Petrology of differentiated gabbro sheets in the Altenes tectonic window, North Norway

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The petrography of two differentiated gabbro sheets in the low-grade metamorphic Karelian supracrustal sequences of the Altenes Teconic Window is described. The intrusions have generally undergone extensive deuteric and low-grade metamorphic alteration. Detailed petrographic studies established the primary parageneses and variation in the gabbro sheets and formed the basis for an interpretation of the geochemical profiles. Both intrusions have a distinct mineralogical and chemical variation suggesting that gabbro sheets in the window probably comprise both sills and slightly inclined intrusions. Magmatic rocks in the Altenes Window describe a definite tholeiitic trend. Zr-FeO*/MgO and Zr-Y plots of the two studied intrusions suggest the existence of two magmatic suites. The Trollvatn sill is interpreted as syngenetic with the mafic extrusive rocks while the Sagelv intrusion probably intruded at a low angle in an early stage of the Svecokarelian orogeny.

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Introduction

The Altenes Window (Fareth 1979) together with the adjacent Alta-Kvænangen and Repparfjord-Komagfjord windows constitute the northwesternmost outcrop of Karelian supracrustal lithologies within the Baltic Shield (Fig. 1a). The supracrustal in the window are collectively termed the Raipas Supergroup (Pharaoh et al. 1983), and the assumed age is Early Proterozoic (Siedlecka et al. 1985). Rocks in the westernmost window, the Alta-Kvænangen Window (Fig. 1a), have been correlated with lithologies in the Kautokeino Greenstone Belt. The lithologies within the windows and within the Kautokeino and Karasjok Greenstone Belts (Fig. 1a) are thought to have been deposited in heterogenous rift environments, subsequently deformed during the Svecokarelian orogeny (Often 1985, Olsen & Nilsen 1985, Siedlecka et al. 1985). The objective of this paper is to present a petrographic and geochemical description and interpretation of the gabbroic intrusions occurring in the Altenes Window. The paper is based on an M.Sc. study of the Altenes Window undertaken in collaboration with Lars M. Nielsen (M.Sc.) during the period 1983–1986. The results of the study are presented in two progress reports (Pratt & Nielsen 1984 and 1985), two unpublished theses (Nielsen 1986, Pratt 1986) and an unpublished summary of these (Nielsen & Pratt 1986).

Geology

The first detailed investigation of the Altenes Window (Fig. 1b) was carried out by Fareth (1973, 1979) and Krog & Fareth (1975), who considered the window as part of the Alta-Kvænangen Window. In a later publication Pharaoh et al. (1983) described the Altenes area as a separate window and this interpretation is adhered to here.

While a certain similarity between the Altenes and Repparfjord-Komagfjord Windows is observed with respect to tectonostratigraphy and structural trend, this is not the case between the Altenes and Alta-Kvænangen Windows (Fig. 2a). There is a definite change in the trend and pattern of magnetic anomalies between the two windows (Fig. 2b) which closely corresponds with the change in structural trend (Fig. 2a). Especially conspicuous is the strong, NW-SE trending anomaly from a gabbro intrusion in the Altenes Window which continues across the Altafjord (Fig. 2b). The implication of this anomaly is that Altenes Window basement extends at least 10km to the southwest beneath the fjord before it dips beneath the Alta-Kvænangen Window. The discordant anomaly pattern and thus the difference in structural trend may therefore be a result of thrusting of Alta-Kvænangen strata over the Altenes Window sequence. A large-scale thrusting would also account for the significant differen-

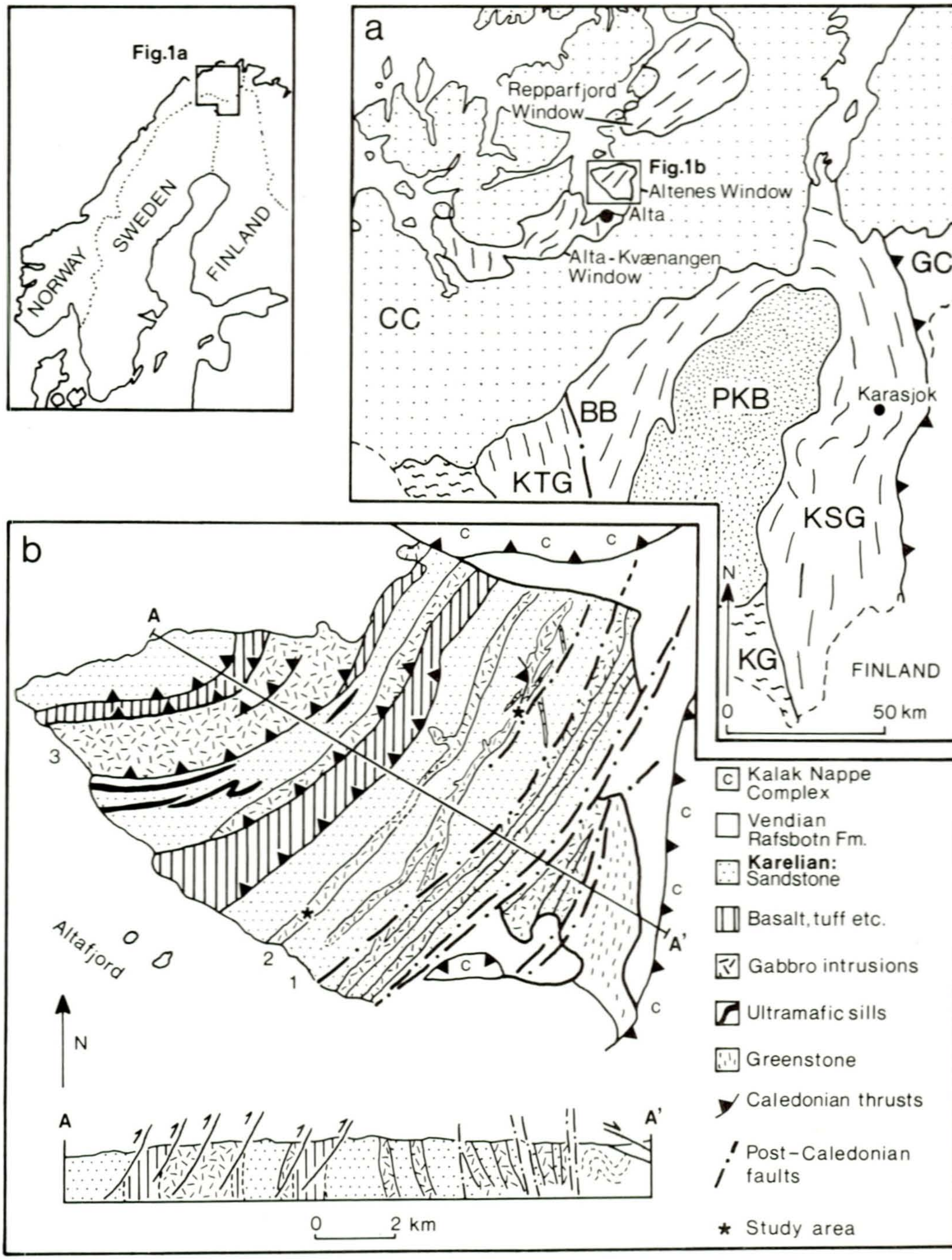

Fig. 1. (a) The Precambrian basement of West and Central Finnmark. CC: Caledonian Cover; BB: Baltic Bothnian Megashear (Berthelsen & Marker 1986); KTG and KSG: Kautokeino and Karasjok Greenstone Belts; KG: Karelian Gneiss; GC: Granulite Complex; PKB: Prekarelian Basement. Modified after Pharaoh et al. (1983).
(b) Simplified geological map and profile of the Altenes Window. 1: Trollvatn sill; 2: Sagelv intrusion; 3: Altenes gabbro. Note that the thicknesses of the ultramafic sills (<30m thick) are not drawn to scale. Modified after Fareth (1979).

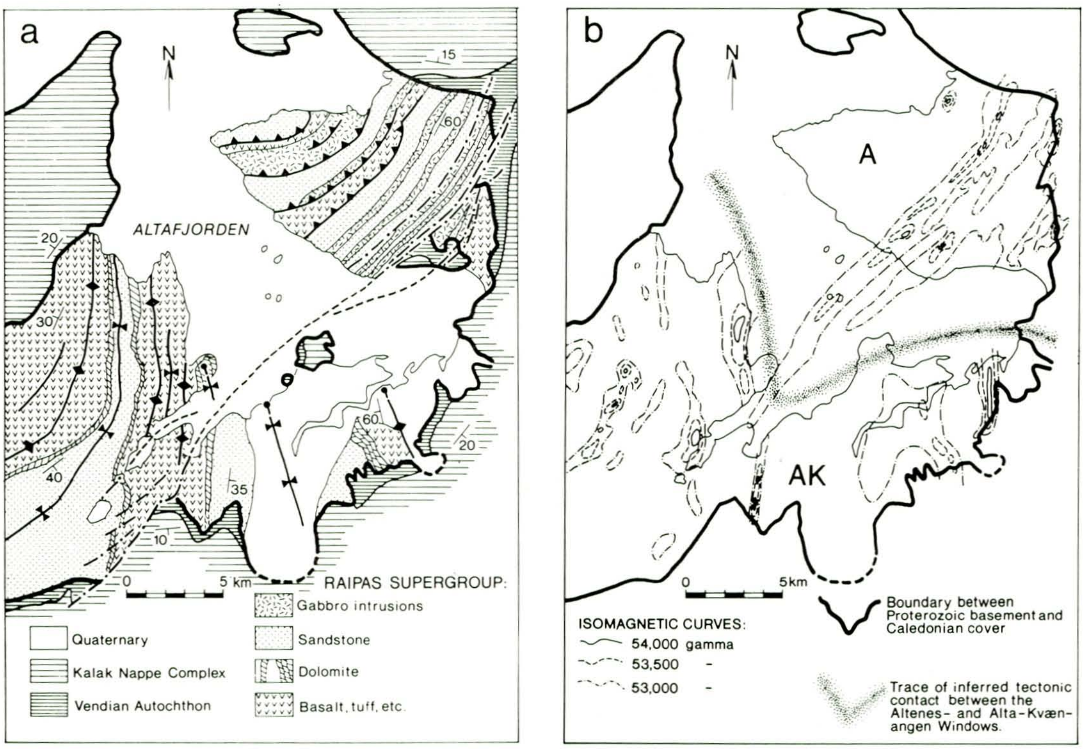

Fig. 2. (a) Simplified geological map of the Altenes (A in Fig. 2b) and Alta–Kvænangen (AK in Fig. 2b) windows. Note the marked difference in structural trend between the two windows. Compiled from Fareth (1979) and Zwaan & Gautier (1980).
(b) Magnetic anomaly map of the same area as Fig. 2a. Note the strong anomaly from a magnetite-rich intrusion in the Altenes Window (A) which can be traced right across Altafjord. Compare with Fig. 1a. Compiled from Håbrekke (1978) and unpubl. magnetic anomaly maps (NGU) 1834 I, 1834 II, 1835 III, 1934 IV and 1935 III.

ces in tectonostratigraphy. The trace of the inferred tectonic contact between the two windows is shown in Fig. 2b.

The Altenes Window consists largely of non- to weakly metamorphosed, steeply imbricated sequences of clastic sediments and volcanites intruded by gabbroic and rarer ultramafic bodies of Svecokarelian age (Fareth 1979) (Fig. 1b). The clastic sediments are dominated by medium- to coarse-grained arkosic sandstones of fluvial origin, with scattered intercalations of fine-grained clastics and carbonaceous shales of a probable lacustrine origin. The mafic volcanic rocks consist largely of interlayered massive basalt, pillow lava and tuff. Both sharp basalt/sandstone and gradational contacts between tuff and immature arkosic sandstone occur, but the contacts between sediments and volcanites are generally obscured by thrusts. Primary features are exceptionally well preserved, except in the easternmost part of the window, and show a younging direction towards ESE (Fareth 1979).

The easternmost part of the window (Fig. 1b) consists mainly of highly deformed and greenschist-facies basalt and gabbro, here referred to as 'greenstone'. The Proterozoic sediments and volcanites are discordantly overlain by a 50-100 m thick sequence of Vendian to Cambrian sediments of the Rafsbotn Formation (Fareth 1979), consisting of a basal conglomerate followed by shale and sandstone. The Rafsbotn Formation is overridden by the Caledonian Kalak Nappe Complex.

The Svecokarelian deformation (c. 1800–1900 Ma ago, Pharaoh et al. 1983) of the sedimentary and volcanic rocks west of the greenstone area (Fig. 1b) has resulted in an imbrication of these with a westerly vergence. Small-scale thrusts and fold are also present. The lateral extent of this imbricated sequence (a minimum of 12 km perpendicular to strike) and the low metamorphic grade suggests a foreland thrust-type imbrication at the margin of a fold-belt. The folded greenstone may represent a more central part of the fold-belt faulted on to the imbricated sequence.

Strong Caledonian deformation with a movement direction from west to east, overprints the Svecokarelian structures in the western part of the window (Fareth 1979). This deformation is largely characterized by a significant compression, imbrication thrusting and a steepening of the dip of the volcanosedimentary sequence. Late Caledonian, low-amplitude and long-wavelength flexures of the nappe thrust planes and subsequent erosion of these have resulted in the present outcrop of the tectonic windows in the region (Pharaoh et al. 1983).

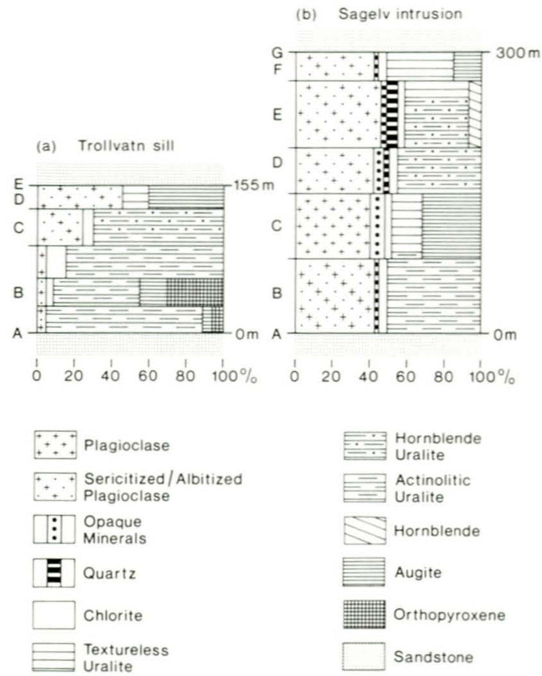

Fig. 3. Mineralogical composition and variation through the Trollvatn (A) and Sagelv (b) intrusions. The intrusions are divided into petrographic zones (A, B, C etc.), where the composition (vol.%) shown within each of these represents an average of 1-3 thin-sections.

The gabbro sheets

Petrography

The Altenes Window is characterized by large number of strike-parallel, mainly gabbroic intrusions emplaced into both sediments and volcanites, with thicknesses ranging from 1m to 2000 m, but generally in the range 150-400 m. The larger intrusions can be followed 5-6 km along strike and have been described as lenticular sheets by Fareth (1979). Two of these sheets, here informally named the *Trollvatn sill* and the *Sagelv intrusion,* were chosen for a detailed petrographic and geochemical study. The intrusions, which are 150-300 m thick, appear not to have been affected by any significant deformation and were intruded into the thick sedimentary sequence in the central part of the window (Fig. 1b).

The *Trollvatn sill,* intruded along sandstone beds (Fig. 1b), has an average thickness of 150-175 m and can be followed 4-5 km along strike. Aphanitic chilled marginal zones are 0.1-0.2 m thick and grade into fine-grained gabbro. Sandstone is bleached and hornfelsed up to 2-3 m from the contact. Scattered and partly assimilated sandstone xenoliths occur up to a few metres below the upper contact.

The mineralogical variations and the subdivision of the sill are shown in Fig. 3a. Apart from the chilled marginal zones, there is a lower ultramafic unit B followed by a mafic gabbro zone C and a gabbro zone D. The mineral assemblage consists of plagioclase, uralite, chlorite, opaque minerals ± orthopyroxene ± augite, with apatite, epidote, leucoxene and serpentine. Petrographic studies have identified augite, orthopyroxene, plagioclase, opaque minerals and apatite as primary phases.

Augite is well preserved in the ultramafic and gabbroic zones B and D (Fig. 3a). Ophitic textures are generally absent except in the mafic gabbro zone C, where uralite replaces ophitic augite. In the centrtal part of zone B augite is subhedral, light brown and weakly pleochroic. In the gabbroic zone D, where the augite is enclosed in poikilitic plagioclase, it is much darker and more strongly pleochroic. The observed colour change and increased pleochroism up through the sill is similar to that in the Palisades sill studied by Walker (1970), where this variation is ascribed to an increasing Fe content. The grain-size of augite varies from «0.5 to 1 mm.

Orthopyroxene is abundant in the central part of the ultramafic zone B, and a few scattered and small grains were observed in zone D. In zone B it is a subhedral and colourless enstatite. In the gabbro zone D, grains are too small for precise optical determination, but judging by the dark colour they are possibly a hypersthenic pyroxene. The grain-size varies from ‹1mm in zone B to ‹0.5 mm i zone D.

Alteration of both ortho- and clinopyroxene to actinolite (Fig. 4), chlorite and hornblende has occurred throughout the sill. In the lower part of the ultramafic zone B, rounded areas (1cm across) with more coarse-grained alteration products are characteristic, and could be relics of a glomeroporphyritic texture. The variation in the alteration products up through the sill (Fig. 3a) is interpreted as the result of both a quantitative and a qualitative variation in the primary paragenesis. Orthopyroxene and low-Fe augite in the lower part of the sill are altered to actinolite and chlorite, while hornblende becomes increasingly dominant in the upper part of the sill due to an increase of Fe in augite and a decrease in the orthopyroxene content.

Plagioclase is abundant only in the leucogabbroic zone D. It has now nearly everywhere undergone complete alteration to chessboard albite (Moorhouse 1956), with an An content of 10—15%, and more seldom to sericite. The distribution of albite and sericite suggests an increase in plagioclase content in the primary paragenesis from ‹5% in zone B to c.55% in zone D. Unaltered plagioclase in the leucogabbroic zone D has an An content of c. 30—35% (optical).

Opaque minerals are dominated by the oxides ilmenite and titanomagnetite. Pyrite and chalcopyrite occur scattered in zones C and D (‹‹1%). The content of oxides nowhere exceeds 1% (vol.) and is normally ‹‹1%, with the highest concentration in zone D. Deuteric oxidation of primary oxides to rutile and hematite is extensive. Ilmenite — the dominant primary oxide — is without exception oxidized to rutile, and in zone D and the lower part of zone B further to hematite. Oxidation of titanomagnetite to ilmenite and subsequently to rutile is widespread in zones B, C and D, where it is commonly completely replaced by ilmenite and rutile. Following Haggerty (1976), this suggests re-equilibration at temperatures greater than 500°C.

Fig. 4. complete deuteric/low-grade metamorphic alteration of orthopyroxene and clinopyroxene to light actinolite. Plagioclase has been altered to chessboard albite (outlined).

Apatite occurs as scattered needles mainly in the leucogabbroic zone D.

Olivine has not been identified in thin-section but small blebs of greenish serpentine in the lower part of zone B could be interpreted as olivine pseudomorphs.

The *Sagelv intrusion*, intruded into the same sedimentary sequence as the Trollvatn sill (Fig. 1b), has an average thickness of 300 m and can be followed at least 5 km along strike. Up-down relations in the field are readily established from the observed increase in grain size from fine-grained melanocratic gabbro at the base to pegmatitic 'pockets' towards the top. The aphanitic gabbro chill zone is well preserved and grades inwards into more coarse-grained gabbro over a width of 0.3-0.5 m. Sandstone up to 3 m from the contact is bleached, hornfelsed and in places enriched in biotite. This kind of contact-metamorphic alteration was only observed along the contacts to larger gabbro intrusions.

Fig. 5. Large, unaltered, ophitic, subhedral augite grain (5 mm across), containing numerous plagioclase laths, and to a lesser degree titanomagnetite (zone C).

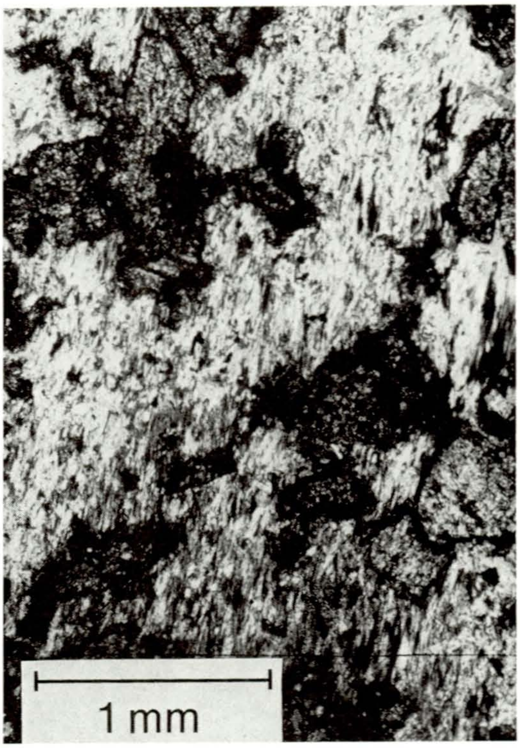

Fig. 6. Actinolite uralite pseudomorph after ophitic augite, with intensely sericitized plagioclase laths (zone B).

The mineralogical variation through the Sagelv intrusion has led to a division into zones A–G (Fig. 3b). Zones A and G are fine- to medium-grained gabbro chill zones, whereas zones B to E reflect increasing plagioclase content towards zone E, which is more mafic and similar to the lower zone B. The mineral assemblage varies, but is dominated by plagioclase, uralite (s.l.), opaque minerals and chlorite ± augite ± quartz, with minor biotite, leucoxene, sericite and epidote. Although alteration is extensive, scattered relics of primary phases are present and most primary phases are pseudomorphed. Plagioclase, augite, opaque minerals, hornblende and quartz have been identified as the primary minerals.

Auguite is the only pyroxene identified in the Sagelv intrusion. It is preserved in the gabbroic zones C and F (partly), and is light to dark brown, weakly pleochroic, subhedral and always subophitic to ophitic (Fig. 5). The grain size of augite varies between <0.5 and 5 mm, the largest grains being concentrated in the middle of the intrusion (zone C). Coarse-grained but non-ophitic augite pseudomorphs are restricted to the coarse-grained pegmatitic zone E.

Alteration of ophitic augite to uralite (s.l.) prevails throughout the intrusion, also in the chilled zones, and three different types of uralitic alteration can be distinguished (Fig. 3b):

Textureless uralite is a colourless to weak brown and pleochroic uralite completely lacking internal texture, and occurs abundantly in the chilled zones and is quite widespread in the gabbroic zones B, C (lower part) and F.

Actinolitic uralite is a colourless to weak brown and actinolitic uralite with fibrous texture and a more marked pleochroism than the textureless uralite. It is the dominant alteration product in zone B and the lower part of zone C (Fig. 6).

Hornblende uralite is a brown to red-brown, strongly pleochroic hornblende with well developed cleavage. Scattered and strongly corroded remnants of augite have been observed in the hornblende and zoned hornblende pseudomorphs also occur. The occurrence of this uralite type is restricted to the coarse-grained and pegmatitic zones D and E. Some of this hornblende may be of a primary origin (see below), due to some difficulty in distinguishing between primary and secondary hornblende as a result of further alteration (oxidation) of hornblende to chlorite and magnetite, and an assemblage of finegrained magnetite, chlorite, biotite and quartz (zones D and E) (Fig. 7). Best (1982) ascribes these assemblages to a deuteric phase pseudomorphed under oxidizing conditions. The observed distribution of the different types of uralite is believed to result from variations in the primary mineralogical compositions of augite crystallized during differentiation of the intrusion. The colour change, as in the Trollvatn sill, is suggested to reflect an increasing content of Fe in the primary augite.

Plagioclase is abundant in all zones and is generally quite strongly sericitised with the exception of the unaltered middle gabbroic zone C, where an An-content of 35—40% has been measured optically. Contents of plagioclase vary between c.45 and 55%, being most abundant in the coarse-grained to pegmatitic zone E. In this zone optical measurements indicate an An content of 28-32%.

Opaque minerals are strongly dominated by the oxides titanomagnetite and ilmenite, but small amounts of pyrite, pyrrhotite and chalcopyrite are also seen. Opaques do not exceed 1% (vol.), except in zones C and D with c.10% and 4%, respectively. As in the Trollvatn intrusion, oxides in all zones have undergone varying degrees of high-temperature re-equilibration (<500°C, Haggery 1976) under deuteric oxidizing conditions. Increasing re-equilibration of titanomagnetite is characterized by exsolution of ilmenite followed by oxidation of exsolved ilmenite to rutile and finally hematite. Re-equilibration of ilmenite is characterized by exsolution of rutile and subsequently hematite. Oxidation increases away from the centre of the intrusion and is most pronounced in the pegmatitic zone E.

Hornblende is widespread in the upper part of the intrusion, but is mainly related to deuteric (late post-magmatic) alteration of augite, except in pegmatitic pockets in zone E where

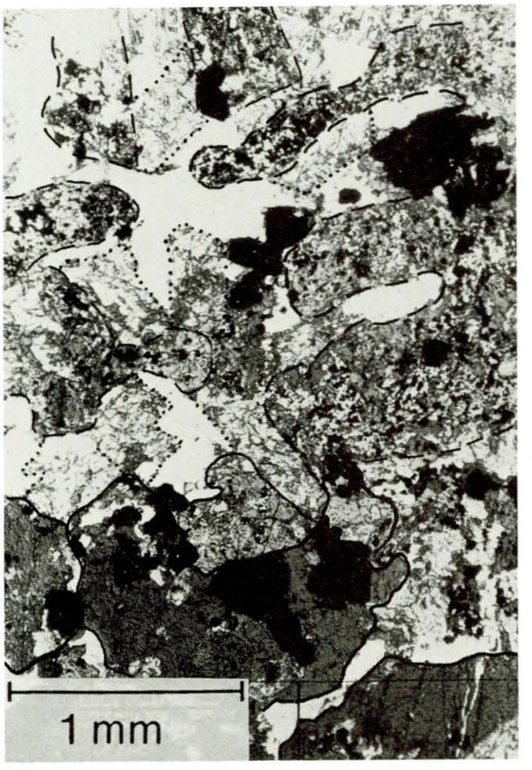

Fig. 7. Secondary hornblende (full line) in zone D further altered to a fine-grained assemblage of magnetite + chlorite + biotite + quartz (dashed line). Also present are quartz grains (white areas) and slightly clouded plagioclase laths (dotted line). Areas between those outlined consist largely of chlorite.

large (up to 2cm long) subhedral crystals of primary amphibole are quite abundant.

Quartz occurs in zones D and E, and is largely of a secondary origin. Large (2-3 mm) homogeneous quartz grains in pegmatitic pockets, however, are interpreted as primary in contrast to the earlier mentioned disseminated quartz (Fig. 7) which is clearly associated with alteration of hornblende.

Alteration and primary paragenesis

The two intrusions described above are characterized by a preservation of primary textures, sections with unaltered primary parageneses, marked variability of the secondary phases (Fig. 8), and lack of deformation on the macroscopic and microscopic scales. These features are hardly compatible with a regional metamorphic event (Best 1982), because the nature of the alteration (Fig. 8) clearly indicates a

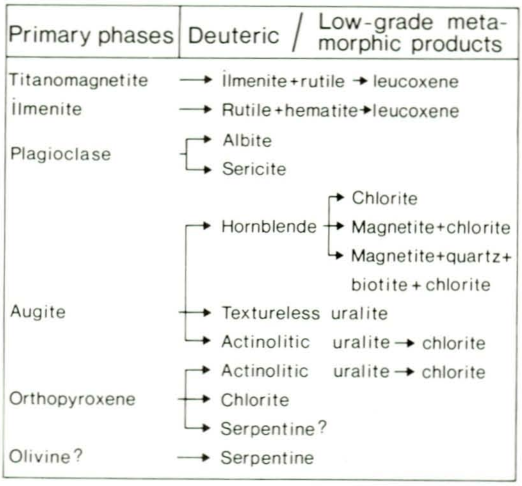

Fig. 8. Summary of the deuteric and low-grade metamorphic reactions and resulting products observed in the two intrusions. Question-marks after serpentine and olivine refer to whether serpentine is a result of alteration of either orthopyroxene or olivine.

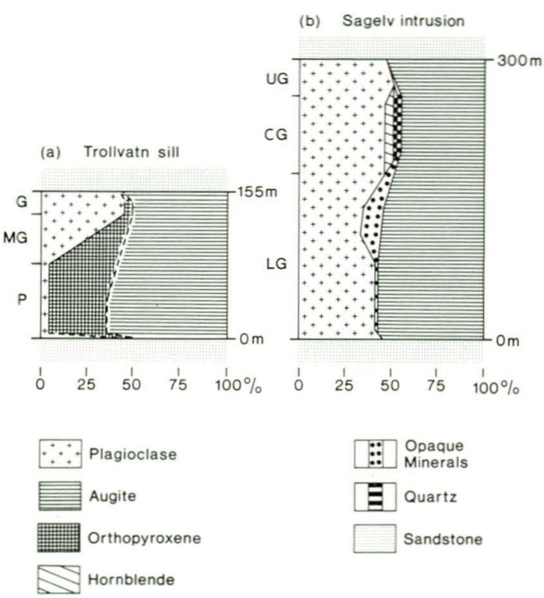

Fig. 9. Schematic presentation of a proposed variation in the primary paragenesis in the Trollvatn (a) and Sagelv (b) intrusions prior to alteration. Abbreviations for the subdivision into cumulate zones are shown at the left side of the diagrams; P: pyroxenite; MG: melagabbro; G: Gabbro (Trollvatn sill); LG: Lower gabbro; CG: coarse-grained/pegmatitic gabbro; UG: upper gabbro (Sagelv intrusion).

low P-T regime and a minimum degree of stress involved during metamorphism of the intrusions. The interpretation of a low-P metamorphism is consistent with the near absence of deformation in the central part of the window, other than imbrication and localized tectonization in the vicinity of faults and thrusts. As regional metamorphism appears to have been neglible in this part of the window, the variation and types of assemblages (Fig. 8) may instead be explained by a combination of deuteric (low-P/high-T) and low-grade metamorphic (low-P and -T) alteration (burial metamorphism). Most of the reactions described in Fig. 8 can occur at both low- and high-T conditions, e.g., uralitization, and no attempt has been made to distinguish between deuteric and low-metamorphic alteration.

Recognizing the many different alteration reactions (Fig. 8) is a precursor for identifying the quantitative variation of the primary parageneses in the two intrusions shown in Figs. 9a and b. Using these diagrams and the geochemical profiles (see below) the two intrusions can be divided into gabbro sub-types representing different cumulate zones. The Trollvatn sill can be divided into a lower pyroxenite unit (P) followed by a pyroxenite/melagabbro unit (MG) with gradually increasing plagioclase content upwards, and finally an upper gabbro unit (G). The Sagelv intrusion consists of a thick lower gabbro unit (LG), an upper gabbro unit (UG), and between these a heterogeneous coarse-grained/pegmatitic gabbro unit (CG). Units in the Sagelv intrusion are generally less well defined than those in the Trollvatn sill.

Geochemical profiles

The major trace element variations are displayed as a function of distance from the base of the intrusions (Figs. 10 and 11), and the chemical analyses are given in Table 1. Trace element profiles (Figs. 11a-d) for each of the intrusions are depicted in two graphs, the division being based on the affinity of elements for either mafic and/or opaque minerals or felsic minerals (Walker 1970, Bailey 1979). The subdivision of the intrusions from Fig. 9 is given in both diagrams.

Major and trace elements were analyzed by XRF at Norges Geologiske Undersøkelse, Trondheim, except for trace elements of chilled margin samples which were analyzed by XRF at the Institute of Petrology, Copen-

	(a) Lower chill	Pyroxenite	Melagabbro	Gabbro	Upper chill	(b) Lower chill	L.Gabbro	Peg.Gabbro	U.Gabbro	Upper chill
	60631	60629	60628	60627	60626	55142	55108	55129	55104	55101
SiO_2	48.48	49.43	46.05	52.90	46.30	48.63	48.67	48.26	48.54	48.01
Al_2O_3	9.67	5.07	8.48	15.03	11.41	12.71	14.48	15.93	13.18	13.04
FeO^*	13.37	10.23	15.27	8.79	13.56	14.03	12.89	13.94	14.43	14.32
TiO_2	1.58	0.90	1.69	1.72	1.84	0.77	0.70	0.92	0.79	0.84
MgO	9.27	13.87	10.18	3.64	7.94	7.01	6.13	3.98	6.66	6.25
CaO	11.61	16.38	12.77	9.00	10.32	11.55	11.16	9.43	11.12	10.93
Na_2O	2.0	0.8	1.3	5.2	2.3	0.6	1.9	2.4	1.6	1.7
K_2O	0.84	0.30	0.38	0.51	0.80	0.16	0.75	1.14	0.66	0.26
MnO	0.15	0.17	0.19	0.07	0.14	0.20	0.21	0.21	0.23	0.18
P_2O_5	0.12	0.05	0.08	0.26	0.15	0.06	0.05	0.08	0.06	0.07
LOI	1.07	1.10	1.24	1.23	1.08	2.54	1.57	1.32	1.07	2.02
Nb	8	5	6	12	11	1	5	5	6	3
Zr	85	59	85	204	124	41	45	49	52	43
Y	19	11	15	32	23	25	20	24	27	26
Sr	246	115	256	316	281	153	150	125	96	224
Rb	33	12	13	12	31	2	22	39	20	4
Zn	71	62	67	23	62	87	83	86	94	83
Cu	177	153	399	8	44	108	147	164	169	116
Ni	234	393	283	31	184	95	75	41	77	7[illegible]
Cr	701	1000	307	5	329	157	67	5	88	91
V	316	248	452	238	337	337	325	337	341	317
Ba	176	60	81	145	143	17	144	173	107	74
Pb	6	< 10	< 10	< 10	3	1	< 10	< 10	< 10	3
Co	57	63	70	60	57	62	50	51	52	51
La	7	-	-	-	11	4	-	-	-	2
Ce	22	-	-	-	30	2	-	-	-	2
Th	1	-	-	-	1	< 1	-	-	-	1

Table 1. Selected geochemical compositions from the cumulate zones and chilled marginal zones in (a) the Trollvatn sill (60631 — 60626) and (b) the Sagelv intrusion (55142 — 55101). Note that Na_2O values are given with only one decimal accuracy.

hagen. Both intrusions are affected by pronounced alteration, enhancing the possibility of mobilization. Following, e.g., Davies et al. (1978) and Condie (1981), moderately to strongly mobile elements up to greenschist-facies metamorphism include: Mg, Ni, Cu, Zn and Na, K, Ca, Rb, Sr, Ba, respectively. To determine possible anomalous distributions of these elements through the intrusions two factors appear important. First, some control on the variation of the elements is given by the reasonably well established quantitative variation of the primary parageneses. Second, the strong indication that alteration of the intrusions is a result of deuteric and burial metamorphic alteration in the central part of the Altenes Window suggests that the chemical variation may be interpreted in terms of the primary paragenetic variation. Strongly mobile elements such as Sr and Ba, however, still show some degree of mobilization as described below.

Major elements

MgO and CaO (Fig. 10) in the plagioclase-depleted Trollvatn sill primarily reflect the accumulation of pyroxene (Fig. 10a). In the Sagelv intrusion (Fig. 10b) a slight decrease in the MgO content from both the lower and the upper chilled margins towards the CG-unit is in accordance with the slight decrease in pyroxene, while the CaO content largely reflects variation in the An-component in plagioclase. The Al_2O_3, Na_2O and K_2O variation (Fig. 10) primarily reflects the variation in plagioclase, which again is most prominent in the Trollvatn sill. Although the upward increase in plagioclase content in the Sagelv intrusion is small (5-10% vol.), this can still be discerned in the variation diagram (Fig. 10b). Na_2O and K_2O reflect the albite and orthoclase components in plagioclase, and the maxima in both intrusions is in the relatively felsic units. Total FeO (FeO^*) shows only minor variations in the Trollvatn sill. Most marked is the decrease in the

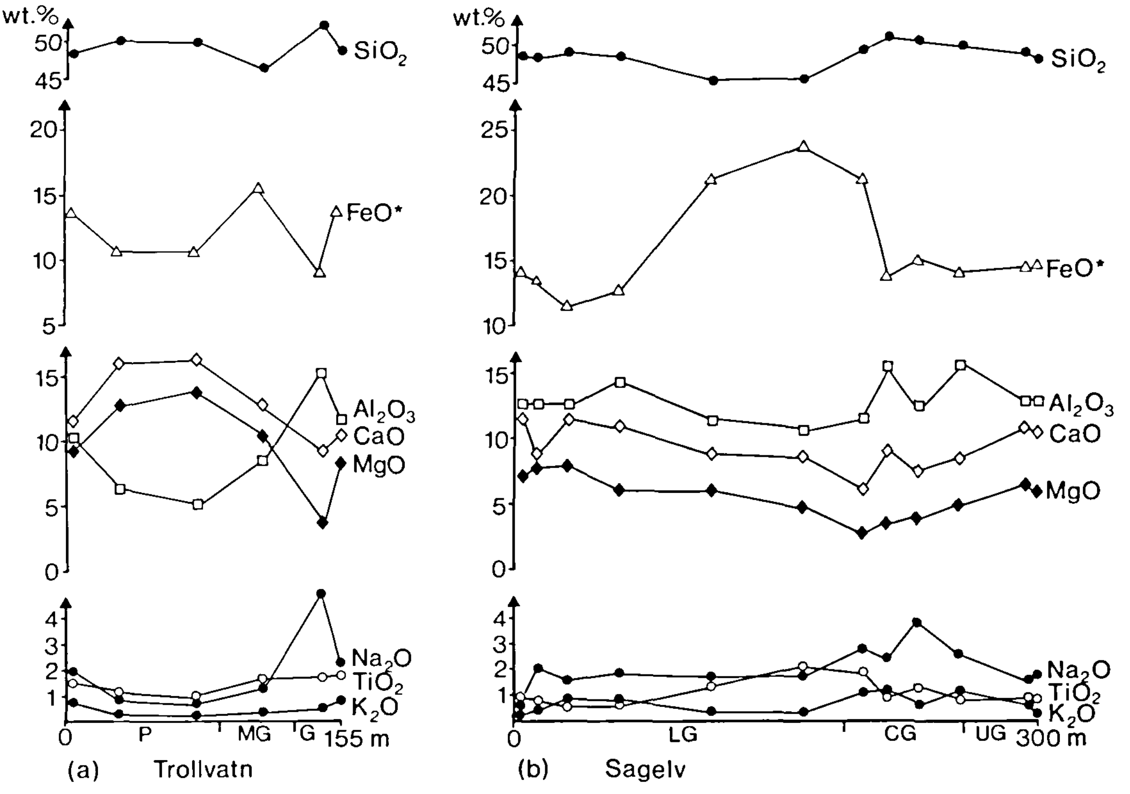

Fig. 10. Major elements (wt.%) plotted as a function of distance from the base of the Trollvatn (a) and Sagelv (b) intrusions.

G-unit. In the Sagelv intrusion (Fig. 10b) the variation is far more pronounced, with a significant increase in the middle to upper part of the LG-unit (Fig. 9b), reflecting the accumulation of Fe-Ti oxides, followed by a rapid decrease in the CG-unit. TiO_2 follows FeO* in both intrusions indicating that most of the TiO_2 is bound in Fe-Ti oxides.

Trace elements

The trace element variations conform with the major element and petrographic observations. In the Trollvatn sill a strong enrichment in Cr (Fig. 11a) in the lower part correlates with the pyroxenite, and the lack of a similar FeO* enrichment suggests that Cr is present mainly in clinopyroxene as opposed to chromite. This is substantiated by the decrease in V which generally strongly partitions into FeTi oxides. The variation of Ni is interpreted as largely reflecting the variation of pyroxene, as neither olivine nor pentlandite has been observed. Accessory serpentine (altered olivine) in the pyroxenite probably contains some Ni, but this is neglgible relative to the Ni contained in the abundant pyroxene.

Cu is concentrated in the MG-unit in the form of oxides and sulphides, closely following the trend of V. Co and Zn show no variation in the pyroxenite and melagabbro, and this agrees with the petrographic observations of an overall low Fe-Ti-oxide concentration. A decrease in all these elements in the G-unit reflects dilution due to increased plagioclase content.

The low concentration of large-ion lithophile (LIL) (Rb, Sr and Ba) and high field strength (HFS) elements (Zr and Y) in the lower part of the Trollvatn sill also reflects the strong accumulation in this part of the sill. Their marked enrichment in the G-unit is consistent with this unit representing the last crystallizing zone. Note that the chilled zone compositions are very similar if not identical. Similar trace

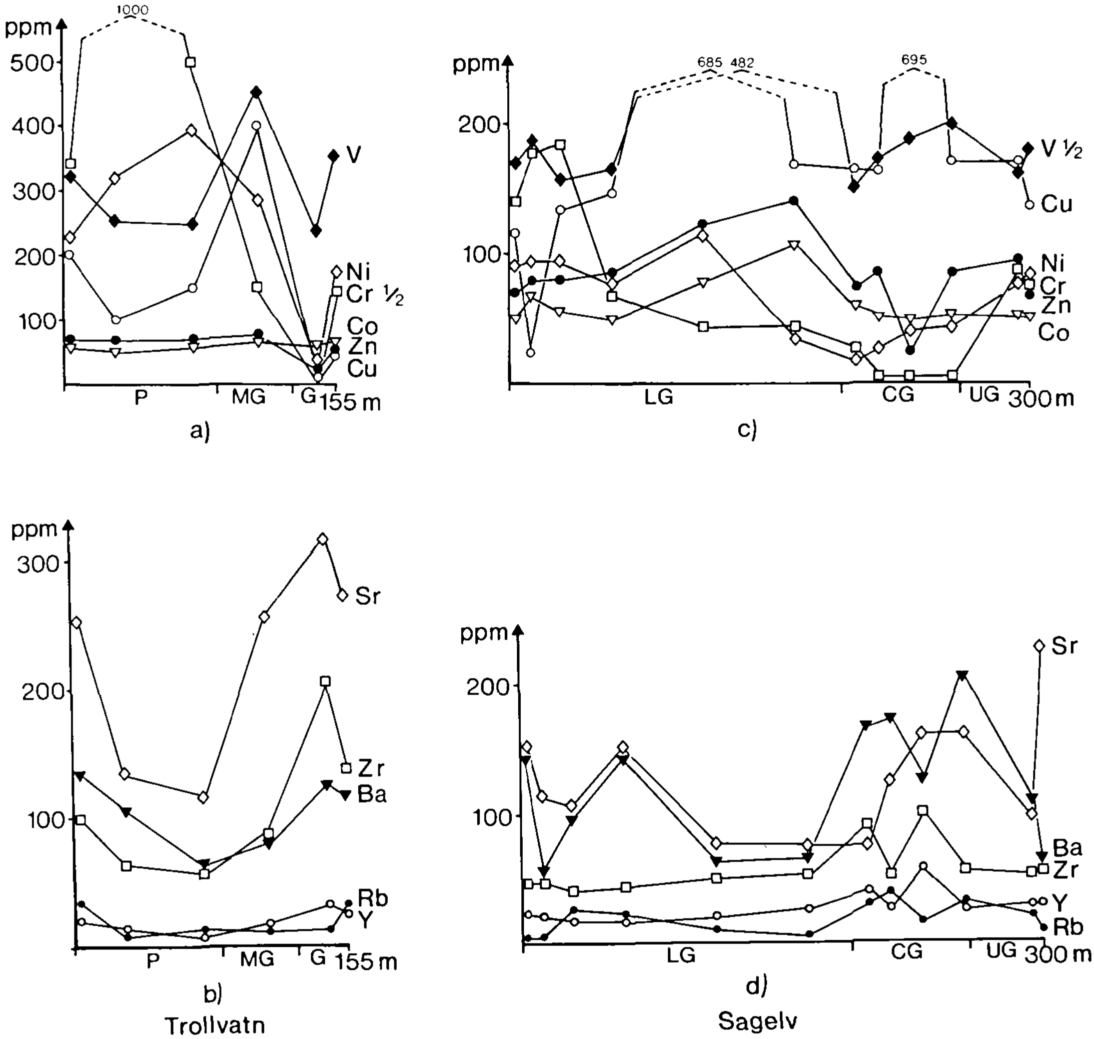

Fig. 11. Trace elements (ppm) plotted as a function of distance from the base of the Trollvatn (a and b) and Sagelv (c and d) intrusions. Note that Cr in (a) and V in (c) are plotted as a half of their real values.

element patterns are observed in the Sagelv intrusion although they are not as prominent as in the Trollvatn sill. A Cr enrichment in the lowest part of the intrusion (Fig. 11c) may reflect a primary pyroxene cumulation. Strong enrichment in Cu and V parallels the increased FeO* and reflects the high Fe-Ti oxide and sulphide concentration in the upper part of the LG-unit. Increases in Ni, Co and Zn in the same zone are also referred to the Fe-Ti oxide and sulphide enrichment.

The UG-unit is similar to the lower part of the LG-unit, agreeing with a suggested crystallization from top and bottom towards the CG-unit. In this unit the above-mentioned elements show a decrease which, as was the case in the Trollvatn sill, reflects dilution due to increased plagioclase content. The anomalous values (high and low) of Cu in the upper and lower parts of the Sagelv intrusion (Fig. 11c) suggest that not all Cu was bound in sulphides and could have been mobilized when liberated from Fe-oxides during both high- and low-T reequilibration/oxidation. The variation of the LIL elements (Fig. 11d) may be readily interpreted in terms of the petrographic variations and record the slight plagioclase enrichment up through the intrusion. Again the chilled zones have very similar compositions with the exception of Cu and Sr.

Comparison between the Trollvatn and Sagelv intrusions

Field observations, quantitative variations of the primary parageneses and chemistry demonstrate significant differences between the Trollvatn and Sagelv intrusions. Field observations made on the *Trollvatn intrusion* show in the area studied (Fig. 1b) that contacts and layering are parallel to bedding suggesting intrusion as a sill. The trends of especially MgO, CaO, Al_2O_3 and Cr reflect the mineralogical compositional change from pyroxenite to gabbro, and indicate strong accumulation and fractionation. The $FeO^*/(FeO^* + MgO)$ ratio of the chills is rather low (0.6). Both Cr and Ni are high in the chills as compared with the chills of the Sagelv intrusion, a factor of 5 and 2, respectively (see Table 1), and point to the more primitive composition of the Trollvatn melt. The variation of the major and trace elements and the occurrence of the coarse gabbro zone immediately below the upper chilled margin, shows that the sill crystallized from base to top.

The *Sagelv intrusion,* while having intruded parallel to bedding, exibits a much less well defined layering than the Trollvatn sill. Also, only two cumulate zones are discerned: a gabbro and a coarse-grained gabbro zone. The slight differentiation can partly be seen as a result of the more evolved nature of the initial melt (chill zones, Table 1b), best illustrated by the higher $FeO^*/(FeO^* + MgO)$ ratio of 0.7 and lower MgO of c.7%. Mineralogically, this is illustrated by the occurrence of relatively Fe-rich ophitic augite containing andesine plagioclase in the cumulate gabbro zones, and primary amphibole and quartz in pegmatitic pockets.

Differentiation from an evolved melt, however, cannot alone explain the poorly defined cumulate units and the general heterogeneous nature of the intrusion. Some other factor appears necessary. A possible solution to this enigma is that the Sagelv intrusion intruded at a slight angle to bedding. As the intrusion is now parallel to bedding it would probably have intruded when the sediments were imbricated, i.e. during the Svecokarelian orogeny. If this is indeed the case, then it is likely that the two intrusions represent different magmatic suites. This possibility is discussed below.

Magmatic affinity and geochemical discrimination

The Trollvatn sill together with the Sagelv intrusion and magmatic rocks in the Altenes Window define a tholeiitic trend in the YTC-diagram (Fig. 12), which clearly separates them from the calc-alkaline trend. The diagram also demonstrates the range in composition from normal tholeiites to Mg-tholeiites. Examples to the geochemical composition of the other magmatic rock-types in the window are given in Table 2. For a description of these intrusive and extrusive rocks the reader is referred to Fareth (1979).

A more rigorous discrimination between various tholeiite-types is given by the Al_2O_3 versus $FeO^*/(FeO^* + MgO)$ discriminant diagram (Fig. 13). Based on Fig. 13 it is reasonable to define the Trollvatn sill as a Mg-tholeiite as opposed to the Sagelv intrusion which largely plots in the Fe-tholeiite field. A sample of the rare ultramafic sills(?) in the window clearly plots in the peridotite field while the Altenes gabbro — a multiple gabbro intrusion series in a basalt sequence — shows a compositional range from Mg-tholeiite to Fe-tholeiite. The

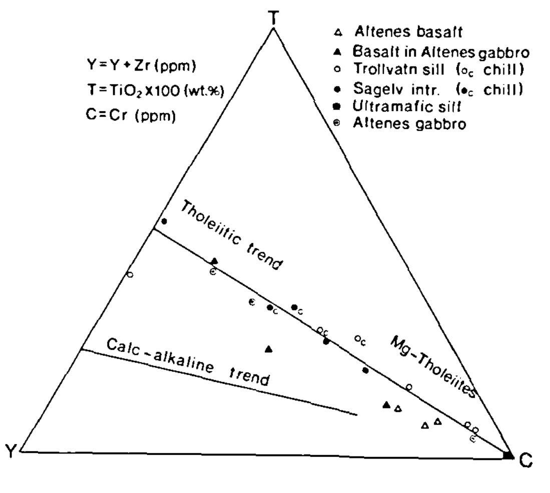

Fig. 12. YTC-diagram of Davies et al. (1978) showing the tholeiitic trend of basalts and gabbros within the Altenes Window. Modified after Nielsen (1986). See also Table 2.

	Altenes Gabbro			Ultram. sill	Mafic dyke	Felsic dyke	Altenes basalt	
	55040	55055	55058	55412	60534	55074	55012	55013
SiO_2	49.60	54.43	53.25	40.79	50.84	71.66	53.01	55.06
Al_2O_3	12.98	11.26	14.61	4.10	14.22	15.25	12.91	13.99
FeO*	14.15	9.08	9.52	10.17	11.23	1.17	9.80	8.66
TiO_2	1.80	0.46	0.69	0.19	1.30	0.09	0.69	0.67
MgO	5.31	11.07	6.11	31.59	5.14	0.68	7.49	6.21
CaO	8.97	7.85	9.71	1.74	7.70	1.19	9.43	9.33
Na_2O	2.24	1.86	2.64	0.05	2.6	6.65	2.74	2.96
K_2O	0.69	1.13	0.70	0.04	1.30	0.99	0.68	1.05
MnO	0.22	0.16	0.17	0.15	0.12	0.02	0.19	0.15
P_2O_5	0.21	0.07	0.06	0.02	0.14	0.04	0.11	0.11
LOI	3.33	2.43	2.22	10.28	1.98	0.98	2.34	2.01
Sum	99.50	99.80	99.68	99.12	98.87	98.72	99.39	100.20
Nb	9.3	3.4	2.4	4	5.8	1.9	6.1	4.9
Zr	142	57	42	70	146	33	94	95
Y	41	11	10	14	24	1	17	18
Sr	310	233	405	118	296	314	316	339
Rb	11	42	25	21	47	29	25	37
Zn	97	71	68	83	35	14	136	74
Cu	195	60	148	2	57	1	17	4
Ni	68	138	37	1767	120	2	85	69
Cr	148	972	26	4834	81	14	503	330
V	404	165	315	80	243	13	201	195
Ba	236	330	253	2	281	598	226	440
Pb	5	3	4	1	1	6	10	6
Co	72	64	70	107	51	53	74	57
La	14	14	13	3	16	5	14	17
Ce	37	26	17	2	32	7	30	32
Th	3	2	4	3	3	1	4	6

Table 2. Selected geochemical analyses of various intrusive and extrusive rocks in the Altenes Window. All samples except No. 60634 (analyzed by XRF at NGU, Trondheim) were analyzed by XRF at the Geological Institute, Copenhagen.

Altenes basalt are relatively Mg-rich bordering the normal tholeiitic field.

The differences between the Trollvatn and Sagelv instrusions discussed earlier, in terms of composition, fractionation and type of intru-

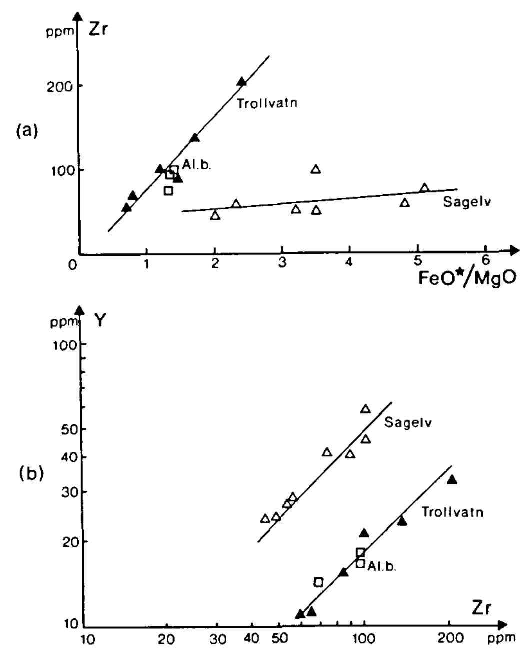

Fig. 14. Cumulate and chill samples from the Trollvatn and Sagelv intrusions plotted in the (a) Zr vs. FeO*/MgO diagram and the (b) Y vs. Zr log-log diagram.

sion (sill/slightly inclined intrusion), suggest that the two intrusions may represent different magmatic types. Although Fig. 13 defines the Trollvatn sill as a Mg-tholeiite and the Sagelv intrusion as a Fe-tholeiite, it does not exclude

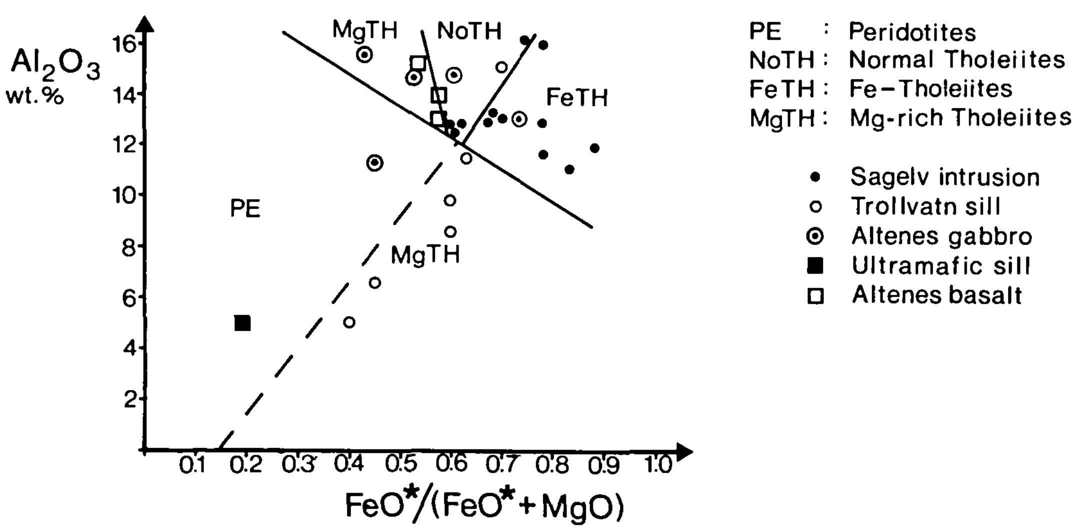

Fig. 13. Data from the Altenes Window plotted in the Al_2O_3 versus FeO*/(FeO* + MgO) discriminant diagram. Full lines are dividing lines after Viljoen et al. (1981). The dashed line is the dividing line used by Arndt et al. (1977). All data are calculated on a water-free basis.

a co-magmatic relationship between them. To resolve this question, data from the two intrusions have been plotted in the Zr vs. FeO*/MgO and Y vs. Zr diagrams (Fig. 14a and b). Also shown are three samples of the Altenes basalt.

The trends of the two intrusions, defined by plots of the HFS element Zr against the FeO*/MgO fractionation index (Fig. 14a), describe fractional crystallization of two different magmas. For the intrusions to have crystallized from the same magma would require similar ratios or that the more evolved Sagelv intrusion plotted on the continuation of the Trollvatn sill trend. Similar conclusions may be drawn from the Y/Zr diagramn (Fig. 14b) where the significantly different Y/Zr ratios of the intrusions can only be explained by crystallisation from different magma types.

It is interesting to note that the Altenes basalt ratios are similar to those of the Trollvatn sill while they show no apparent relation to the Sagelv intrusion. An intriguing interpretation of this relationship is that the Trollvatn sill is syngenetic with the extrusion of basalts while the Sagelv intrusion is probably related to a later magmatic phase. Taking into consideration that the Sagelv intrusion has intruded parallel to bedding, as mentioned earlier, it would be logical to set the time of intrusion to an early stage of the Svecokarelian imbrication of the Altenes Window volcanosedimentary sequence. Thus, the Sagelv intrusion and others of the same type in the Altenes Window may be comparable to the gabbro intrusions in the Komagfjord Window, where Pharaoh et al. (1983) also suggest intrusion during an early stage of the Svecokarelian orogeny.

Summary of conclusions

1) Two representative gabbro sheets studied in the Altenes Window show significant differences with respect to petrography, geochemical composition and differentiation. These differences are thought to result from the Trollvatn intrusion intruding as a sill while the Sagelv intrusion intruded at a slight angle to bedding. The pronounced alteration is related to deuteric alteration and burial metamorphism. Despite the alteration, petrographic studies allow the quantification of primary parageneses, a premise for the interpretation of the geochemical profiles.
2) Magmatic rocks in the Altenes Window define a clear tholeiitic affinity. Intrusive and extrusive rocks range from ultramafic/Mg-tholeiitic to evolved tholeiitic. Zr vs. FeO*/MgO and Y vs. Zr discrimination diagrams show that the Trollvatn and Sagelv intrusions crystallized from different magmas. It is suggested that the Trollvatn sill is syngenetic with the Altenes basalts while the Sagelv intrusion intruded during an early stage of the Svecokarelian orogeny.

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References

Arndt, N.T., Naldrett, A.J. & Pyke, D.R. 1977: Komatiite and iron-rich tholeiitic lavas of Munro Township, Northeast Ontario. *Jour. Petrol. 18,* 319—369.

Bailey, J.C. 1979: *Geochemistry of Igneous Rocks.* Intern. publ. Inst. of Petrology, Copenhagen, 1—50 and 186—219.

Berthelsen, A. & Marker, M. 1986: 1.9—1.8 Ga old strike-slip megashears in the Baltic shield, and their plate tectonic implications. *Tectonophysics 128,* 163—180.

Best, M.G. 1982: *Igneous and Metamorphic Petrology.* W.H. Freeman and Company, San Fransisco, 167—169, 276—298 and 342—380.

Condie, K.C. 1981: *Archean Greenstone belts,* Elsevier Sci. Publ. Com., Amsterdam, 67—108.

Davies, J.F., Grant, R.W.E. & Whitehead, R.E.S. 1978: Immobile trace elements and Archean volcanic stratigraphy in the Timmins mining area, Ontario. *Can. Jour. Earth Sci. 16,* 305—311.

Fareth, E. 1973: Geologisk kartlegging, Altenes, Alta kommune, Finnmark fylke. *Unpubl. NGU-report 1164/9A,* 17 pp.

Fareth, E. 1979: Geology of the Altenes Area, Alta—Kvænangen Window, Norway. *Nor. geol. unders. 351,* 13—29.

Haggerty, S.E. 1976a: Oxidation of opaque mineral oxides in basalts. *In:* Rumble, D. (ed.): *Oxide Minerals, Reviews in Mineralogy vol. 3.* Min. Soc. Am. 1—98.

Haggerty, S.E. 1976b: Opaque mineral oxides in terrestial igneous rocks. *In:* Rumble, D. (ed.): *Oxide Minerals, Reviews in Mineralogy vol. 3,* Min. Soc. Am. 101—169.

Håbrekke, H. 1978: Magnetiske, elektromagnetiske og radiometriske målinger fra helikopter over den delen av Kvænangen Vinduet som hører til Alta kommune i Finnmark fylke. *Unpubl. NGU-report 1594/1-2,* 11pp.

Krog, J.R. & Fareth, E. 1975: Geokjemiske og malmgeologiske undersøkelser, Altenes-halvøya, Alta, Finnmark. *Unpubl. NGU-report 1164/9B,* 15pp.

Moorhouse, W.W. 1956: *The Study of Rocks in Thin Sections.* Harper & Row Publishers, New York.

Nielsen, L.M. 1986: *Lithostratigrafisk, sedimentologisk og lithogeokemisk undersøgelse af Altenes Vinduet.* Unpubl. thesis, Univ. of Copenhagen, 93pp.

Nielsen, L.M. & Pratt, A.O. 1986: *En lithostratigrafisk, geokemisk og strukturel undersøgelse af de proterozoiske suprakrustaler i Altenes Vinduet og en sammenligning med Alta-Kvænangen og Komagfjord vinduerne, Finnmark, Norge.* Unpubl. summ. of theses, Univ. of Copenhagen, 24pp.

Olsen, K.I. & Nilsen, K.S. 1985: Geology of the southern part of the Kautokeino Greenstone belt: Rb-Sr geochronology and geochemistry of associated gneisses and late intrusions. *Nor. geol. unders. Bull. 403,* 131—161.

Often, M. 1985: The Early Proterozoic Karasjok Greenstone Belt, Norway: a preliminary description of lithology, stratigraphy and mineralization. *Nor. geol. unders. Bull 403,* 75—89.

Pharaoh, T.C., Ramsay, D.M. & Jansen, Ø. 1983: Stratigraphy and structure of the northern part of the Repparfjord-Komagfjord Window, Finnmark, Northern Norway. *Nor. geol. unders. 377,* 45pp.

Pratt, A.O. 1986: *Intrusive bjergarter og den strukturelle udvikling indenfor Altenes Vinduet, Finnmark, Norge.* Unpubl. thesis, Univ. of Copenhagen, 95pp.

Pratt, A.O. & Nielsen, L.M. 1985: The geology of the Altenes Window and its correlation to the Alta-Kvænangen and Repparfjord-Komagfjord windows, Finnmark, Norway. *Unpubl. NGU-report 85.186.* 57—60.

Pratt, A.O. & Nielsen, L.M. 1984: Geologisk kortlægning på Alteneset og beskrivelse af de Cu, Fe og Ti-mineraliseringer og de instrusive bjergarter. *Unpubl. NGU-report 84.072,* 40pp.

Siedlecka, A., Krill, A.G., Often, M., Sandstad, J.S., Solli, A., Iversen, E. & Lieungh, B. 1985: Lithostratigraphy and correlation of the Archean and Early Proterozoic rocks of Finnmarksvidda and the Sørvaranger district. *Nor. geol. unders. Bull. 403,* 7—37.

Walker, K.R. 1970: The Palisades Sill, New Jersey: A Reinvestigation. *Geol. Soc. Am. Spec. Pap. 111,* 178pp.

Viljoen, M.J., Viljoen, R.P. & Pearton, T.N. 1981: The nature and distribution of Archean komatiite volcanics in South Africa. *In:* Arndt, N.T. & Nisbet, E.G. (eds.): *Komatiites.* George Allen & Unwin, Boston, 53—78.

Zwaan, K.B. & Gautier, A.M. 1980: Alta og Gargia, beskrivelse til de berggrundsgeologiske kart 1834 I og 1934 IV, M 1:50.000. *Nor. geol. unders. 316,* 47pp.