. Note that the mineral species related to the 'cleavelandite' zones (Bi-minerals, schorl?, microlite and tantalite group minerals, gadolinite-(Y), bertrandite, bavenite, and bastnäsite-(Ce) have been reported only from the Li 6 mine, which is probably situated in the same pegmatite body as Li gruve (Fig. 2.37). Modified from Mindat (2017).

Mineral name	Mineral name
Albite (var. 'Cleavelandite')	Bismutite
Allanite-(Ce)	Euxenite-(Y)
Almandine-Spessartine series	Gadolinite-(Y)
'Ancylite Group'	Microlite Group
Bastnäsite-(Ce)	Monazite-(Ce)
Bavenite	Muscovite (Fe muscovite)
Bertrandite	Quartz
Beryl	Schorl?
'Biotite' (Siderophyllite)	Siderophyllite
Bismite	'Tantalite Group'
Bismuth	Xenotime-(Y)
Bismuthinite	Zircon

Locality 2.9: Oddestemmen Steinsliperi (Stone Workshop)

Highlights

Stone workshop producing jewelry such as polished cabochons of local and international semi-precious gemstones and coloured rocks

Coordinates EU89-UTM Zone 32V 432761E/6496184N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Gautestadvegen (Road 306) c. 2 km NE of the town centre of Evje. Travel eastwards for about 1 km passing the Evje church. The Oddestemmen Steinsliperi is on the left (north) of the road (Fig. 2.42). The parking site is next to the road. The stone shop is open daily during the summer season (June to September), from 10:00-16:00. During the rest of the year, group visits are arranged by appointment only. Address: Jarl J. Verhagen, Oddestemmen Camping, N-4735 Evje (http://www.oddestemmen.com), phone: +47 37930161, E-mail: steinsliperi@oddestemmen.com.

Distance to walk: 0 km
Elevation changes: 0 m
Excursion time: 1 hour

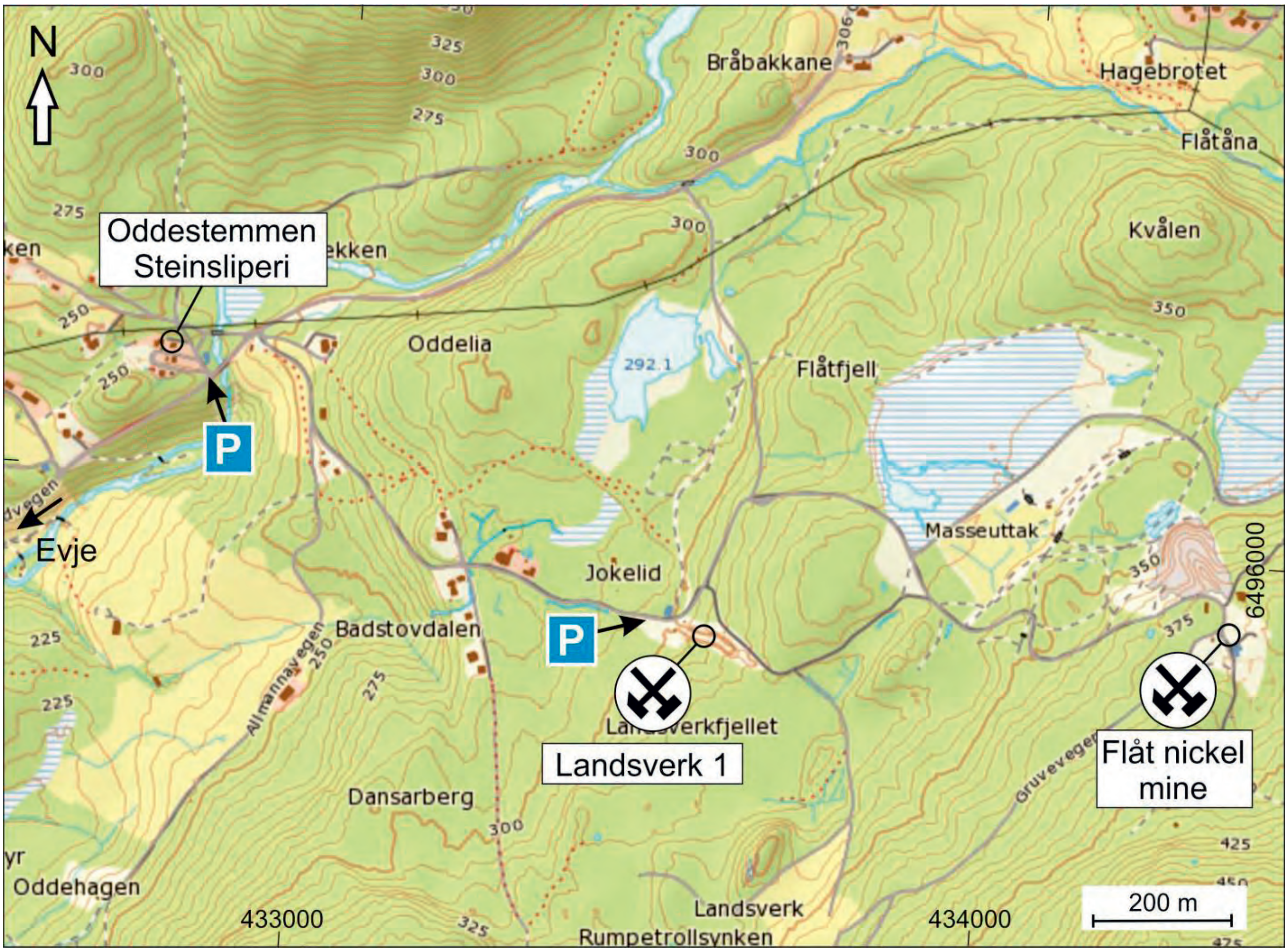


Fig. 2.42. Access map for the Oddestemmen Steinsliperi and Landsverk 1 gruve.

Oddestemmen Steinsliperi is the only stone workshop in Norway, which produces jewelry made of polished cabochons of semi-precious gemstones and beautifully coloured rocks on the base of a full-time job. Beside the stone workshop the facilities at Oddestemmen include a jewelry shop and a small campsite. The workshop and campsite are run by Jarl J. Verhagen who is a qualified gemstone cutter educated in Idar Oberstein, Germany. Jarl has worked as a gemstone cutter since the early seventies, first in the Netherlands and since 1995 at Oddestemmen in Evje (Fig. 2.43).

The machinery at Oddestemmen Steinsliperi includes two German-made cabochon machines for the mass production of high-quality cabochons. Further grinding and polishing is done through several stages, for which carborundum, corundum and/or diamond is used. Jarl has a long list of customers in Norway including the Crown Princess of Norway Mette-Marit.

Fig. 2.43. Jarl J. Verhagen cutting a precious stone in his workshop at Oddestemmen Steinsliperi.

Locality 2.10: Landsverk 1 pegmatite

Highlights

Mixed NYF-LCT rare element pegmatite which underwent intense hydrothermal, post-pegmatite-stage brecciation resulting in pegmatite-atypical mineral assemblages

Coordinates EU89-UTM Zone 32V 433533E/6495839N

Directions and Access

Coming from Kristiansand leave National Road 9 at junction Gautestadvegen (Road 306) c. 2 km NE of the town centre of Evje. Travel eastwards and turn right approximately 1.5 km after passing the Evje church and follow the sign “Mineralsti” on the dirt road for 400 m (Fig. 2.42). At the next junction turn right and continue for another 200 m. The parking place is next to the Landsverk mine shop (Fig. 2.42). The Landsverk 1 mine is an official mineral collecting site opened for tourists. The entrance fee for entering the mining area is 75 NOK (2017). The mine is run by Reidar Kjetså. The mine shop provides drinks and snacks and hosts a mineral shop selling minerals from the Landsverk 1 pegmatite. Hard hats must be worn when entering the mine. Opening hours are 11:00 to 16:00 from 15 June to 15 August. Outside the opening hours the entrance fee is paid on the basis of trust. Contact details: phone +47 971 58 909, E-mail reidar@flaatgruve.com (http://www.mineralstien.flaatgruve.com/)

Distance to walk: 0.2 km
Elevation changes: 5 m
Excursion time: 1 ½ hour
Conservation status: None

Pegmatite zoning and host rocks

The Landsverk 1 pegmatite is one of the most classical Evje-Iveland locations frequently described in literature (Schei 1905; Brøgger 1906; Andersen 1926, 1931; Bjørlykke 1934; Taylor et al. 1960; Menzel 1982; Taylor & Friedrichsen 1983; Larsen 2001; Werner 2004; Revheim 2006, 2007). It is one of the oldest feldspar and quartz mines in the area. The quartz from Landsverk was used as flux for melting nickel ore from the Flåt nickel mine, which was just 800 m E of the Landsverk 1 mine. Already Andersen (1926) noticed that the Landsverk 1 pegmatite is “merkelig” (‘strange’; p. 70) because it “consists of large and small fragments of feldspar together with fragments of the host rock which form a breccia with interstitial quartz”. He called Landsverk 1 a pegmatite breccia.

The Landsverk 1 pegmatite forms a sub-vertical, c. 150 m long and up to 25 m wide dyke in the northern part of the Evje-Iveland pegmatite field (Fig. 2.44). Emplaced within metagabbro of the Flåt-Mykleås mafic intrusion (1034 ± 2 Ma; Pedersen et al. 2009), the internal structure of the body is difficult to define due to extensive post-pegmatitic hydrothermal brecciation of large parts of the pegmatite. All primary pegmatite minerals have undergone widespread fracturing and brecciation with subsequent infill and replacement by hydrothermal quartz and epidote (Fig. 2.45). During the brecciation gabbro (host rock) fragments entered the pegmatite body due to the collapse of the pegmatite roof and sidewalls. The hydrothermal nature of the interstitial and cavity quartz at Landsverk 1 is evident from the oxygen isotope and trace element signature of quartz (see following chapter). In the brecciated areas, pegmatite-forming minerals are fragmented at macro and micro scale. Open cavities up to 1.5 m in diameter in interstices between larger fragments are very common. In the central and NW part of the body the number of cavities is so high, that the rock resembles a Swiss cheese (Fig. 2.46). The walls of the cavities are lined with long-prismatic hydrothermal quartz crystals (Fig. 2.47) and filled with a pegmatite-atypical hydrothermal mineral assemblage (described below).

In general, open cavities are extremely rare in Evje-Iveland pegmatites owed to the primary emplacement depth corresponding to ~5 kbar. At such high lithostatic pressure and due to the ductile behavior of the host rock, cavities cannot be preserved. Exceptions are a few late-stage cavities in replacement zones recorded from the Røykkvartsbrudd at Birkeland and the Solås mine. According to Černý & Ercit (2005) cavities of the size and frequency developed at Landsverk 1 are stable up to the pressure of 3 kbar. This implies that the Landsverk 1 pegmatite has been exhumed tectonically to depth corresponding 3 kbar or less after solidification and prior to the brecciation. Thus, the event of pegmatite brecciation is much younger than the crystallization age of the pegmatite.

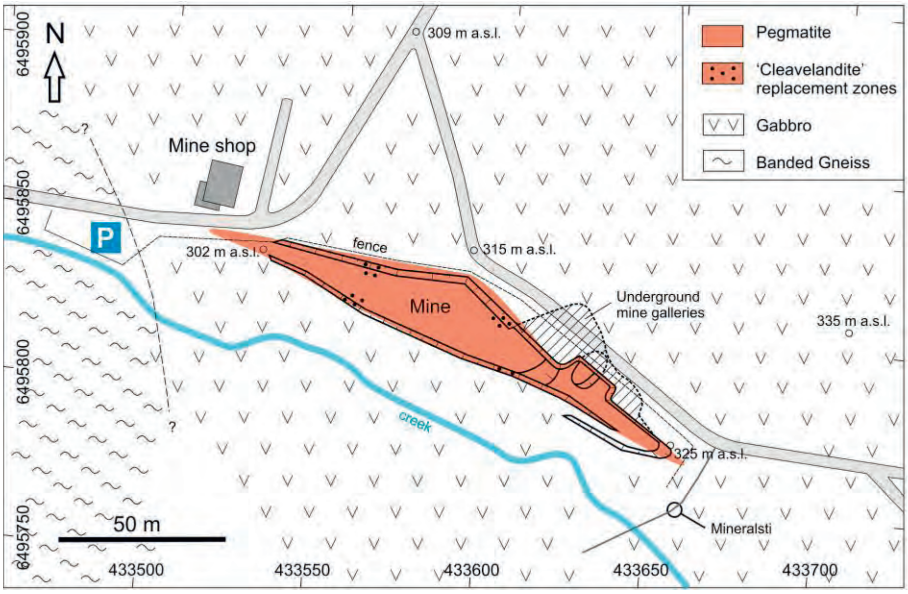


Fig. 2.44. Geological map of the Landsverk 1 mine.

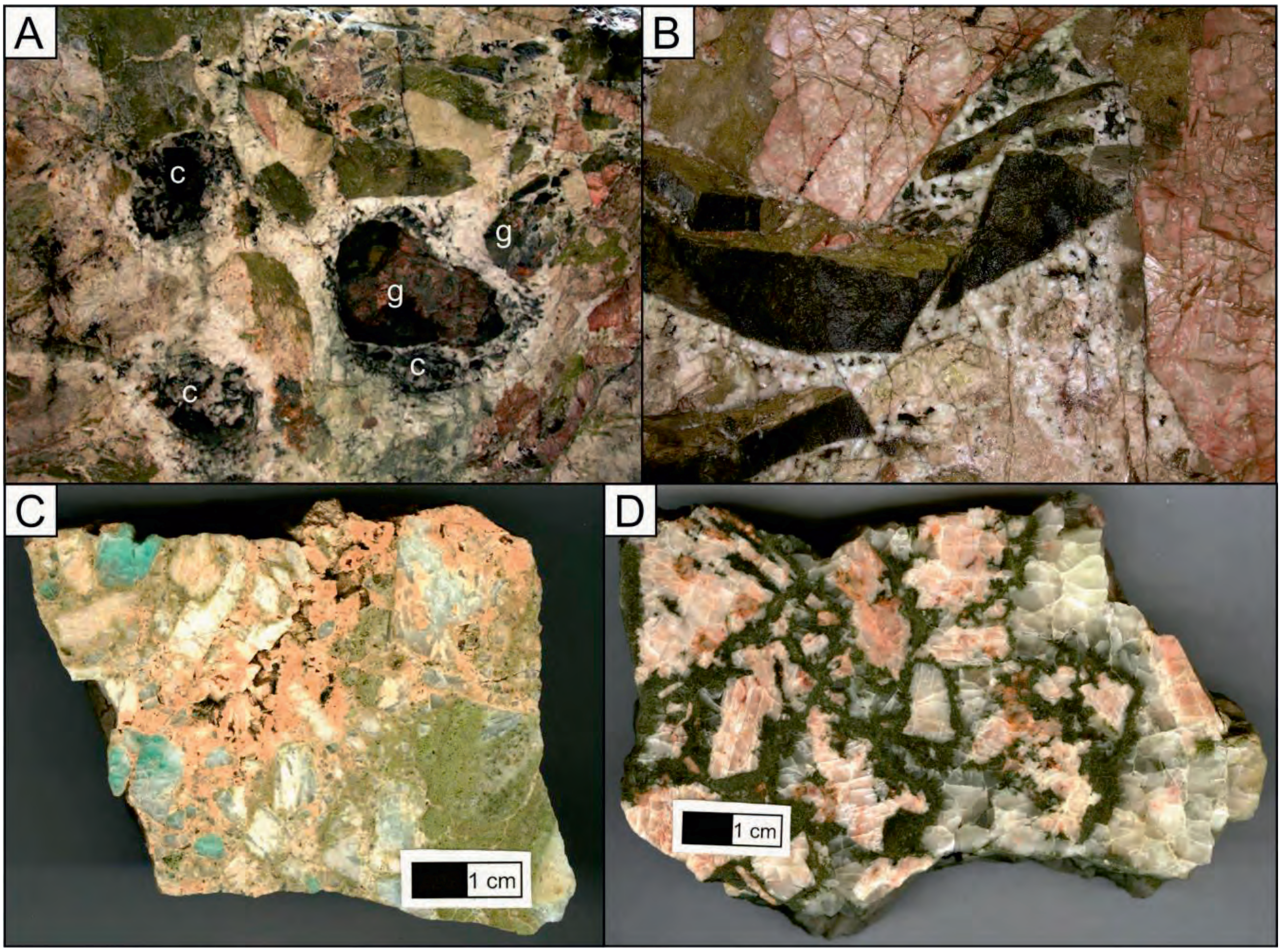


Fig. 2.45. A - Roof of the mining gallery at the E end of the Landsverk 1 mine showing fragments of brecciated pinkish K-feldspar mecacrysts, greenish epidotized plagioclase, and dark gabbro (host rock; g) healed by hydrothermal quartz (white). Field of view is about 4 m. c – cavity filled with hydrothermal quartz crystals. B – Face in the mine gallery with fragments of dark gabbro (host rock) and pinkish K-feldspar megacryst partially replaced by epidote. The fragments are cemented by whitish hydrothermal quartz. Field of view is about 1.5 m. C – Polished hand specimen with fragments of 'amazonite' and whitish K-feldspar cemented by epidote and brick-red microcline. D – Pinkish K-feldspar fragments cemented and replaced by dark green epidote. Milky hydrothermal quartz cementing feldspar fragments is dominant on the right side of the sample.

Fig. 2.46. Bottom of the N face of the Landsverk 1 mine showing numerous open cavities that were originally filled by hydrothermal quartz crystals. Field of view is about 4 m.

Fig. 2.47. Hydrothermal quartz crystals from a cavity in the north wall. Field of view is about 50 cm. Photo by Ronald Werner.

There are three additional pegmatite bodies in the Landsverk area showing similar intense brecciation and hydrothermal mineral assemblages: the Gudmundsgruve, Haugen 1 and Haugen 2 (Fig. 2.48). These pegmatites are aligned in N-S-direction forming a c. 1.5 km long structure-like feature. Snook (2014) reported a 1 m thick quartz vein mineralized with pyrite and epidote 200 m NW of the Landsverk 1 pegmatite that may be represent another expression of this hydrothermal event. It is suggested that the hydrothermal fluids ascended along this structure and overprinted these pegmatite bodies. However, the age of the brecciation event and origin of the hydrothermal fluids is uncertain, but they are definitely not related to the primary pegmatite formation.

In the eastern roof of the Landsverk 1 pegmatite the primary texture of the pegmatite is essentially preserved. Here, in the upper intermediate zone, K-feldspar forms large megacrysts up to 3 m in size, and occurs together with 4 m long fan-like 'biotite' sheets, which are variably altered to chlorite. Plagioclase masses appear to be spatially coincident to muscovite sheaves. It can be noted that muscovite generally occurs in the centre of the pegmatite, whereas 'biotite' is concentrated in the upper wall and intermediate zone in the roof of the body. There are at least two large (>10 m^3) 'cleavelandite' replacement zones with associated 'amazonite'.

Fig. 2.48. Map of the Landsverk area showing the distribution of pegmatites affected by intense post-pegmatitic, hydrothermal brecciation (Landsverk 1, Gudmundsgruva, Haugen 1, Haugen 2).

Mineralogy

The complex mineralogy of Landsverk 1 is a result of (1) the crystallization of primary pegmatite minerals; (2) the formation of 'cleavelandite' replacement zones; and (3) overprint by pegmatite-extrinsic hydrothermal fluids causing the brecciation, alteration and partial replacement of the pegmatite minerals. In the following the mineralogy is described in the order of these stages.

Major *primary pegmatite minerals* are K-feldspar, plagioclase, 'biotite' and Fe muscovite. All quartz samples analysed so far from Landsverk 1 (Taylor & Friedrichsen 1983; Snook 2014) have hydrothermal isotopic and trace element signature. The process responsible for the more or less complete replacement of primary pegmatite quartz by hydrothermal quartz remains unclear (see also discussion below). Primary plagioclase has albite composition (An 3.4%; Table 2.9). The primary K-feldspar (Or 70.2 %) is light pinkish in colour and forms crystals up to 5 m in size.

Table 2.9. Composition of pegmatite-stage feldspars from Landsverk 1. Bulk XRF analyses. Data from Müller, unpublished.

	plagioclase	pink K-feldspar	'amazonite'	'cleavelandite'
sample nr.	12070803	12070802	16091002b	24061307
major elements (wt.%)				
SiO_2	66.0	65.6	65.03	68.13
Al_2O_3	19.5	18.3	18.57	19.5
Fe_2O_3	0.11	0.09	0.13	0.05
TiO_2	0.01	<0.01	<0.01	<0.01
MgO	<0.04	<0.04	<0.01	0.01
CaO	0.76	0.02	0.01	0.04
Na_2O	11.5	3.4	3.27	11.64
K_2O	0.74	12.2	11.9	0.3
MnO	0.01	<0.01	<0.01	<0.01
P_2O_5	<0.01	0.01	0.02	0.05
LOI	0.21	0.09	0.9	0.2
Sum	98.8	99.6	99.88	99.92
An	3.4	0.1	0	0.2
Ab	92.7	29.7	29.5	98.1
Or	3.9	70.2	70.5	1.7
trace elements (ppm)				
Ba	14	51	36	2
Cs	<10	33	577	18
Ga	52	43	59	77
Pb	110	233	522	29
Rb	24.5	1690	4394	73
Sr	16	10	8	18
Ta	<4	<4	0.1	30
Y	3.2	3.9	0.2	0.7

However, in most cases only fragments of these crystals are observed within the brecciated parts of the pegmatite. 'Biotite' has Mg siderophyllite to siderophyllite composition. However, most of the 'biotite' is altered to fine-grained masses of 'chlorite'. The alteration is related to the hydrothermal stage.
Accessory minerals related to the primary pegmatite stage are listed in Table 2.10. Garnets are rare at Landsverk 1 and form relative small crystals (up to 1 cm) of spessartine-almandine composition. Magnetite forms euhedral crystals (up to 1 cm) or crystal masses (up to 3 cm). Ilmenite occurs as platy crystals up to 15 cm in length.
Monazite-(Ce) forms clusters of brownish pyramidal crystals with step-like faces associated with 'biotite' in the eastern, less-brecciated part of the mine. Some of the finest Evje-Iveland specimens have been found here (Fig. 2.49A). Large single, subhedral to anhedral crystals and crystal masses occur in K-feldspar. In 2015 a large, 3-kg mass of dark brown 'monazite' was found by Reidar Kjetså. Occurrences of beryl are only recorded in older literature (Bjørlykke 1935) and no recent findings have been made.

Table 2.10. Pegmatite minerals identified at Landsverk 1. Modified from Mindat (2017).

Mineral name	Mineral name	Mineral name
Aeschynite-(Y)	Fluorite	Quartz (pegmatite-stage?)
Albite (car. 'Cleavelandite')	'Garnet'	Rutile (var. Ilmenorutile)
Allanite-(Ce)	Hematite	Samarskite-(Y)
'Apatite'	Ilmenite	Siderophyllite
Bavenite	'K-feldspar'	Sphalerite
Beryl	Magnetite	Thorite (var. Orangite)
'Biotite' (Siderophyllite)	Microcline (var. 'Amazonite')	Thortveitite
Bismuthinite	Microlite Group	Titanite
Columbite-(Fe)	Molybdenite	Topaz
Euxenite-(Y)	Monazite-(Ce)	Uraninite
Fergusonite-(Y)	Muscovite (Fe muscovite)	Xenotime-(Y)
Fersmite	Pyrophanite	Zircon (var. Alvite)
Fluorapatite	Polycrase-(Y)	

Euxenite-(Y) is one of the most common REE minerals at Landsverk 1 and was already collected by Brøgger (1906) in 1902 (and in 1903 by Schei and in 1905 by Hornemann) in form of black masses and single crystals. The crystals have a 'pressed flat' habit, which distinguish them from polycrase and aeschynite-(Y) (Revheim 2006, 2007). Small black crystals of fergusonite-(Y) were first found by Schei (1905) which was the first record of fergusonite-(Y) from the Evje-

Iveland area. Revheim (2006) reported the finding of several crystals up to 7 cm in length in muscovite splays. They occur as radiating crystals with square cross-section. Polycrase-(Y) occurs as shiny black crystals in feldspar together with biotite and ilmenite. The crystals look like euxenite-(Y) but are more prismatic. Columbite-(Fe) crystals up to 10 cm are reported from Landsverk 1 (Revheim 2006, 2007). Typically for the minerals mentioned above is that they contain uranium and consequently they are all metamict. For this reason, and because of the chemical similarity between many of the black minerals in Evje-Iveland they are only distinguished based on their crystal habits.

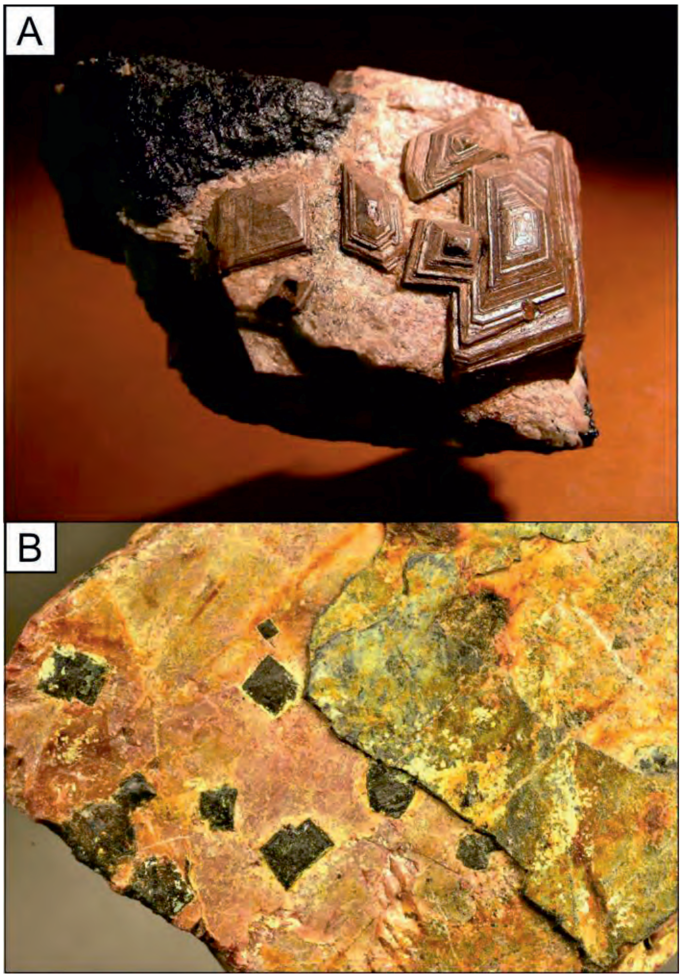


Fig. 2.49. A - Monazite-(Ce) from Landsverk 1. Photo by Olav Revheim published by MinDat (2017). B - Black cubic uraninite crystals embedded in K-feldspar and partially covered by platy ilmenite. The yellowish powder-like coating is 'thorogummite', a mineral which has been discredited as a valid species by the IMA in 2014 (Piilonen et al. 2014). Field of view is 26 mm. Photo by Ronald Werner.

The Landsverk 1 pegmatite is unusual rich in U-Th-bearing minerals, e.g. thorite and uraninite. The enrichment in U and Th seems to be a common feature of pegmatites at the northern margin of the Evje-Iveland pegmatite field. Similar enrichments are known from the Ås pegmatite (4 km W) and the Einerkilen pegmatite (4 km E). The latter was mined for U from 1950 to 1951. At Landsverk 1 uraninite occurs as cubic crystals with edge length up to 1 cm (Fig. 2.49B). They occur in K-feldspar together with ilmenite. Up to 4 mm large thorite (var. 'orangite') crystals have been described by Revheim (2006, 2007). Radioactive zircon is relative common at Landsverk 1. It occurs as radiating crystal groups or as single crystals together with ilmenite, euxenite-(Y) and other REE minerals (Revheim 2006, 2007). The zircons from the Evje-Iveland pegmatite field have elevated Hf contents and are typically the variety alvite. The only known sulphide which is related to the pegmatite stage is molybdenite. It has been found as crystal aggregates up to 5 cm in size, some of those are exhibited at the Fennefoss Geomuseum in Evje.

Minerals of the *'cleavelandite' replacements zones* comprise 'cleavelandite', spessartine, topaz, zircon, fluorite, muscovite, and microlite group minerals. 'Amazonite' is also considered to be associated with the replacement zones because it always occurs next to 'cleavelandite'. Due to the brecciation and the associated hydrothermal overprint the 'cleavelandite' zones are only partially preserved. There are at least two major 'cleavelandite' zones at Landsverk 1: one in the western part of the mine and one in the central part. These 'cleavelandite' zones are some of the largest at the northern margin of the Evje-Iveland field (The largest replacements zones occur at Birkeland in the centre of the pegmatite field).

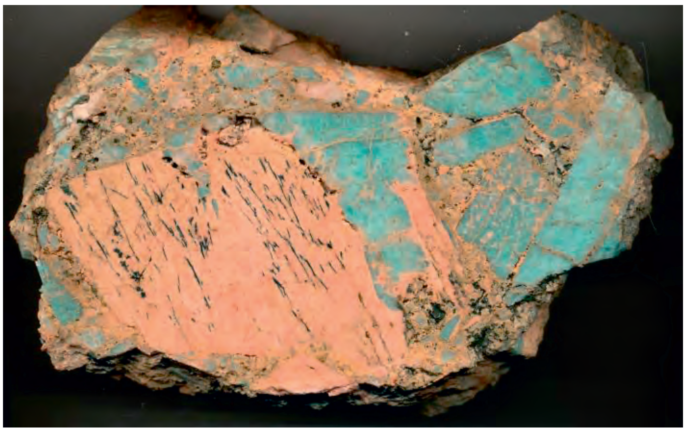


Fig. 2.50. Brecciated 'amazonite' cemented and partially replaced by brick-red microcline. Field of view is about 20 cm.

The Landsverk 1 'amazonite' has the most intense greenish colour recorded from the Evje-Iveland pegmatites. A large ‘amazonite’ block (about 2 m in size) can still be seen in the upper part of central south face of the mine, opposite to the mine galleries. The Pb content in the ‘amazonite’ is twice as high (522 ppm) as in the primary pinkish K-feldspar (233 ppm; Table 2.9). ‘Amazonite’ is commonly brecciated, cemented and partially replaced by hydrothermal, brick-red low-temperature microcline (Fig. 2.50). The replacement and colour transition of ‘amazonite’ is related to the hydrothermal brecciation event. ‘Cleavelandite’ from Landsverk 1 is slightly bluish and occurs as fan-like crystal aggregates with plate length of up to 10 cm and they have an usual high Ta content of 30 ppm compared to other feldspars (Table 2.9). Muscovite, greenish to pinkish in colour occurs as small crystal clusters in ‘cleavelandite’ aggregates.

The post-pegmatite, *hydrothermal stage* (brecciation stage) resulted in a complex mineral assemblage which is atypical for pegmatite settings. The hydrothermal minerals are listed in Table 2.10 and their crystallization sequence is illustrated in Figure 2.51. Some of these minerals grew in several generations, forming phantoms, sceptre crystals, replacements and overgrowths. The paragenesis can best be studied in the open cavities.

As mentioned above, quartz as one of the most common minerals at Landsverk 1, has hydrothermal isotopic and trace element signature.

Table 2.10. Hydrothermal minerals identified at Landsverk 1. Modified from Mindat (2017).

Mineral name	**Mineral name**
Analcime	Microcline
Calcite	Montmorillonite
‘Chabazite’	Pyrite
Chalcopyrite	Quartz (var. Amethyst, Citrine, Smoky Quartz)
‘Chlorite Group’	Schröckingerite
Epidote	‘Stilbite’
Fluorite	Stilpnomelane
Galena	

Also the macroscopic appearance of massive quartz from Landsverk 1 is different compared to quartz from other Evje-Iveland pegmatites. It is very milky and rarely smoky with matte fracture surfaces (compared to shiny fracture surfaces of quartz from other localities). In addition, long-prismatic, clear quartz crystals, including the colour varieties amethyst, smoky quartz and citrine, are very common in open cavities with crystal sizes of up to 30 cm (Fig. 2.52).

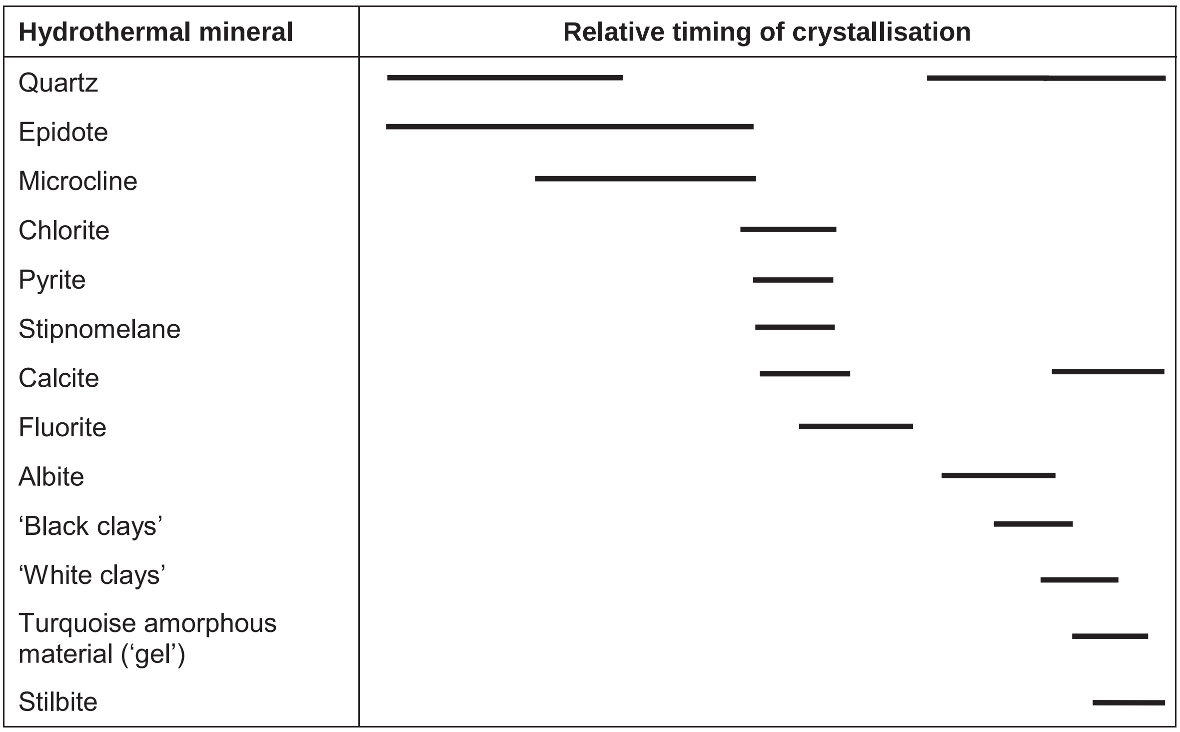


Fig. 2.51. Paragenetic diagram for the hydrothermal mineral assemblage of the Landsverk 1 pegmatite. Relative timing relations were established from mineral textures. The diagram does not include all minerals related to the hydrothermal stage. Modified from Snook (2014).

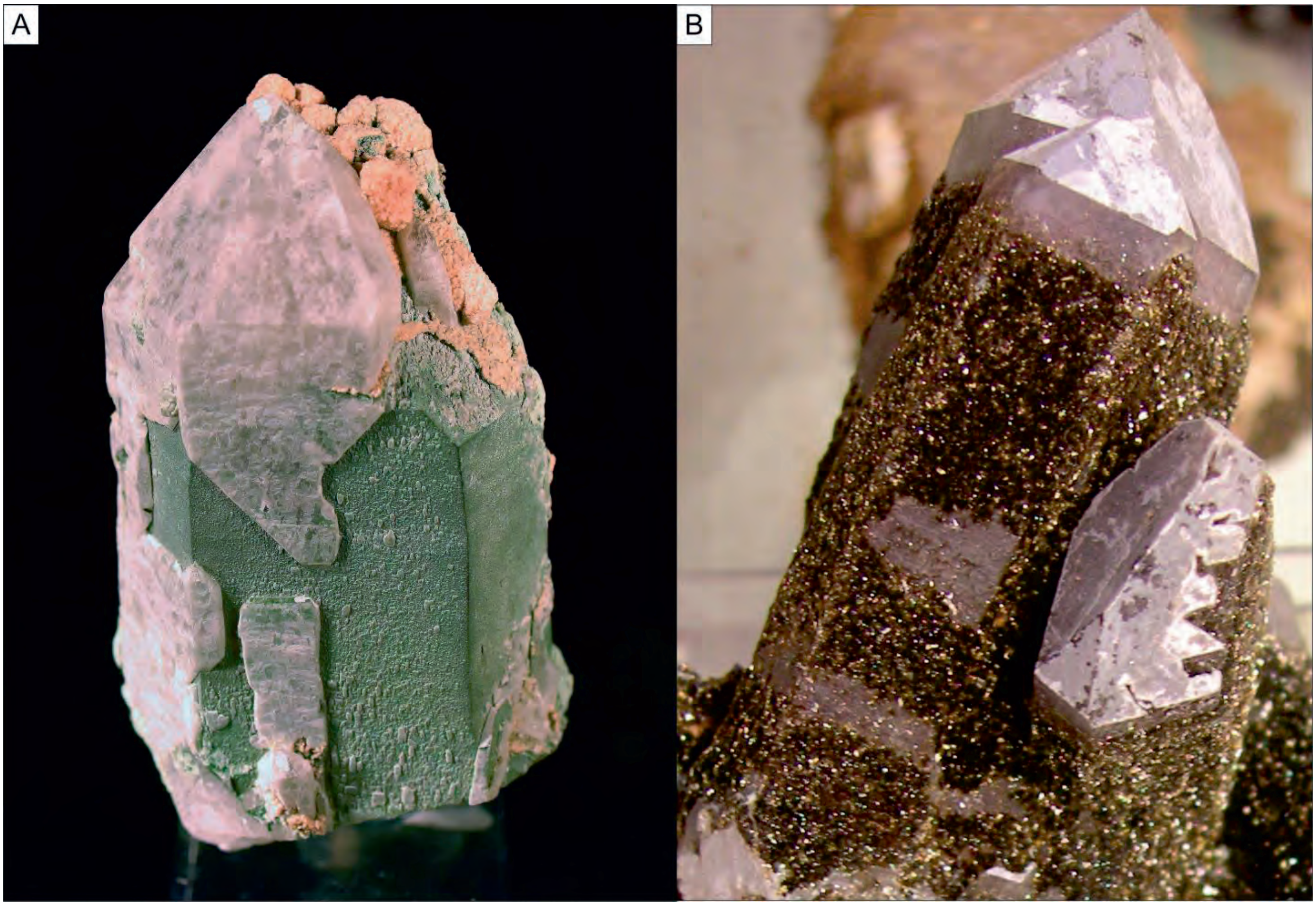


Fig. 2.52. A - Hydrothermal quartz crystal from a Landsverk 1 cavity coated with greenish ‘chlorite’ and subsequently overgrown by milky quartz and pinkish feldspar. Size of crystal is 7 cm. Fennefoss Geomuseum Evje. Photo by Ronald Werner. B - Hydrothermal quartz crystal from a Landsverk 1 covered with stilpnomelane. Size of crystal is 6 cm.

Oxygen isotope data for quartz from the Landsverk 1 and other Evje-Iveland pegmatites have been reported by Taylor & Friedrichsen (1983) and Snook (2014). Taylor & Friedrichsen (1983) determined $\delta^{18}O$ values of quartz from several Evje-Iveland pegmatites ranging from 8.3 to 10.3‰. Data from Snook (2014), presented in Figure 2.53, confirmed the values. Four quartz samples from the wall and core zones of the Steli and Solås pegmatites display consistent $\delta^{18}O$ values of 8 to 9‰, which are typical of granites and pegmatites (6 – 10‰, e.g. Hoefs 1997). This variation reflects the expected values from equilibrium isotope-fractionation factors for relevant pegmatite crystallization temperatures. However, the hydrothermal quartz from Landsverk 1 displays extreme variation in $\delta^{18}O$ values, ranging from -8.98‰ in the crystal core to 11.74‰ in the outermost growth zone of the hydrothermal crystals (Snook 2014). Taylor & Friedrichsen (1983) detected similar high $\delta^{18}O$ variability within individual quartz crystals form Landsverk 1. The low $\delta^{18}O$ values indicate an influx of meteoric water during the brecciation event which is unrelated to the pegmatite petrogenesis (Taylor & Friedrichsen 1983). According to Taylor & Friedrichsen (1983) and Rainer Thomas (unpublished) the crystallization temperature of the hydrothermal quartz was 200 to 250ºC.

The low crystallization temperature of the hydrothermal quartz is supported by quartz trace element studies. The Ti content in Landsverk 1 quartz is below 1 ppm indicating crystallization temperatures <350ºC (Huang & Audétat 2012) (Fig. 2.54). In scanning electron microscope cathodoluminescence (SEM-CL) images the hydrothermal quartz shows fine-scale oscillatory growth zoning which is typical for hydrothermal quartz (Figs. 2.55A, B). In contrast, primary pegmatite quartz does not show growth zoning (Fig. 2.55C).

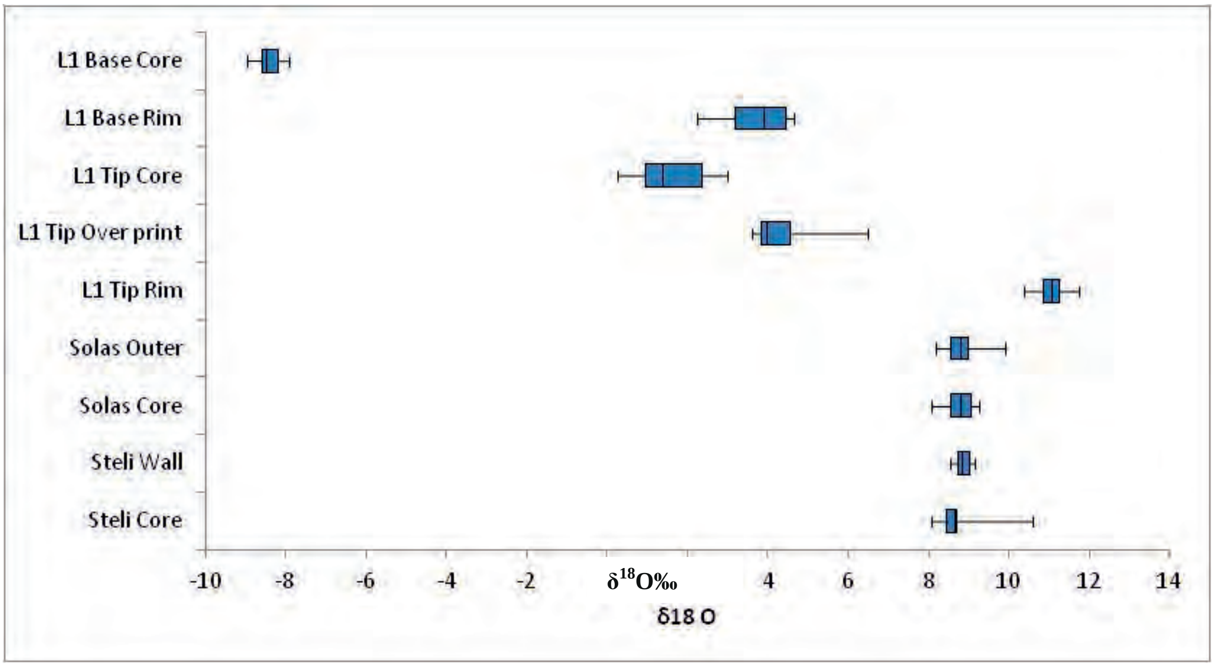


Fig. 2.53. Summary of $\delta^{18}O$ values for the quartz from Evje-Iveland. The samples from the Solås and Steli pegmatites show $\delta^{18}O$ values between from 8.3 to 10.3‰ common for granitic and pegmatitic systems. The L1 samples – growth zones (core to rim) of hydrothermal quartz crystals from Landsverk 1 have an initial -8.98‰ value (inner core of the L1 crystal) corresponding an almost pure meteoric water signature. During further crystal growth ('L1 base rim' to 'L1 tip rim') the $\delta^{18}O$ values increase towards magmatic signatures caused by 'recycling' of the magmatic signature of the replaced magmatic quartz. From Snook (2014).

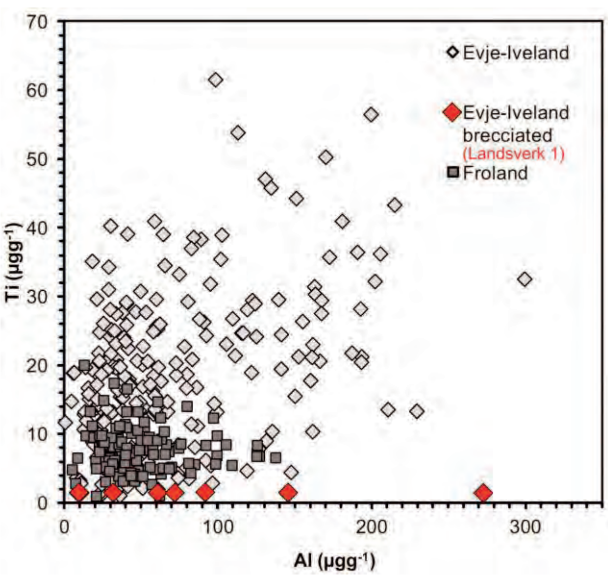


Fig. 2.54. Plot showing the variability of Al and Ti in quartz from the Evje-Iveland and Froland pegmatites. Quartz from Landsverk 1 (red diamonds) has exceptionally low Ti (<1 μgg^{-1}) and high Al variability both typically for hydrothermal quartz. From Müller et al. (2015).

The crystal quartz from the pockets is commonly covered or intergrown with chlorite, stilbite, albite, and/or bronze-coloured stilpnomelane (Fig. 2.52). Chlorite and clay minerals, such as montmorillonite, commonly fill the cavities. Epidote represents an early-hydrothermal-stage mineral and forms masses of tiny green crystals cementing and replacing primary pegmatite minerals. In open spaces the crystals can be euhedral and up to 5 mm in size.

Violet to almost black octahedrons or masses of hydrothermal fluorite (up to 1 cm) are very common in the cavities. (Note that the 'cleavelandite' replacement zones contain pegmatite-stage-related fluorite which is commonly greenish in colour but much rarer.) Hydrothermal fluorite occurs also along fractures in primary pegmatite minerals.

Sulphides are common constituents of the hydrothermal stage at Landsverk 1. Pyrite is associated with brick-red microcline and chlorite and forms single cubes or intergrown cubes up to 8 cm in size. Chalcopyrite is rare and occurs as relative large crystals (3 cm) and crystal masses in hydrothermal quartz. Galena is very rare and is found in hydrothermal quartz as small masses up to several cm in size.

Calcite from Landsverk 1 was described first by Andersen (1926, 1931). The euhedral, face-rich whitish to yellowish crystals are up to 12 cm in size and occur as single crystals or in groups. Calcite is one of the last phases of the hydrothermal assemblage. Crystals are commonly etched. 'Chabazite' has been identified more recently and forms yellowish-greenish crystals and crystal aggregates up to 1 cm in size associated with stilpnomelane at open fractures in primary feldspar (Revheim 2006, 2007). Yellow crystals occur together with quartz and chlorite. Orange crystals are very rare. Stilbite represents the latest stage of the hydrothermal sequence and occurs in the cavities with different habits and colours up to 4 mm in size. Most common are brownish-yellowish, glass-like spheres growing on microcline. Greenish crystals are rarer. Analcime crystals up to 2.5 cm have been found at Landsverk 1. They occur in open fractures in feldspar and seem not to be related to a particular paragenesis (Revheim 2006, 2007). Fersmite is described as a hydrothermal alteration product of columbite-(Fe) (Larsen 2001). However, it is not clear if this alteration is related to the brecciation event.

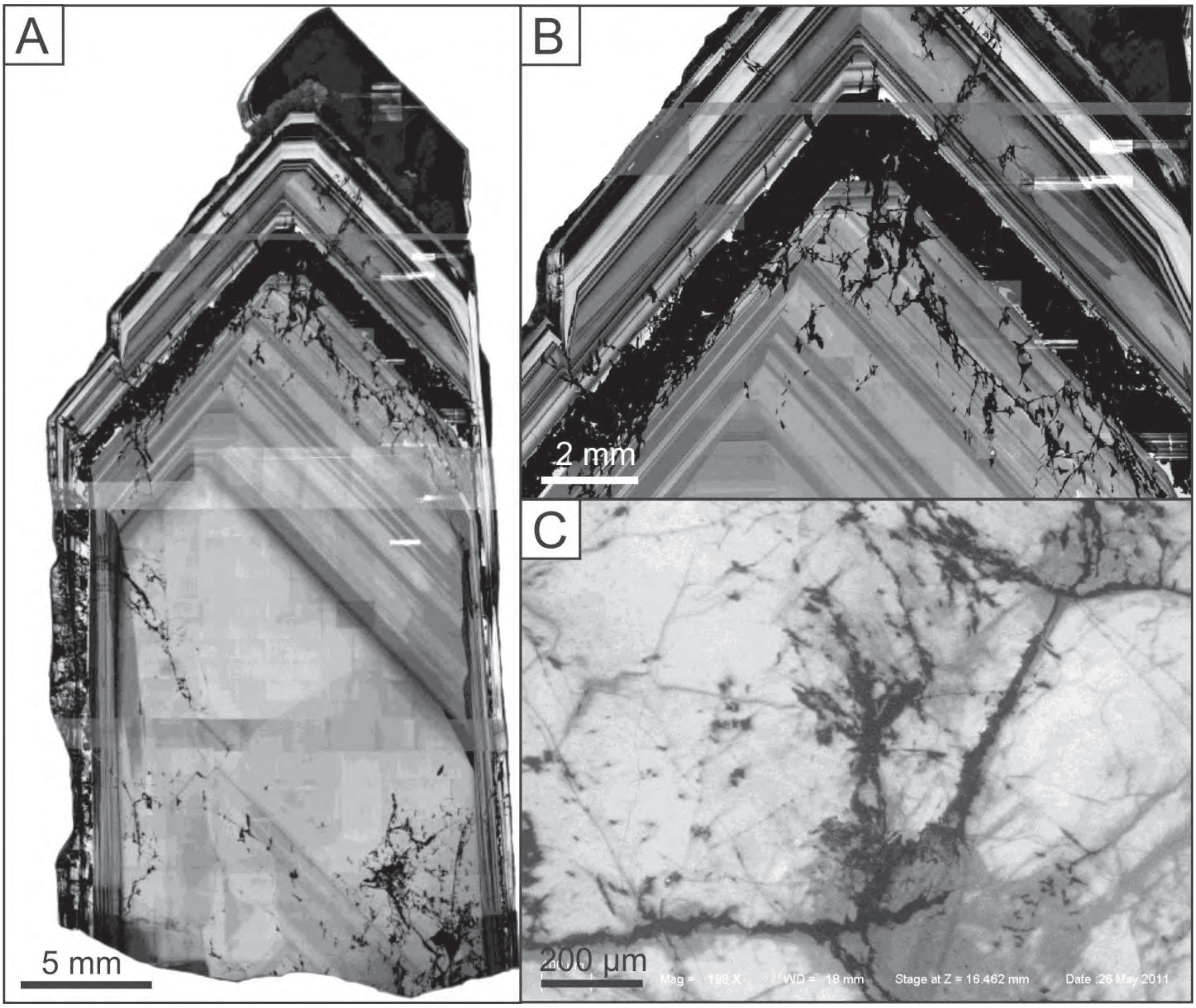


Fig. 2.55. Scanning electron microscope cathodoluminescence (SEM-CL) images of quartz. A – Hydrothermal quartz crystal from Landsverk 1 showing oscillatory growth zoning typical for hydrothermal quartz. B – Detail of (A) illustrating that one of the growth zones is secondarily replaced by non-luminescent quartz (black). C – Representative SEM-CL image of typical pegmatite quartz from Evje-Iveland (Slobrekka pegmatite) showing exclusively secondary structures and no growth zoning. Modified from Snook (2014).

Plate 2.1. Photographs of minerals from pegmatites of the Evje-Iveland area. All photographs by Øivind Thoresen. A – Gadolinite-(Y) from Iveland (mine unknown). The crystal is 4.2 cm in size. Collection of the Natural History Museum Oslo, Nr. 21722. B - Gadolinite-(Y) from Surtefjell, Frikstad. The crystal is 3.5 cm in size. Collection of Øivind Thoresen. C – Monazite-(Ce) from Landsverk 1 mine. The specimen is 3.5 cm in size. Collection of Øivind Thoresen. D – Thortveitite from Iveland (mine unknown). The crystals are 8 cm in length. Collection of Øivind Thoresen. E – Garnet of the almandine-spessartine series from the Høyland mine. The largest crystal is 2.5 cm in size. Collection of Øivind Thoresen. F – Chrysoberyl on quartz from the Skavdalen mine. The crystal is 3 cm in length. Collection of Øivind Thoresen.

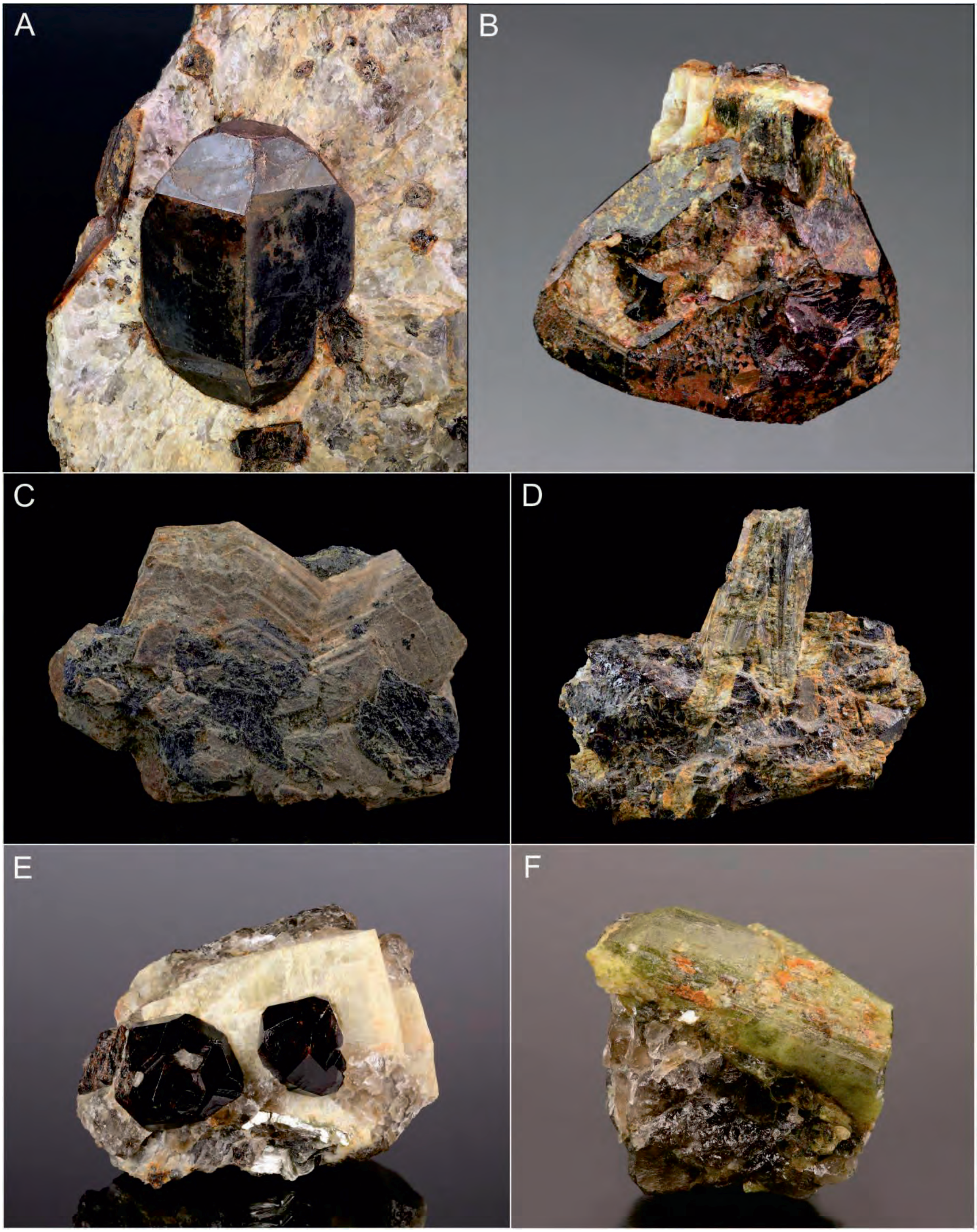

A
B
C
D
E
F

Plate 2.2. Photographs of minerals from pegmatites of the Evje-Iveland area. All photographs by Øivind Thoresen. A – Monazite-(Ce) from Iveland (mine unknown). The crystal is 4 cm in length. Collection of the Iveland municipality. B – Gadolinite-(Y) from the Slobrekka mine. The crystal is 7 cm in size. Collection of the Iveland municipality. C – Davidite-(Ce) from the Tuftane mine. The specimen is 10.5 cm in length. Collection of the Iveland municipality. D – Beryl from Iveland (mine unknown). The crystal is 22 cm in length. Collection of the Iveland municipality.

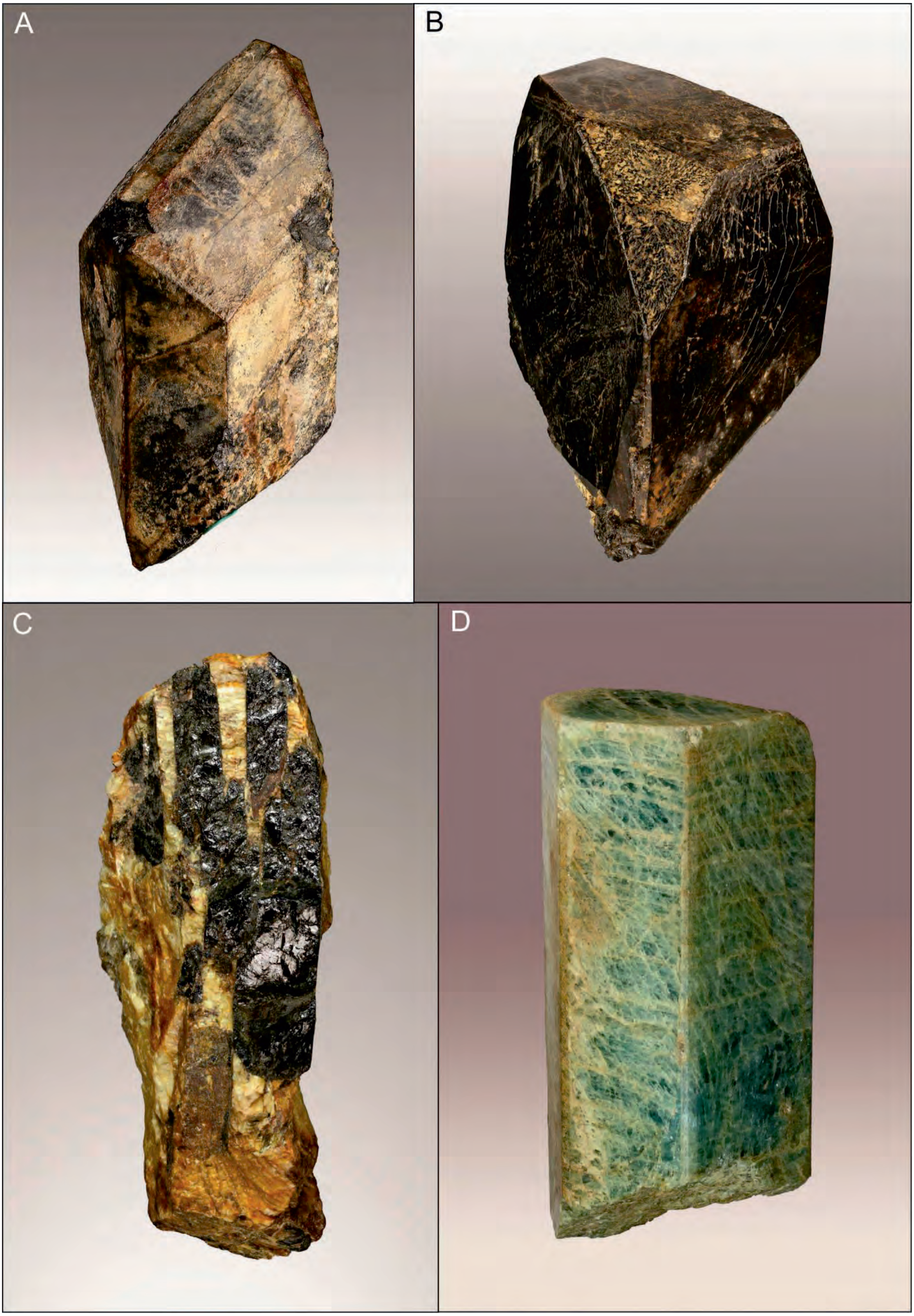
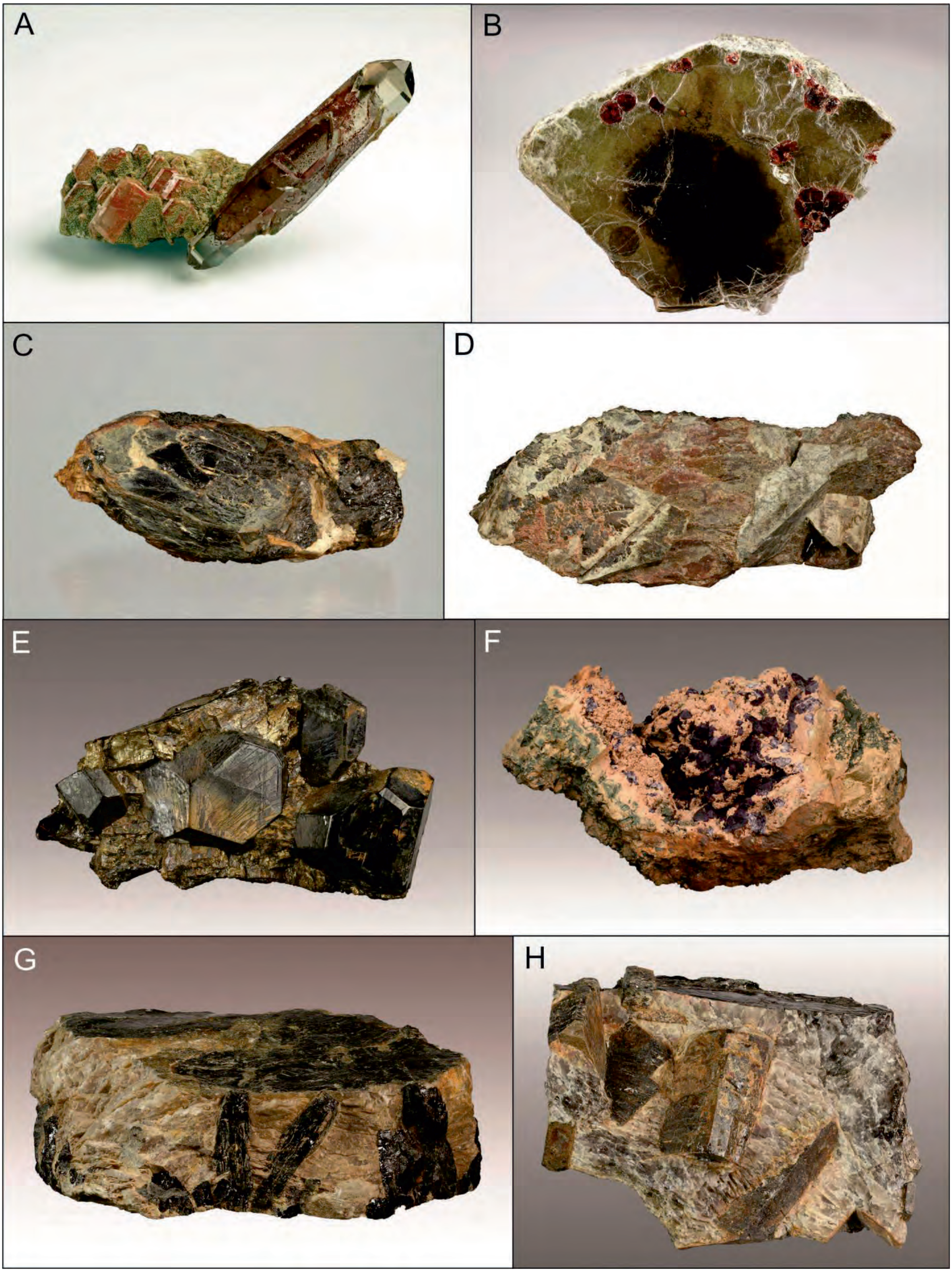

A
B
C
D

Plate 2.3. Photographs of minerals from pegmatites of the Evje-Iveland area. All photographs by Øivind Thoresen. A – Quartz with phantoms on albite from the Ljoslandåsen mine. The quartz crystal is 4.5 cm in length. Collection of the Iveland municipality. B – Flattened spessartine crystal in muscovite from the Fossbekk mine. The largest spessartine is 1.2 cm in size. Collection of Øivind Thoresen. C – Euxenite-(Y) from Knipane. The crystal is 7 cm in length. Collection of the Iveland municipality. D – Xenotime-(Y) from the Hilltveit mine. The crystal aggregate is 14.5 cm in length. Collection of the Iveland municipality. E – Albite covered with pyrrhotite from the Storsynken mine. The specimen is 8 cm in size. Collection of the Iveland municipality. F – Hydrothermal fluorite embedded in microcline from Landsverk 1 mine. The specimen is 30 cm in length. Collection of the Iveland municipality. G – Fergusonite-(Y) from the Rossås area. The specimen is 7 cm in length. Collection of the Iveland municipality. H – Aeschynite-(Y) from the Mølland area. The specimen is 11 cm in size. Collection of the Iveland municipality.


A
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C
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3. Syenite and nepheline syenite pegmatites of the Langesundsfjord area

Øyvind Sunde, Henrik Friis, Tom Andersen & Øivind Thoresen

Introduction

The Oslo Graben

The geology of SE Norway is uncommonly varied, with Precambrian basement rocks belonging to the Fennoscandian Shield (formed during the 1.50-1.60 ”Gothian” and 1.20-0.90 Sveconorwegian / Grenvillian periods), covered by sedimentary rocks of lower Paleozoic age and rift-related sedimentary, volcanic and intrusive rocks formed in late Carboniferous to Permian time. The geology of the Oslo region was ”discovered” by geologists (L. von Buch, C. Lyell, B.M. Keilhau and others) in the early 19th century and since the work by W.C. Brøgger (Brøgger 1890, 1906) and his contemporaries in the late 19th and early 20th century it has been recognized as a classical province of alkaline igneous rocks (Dons 1978).

A note on nomenclature

Oslo is the capital of Norway (ca. 560 000 inhabitants). Oslo is the historical name of the town, but from 1624 to 1924 it was known as Christiania (also spelled Kristiania). The region with Paleozoic rocks around Oslo has traditionally been known as the *Oslo Region* (Oslofeltet in Norwegian, Oslogebiet in German), or prior to 1924, the Christiania Region. W.C. Brøgger published his monographs on the igneous rocks under the serial heading ”Die Eruptivgesteine des Christianiagebietes”, for the seventh and last of his volumes this was changed to ” Die Eruptivgesteine des Oslogebietes”. Today, ”Oslo Region” is used as a descriptive term referring in general to the area with Paleozoic rocks.

The *Oslo Graben* refers to the downfaulted blocks of Phanerozoic sediments, lavas and intrusions cutting through the Precambrian basement of the Fennoscandian Shield (Fig. 3.1). The Oslo Graben consists two graben segments: The *Akershus Graben* in the north, and the *Vestfold Graben* in the south (Fig. 3.2). The Oslo Graben forms part of the larger *Oslo Rift*, which includes the off-shore Skagerrak graben, and ties up with a system of post-Variscan rift structures in the North Sea and northwestern Europe (Wilson et al. 2004 and references therein; Larsen et al. 2008).

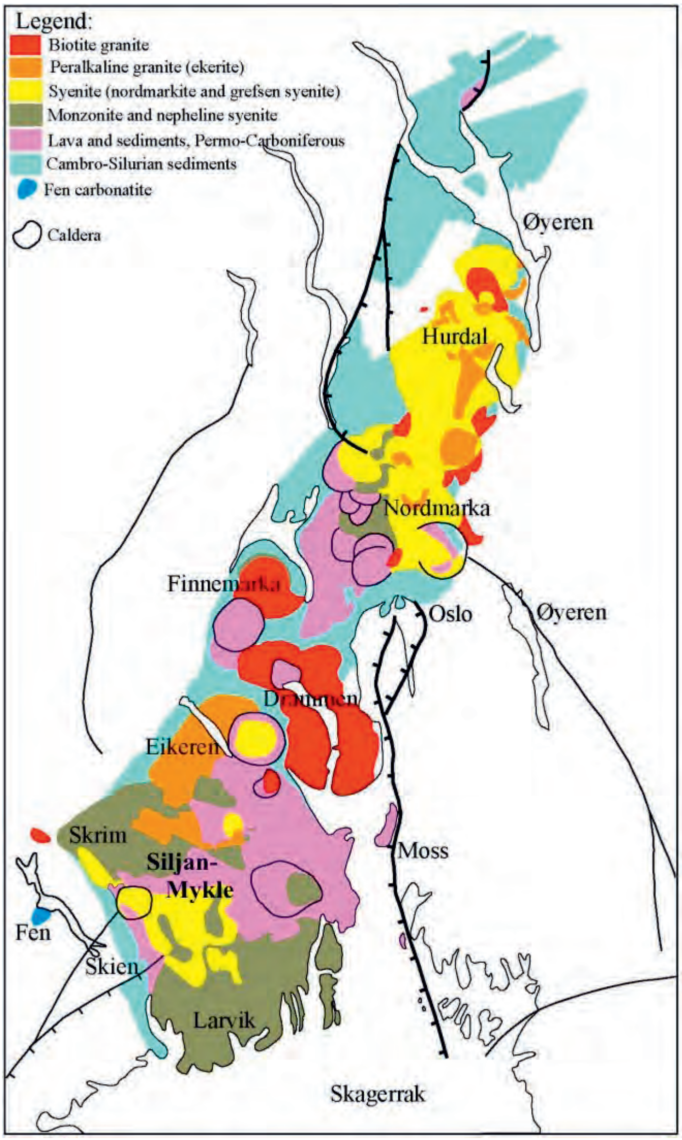

Fig. 3.1. Simplified geological map of the Oslo Graben.

Tectonomagmatic evolution of the Oslo Rift

Two aspects of the Oslo Graben have attracted the attention of geologists since the early 19th century: (1) The early Paleozoic sedimentary sequence and (2) the igneous and minor sedimentary rocks related to late Paleozoic rifting. Owen et al. 1990). Prior to rifting, such rocks must have covered large parts of southwestern Fennoscandia. The sedimentary rocks were folded during the Caledonian orogeny (approximately 490 – 390 Ma). The youngest early Paleozoic sedimentary rocks make up an up to 1250 m thick redbed sequence (the Ringerike Group, Worsley et al. 1983). Early Paleozoic marine shales and limestones are preserved within the Oslo Graben (Worsley et al. 1983). By the late Carboniferous, the early Paleozoic sedimentary rocks had been eroded down to a peneplain, and a thin

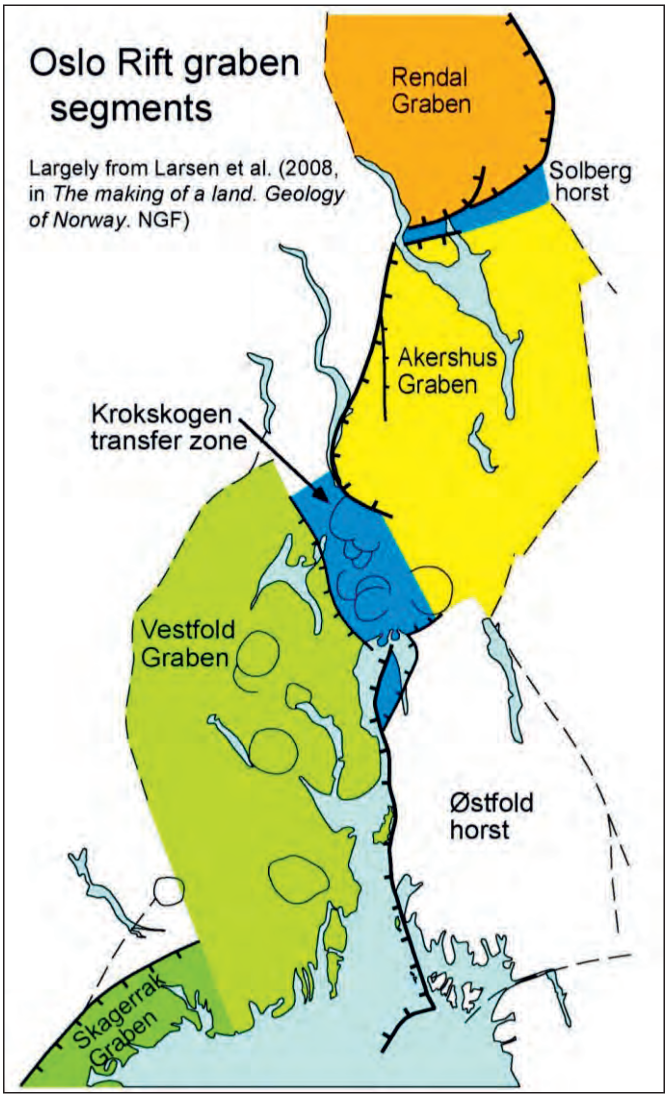

Fig. 3.2. Graben segments of the Oslo Rift.

sequence of continental sediments (conglomerate, sandstone, shale) of upper Westphalian age (the Asker group) was deposited with an angular unconformity to the underlying Silurian sandstone. The presence of thin limestone units in the Asker Group indicates marine transgression from the south or east (Olaussen et al. 1994; Larsen et al. 2008).

The late Paleozoic evolution of the Oslo Rift can be divided into five or six distinct stages (Ramberg & Larsen 1978; Neumann et al. 2004; Larsen et al. 2008). Constrains on timing of events are provided by a large set of Rb-Sr isochron ages (Sundvoll et al. 1990), which are now slowly being superseded by U-Pb ages, mainly from ziron (Table 3.1). In general, U-Pb geochronology seems to indicate narrower time intervals for each of the tectonomagmatic stages, and in general marginally older ages than suggested by Rb-Sr isochrones, but possibly also suggesting an earlier termination of magmatism (i.e., 268 Ma, rather than 241 Ma suggested by Rb-Sr data).

Table 3.1. Major tectonomagmatic stages of the Oslo rift according to Sundvoll et al. (1990), Pedersen et al. (1995), Dahlgren et al. (1998), Neumann et al. (2004), Haug (2007), and T. Andersen (unpublished data).

Stage	**Products**	**Stratigraphic or Rb/Sr age ranges**	**U-Pb age ranges**
1: Pre-rift	Asker group	c. 300-312 Ma	< 319 Ma
2: Initial rifting	Basaltic volcanism	304-291 Ma	(305)-299 Ma
3: Main rifting	Intermediate lava (Rhomb Porphyry), larvikite intrusions	294-276 Ma	298-292 Ma
4: Central volcano	Calderas, diverse volcanic rocks, ring-dikes	280-243 Ma	
5: Batholith and 6: Terminal	Larvikite, Syenites, granites	273-241 Ma	286-268 Ma

Stage 1: The *pre-rift evolution* is characterized by deposition of the Asker group in a delta environment. A maximum age limit for deposition is given by a 319±5 Ma ID-TIMS age of a detrital zircon (Dahlgren & Corfu 2001), which agrees with fossils indicating an upper Westphalian (300-312 Ma) age of deposition for the Asker Group (Olaussen et al. 1994). Detrital zircons in the Asker Group span a large range of Mesoproterozoic, to late Archean ages, suggesting extensive recycling of earlier Fennoscandian cover sequences, but also comprise a minor late Neoproterozoic age fraction of non-Fennoscandian, presumably Variscan origin (Dahlgren & Corfu 2001; Kristoffersen et. al. 2014).

Stage 2: Initial rifting. The oldest volcanism within the Oslo Graben produced basaltic lavas (B1) which form thick sequences in the Vestfold Graben, and thins northwards until the Oslo area where it is not present. These lavas have been dated to late Carboniferous to earliest Permian ages, but they are pre-dated by a series of sills of trachyandesitic to rhyolitic composition that intrude the Asker group and underlying lower Paleozoic sedimentary rocks. The maximum Rb-Sr age obtained from these sediments also indicate a latest Carboniferous age (Sundvoll et al. 1992).

Stage 3: In the *main rifting stage*, the Oslo Graben subsided, and large volumes of rhomb porphyry (trachyandesite, latite) and minor basalt erupted by fissure eruptions. The composite Larvik pluton intruded in this stage, and has been dated to 298-292 Ma by U-Pb on zircons (Dahlgren et al. 1996, 1998).

Stage 4: In the *central volcano stage*, volcanic activity was concentrated on distinct volcanic centers with local trends of magmatic evolution, terminating in caldera collapse. The central volcanoes are preserved as between 15 and 20 cauldron structures, representing sections through subvolcanic magma chambers, ring-dike systems and downfaulted blocks of volcanic rocks. The Rb-Sr ages suggest stage four lasted for up to 40 Ma, which is a relatively long time for the Oslo Rift. Unfortunately, U-Pb ages are not yet available for rocks formed in the central volcano stage.

Stage 5: Emplacement of the intermediate-felsic batholiths. In the final stage, the large intrusions of syenitic to granitic composition were emplaced and many smaller larvikite intrusions (the Larvik pluton itself intruded earlier, in Stage 3). U-Pb ages for different intrusive members of the Drammen biotite granite pluton suggest ages in the range 286-272 Ma (Haug 2007), whereas larvikite and syenite in the Sande intrusion in the northern part of the Vestfold Graben yield ages around 282±3 Ma (Andersen, unpublished data), and the Grefsen syenite and Tryvann granite ages on the range 268-265 Ma (Olsen & Andersen, work in progress). Some studies of the Oslo Rift (e.g. Larsen et al. 2008) regard the youngest granitic intrusions and late dikes as belonging to a distinct, terminal stage of evolution (Stage 6 in Table 3.1).

The Larvik Plutonic Complex

The plutonic rocks of the Oslo Graben are distributed in three main complexes, which intruded the Cambro-Silurian sedimentary rocks (Fig. 3.1). The northern Akershus Graben segment is occupied by the Nordmarka-Hurdalen batholith of mostly syenitic and granitic alkaline rocks and some intrusions of biotite granite and monzonite. Biotite granites of the Drammen and Finnemarka batholiths dominate the central part of the Oslo Graben (northern part of the Vestfold Graben). These batholiths cover areas of 650 and 125 km^2 respectively, and the Drammen batholith is the largest granitic complex in the rift. The largely monzonitic batholiths of the Larvik Plutonic Complex (LPC) and the compositionally more diverse Siljan-Mykle Complex occupy the southern and central parts of the Vestfold Graben segment.

The petrographic nomenclature used for plutonic rocks in the Oslo Graben has been heavily influenced by W.C. Brøgger (e.g. Brøgger 1906), who introduced a large number of locally defined rock names, not all of which appear to have been well justified. Some of his more obscure terms have mercifully been discarded (e.g. "pulaskitic ekerite" – literally a nepheline-bearing alkali granite (!), but used to denote a local variety of quartz- and nepheline free alkali feldspar syenite in one of the plutons). However, any geologist working in or visiting the Oslo Graben must learn to live with local rock names such as *larvikite*, *lardalite*, *ekerite* and *nordmarkite*. These are deeply entrenched in the literature, and are unlikely to be replaced by their approved QAFP or TAS classification equivalents in the foreseeable future. Definitions of the local petrographic terms are summarized by Le Maitre et al. (2003).

According to the IGUS Glossary of Igneous Rock names, larvikite is *"a variety of augite syenite or monzonite consisting of rhomb-shaped ternary feldspars (with a distinctive schiller), barkevikite, titanian augite and lepidomelane. Minor nepheline, iron-rich olivine or quartz may be present"* (Le Maitre et al. 2003). Larvikite and associated rocks such as lardalite (nepheline-rich larvikite), kjelsåsite (plagioclase-rich larvikite) and tønsbergite (red, quartz-bearing larvikite) make up a family of intermediate intrusive rocks characteristic of the Oslo Rift. In terms of normative composition, larvikite qualifies as monzonite to monzodiorite, but because of its peculiar feldspar mineralogy it has proved difficult to classify in terms of QAFP components (c.f. definition above).

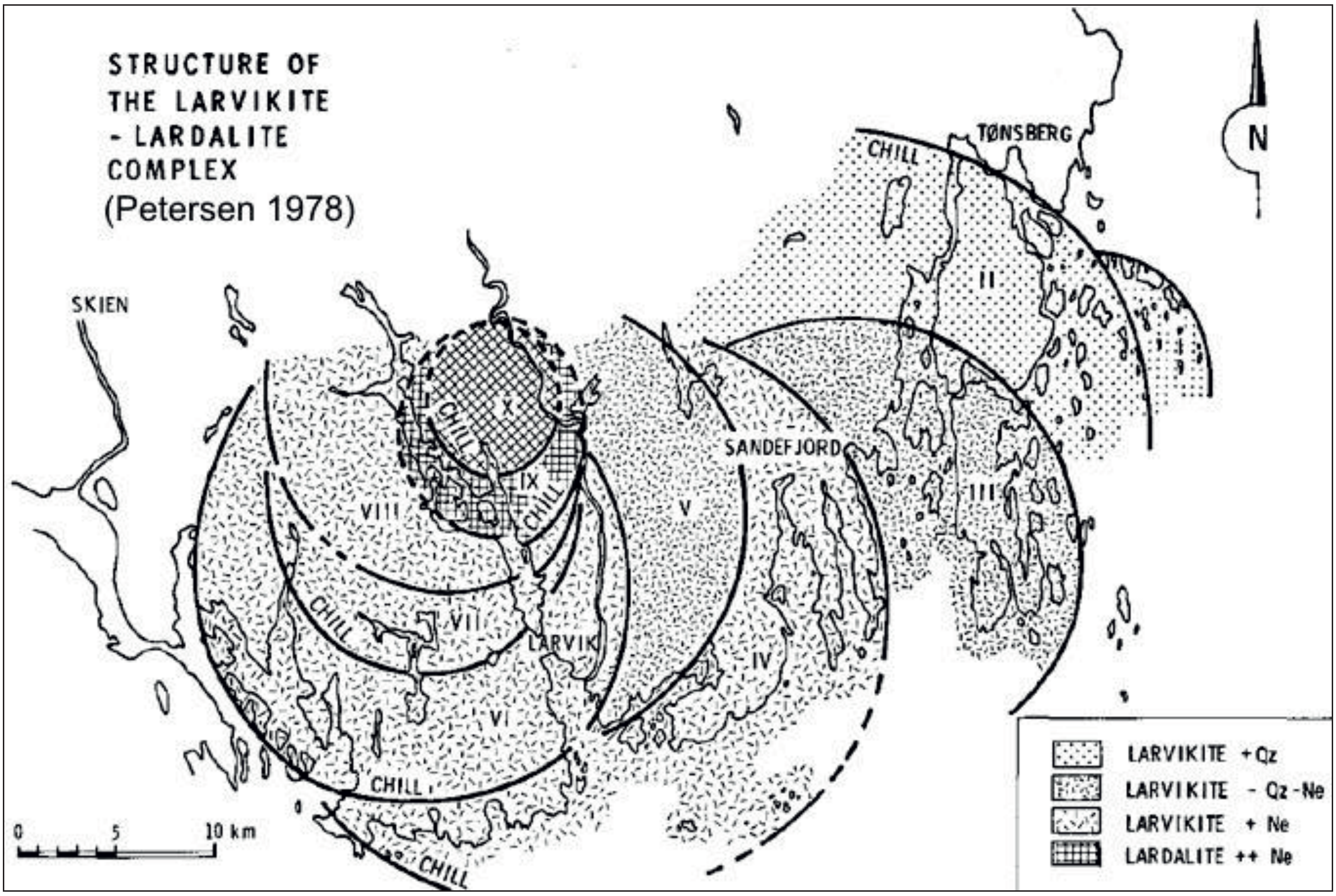

Fig. 3.3. Simplified geological map of the Larvik plutonic complex (Petersen 1978). The ring sections marked from I to X are progressively younger intrusive members of the complex.

The largest body of larvikite in the Oslo Graben comprises the composite LPC which makes up the southernmost part of the on-shore graben. This complex was emplaced as a series of ring-shaped intrusions with internal intrusive contacts marked by chill-zones (Petersen, 1978). The intrusive center migrated westwards and northwards with time (Fig. 3.3), at the same time the composition changed from quartz normative, through silica saturated to olivine- and nepheline bearing varieties. The youngest intrusive members of the complex are lardalite (nepheline monzonite, zones IX and X in Figure 3.3) and nepheline syenite / foyaite crosscutting these.

Larvikite makes up a significant component in the Siljan-Mykle complex, where it belongs to the first period of magma emplacement. It is furthermore found in the Nordmarka-Hurdal batholith and in several of the smaller composite intrusions (e.g. Sande pluton; Andersen, 1984). Emplacement of larvikite thus spans stages 3 and 4 of the rift evolution.

The most characteristic mineralogical feature of larvikite is the presence of a partly exsolved anorthoclase feldspar. In some varieties, the spacing of cryptophertitic exsolution lamellae causes selective diffraction of blue and green spectral colours, which causes the very characteristic schiller of ornamental larvikite (Rosenqvist 1965). However, larvikite varieties containing primary plagioclase and alkali feldspar are known (e.g. in the Sande pluton; Andersen 1984).

Trace element distribution patterns and radiogenic isotopic signatures of larvikite (and its rhomb porphyry extrusive equivalent) point towards an origin from a mildly alkaline mafic mantle-derived parent magma (Neumann et al. 2004 and references therein). If so, extensive evolution by fractional crystallization at crustal levels is required (Neumann 1980). The range of compositions observed within the Larvik pluton (from mildly quartz normative to strongly nepheline normative compositions) is explicable by polybaric fractionation combined with density filtering in the crust (Neumann 1980).

The schiller effect of larvikite feldspar has made the rock into a very popular dimensional- and ornamental stone (Selonen & Suominen 2003). Examples of its use in buildings and sculpture can be found all over Oslo. Dimension stone has been produced in the Larvik pluton since the 1880s. Today two industries are in operation (Lundhs and Larvik Granite), exporting larvikite for ca. 500 million NOK/year (Heldal et al. 2008). The feldspar in economically interesting varieties of larvikite should have a well-developed schiller-effect, and its fracture pattern should allow quarrying of large, homogeneous blocks. Several distinct larvikite types are recognized within the complex (Fig. 3.4), the most economically interesting of which are the dark ”Emerald Pearl” or Klåstad type (Fig. 3.4), the bluish grey ”Marina Pearl” or Stålaker type and the bright blue ”Blue Pearl” or Tvedal type. All of these form part of zones IV, V and VI in the intrusive chronology of Petersen (1978). In the 19th and early 20th century, the dark red larvikite variety known as tønsbergite was also widely used in architecture, and central Oslo shows many good examples (e.g. the Freemasons' hall).

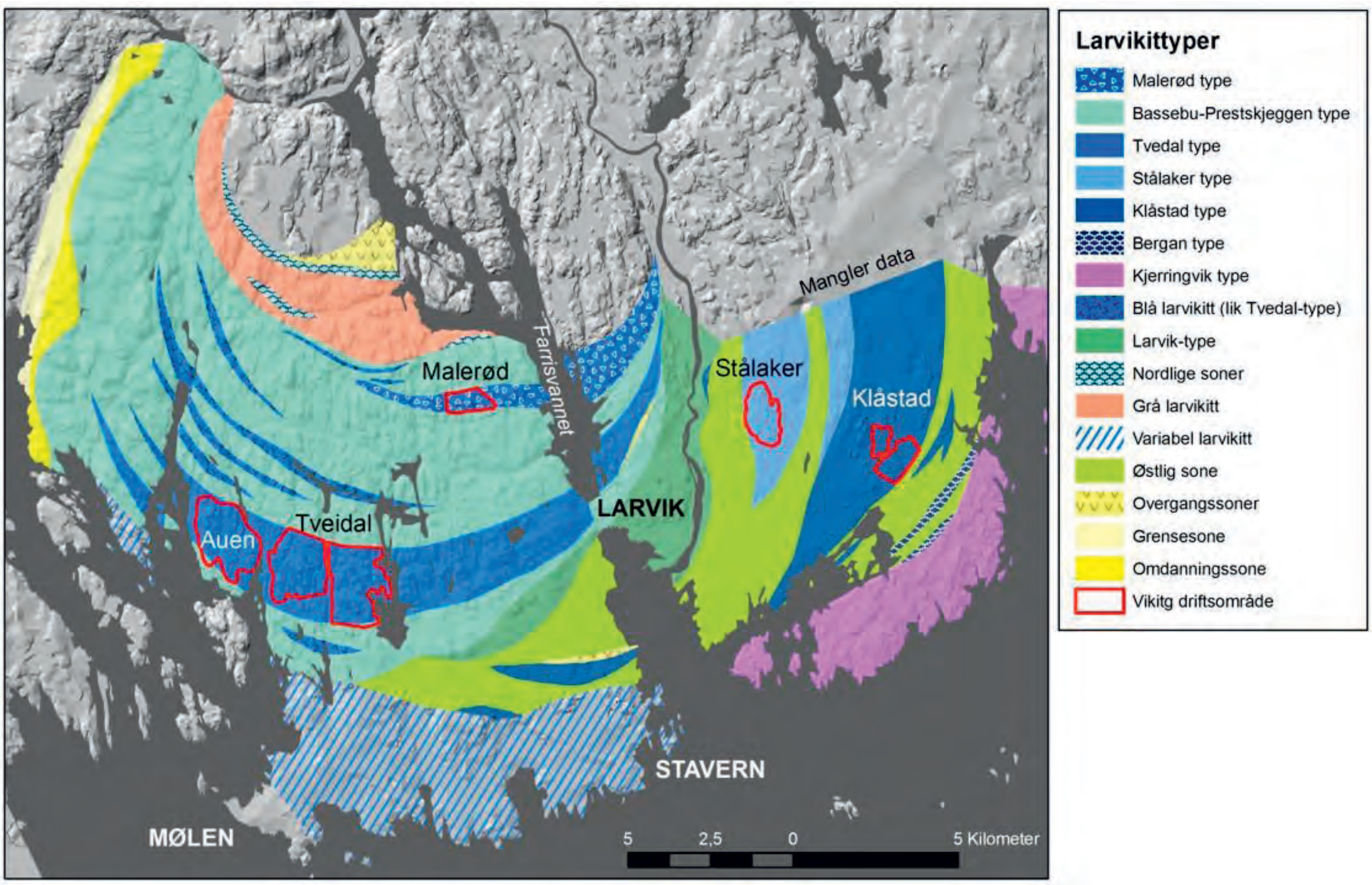

Fig. 3.4. Distribution of larvikite types and quarrying districts within the Larvik pluton. Based on field studies by the Geological Survey of Norway (Heldal et al. 2008 and http://www.ngu.no/upload/Georessurser/Naturstein/Forekomster/Larvikittforekomster/fig9.jpg).

The main occurrences of silica- undersaturated nepheline-bearing plutonic rocks in the Oslo Graben are in the northern part of the LPC, but minor bodies of nepheline syenite are also found in the Siljan-Mykle complex (Andersen & Sørensen 1993) and in the Nordmarka-Hurdal massif (Sæther 1962).

Nepheline syenite occurs in masses on the southern Bjønnes peninsula and as sills primarily in the Tveidal district and Barkevika area. This nepheline syenite was termed *ditroite* (Brøgger, 1890). It has a foliated texture with visible sub- to euhedral fine- to mediumgrained nepheline phenocrysts (Dahlgren 2010). Recent studies indicate a genetic relationship between the Bjønnes nepheline syenite and the numerous nepheline syenite dikes in the Tveidalen area (Groom et. al., work in progress).

Lardalite is a nepheline monzonite containing ternary feldspar similar to that of the larvikite. Normative Ne contents are in the range 20-25 % (Neumann 1980). Lardalite makes up the two youngest intrusive members in the LPC (ring section IX and X in Figure 3.3), which represent the largest volumes of nepheline-bearing intrusive rocks in the Oslo Graben. Lardalite is genetically associated to the spatially related larvikite, but the nature of the relationship is still not properly understood. Positive Eu anomalies in samples of lardalite suggest that accumulation of feldspar in a strongly silica undersaturated magma has been one of the processes involved (Neumann 1980).

The lardalite massif is intruded by different types of syenitic rocks, whose genetic relationship to each other and to larvikite remains unclear (Neumann 1980). A prominent rock-type among these is a white, medium-grained nepheline syenite which was named *hedrumite* by Brøgger (1906). This rock type commonly contains minor amounts of blue to pale bluish grey sodalite, and locally ranges into sodalite foyaite (Oftedahl & Petersen 1978). In places it has a well-developed trachytoidal texture.

The syenite and nepheline syenite pegmatites of the LPC

Syenite and nepheline syenite pegmatites occur throughout the LPC and in its surroundings. The pegmatites (Fig. 3.5) have been known as a source of rare minerals (Plates 3.1 and 3.2) for almost two centuries (Raade et al. 1980; Andersen et al. 1996; Larsen 1996, 2010; Andersen et. al. 2010, 2013). The work by Brøgger (1890) established these rocks and their constituent minerals as classics of their kind. In his monograph, Brøgger aimed to characterize the mineralogy of the pegmatites, including first description of several new species (Table 3.2), and to understand their genesis. Since his time, much research has been done on minerals and mineral groups, but less on the mineral assemblages and the petrology of the pegmatites. The pegmatites occur as fissure fillings with more or less sharp boundaries against the wall-rock. Some of the pegmatites show agpaitic mineralogy, with the presence of complex Na-Ca-Zr silicate minerals (eudialyte *s.l.*, catapleiite, wöhlerite, rosenbuschite, hiortdahlite, låvenite, grenmarite and others) instead of zircon. These are the only examples of agpaitic rocks in the Oslo Rift, which represent an important and so far not fully understood part of the magmatic evolution in the rift. Brøgger (1890) distinguished between two types of pegmatites: A western type occurring in the Langesundsfjord area, and an eastern type occurring in Brunlanes-Larvik-Tjølling-Sandefjord area. The latter type was previously called Stavern-type dikes (*Fredriksvärn-type* by Brøgger). These pegmatites may attain large dimensions. Dikes with a thickness of 1 m are quite common, and some dikes are 10-20 m thick and 120 m long. They have sharp borders against the wall-rock, and are usually coarsegrained with feldspar individuals up to 2 m in size. The main minerals are greyish to reddish microcline (microperthite to cryptoperthite, often schillerising) and black amphibole (hastingsite, magnesiohastingsite or magnesiokatophorite) ± nepheline (often altered to *spreustein*) ± magnetite ± biotite ± a suite of accessory minerals. The number of accessory minerals is, with few exceptions, rather limited. The pegmatites of the western type, i.e. in the border zone on the island in the Langesundsfjord and on the mainland in the immediate vicinity of the fjord, occur as more or less irregular veins, often not particularly coarse-grained. This type of pegmatites shows a more agpaitic mineralogy than the previous type, and are classified as nepheline syenite pegmatites. The main minerals are white or greyish microcline, nepheline (often more or less altered to *spreustein*) ± aegirine ± ferro-edenite (*barkevikite*) ± magnetite ± biotite. In addition, a large variety of minor to accessory minerals may be present, and the abundance of Zr-, Ti-, Nb-, REE- and Be-minerals are conspicuous. The basaltic rocks close to the border of the larvikite massif are locally transected by huge pegmatite dikes, mainly of the western type. In most nepheline syenite pegmatite dikes, apart from the primary, magmatic stage, a secondary, hydrous stage is discernible in some of the pegmatites. The hydrous stage is characterised by extensive zeolitisation and alteration of the magmatic minerals, and with crystallisation of low-temperature hydroxides and hydrous silicates. Many of the rare REE-minerals and Be-minerals belong to this late stage of pegmatite formation. A few minerals have crystallized as the result of supergene prosesses, but are never the less part of the complete history of the syenite pegmatite dikes in the Larvik plutonic complex.

Table 3.2. Mineral list with first time descriptions from pegmatites in the LPC.

Mineral name	**Formula**	**Reference**
Aegirine (Plate 3.2I)	$NaFeSi_2O_6$	Berzelius (1835)
Alflarsenite	$NaCa_2Be_3Si_4O_{13}(OH) \cdot 2H_2O$	Raade et al. (2009)
Astrophyllite	$K_2NaFe_7Ti_2(Si_4O_{12})_2O_2(OH)_4F$	Scheerer (1854)
Cappelenite-(Y)	$BaY_6B_6Si_3O_{24}F_2$	Brøgger (1884)
Catapleiite	$Na_2ZrSi_3O_9 \cdot H_2O$	Weibye (1850)
Chiavennite (Plate 3.1D)	$CaMn(BeOH)_2Si_5O_{13} \cdot 2H_2O$	Raade et al. (1983)
Eirikite (Plate 3.1F)	$KNa_6Be_2(Si_{15}Al_3)O_{39}F_2$	Larsen et al. (2010)
Eudidymite (Plate 3.1C)	$Na_2Be_2Si_6O_{15} \cdot H_2O$	Brøgger (1887a)
Ferrochiavennite	$Ca_{1-2}Fe[(Si,Al,Be)_5Be_2O_{13}(OH)_2] \cdot 2H_2O$	Grice et al. (2013)
Gadolinite-(Ce)	$Ce_2FeBe_2(SiO_4)_2O_2$	Segalstad & Larsen (1978)
Grenmarite (Plate 3.1E)	$Na_4MnZr_3(Si_2O_7)_2O_2F_2$	Bellezza et al (2004)
Hambergite	$Be_2BO_3(OH)$	Brøgger (1890)
Hansesmarkite	$Ca_2Mn_2Nb_6O_{19} \cdot 20H_2O$	Friis et al. (2017)
Hiortdahlite I	$(Na,Ca)_2Ca_4Zr(Mn,Ti,Fe)(Si_2O_7)_2(F,O)_4$	Brøgger (1890)
Homilite (Plate 3.2G)	$Ca_2FeB_2(SiO_4)_2O_2$	Paijkull (1876)
Hydroxylgugiaite	$(Ca,\square)_2(Si,Be)(Be,Si)_2O_5(OH)_2$	Grice et al. (2016)
Leucophanite (Plate 3.1A, B)	$NaCaBeSi_2O_6F$	Erdmann (1840)
Låvenite	$(Na,Ca)_2(Mn,Fe)Zr(Si_2O_7)(O,OH,F)_2$	Brøgger (1884b)
Melanocerite-(Ce)	$(Ce,Ca)_5(SiO_4,BO_4)_3(OH,F)$	Brøgger (1887b)
Meliphanite	$Ca_4(Na,Ca)_4Be_4AlSi_7O_{24}(F,O)_4$	Scheerer (1852)
Microcline	$KAlSi_3O_8$	Tychsen (1794)
Mosandrite	$(Ca,Ce)_4(\square,Ca,Na)_3Ti(Si_2O_7)_2(H_2O,OH,F)_4 \cdot H_2O$	Erdmann (1840)
Nordenskiöldine	$CaSn(BO_3)_2$	Brøgger (1890)
Peterandresenite	$Mn_4Nb_6O_{19} \cdot 14H_2O$	Friis et al. (2014)
Pyrochlore	$(Ca,Na)_2Nb_2O_6(OH,F)$	Wöhler (1826)
Rosenbuschite (Plate 3.2E)	$Na_2(Na,Ca)_4Ca_6Zr_3Ti(Si_2O_7)_4O_4F_4$	Brøgger (1887b)
Sveinbergeite	$Ca(Fe^{2+}_6Fe^{3+})Ti_2(Si_4O_{12})_2O_2(OH)_5 \cdot 4H_2O$	Khomyakov et al. (2011)
Thorite (Plate 3.2H)	$ThSiO_4$	Berzelius (1829)
Tritomite-(Ce)	$Ce_5(SiO_4,BO_4)_3(OH,O)$	Weibye (1850)
Tvedalite	$Ca_4Be_3Si_6O_{17}(OH)_4 \cdot 3H_2O$	Larsen et al. (1992)
Wöhlerite (Plate 3.2F)	$NaCa_2(Zr,Nb)(Si_2O_7)(O,F)_2$	Scheerer (1843)

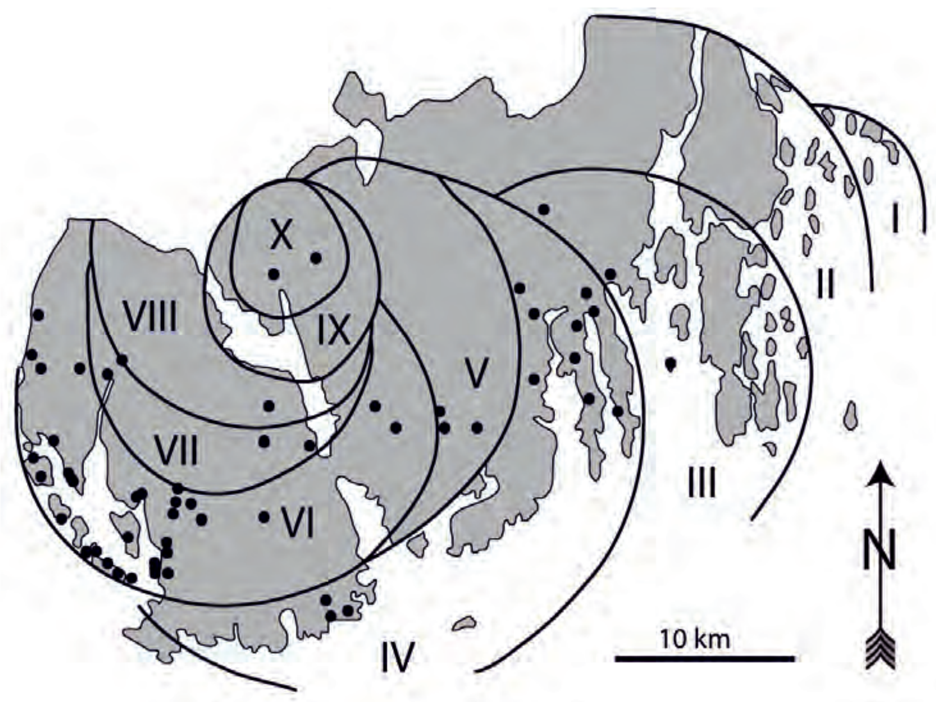

Fig. 3.5. Known pegmatite localities in the LPC area (black dots). Additional information with mineral content listed in the online mineral database *www.mindat.org*.

Field locations

Locality 3.1: Johs Nilsen quarry

Highlights

Nepheline syenite pegmatites and nepheline syenite dikes

Coordinates EU89-UTM Zone 32V 548622E/ 6545144N

Directions and Access

Exit E18 at junction #48 towards Landgangen and Kjose, and then continue towards Kjose through the roundabout. Just a few meters after the roundabout follow the sign towards Tveidalen and continue south onto the Tveidalsveien, and around a sharp 90° turn you reach the Tveidalen quarry area. The Johs Nilsen quarry is located within the active quarry area, and visitors must park outside the main gate with a walking distance of approximately 500-800 m. Outside of the PEG2017 conference, any visit to the quarry must be done outside working hours (07:00 - 16:00) as the area is in operation and only after prior agreement with the owners. The conference buss will drive up to the quarry.

Distance to walk: Within the quarry (500 m)
Elevation changes: 10-20 m
Excursion time: 1 hour.

The Tveidalen area (Fig. 3.6) consists of several open pit quarries where extraction of larvikite blocks is carried out with a special sawing technique utilizing diamond-coated wires. This leaves clean-cut vertical outcrops with numerous exposed pegmatite bodies in a 2D and 3D view. Most of the quarries are in operation leaving pegmatite outcrops exposed for a limited time as material is extracted, but a few quarries are currently abandoned with *in situ* pegmatites available to study. The Johs Nilsen is one of several active quarries operated by Lundhs and the PEG2017 excursion will stop at the active Johs Nilsen quarry to look at fresh outcrops and learn how the industry operates the dimension stone. Because it is an active quarry we cannot describe in details what we will see, as new pegmatites and veins are continuously exposed. However, at this locality the complex 3D spatial distribution of the pegmatites are clearly visible, and the contemporaneous relationship between pegmatite melt and the nepheline syenite is clearly exhibited. The alkaline pegmatites occur in three different modes:

- Nepheline syenite pegmatites
- Nepheline syenite pegmatites with nepheline syenite in the central core
- Nepheline syenite pegmatites with nepheline syenite along the border zone

Field evidence of pegmatite melt exploiting intraplutonic fracture systems (e.g., local shear zones, tension cracks) with local brecciated larvikite is clearly visible.

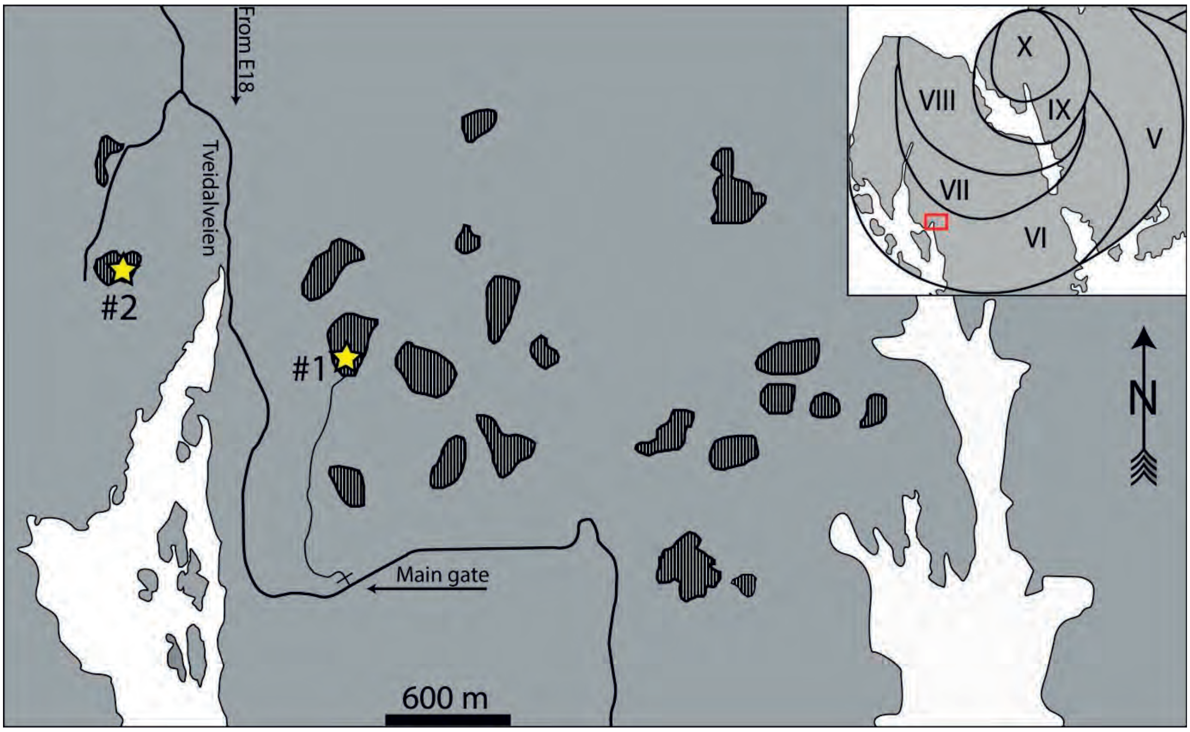

Fig. 3.6. Overview of the Tveidal quarry district. Quarries are indicated by the hatched areas. The inset shows the location of the area within the LPC. The PEG2017 excursion will stop at two localities: the Johs Nilsen quarry (#1) and Sagåsen quarry (#2).

Locality 3.2: The Sagåsen quarry

Highlights

Cross section of a large nepheline syenite pegmatite

Coordinates EU89-UTM Zone 32V 547613E/6545252N

Directions and Access

Exit E18 at junction #48 towards Landgangen and Kjose, and then continue towards Kjose through the roundabout. Just a few meters after the roundabout follow the sign towards Tveidalen and continue south. After approximately 3.3 km take a right turn onto a gravel road (also marked with a small sign "Blue Pearl"). Follow the gravel road and the first quarry on the left hand side is the Sagåsen quarry.

Distance to walk: Within the quarry
Elevation changes: 10-20 m
Excursion time: 3h

The Sagåsen quarry (Fig. 3.7) is an abandoned quarry which contains the main rock-units larvikite, nepheline syenite, and nepheline syenite pegmatites. Larvikite is the host rock intruded by sheet-like pegmatites and minor syenite dikes. The larvikite consists of an internal magmatic layering with cm-thick mafic and felsic bands. The nepheline syenite dikes are not easily observed in the field as they blend with the larvikite, however, these dikes are characterized by a fine-grained texture with high nepheline content. The excursion will have three stops in this quarry to look at two different cross-sections of two pegmatites (stop 1 and 2) and hunt minerals in the stockpiled pegmatite material (stop 3).

Stop 1 – Vertical cross-section of a large nepheline syenite pegmatite

The pegmatite is exposed along a vertically cut section in the larvikite with a lateral cross-section of the exposed pegmatite body stretching approximately 55 m (Fig. 3.8). The pegmatite is only partly exposed from the NW end towards the SE. The contact to the host larvikite is sharp and characterized with a comb texture of primary microcline, nepheline, and biotite. In the central part of the exposure the pegmatite is surrounded by nepheline syenite, possibly as a precursor to the pegmatite emplacement.

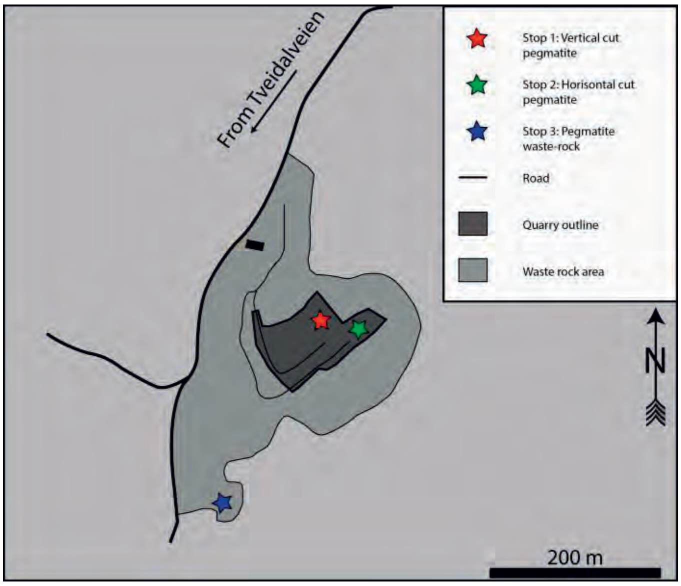

Fig. 3.7. Overview of the Sagåsen quarry. Stop 1: Nepheline syenite pegmatite (large); Stop 2: Nepheline syenite pegmatite (small); Stop 3: Stockpiled pegmatite material originating from stop 1.

The pegmatite is zoned in respect to texture and mineral composition, but the zonation is not primarily induced by crystallization sequence. A typical zonation occurring in horizontal pegmatites in the LPC are accumulation by gravity of dense, early crystallized minerals, along the sole of the pegmatite. Texturally, the pegmatite is characterized by two different settings; a coarse grained texture defined by medium- to coarse grained microcline, nepheline, biotite, amphibole, magnetite, and sodalite, which crystallized from the contact interface. A fine-grained texture is characterized by albite, aegerine, biotite, ±analcime, ±hydrous alteration and secondary mineralization. The fine-grained zones define a central core in the peripheral segment of the profile, and trapped pockets between large crystals (e.g., microcline, nepheline, sodalite). These fine-grained pockets typically carry secondary pyrochlore, zircon, aegirine, EGM, and cancrinite by hydrous alteration of enclosing sodalite, wöhlerite, and nepheline (Fig. 3.9).
Alteration of early-crystallized minerals is common and the most typical alteration is related to hydration where nepheline and sodalite are altered to a reddish zeolite composition (*spreustein*), cancrinite replacement in sodalite, and annite replacement in magnetite.

Fig. 3.8. Crosssection of the pegmatite at Stop 1. Field of view is 4 m.

Mineralogy

As mentioned above, the pegmatite shows zonation in respect to both mineralogy and texture. Because the pegmatite was never investigated during the period of active mining the nature of the zonation is not known. However, at different stages of mining of the pegmatite specific minerals would appear in large volumes, e.g. leucophanite (Plate 3.1A and B) or astrophyllite, but then becoming relatively rare in the pegmatite again. Natrolite, together with analcime, is the most abundant zeolite of the LPC, where it typically occurs as alteration after primary feldspathoids, particularly nepheline. This type of natrolite typically forms radiating white to faint reddish aggregates as pseudomorphs after the primary feldspathoid. Historically, such secondary natrolite has been called 'spreustein'. When spreustein contains cavities the natrolite often forms small bunches of crystals terminating in the cavity, but without clear termination. These cavities can also host a series of interesting minerals. The most colourful being diaspore, which forms ruler-shaped, purple or green crystals up to 3 mm in length. Other Al-hydroxides such as light brown coloured böhmite or colourless gibbsite can also occur in these cavities with crystal sizes up to about 1.5 mm, but usually in larger aggregates. In the older pegmatite (visible top right in the quarry) such cavities could also contain behoite and berborite. Sodalite occurs as greenish large aggregates in the eastern part of the pegmatite and can be mistaken for nepheline, but the latter is typically reddish brown. Sodalite can also form as a clearly secondary mineral and then the colour is light blue. Often this type of sodalite will be tenebrescent. When carbonate has been around for the alteration rather than chlorine, cancrinite can be a common secondary mineral and occurs in up to dm sized faint yellow coloured aggregates. It is not uncommon to find it partly replacing nepheline. Being the only other abundant yellow coloured mineral, the other being wöhlerite, it is easy to spot in the dumps and can be distinguished from wöhlerite by the lighter colour and different mode of occurrence. Wöhlerite forms up to five cm platy, dark yellow crystals. When viewed in the hand lens, crystals appear to have a 'grainy' colour distribution. Although wöhlerite is relatively rare worldwide, it is a common primary mineral in many of the pegmatites of the LPC. In Sagåsen, it is possible to find hiortdahlite associated with wöhlerite.

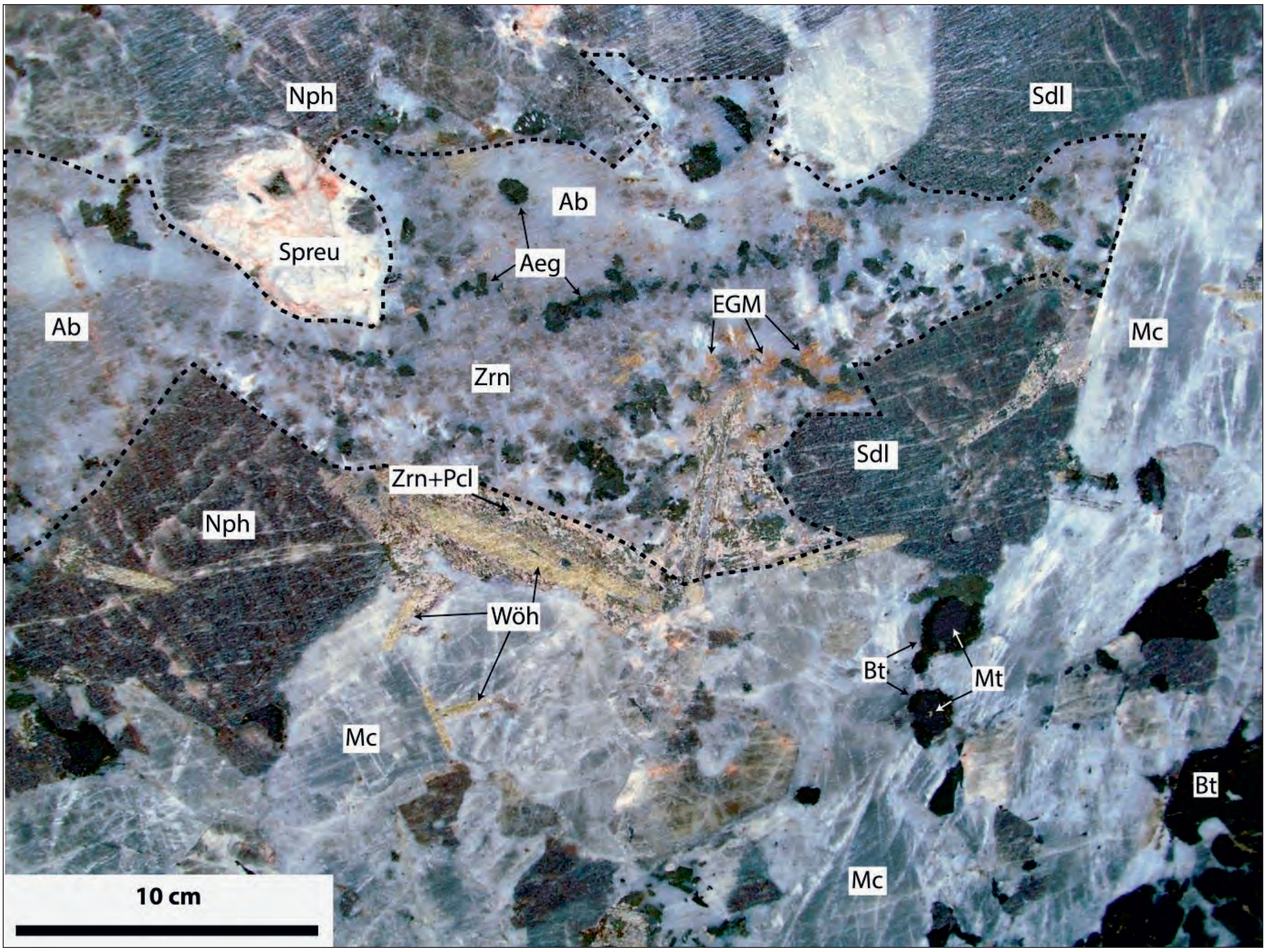

Fig. 3.9. Alteration features observed in the Sagåsen pegmatite. Dashed line highlights pocket with mainly fine-grained albite (ab), secondary aegerine (aeg), zircon (zrn), and eudialyte group minerals (egm). Wöhlerite (wöh) is altered *in situ* to zircon and pyrochlore (pcl), which defines a white to grey colored rim around the crystal. Magnetite (mt) occurs with a secondary biotite rim (bt). Sodalite (sdl) and nepheline (nph) are altered to a different extent into spreustein (spreu).

Although hiortdahlite is not that common in Sagåsen, it can be found as elongated greenish yellow crystals growing close to wöhlerites, often with some purple fluorite. In Sagåsen astrophyllite has been found in two main habits. One is large individuals or parallel grown, platy crystals up to 15 cm in size, or as radiating aggregates of individual crystals. The latter type can still be seen in the eastern part of the large pegmatite. A saccharoidal albite occurs in the late stage pegmatite formation, and is likely a result of late stage alteration. The fine-grained albite can have a high content of leucophanite, which is only visible under UV-radiation. The saccharoidal albite can also contain members of the eudialyte group - ferrokentbrooksite and zirsilite-(Ce) have been described as dark reddish to orange aggregates. The saccharoidal albite can also host minerals of the låvenite group and radiating tadzhikite-(Ce).

In short three main mineral and textural varieties can be summarized along the profile:

1) Peripheral segment (Fig. 3.10): horizontal layered structure with a sharp contrast defined by an albite + aegirine rim between coarse-grained and fine-grained zones. The coarse grained minerals are 0.5 - 1 m large crystals of (typically) nepheline, microcline, and sodalite. The fine-grained zone contains < 0.5 cm small crystals of albite, zeolite, aegirine, and biotite. Cancrinite appear as a relative abundant mineral along the footwall.
2) Intermediate segment: The fine-grained zone (clearly) narrows in and thins out, and the pegmatite body is more homogenous and coarse-grained relative to the peripheral segment. Wöhlerite is distributed abundantly with microcline, magnetite, biotite, and

nepheline along the footwall in this part of the pegmatite.

3) Middle segment (Fig. 3.11): In this part of the profile the pegmatite consists of homogenously distributed coarse crystals of microcline, sodalite, nepheline, and biotite, but pockets of fine-grained albite (e.g., Fig. 3.9) are typically trapped locally between coarse microcline, sodalite, and nepheline. This zone is particularly rich in sodalite (both green and blue varieties). The pockets containing fine-grained albite are also typically rich in secondary alteration derived minerals (e.g., eudialyte, zircon, and pyrochlore)

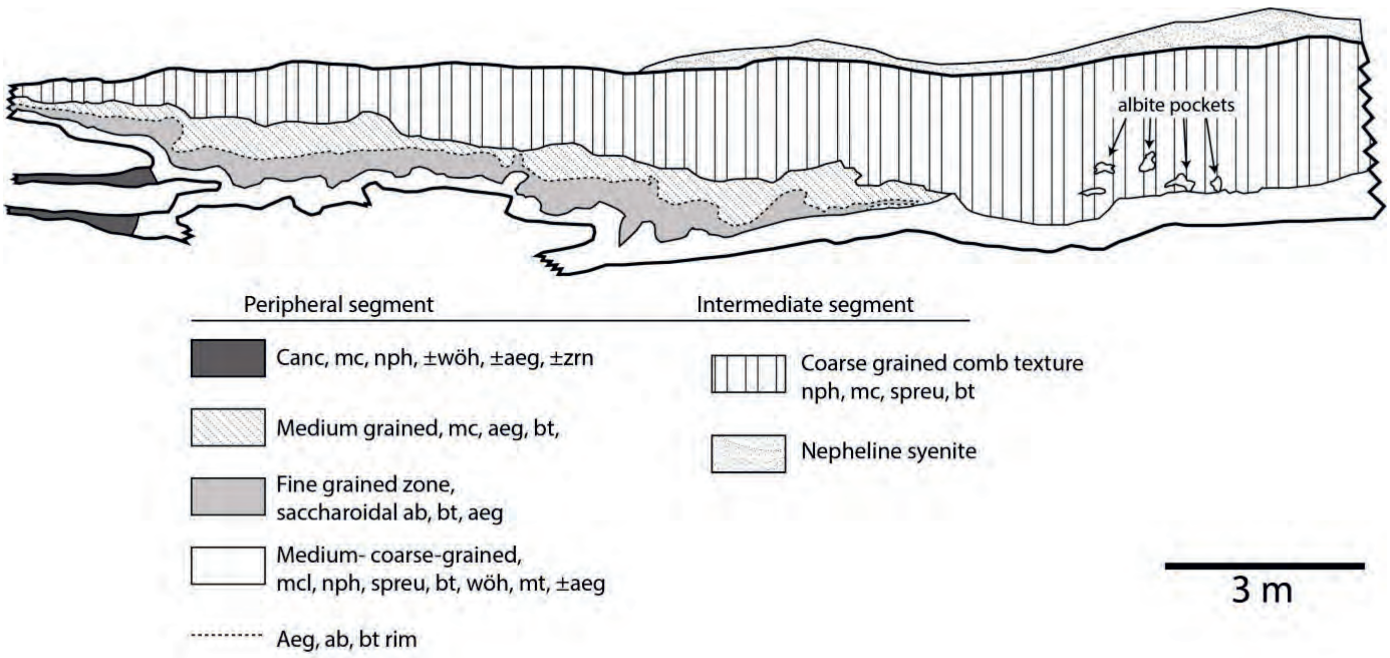

Fig. 3.10. Simplified sketch of main textural and mineralogical features observed in the distal section of the exposed pegmatite (stop 1). Canc=cancrinite, wöh=wöhlerite, bt=biotite, aeg=aegirine, zrn=zircon, mc=microcline, ab=albite, spreu=spreustein alteration.

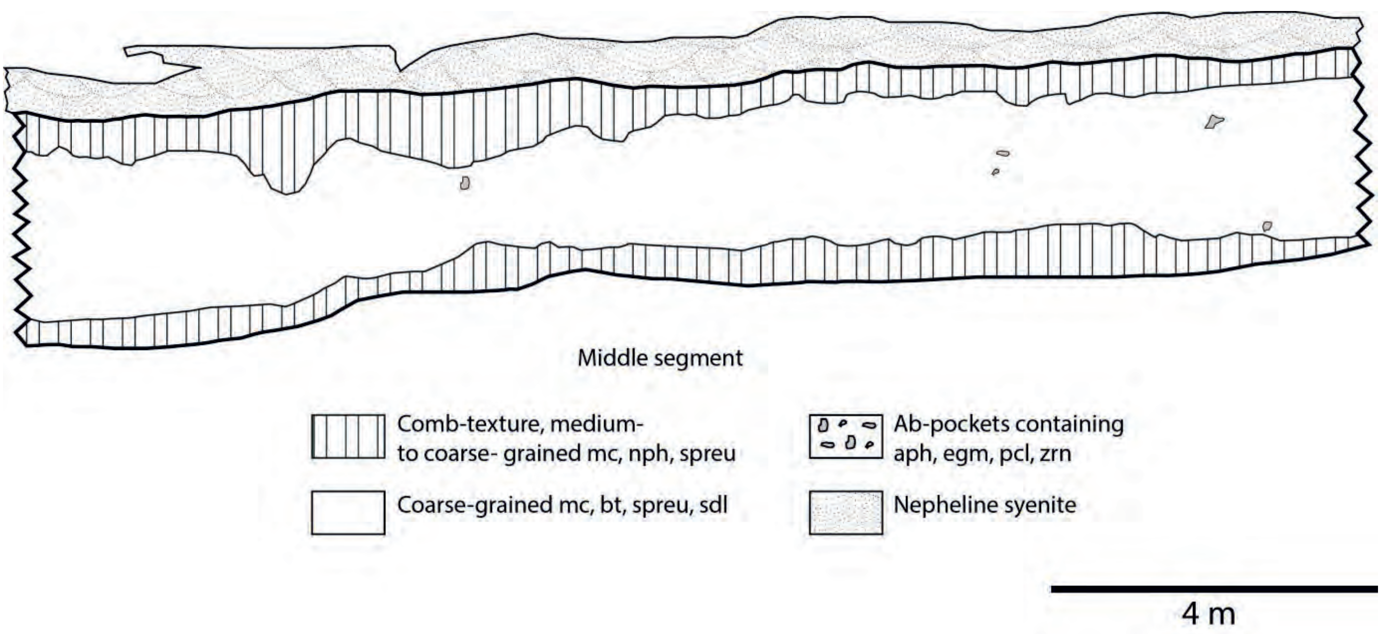

Fig. 3.11. Simplified sketch of main textural and mineralogical features observed in the central section of the exposed pegmatite (stop 1). Aph=astrophyllite, sdl=sodalite, egm=eudialyte group mineral, pcl=pyrochlore.

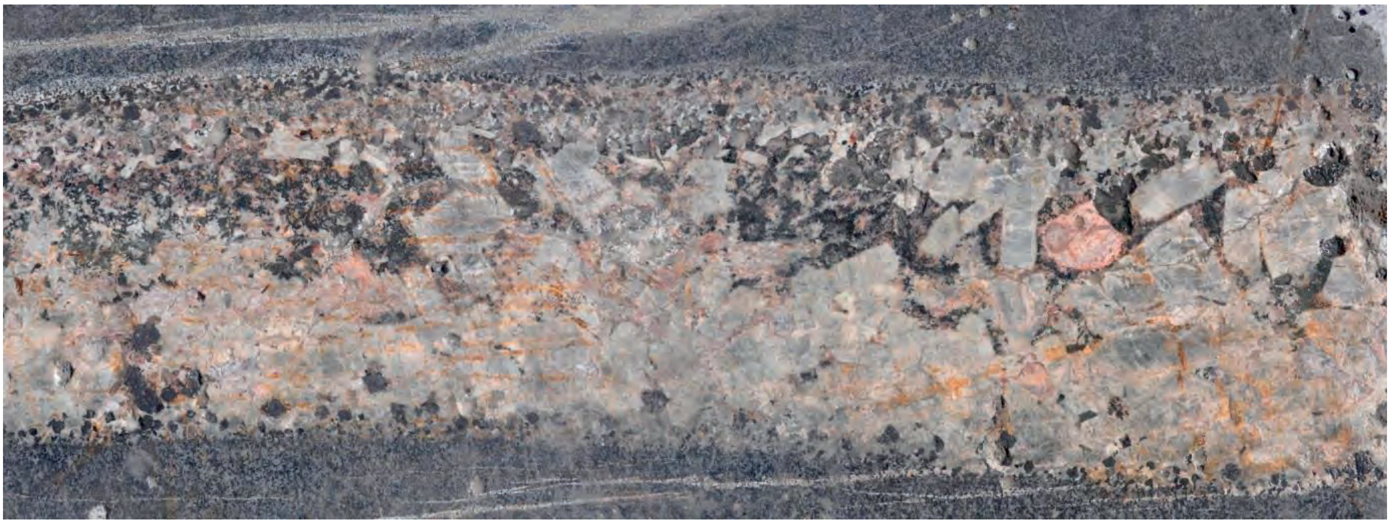

Fig. 3.12. Cross-section of the pegmatite at Stop 2. Field of view is 2 m.

Stop 2 – Horizontal cross-section of a nepheline syenite pegmatite

One level above stop 1 provides 3D view of thin (10 – 30 cm) sheet-like pegmatites, and a cross-section of a similar pegmatite to stop 1 in an approximately 8 m long exposure (Fig. 3.12). Similar features are seen here with a gravitational zonation and hydrous alteration. Albite and aegirine are characteristic assemblages in the fine-grained albite zone, which forms the core of the exposed profile. Despite the smaller size of this pegmatite compared to the one at Stop 1, it clearly reveals a mineralogical variation and zonation.

Stop 3 – Stockpiled pegmatite material

During operation of the quarry material from the large nepheline syenite pegmatite at stop 1 was deposited at stop 3. Approximately 70 different mineral species have been identified from the pegmatite and the material is still rich in many rare species (Table 3.3). Numerous blocks of larvikite with pegmatite litter the waste-rock area which show different contact features (e.g., nepheline syenite boarder, nepheline-free boarder zone).

Table 3.3. Examples of minerals occurring in the pegmatite tailing at stop 3 (Larsen 1998, 2010).

Mineral name	**Formula**
Aegerine	$NaFeSi_2O_6$
Albite	$NaAlSi_3O_8$
Amphibole (e.g., ferro-edenite)	$NaCa_2Fe_5(Si_7Al)O_{22}(OH)_2$
Ancylite-(Ce)	$CeSr(CO_3)_2(OH)*H_2O$
Apophyllite	$KCa_4Si_8O_{20}F*8H_2O$
Astrophyllite	$K_2NaFe_7Ti_2(Si_4O_{12})_2O_2(OH)_4F$
Bastnäsite-(Ce)	$CeCO_3F$
Behoite	$Be(OH)_2$
Berborite	$Be_2BO_3(OH)*H_2O$
Biotite (annite)	$KFe_3AlSi_3O_{10}(OH)_2$
Cancrinite	$[(Ca,Na)_6(CO_3)_{1\text{-}1.7}][Na_2(H_2O)_2](Si_6Al_6O_{24})$
Cerite-(Ce)	$(Ce,La,Ca)_9(Mg,Fe^{3+})(SiO_4)_3(SiO_3OH)(OH)_3$
Epididymite	$Na_2Be_2Si_6O_{15}*H_2O$
Eudialyte group (e.g., ferrokentbrooksite)	$Na_{15}Ca_6(Fe,Mn)_3Zr_3NbSi_{25}O_{73}(O,OH,H_2O)_3$
Eudidymite	$Na_2Be_2Si_6O_{15}*H_2O$
Fluorite	CaF_2
Hiortdahlite I	$(Na,Ca)_2Ca_4Zr(MN,Ti,Fe)(Si_2O_7)_2(F,O)_4$
Magnetite	Fe_3O_4
Microcline	$KAlSi_3O_8$
Molybdenite	MoS_2
Nepheline	$NaAlSiO_4$
Parisite-(Ce)	$CaCe_2(CO_3)_3F_2$
Pyrochlore	$(Ca,Na)_2Nb_2O_6F$
Sodalite	$Na_8Al_6Si_6O_{24}Cl_2$
Thorite	$ThSiO_4$
Wöhlerite (Plate 3.2F)	$Na_2Ca_4Zr(Nb,Ti)(Si_2O_7)(O,F)_4$
Zircon	$ZrSiO_4$

Plate 3.1. Photographs of minerals from syenite pegmatites of the Langesundsfjord area. All photographs by Øivind Thoresen. A – Leucophanite from Eikaholmen. The specimen is 17.5 cm across. Collection of the Natural History Museum Oslo, Nr. 9048. B - The specimen shows four of the seven minerals Låven is the type locality for: Leucophanite, aegerine, catapleiite, and astrophyllite. The specimen is 9 cm across. Collection of the Natural History Museum Oslo, Nr. 28552. C – Eudidymite from Vesle Arøya. The specimen is 5 cm across. Collection of Øivind Thoresen. D - Chiavennite from Sagåsen quarry. The specimen is 19 cm across. Collection of Øivind Thoresen. E - Grenmarite from Sagåsen quarry. The crystal is 2.6 cm in length. Collection of the Natural History Museum Oslo, Nr. 43715. F – Eirikite from Vesle Arøya. The specimen is 11 cm across. Collection of Øivind Thoresen.

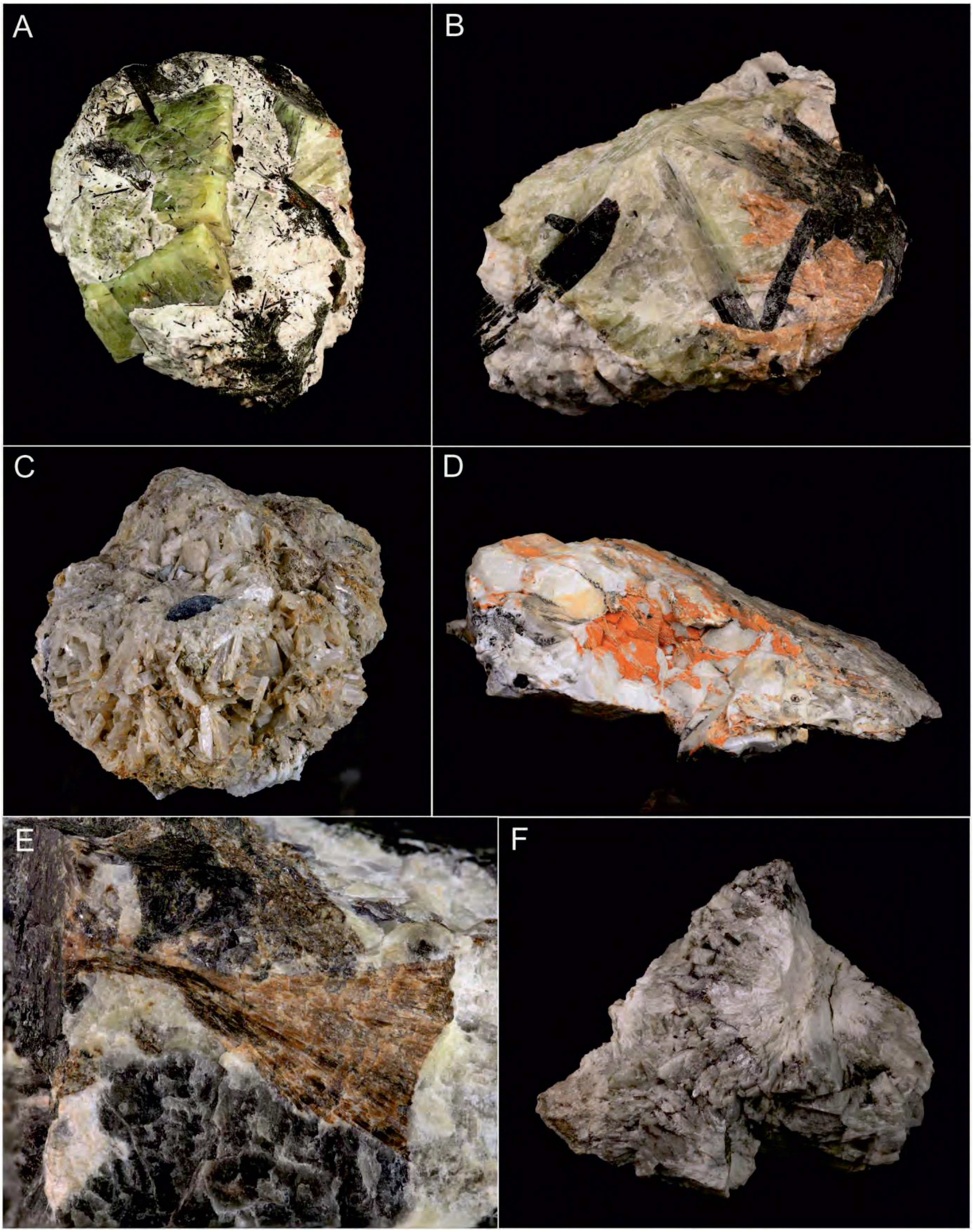
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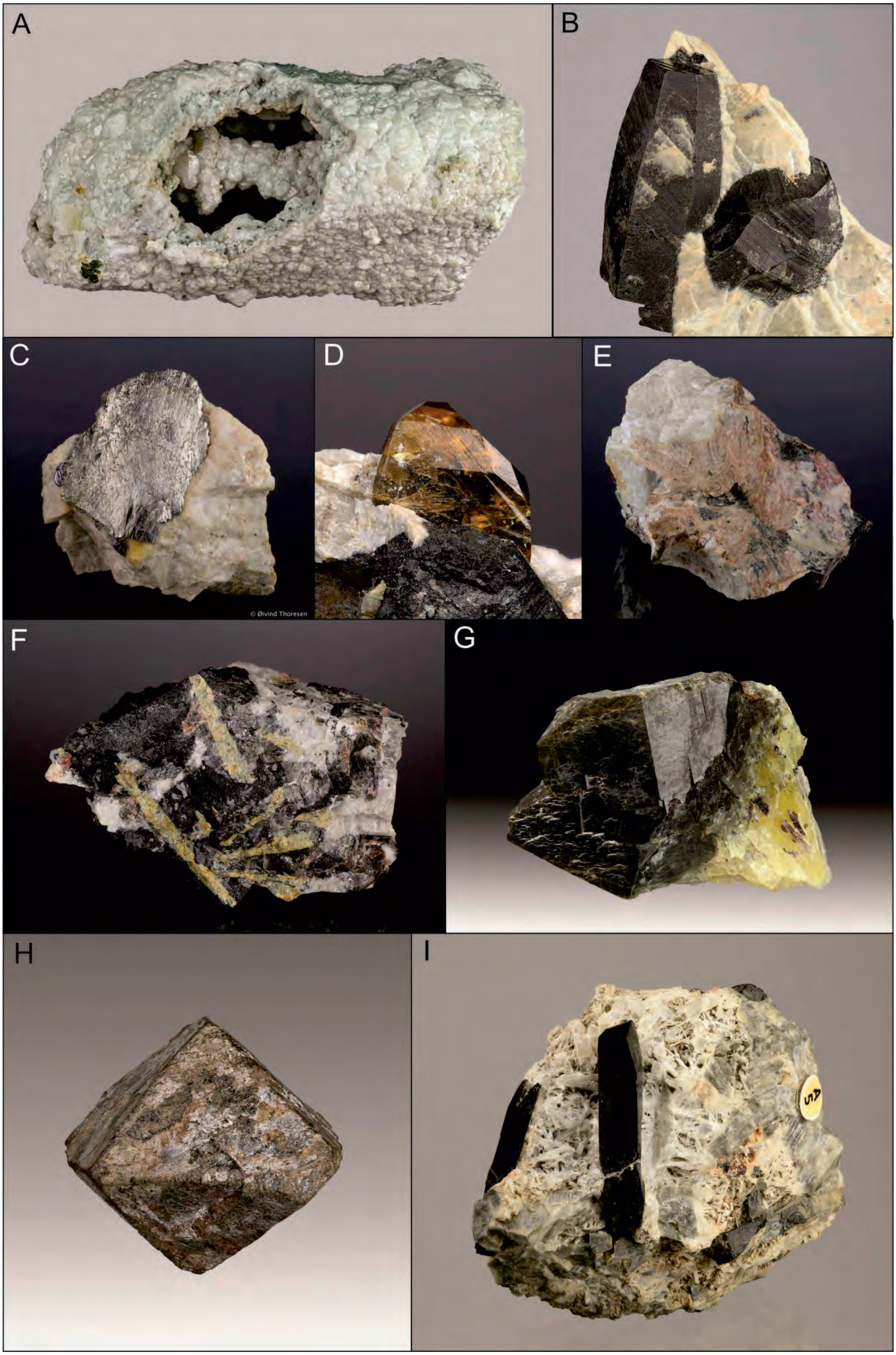
Plate 3.2. Photographs of minerals from syenite pegmatites of the Langesundsfjord area. All photographs by Øivind Thoresen. A - Analcim from Tuften quarry. The specimen is 9 cm across. Collection of Øivind Thoresen. B – Annite in microcline from Sagåsen quarry. The larger crystal is 7 cm in size. Collection of Øivind Thoresen. C – Löllingite from Heia quarry. The specimen is 7 cm across. Collection of the Natural History Museum Oslo, nr. 43713. D - Zircon from Hauane. The crystal is 1.2 cm in size. Collection of Øivind Thoresen. E – Rosenbuschite from Skutesundsskjær. The specimen is 5 cm across. Collection of Øivind Thoresen. F - Wöhlerite from Sagåsen quarry. The largest crystal is 5.5 cm in size. Collection of Øivind Thoresen. G – Homilite and meliphanite from Stokksund. The specimen is 3 cm across. Collection of Øivind Thoresen. H – Thorite from Langesundsfjord (location not specified). The crystal is 2.5 cm in size. Collection of the Natural History Museum Oslo, nr. 6008. I – Aegerine from Vesle Arøya. The largest crystal is 3.8 cm in size. Collection of Øivind Thoresen.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