Petrology of the Skien basaltic rocks, southwestern Oslo Region, Norway

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The pile of Permian continental basaltic rocks near Skien has a minimum thickness of 1 500 m, dipping 40° towards NE, consisting of several thin lava flows. Most flows are porphyric, though both tuffs and aphyric flows occur to a lesser extent. Amygdules are abundant and a characteristic feature. The flows in the lower 2/3 of the basalt pile are mainly classified as melanite-ankaramite; some in the middle part as melanite-nephelinite; and the upper 1/3 of the flows as basanite. The basaltic rocks evolved from an assumed olivine-nephelinitic magma at great depths principally by clinopyroxene crystal fractionation accompanied by later olivine and maybe melilite reactions at moderate pressure in minor shallower magma chambers.

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The towns of Skien and Porsgrunn are situated in the NW-SE striking Gjerpen valley some 105 km SW of Oslo (Fig. 1). Basaltic rocks form the northeastern ridge of this valley. A northern body of basalts some 12 km NNW of Skien has a surface area of approximately 5 km², while the main body of basalts E of Skien covers some 45 km².

Early descriptions of basalts in the Oslo Region include Keilhau (1826), who called the rocks 'schwarze Porphyre (oder Basaltmassen) mit Augit-Krystallen', while Kjerulf (1855) called them 'Augit-Porhyr'. Brøgger (1884) introduced the name 'Essexitmelaphyr' as a synonym for the former names. The basalts of different stratigraphic positions in the Oslo Region were given designations such as E_1, E_2, and E_3. Brøgger's 'essexites' were later called basalts by Barth (1945), and Oftedahl (1952) replaced the 'E'-symbols with 'B'-symbols.

A profile through the geology of the Skien district was given by Dahll (1857). Brøgger (1884) mapped the faults, especially in the Langesundsfjorden area S of the Skien District. Kiær (1906) described the geology of the Cambro-Silurian sedimentary rocks, while Brøgger (1933a) discussed the volcanic rocks in this district. Oftedahl (1952) placed the Skien basalts among the B_1 Oslo basalts; Weigand (1975) has presented five chemical analyses of the Skien basalts. Segalstad (1975) showed that the upper part of the block of basalts is cut by two cauldrons; the Vealøs and Skrehelle cauldrons.

The Skien basalts rest on Permian sedimentary rocks, which are poorly described except for the plant fossils (mainly *Cordaites*) reported by Høeg (1936). The sedimentary strata are continuous and not disturbed by early faults or joints as at Ringerike (B. Larsen, pers. comm.). In accordance with Brøgger (1933a) the basaltic sills in the upper sedimentary strata reported by Dahll (1857), appear to be discordant dikes.

The Permian sedimentary rocks consist mostly of red-coloured (some grey-coloured) sandstones and shales. The rocks are multicyclic composed dominantly of fine-grained clastic quartz and occasional small pyroclastic fragments of pyroxene, which are thought to be of tephraic origin from within a short distance. The red rock colour is due to the hematite-rich matrix. The upper 30 m of the Permian sediments were erroneously called tuffs by Dahll (1857). He described the dense hematite-rich rocks as 'tuffartige Straten'. The Permian sediments are terminated by a 1-2 m thick monomict conglomerate (also described by Dahll 1857) with 1-2 cm well-rounded quartz pebbles, medium sorted and scattered throughout the matrix. Near the plutons the sandstone appears as metamorphic quartzite as in the north near the nordmarkite (syenite). In the Skien district the
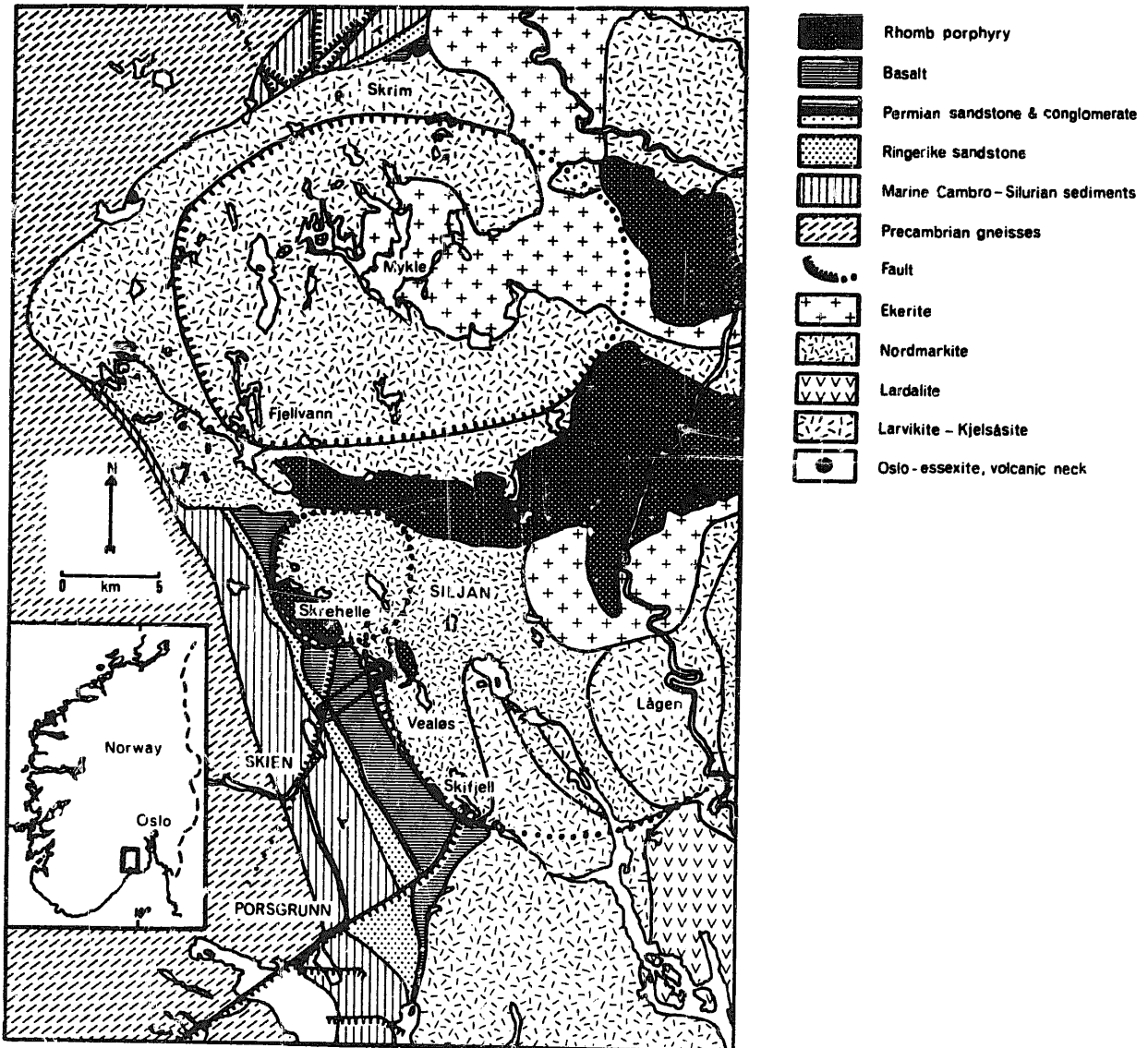
Fig. 1. Geological map of the Skien district (after Segalstad 1975). The situation of the profile through the basaltic rocks (Figs. 2, 4) is shown between Skien and Siljan.

Permian sedimentary rocks and conglomerate sequence are estimated to be between 110 and 125 m thick. This thickness is greater than that of the similar well-known sequences near Oslo: 40 m thickness at Asker (Størmer 1966) and 23–35 m at Kolsås (Dons & Györy 1967).

The basalts occur concordantly above the Permian sedimentary rocks, with nearly constant strike 150ᵉ and dip 40ᵉ towards NE. There are minimal thermal metamorphic effects on the underlying sedimentary rocks. Tuffs are of local and restricted distribution and occur mostly in the south.

Due to the very uniform appearance of the Skien basalts, it was decided to carry out a

detailed investigation of a profile through the basalts. This profile should ideally show fresh basalts unaffected by plutonic contact metamorphism or tectonism. It should also give an idea of the true thickness of the pile of basalts.

A profile with nearly continuous fresh road cuttings through the whole pile of basalts was found E of Skien along the highway from Skien to Siljan (Fig. 1). It is 2.5 km long and runs in a SW-NE direction from Åmot (3.7 km NE of Skien cathedral) to Heivann (Fig. 2).

As the profile contains mainly thin flows (Fig. 3) there are reasons to assume that the lava originated from shields or fissures. The profile is
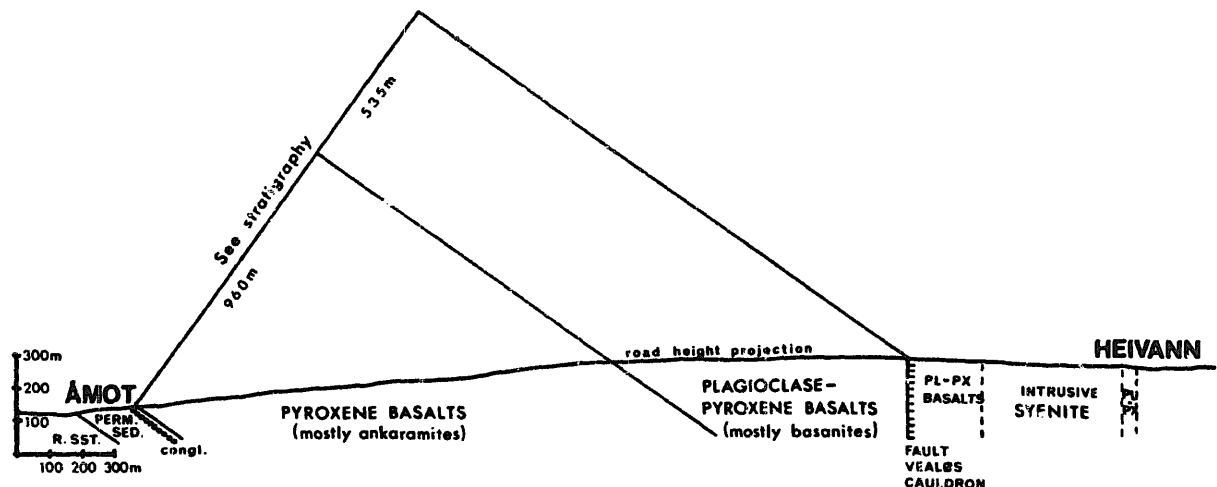
Fig. 2. Vertical projection of the road profile between Åmot and Heivann. R.SST. = Ringerike sandstone. For stratigraphy see Fig. 4.

intended to give an impression of the magmatic conditions during the initiation of the rifting and volcanic episode in this part of the Oslo Region.

Dip is constant at 40ᵍ up to the border of the Vealøs cauldron, giving 1495 m as the total apparent thickness of the basalts outside the Vealøs cauldron. This must be considered a minimum thickness of the Skien basalts, since huge xenoliths composed of basalts are found in the nordmarkite (syenite) inside the Vealøs cauldron. These xenoliths may have sunk in the syenite magma from a higher position in the lava flow sequence than is exposed today. Brøgger (1911, 1933a) believed the thickness of the Skien basalts to be 100 m (1911) or > 170 m (1933), and suggested that the apparently huge thickness of the basalts was due to tectonic repetition. However, neither Oftedahl (1952) nor the present writer have found indications of faults parallel to the strike, and the apparent thickness seems to be real. Oftedahl (1952) indicated a basalt thickness of > 200 m, but recognized the possibility of the thickness being as much as 500 m or more. Ramberg (1976) contests Oftedahl's estimates of the basalt thickness, and states that the observed gravity anomaly applies to a slab of basaltic rocks with apparent stratigraphic thickness of about 2 km, extending down to at least 2.5 km depth.

Petrography

The Skien basaltic rocks may be divided petrographically into three groups – porphyric basalts, aphyric basalts, and tuffs containing
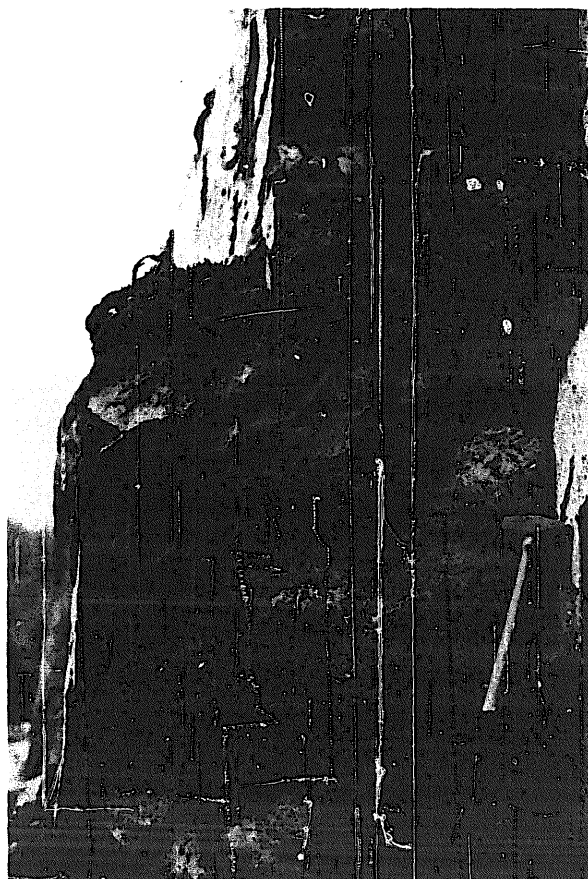

Fig. 3. Thin lava flows of melanite-nephelinite (sample S36). Tilted picture to show stratigraphy; the dip is false. Length of hammer 40 cm.

xenocrysts or xenoliths. Though most of the Skien basalts lack calcic plagioclase and therefore do not qualify to be called true basalts according to Streckeisen (1967), they are nevertheless throughout this paper called basalts for convenience, synonymously with 'basaltic rocks'.

Amygdules are abundant and a characteristic feature of the Skien basalts. They are most often filled with calcite, but epidote, chlorite, zeolites, and albite also occur. The lava pile is composed of numerous small lava flows, usually 1–5 m thick, though both thinner (20 cm) and thicker (up to 15 m) flows occur. Pyroclastic rocks (tuffs and agglomerates) are seldom observed. The lower flows are dominated by pyroxene phenocrysts, while plagioclase also occurs as phenocrysts in the upper flows. No ultramafic nodules have ever been found in the Skien basalts despite an intensive search.

Porphyric basalts

Abundant euhedral clinopyroxene phenocrysts (3–10 mm across) are short, prismatic, and often found in groups or clusters. They are twinned and/or zoned, often in complex forms showing hour-glass structure. First and second generation pyroxenes have no pleochroism and may be corroded, third generation pyroxenes usually show a pale violet pleochroism due to their higher Ti contents (see below).

Unaltered olivine occurs in the lowest flows as euhedral phenocrysts (5–10 mm across) often with a serpentine-magnetite-clinopyroxene reaction rim (corona). Cracks are often filled with brown iddingsite. In some flows all olivine is altered to serpentine and magnetite or to green bowlingite and magnetite. Inclusions in olivine are rare, but are usually Cr-rich magnetite.

Plagioclase phenocrysts occur in the upper flows as 10–15 mm elongated clusters or laths. They may be saussuritized and sericitized, and often show undulating extinction. Kaersutite occurs as elongated subhedral to euhedral phenocrysts (0.5–1.5 mm long).

The groundmass consists of apatite, melanite, magnetite, calcite, and occasionally sphene, nepheline, chalcopyrite. Apatite may appear as euhedral laths or basal sections as microcrysts. Melilite may be present in the groundmass as 1–3 μm long grains (microprobe identification).

Secondary minerals are chlorite, epidote, serpentine, bowlingite. The texture is intergranular to intersertal.

Aphyric basalts

Euhedral clinopyroxene (usually 0.2–0.4 mm across, occasionally as phenocrysts 5 mm across) are short, prismatic, and often found in groups or clusters. They are less zoned than the phenocrysts in the porphyric basalts, and are generally of the corresponding second generation with no pleochroism.

Plagioclase occurs as (0.3–0.4 mm long) thin elongated albite-twinned laths, often with undulating extinction. Magnetite occasionally occurs in euhedral (0.5 mm across) crystals.

Secondary minerals are chlorite, serpentine, epidote, and bowlingite. The texture is intergranular to intersertal.

Tuffs

The tuffs can be subdivided into two types. *Lapilli tuff* occurs in the upper part of the profile (sample S63) with xenoliths (3–5 cm size) composed of porphyric basalt with pyroxene and plagioclase phenocrysts in a porphyric matrix of the same composition. *Crystal tuff* occurs in the lower part of the profile (sample S20, sample S27).

The pyroxenes are anhedral (3–5 mm across) and typically xenocrysts; they may be twinned and have strong violet pleochroism. Euhedral, now corroded, phenocrysts like those described from porphyric basalts also occur. The groundmass consists of brown-to-black basaltic glass (pumice), magnetite, calcite, and occasionally minor vesicles containing sphene. Secondary minerals are chlorite, serpentine, epidote, and bowlingite. The texture is intersertal and pumiceous.

Alteration and metamorphism

All samples have been subjected to some degree of deuteric alteration. Hydrothermal alteration has taken place in the vicinity of larger joints. Thermal metamorphism from the nordmarkite intrusion and associated fluids have played some role in changing the original mineralogy of the basalts, especially in the upper part of the profile. Plagioclase is changed to sericite and epidote, pyroxene has been recrystallized or changed to chlorite and amphibole, olivine to serpentine or bowlingite. A few small crystals of idocrase, grossular, and recrystallized calcite have been observed in the huge contact metamorphic basalt xenoliths inside the Vealøs cauldron, indicating hornfels-class X (Goldschmidt 1911) in Eskola's (1920–21) pyroxene-hornfels facies (K-feldspar-cordierite-hornfels facies of Winkler (1967)).

Classification

Oftedahl (1952, 1957) classified the Oslo basalts as

1. Augite basalt (pyroxene basalt)
2. Plagioclase basalt (plagioclase basalt)
3. Non-porphyric basalt (aphyric basalt)
4. Augite-plagioclase basalt (plagioclase-pyroxene basalt)

The classification was also adopted by Weigand (1975); his notation is shown in parentheses above. The distribution of basalt types is presented in Table 1 and Fig. 4.

The presence of clinopyroxene as the only pyroxene indicates alkali basalt affinities. Some of the plagioclase-free lava flows contain abundant pyroxene and olivine (only the lowermost lava flows have fresh olivine, others have distinct pseudomorphs or relicts of olivine) with pyroxene in excess of olivine. They would be called *ankaramites*. The abundance of melanite

Table 1. Distribution of basalt types in the profile Åmot–Heivann, Skien.*

	Apparent thickness (m)	Abundance (%)
Aphyric basalts -	71	4.3
Porphyric basalts:		
Plagioclase basalts	60	3.7
Plagioclase-pyroxene basalts	607	36.9
Pyroxene basalts		
(with amygdules 725 m, 44.1%) (without amygdules 109 m, 6.6%)	834	50.7
Pyroclastics	4	0.2
Hidden	65	4.0
Sum	1 641	99.8
Total apparent thickness	1 645	100.0

* 75% of the basalts contain amygdules. Sediment layers or erosion horizons between the lava flows are most often lacking and may be only 1–2 cm thick if observed. Long eruption breaks are therefore unlikely.
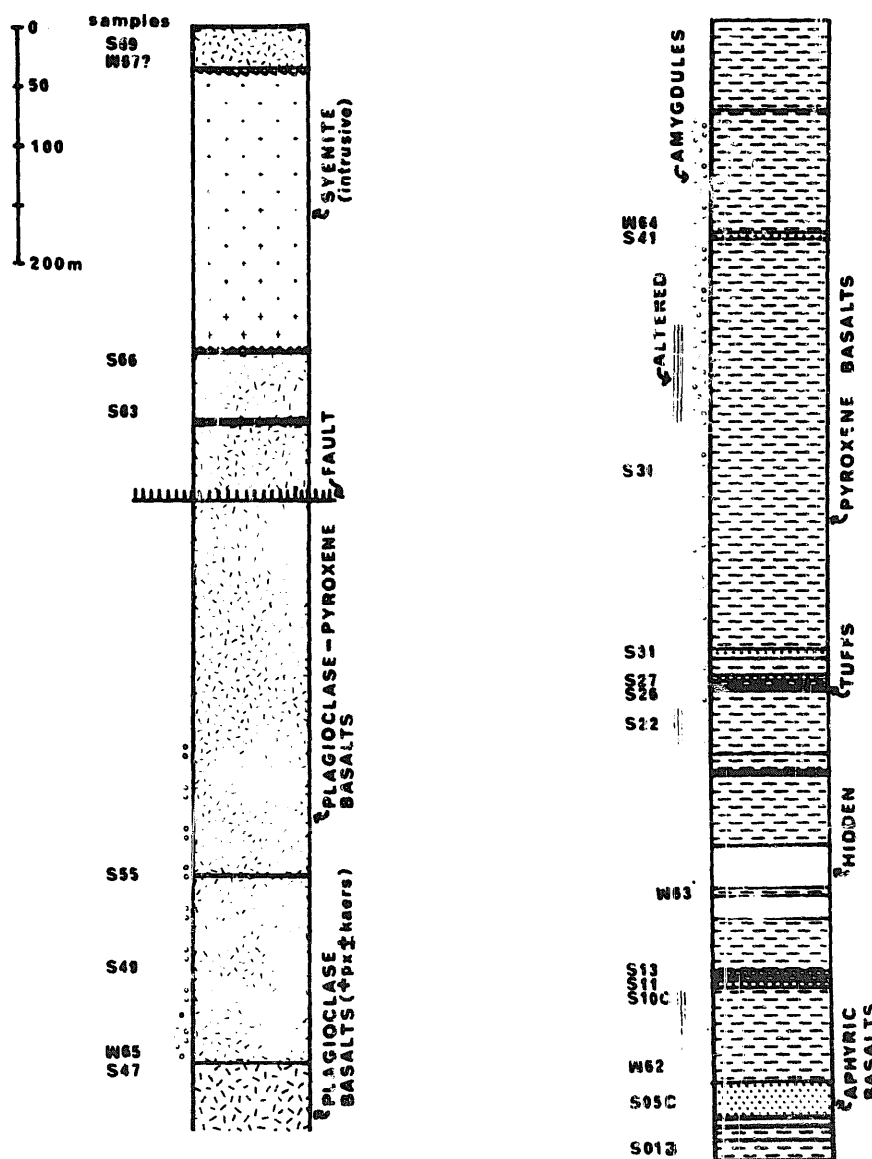

Fig. 4. Stratigraphy of the Skien basaltic rocks. Dikes (diabase- and syenite dikes) are very scarce in this profile. They are often less than 1 m thick, striking NW-SE or NE-SW with vertical dip. (Top of the sequence in the left hand column.)

in groundmass justifies the name *melanite-ankaramite* for the grey-coloured varieties.

The plagioclase-bearing flows and flows with abundant pyroxene are called *basanites* if modal nepheline is present, and basanitiodes where it is absent. Staining (Shand 1939; Mörtel 1971) showed that nepheline is present in the ground-mass. *Melanite-nephelinite* thus occurs in the middle part of the basalt pile.

Mineralogy

Analytical procedures

Minerals were analysed with an ARL-EMX microprobe at the Central Institute of Industrial Research, Oslo, using series of natural and synthetic standards. The raw data were corrected for dead-time and background. Corrections for mass absorption and fluorescence were

made by a procedure described by Bence & Albee (1968) using correction factors from Albee & Ray (1970). Each analysis represents the mean of 3–4 analysed points.

Contents of ferric iron have been calculated from charge balance according to Neumann (1976).

Pyroxene

The only pyroxene phase is a Ca-rich clino-pyroxene. Typical pyroxene compositions from the Skien basalts are shown in Table 2. Chemical characteristics of the pyroxenes are listed in Table 3.

The pyroxene compositions are shown in a part of the Ca-Mg-Fe diagram in Fig. 5. The nomenclature of the clinopyroxenes is adopted from Poldervaart & Hess (1951). It is seen from Fig. 5 that the pyroxene cores are diopsidic, while the intermediate zones and rims are salitic.

Table 2. Compositions of some typical pyroxenes from the Skien basalts.

Analysis No.	Diopside		Titaniferous salite		Titansalite	
	111	363	119	138	237	2521
SiO_2	52.9	54.1	48.3	47.1	43.3	45.1
Al_2O_3	2.2	1.0	5.6	6.3	8.3	6.7
TiO_2	.7	.4	2.2	2.6	4.1	3.7
Fe_2O_3	1.4	1.1	3.6	2.4	7.2	4.4
MgO	16.9	18.0	13.9	12.4	11.5	12.4
FeO	2.5	2.8	3.3	5.4	1.7	3.7
CaO	22.4	22.2	22.8	22.2	22.7	22.8
Na_2O	.5	.4	.5	.5	.9	.5
K_2O	.1	n.d.	.1	.1	.1	n.d.
Sum	99.6	100.0	100.3	99.0	99.8	99.3
Structural formula based on 4 cations:						
Si	1.932	1.964	1.786	1.774	1.630	1.701
Al	.068	.036	.214	.226	.369	.299
Ti					.001	
	2.000	2.000	2.000	2.000	2.000	2.000
Al	.027	.008	.030	.054		
Ti	.020	.011	.061	.074	.117	.104
Fe^{3+}	.040	.031	.099	.068	.204	.126
Mg	.922	.976	.766	.694	.644	.695
Fe^{2+}	.077	.084	.101	.170	.053	.117
Ca	.877	.863	.904	.897	.914	.923
Na	.033	.026	.034	.039	.064	.035
K	.005		.004	.005	.004	
	2.000	2.000	2.000	2.000	2.000	2.000
Al in Z(%)	3.39	1.78	10.68	11.30	18.45	14.97

n.d. = not detected.

Table 3. Characteristic chemical features of pyroxenes in the Skien basaltic rocks.

	Diopside	Titaniferous salite	Titansalite
	1st generation Often C	2nd generation Often I	3rd generation Often R
Ti	Low $TiO_2 < 1.7$	Intermediate $1.7 < TiO_2 < 3.0$	High $TiO_2 > 3.0$
Mg	High $MgO > 14.5$	Intermediate $13.0 < MgO < 14.5$	Low $MgO < 13.0$
Al	Low $Al_2O_3 < 4.0$	Intermediate $4.0 < Al_2O_3 < 7.0$	High $Al_2O_3 > 6.5$
Al in Z	Low $Al_Z < 7$	Intermediate $7 < Al_Z < 14$	High $Al_Z > 14$

C = core, I = intermediate, R = rim. Values in wt.% metal oxide (TiO_2, MgO, Al_2O_3) or % abundance (Al in Z). Limits are approximate. Cr and Mn are analysed in few pyroxenes; Cr seems to follow a trend from high Cr (0.4%) in diopside towards low Cr (0.1%) in salite.

Huckenholz (1965) and Deer et al. (1966) choose a lower limit of 3% TiO_2 for titanaugites or titansalites, and call those with 2 to 3% TiO_2 titaniferous augites or titaniferous salites. These limits compare well with the observed TiO_2 limits between the Skien pyroxenes, which in general may be said to have *diopsidic cores, titaniferous salitic intermediate zones,* and *titansalitic rims* (Table 3).

Cata-norms calculated often show hypersthene and olivine but no nepheline in norms for the pyroxene cores, while the rims have norms with nepheline, negative values for quartz, and lack hypersthene and olivine. This presumably reflects the degree of undersaturation of the host magma producing the respective pyroxenes (see below).

The Al_Z and Ti contents of the salites tend to vary sympathetically. Yagi & Onuma (1967) have suggested that these ions are mainly pre-

sent as the hypothetical titanpyroxene molecule $CaTiAl_2O_6$ whose maximum solubility in diopside at atmospheric pressure is about 11%, corresponding to 4% TiO_2. At high pressures (10–25 kbar) the solubility of $CaTiAl_2O_6$ in diopside decreases markedly, suggesting that most titanaugites are relatively low-pressure phases. Any Al in octahedral co-ordination is probably present mainly as Ca-Tschermak's molecule $CaAl_2SiO_6$. This substitution is favoured by high pressures according to Clark et al. (1962).

With the reservation that there has been no major change in magma composition during the time of pyroxene crystallization, the Skien basalts' pyroxene cores must have formed at higher pressures than the other pyroxene zones. This is consistent with the often observed resorption of the pyroxene cores.

The grass-green xenocryst salite pyroxenes in the crystal tuff sample S20, however, show

Fig. 5. Some typical clinopyroxene analyses from the Skien basaltic rocks plotted in a part of the DI-HD-EN-FS field (shaded area of the key figure to the lower right). Arrows point from pyroxene core to rim. Nomenclature is adopted from Poldervaart & Hess (1951). DI = $CaMgSi_2O_6$. HD = $CaFeSi_2O_6$. EN = $MgSiO_3$. FS = $FeSiO_3$.
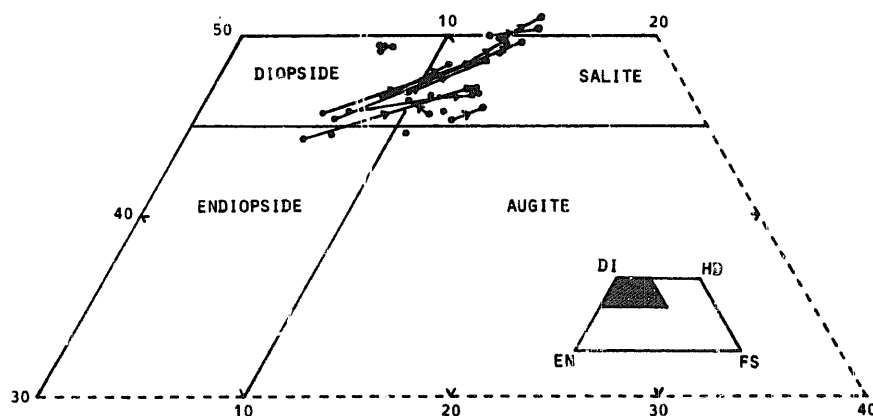
reverse zoning (Fig. 5). This feature has been described from several places, as for instance from east Greenland by Brooks & Rucklidge (1973). They assume that these pyroxenes were subjected to an accidental change in O_2-fugacity which might also have been the case during the extrusion history of the crystal tuff at Skien.

Olivine

A typical olivine analysis is shown in Table 4. Olivines in sample S01 all give the composition Fa_{13}. Zoning has not been observed in these olivines.

Plagioclase

The plagioclase lath compositions in the aphyric basalts are usually in the labradorite range (An 54). Plagioclase phenocrysts in the higher basalt flows, however, show compositions in the oligoclase range (An 20–30). Zoning has not been observed in the plagioclase.

Kaersutite

Kaersutite is a pargasitic amphibole in which Ti ranges from about 0.5 to 1 atom per formula unit. One typical kaersutite composition from sample S47 is presented in Table 4. The TiO_2-contents of kaersutites from the Skien basalts is among the highest reported from rocks with similar chemistry.

Wilkinson (1974) states that the norms of many kaersutites are similar to those of olivine nephelinites, while Kesson & Price (1972) assert that the composition of the nephelinitic 'minimum melt' is very close to that of kaersutite. Green (1970a) has suggested that increasing degrees of partial melting in the low velocity zone produce basaltic liquids whose compositions pass gradually from nephelinite through basanite and alkali basalt to tholeiite. Kesson & Price (1972) therefore conclude that kaersutite must be an accessory phase in the upper mantle.

Recent experimental work on the stability of kaersutite by Yagi et al. (1975) indicates that hornblendes can be stable up to 23–25 kbar at temperatures as low as 600–700°C, i.e. hornblende can be stable not only in the lower crust, but also in the upper mantle. It is espe-

cially noteworthy that kaersutite is associated in these experiments with Ti-poor clinopyroxene, garnet, and perovskite. The chemistry of this paragenesis is equivalent to the chemistry of the mineral paragenesis in the Skien basalts, as discussed below.

Melanite

The reddish coloured groundmass mineral with brownish or greyish shades is fairly abundant in some of the Skien basalts. Three samples of groundmass from S01, S36, and S41 were separated from the crushed rock specimens under a binocular microscope, and X-ray films made at the Geological Museum, Oslo, showed typical garnet (andradite) patterns. An average of seven groundmass melanite analyses from samples S01, S36, and S41 is shown in Table 4. There was great spread in compositions due to the small size of the analysed grains.

Melanite is normally associated with rocks of the ijolite-melteigite series or their late-stage differentiation products. Bailey (1974) states that melanite and melilite are accessory minerals in nephelinite lavas, without giving any examples. He further states that porphyric melanite may be present in olivine-free nephelinite. Yoder (1973) ascertains that melanite is a common associate of melilite.

Sphene

Sphene occurs in small vesicles of assumed late-stage crystallization in tuffs. One typical analysis from sample S27 is shown in Table 4.

Magnetite

Three chemically different types of magnetite occur in the Skien basaltic rocks. Titano-magnetite occurs as the normal groundmass ore. Cr-rich magnetite is found in minor amounts as inclusions in olivine. Nearly pure magnetite is found in the reaction zone around olivine phenocrysts, between olivine and serpentine. The groundmass titano-magnetite is the common groundmass ore through almost the whole section of basalts, though ilmenite exsolution lamellae are seen in magnetite in the highest lava flows.

Table 4. Compositions and structural formulas of typical olivine (Fa$_{13}$), kaersutite, sphene, and average of 7 melanites from the Skien basalts.

Mineral Analysis No.	Olivine 012	Kaersutite 472	Melanite average	Sphene 272
SiO$_2$	40.7	39.1	36.98	31.6
Al$_2$O$_3$	n.d.	11.9	6.70	2.4
TiO$_2$	tr.	7.0	6.32	31.7
Fe$_2$O$_3$*			16.75	5.0
MgO	46.5	13.3	3.15	1.3
FeO*	12.6	11.4		
MnO	.3	.3	n.a.	n.a.
CaO	.5	11.5	27.23	25.9
Na$_2$O	tr.	2.8	.56	.2
K$_2$O	tr.	1.0	.99	.2
Cr$_2$O$_3$	tr.	tr.	n.a.	n.a.
H$_2$O		2.00		
Sum	100.6	100.3	98.68	98.3
Oxygens	4	23	24	20
Si	1.006	5.798	5.946	4.106
Al		2.086	.054	
Ti		.116		
	1.006	8.000	6.000	4.106
Al			1.216	.366
Ti		.669	.764	3.096
Fe^{3+}			2.027	.487
Mg	1.710	2.932	.755	.256
Fe^{2+}	.260	1.407		
Mn	.007	.031		
Ca	.012	1.830	4.691	3.599
Na	tr.	.813	.175	.050
K	tr.	.183	.203	.040
Cr	tr.	.005		
	1.989	7.870	9.830	7.894

* As total Fe. n.a. = not analysed, n.d. = not detected, tr. = trace. The kaersutite composition was calculated assuming 2.00% H$_2$O.

Whole rock geochemistry

Whole rock major element analyses were executed by X-ray fluorescence spectrometry (Si, Ti, Al, Fe (total Fe as Fe$_2$O$_3$), Mn, Mg, Ca, K, P), instrumental neutron activation analyses (Na), and wet-chemical analyses (FeO).

Whole rock chemical analyses and cata-norms of volcanic rocks from the Skien district are listed in Table 5. Samples denoted with the prefix 'W' are from Weigand (1975). Mean, precision, range, and accuracy of the basalts analysed by the author are shown in Table 6.

The high TiO$_2$ content is noteworthy and was confirmed in two samples by wet chemical analyses by B. Bruun: S01B with 3.21% TiO$_2$, and S31 with 4.00% TiO$_2$. These analyses indi-

cate that the values obtained by the X-ray fluorescence spectrometer might even be a little too low.

The difference in sums from 100% is caused by the loss of volatiles (H$_2$O + CO$_2$ (mainly) and F + Cl + S) during sample preparation. This is especially true of sample S47, which contains abundant hydrous silicates (kaersutite and serpentine).
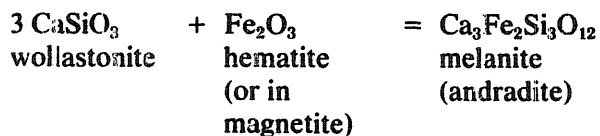
The norm calculations give abundant nepheline and olivine as a common feature of nearly all samples. A strange feature, however, is that the norms of samples S01 and S36 show negative quartz values. This is due to the extremely high Ca contents, which results in silica undersaturation. The 'excess' Ca is calculated into anorthite and wollastonite (as in S36), in-

Table 5. Whole rock chemical analyses and cata-norms of volcanic rocks from the Skien district.

Rock Sample	Am S0IB	Am S05C	Am W62	Am S10C	Am S11	Bn S13	Am W63	AtAm S22	Am S26	TuAm S27	AtAm S31	Ne S36B
SiO_2	41.8	42.8	44.7	43.0	44.3	45.0	42.3	44.7	45.2	46.0	43.1	36.9
TiO_2	3.09	2.94	2.88	3.46	3.24	3.40	3.95	3.14	3.04	3.13	3.89	3.32
Al_2O_3	8.0	10.6	11.2	12.5	11.0	15.2	11.4	13.7	9.2	11.0	13.0	10.6
Fe_2O_3	7.3	7.7	7.0	7.0	6.3	6.7	5.5	5.3	6.4	5.3	6.7	8.4
FeO	3.3	5.0	5.4	6.6	6.4	7.6	8.5	6.2	6.3	7.3	7.0	4.1
MnO	.18	.20	.17	.21	.20	.24	.18	.18	.19	.19	.28	.27
MgO	11.5	11.0	8.27	8.5	10.8	6.6	7.79	8.6	11.5	10.0	6.7	7.7
CaO	18.78	13.36	13.56	12.63	12.85	7.91	12.70	10.04	12.16	10.42	12.07	19.04
Na_2O	1.45	1.78	1.55	2.03	1.94	3.05	2.93	3.86	2.79	3.33	4.40	3.38
K_2O	1.89	2.55	2.17	2.28	2.21	3.53	1.22	1.44	1.64	1.75	.78	1.32
P_2O_5	.59	.35		.35	.39	.60		.53	.45	.50	.61	1.81
Sum	97.9	98.3	96.90	98.6	99.6	99.8	96.47	97.7	98.9	98.9	98.5	96.8
Rb			26									
Sr			1 409									
Th			5.9				6.8					
U			1.4				1.5					
Cata-norms:												
Q	-1.96											-2.92
OR		11.27	13.49	13.90	13.21	21.18	7.59	8.67	9.81	10.46	4.72	
AB			8.52	5.34	5.26	15.50	7.47	19.07	12.06	17.96	15.90	
AN	10.03	13.74	18.10	18.85	14.96	17.64	15.12	16.13	7.84	10.02	13.75	10.29
LC		3.33										
NE	8.04	9.83	3.67	8.08	7.42	7.39	12.13	9.77	7.99	7.37	14.74	18.99
KP	6.89											4.88
WO												7.74
HY												
DI	65.50	41.47	42.15	34.75	37.56	14.59	40.97	24.91	40.22	31.17	34.79	45.24
OL	.16	8.04	2.43	5.79	9.55	10.50	4.87	10.21	10.07	11.95	2.08	
MT	1.25	5.61	6.87	7.55	6.66	7.11	6.05	5.65	6.77	5.60	7.17	2.70
HE	4.40	1.76	.55									4.30
IL	4.43	4.20	4.22	4.97	4.57	4.81	5.79	4.46	4.29	4.41	5.55	4.83
AP	1.27	.75		.76	.82	1.27		1.13	.95	1.06	1.31	3.95

volving more SiO_2 than is present in the analyses. The presence of melanite in the samples will produce a silica-deficient norm. Attention must at this point also be drawn to the pyroxene norm calculations in which the salitic pyroxenes display the same feature.

This feature also occurs in the East African undersaturated rocks, and in agreement with King (1965) the silica deficiency is accounted for largely by the following relationship among normative and modal minerals:

$$3\ CaSiO_3 + Fe_2O_3 = Ca_3Fe_2Si_3O_{12}$$

wollastonite   hematite   melanite
          (or in   (andradite)
          magnetite)

Main elements as wt.% oxides are plotted in the SiO_2–$Na_2O + K_2O$ variation ('Harker') diagram together with a number of empirical dividing lines (Fig. 6). The 'Hawaii' line by Macdonald & Katsura (1964) separates the alkaline (NE-normative) and subalkaline (HY-normative) rocks in Hawaii. The 'Japan' line by Kuno (1960) separates his high-alumina basalts (NE = O, HY < 10%) from tholeiites (Q-normative) in Japan.

Weigand (1975) classified the Oslo basalts in accordance with this scheme, and showed that they are members of the alkali basalt association, though the aphyric basalts from B_1 in Bærum have tholeiitic characteristics. The alkali basalts may be further subdivided with the 'Moheli' line of Strong (1972), separating basani-

Am S41	Am W64	Bn S47	Am W65	Am S49	Am S55	TuBn S63	Bn S66	Bn W67	Bn S69	RP B05	Rock Sample
46.3	45.9	42.7	43.8	46.1	43.7	43.7	46.0	45.2	45.4	57.6	SiO_2
2.56	2.81	2.79	3.35	2.63	3.63	3.06	2.95	3.13	2.56	1.89	TiO_2
7.8	13.9	14.5	12.7	10.5	9.7	14.1	14.0	13.7	15.2	16.1	Al_2O_3
7.2	4.7	5.8	7.8	7.0	10.5	7.1	9.4	8.0	8.3	7.6	Fe_2O_3
5.6	7.3	5.2	5.9	5.1	4.3	5.4	3.4	5.1	3.2	1.1	FeO
.21	.16	.16	.19	.18	.21	.20	.20	.19	.18	.16	MnO
11.8	6.24	8.1	7.24	10.4	10.5	8.8	7.8	6.33	8.4	2.3	MgO
14.16	11.06	7.83	10.80	12.38	12.38	8.96	8.98	8.96	11.01	3.29	CaO
2.20	3.20	2.90	2.70	2.27	1.82	2.91	2.60	3.23	3.12	5.39	Na_2O
1.24	1.99	2.84	2.72	1.45	1.80	2.83	2.36	2.61	1.87	3.86	K_2O
.39		.75		.32	.44	.53	.38		.40	.62	P_2O_5
99.5	97.26	93.6	97.20	98.3	99.0	97.6	98.1	96.45	99.6	99.9	Sum
	58										Rb
	1692										Sr
	5.3		7.0					4.9			Th
	1.2		1.9					1.4			U
										3.20	Q
7.42	12.20	17.92	16.79	8.77	10.97	17.18	14.41	16.20	11.11	22.88	OR
13.14	15.75	17.57	9.07	17.94	11.93	12.98	24.14	19.71	15.44	48.56	AB
7.85	18.36	19.41	15.16	14.53	13.40	17.54	20.24	15.95	22.08	8.37	AN
											LC
4.12	8.44	6.15	9.76	1.76	2.96	8.32		6.45	7.64		NE
											KP
											WO
							.76			5.05	HY
48.56	30.86	13.48	32.66	36.99	37.60	19.67	18.61	14.60	24.17	3.15	DI
6.85	5.24	13.17	3.65	8.41	8.59	11.60	9.40	4.78	8.64		OL
7.62	5.10	6.48	7.01	6.51	2.48	6.32	1.79	5.58	2.10		MT
		1.01	.66		5.89	.87	5.58	2.14	4.42	5.31	HE
3.61	4.06	4.15	4.88	3.75	5.22	4.38	4.25	4.58	3.59	1.71	IL
.83		1.68		.69	.95	1.14	.82		.84	1.30	AP

Samples with prefix 'S' are Skien basalts from the profile Åmot–Heivann, prefix 'W' are Skien basalts analysed by Weigand (1975), from the same profile. Sample B05 is a latite (RP) from trigonometric point 552 m above sea level at the peak Skrehelle 8 km NE of Skien. All values are in wt.%, except for Rb, Sr, Th, U listed as ppm. Mean, precision, range, and accuracy of the basaltic rocks analysed by the author are shown in Table 6. Am = ankaramite, Bn = basanite, Ne = nephelinite, Tu = tuff, At = altered.

tic rocks (NE > 5%) and alkali basalts (NE < 5%) in the Western Indian Ocean. The 'Kenya' line of Saggerson & Williams (1964) separates nephelinitic (modal nepheline-bearing; corresponding to approx. NE > 10%) and basanitic rocks (nepheline occult or lacking, 5% < NE < 10%) in East Africa.

In the SiO_2–Na_2O + K_2O diagram with the dividing lines described above (Fig. 6), the samples of the Skien basalts plot in the alkali basalt field; a few as alkali basalt, most in the basanite field, while some plot in the nephelinite field.

The ankaramites group around the basanite field at lower alkali values (3–4.5%) than the basanites which cluster around the 'Kenya'-line between basanites and nephelinites at a higher alkali content (5–6.5%). One nephelinite sample plots in an isolated position at low silica (~37%) and medium alkalis (~ 4.7%). Some altered samples assumed to be ankaramites plot near or inside the lowest part of the basanite field.

Petrological evolution

The experimental work of Green & Ringwood (1967) demonstrated that magmas might fractionate to yield different fractionation trends at different pressures (depths). Low pressure or shallow crustal fractionation (< 15 km depth) is dominated by olivine as the liquidus phase with clinopyroxene ± plagioclase appearing at lower

Table 6. The Skien basaltic rocks; mean, precision, range, and accuracy of the whole rock chemical analyses. (Analyses by Weigand (1975) are omitted.)

Oxide	Mean	Precision ±% relative	Range	Accuracy ±% relative
SiO_2	43.92	0.35	36.9 –46.3	2.26
TiO_2	3.11	0.26	2.56– 3.89	4.05
Al_2O_3	11.80	0.69	7.8 –15.2	3.78
Fe_2O_3	7.2		4.7 –10.5	
FeO	5.4		3.2 – 7.6	
MnO	0.21	0.73	0.16– 0.28	6.51
MgO	9.34	1.53	6.6 –11.8	2.07
CaO	12.06	0.58	7.83–19.04	0.97
Na_2O	2.70	1.66*	1.45– 4.40	
K_2O	1.99	0.21	0.78– 3.53	0.57
P_2O_5	0.55	2.63	0.32– 1.81	7.83
Sum	98.28			
Total iron as Fe_2O_3	13.18	0.48	10.93–15.32	0.90

* Based on only 7 duplicates.

The *precision* of the analyses is given as standard error of the mean, determined using pooled estimate of variance for all samples determined in duplicate. The *accuracy* of the standard curve is an expression of the scatter of the standard points about it, called the relative standard deviation from the standard curve.

temperatures. Fractionation at about 15–35 km depth is dominated at the early stage by olivine, but the olivine is joined by clinopyroxene as the second phase in the alkali basalt composition. Plagioclase only appears at temperatures very near the solidus. Fractionation at about 35–70 km depth is dominated by separation of aluminous orthopyroxene or orthopyroxene + subcalcic augite. This fractionation yields olivine-rich alkali basaltic magmas. Fractionation at atmos-

pheric pressure gives increase in silica and moderate increase in alkalis; while fractionation at about 13–18 kbar (40–60 km) gives a silica-deficient melt strongly enriched in alkalis. The chemical variation as a function of the stratigraphy has been tested for the Skien basalts. The analyses of the bottom (B), middle (M), and the top (T) sequences of the basalts plot differently in an alkali-silica diagram shown in Fig. 7. Samples S13 (C), S36 (D), S41 and S49
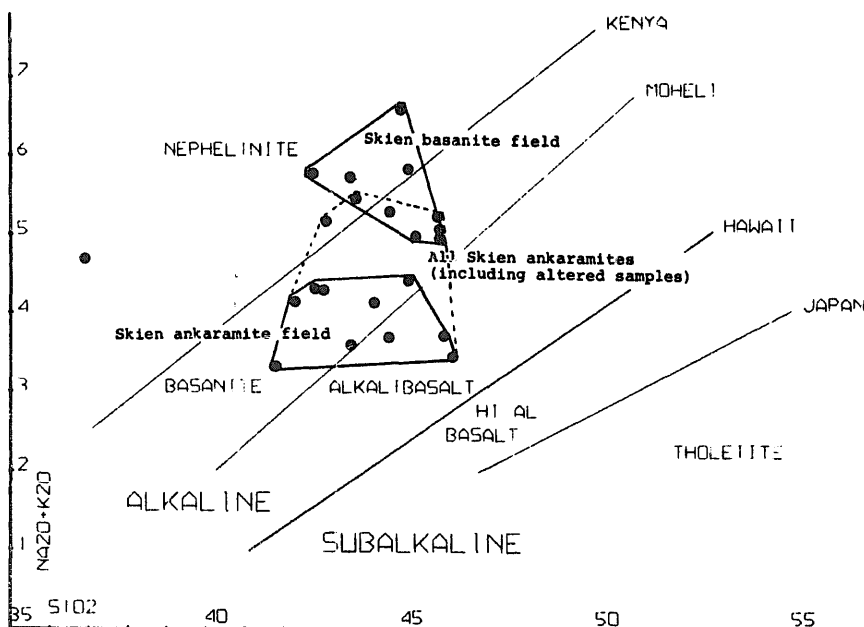

Fig. 6. SiO_2 – $Na_2O + K_2O$ variation diagram with plots from the Skien basaltic rocks.
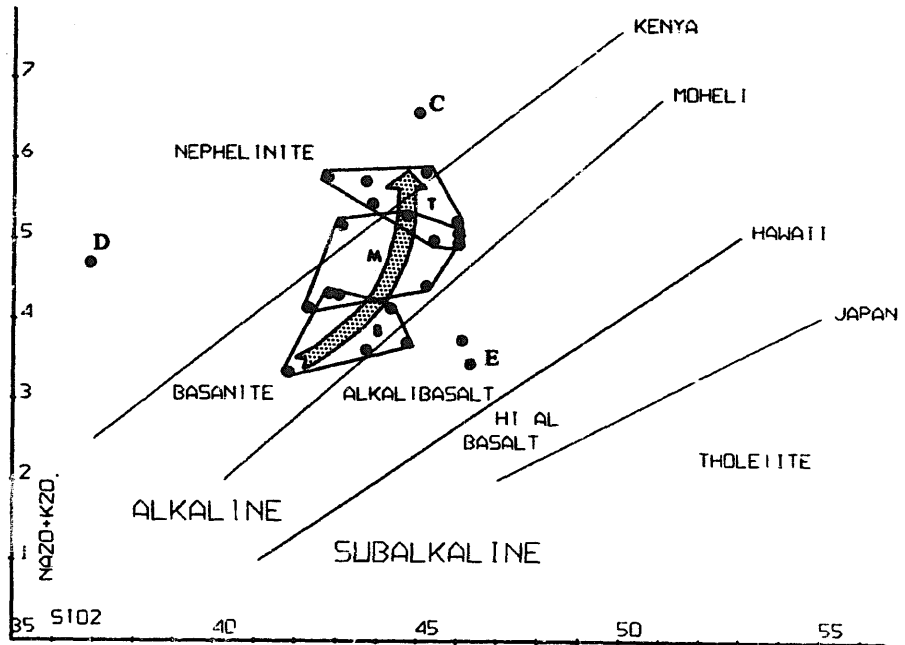
Fig. 7. SiO_2 – $Na_2O + K_2O$ variation diagram with plots from the Skien basaltic rocks. Arrow shows the general trend of evolution from bottom (B) through middle (M) to top (T) sequences of basaltic rocks.

(E), and S55 (within the B field) are exceptions to a continuous chemical evolution from bottom to top, where an arrow shows the general trend of evolution, which is to be expected as a result of olivine and pyroxene fractionation for alkaline rocks at about 9 kbar, 30 km depth (Green & Ringwood 1967:156–157).

The alkali ($Na_2O + K_2O$)–iron ($FeO + Fe_2O_3$)–magnesia (MgO) or 'AFM' diagram has proven to be useful to visualize magmatic differentiation. Differentiation trends for alkali basalt melts start as rich in magnesia, move towards a weak iron enrichment, and end enriched in alkalis. Seen from the AFM diagram (Fig. 8) the differentiation trend of the Skien basalts seems to follow the common route for alkali basalts. The diagram also shows that the direction of the
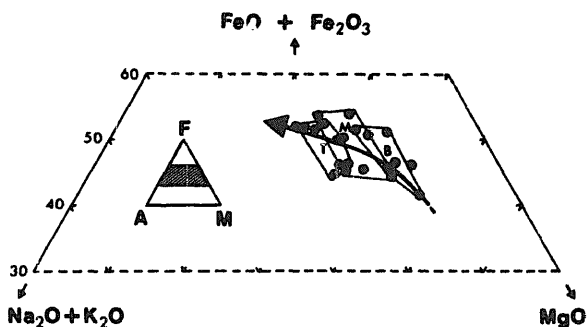
Fig. 8. Differentiation trend of the Skien basaltic rocks in an AFM diagram.

differentiation trend follows the observed stratigraphy from bottom (B) through middle (M) to the top (T) sequence of the basalts.

The Skien basalt samples are also plotted in the phase diagrams (Fig. 9), both as originally analysed, and with all iron calculated as FeO. The points would be expected to lie along the cotectic lines, but do not reach them, due to the fact that the diagram is drawn from 1 atmosphere pressure experimental runs and the analysed samples are believed to contain phenocrysts formed before the complete crystallization took place at 1 atmosphere pressure. Only few high pressure experimental studies are known to have been done as yet in these systems (Onuma & Yamamoto 1976). Therefore we don't know exactly where the cotectic lines will lie at elevated pressures. Since iron is expected to be an important component in a basalt melt, one must take into account that the diagram represents only an iron-free system. There are also uncertainties concerning the norm calculations as discussed earlier. Al can also enter the diopside structure as Tschermak's molecule, and plagioclase in basalts also contains some anorthite molecule. With the An-content of the plagioclase in S63 and S69 (An_{20}–An_{30}) in mind it is interesting to note that a bulk composition near the diopside-albite join crystallizes into a plagioclase with An_{25} and aluminous diopside according to Yagi (1967).
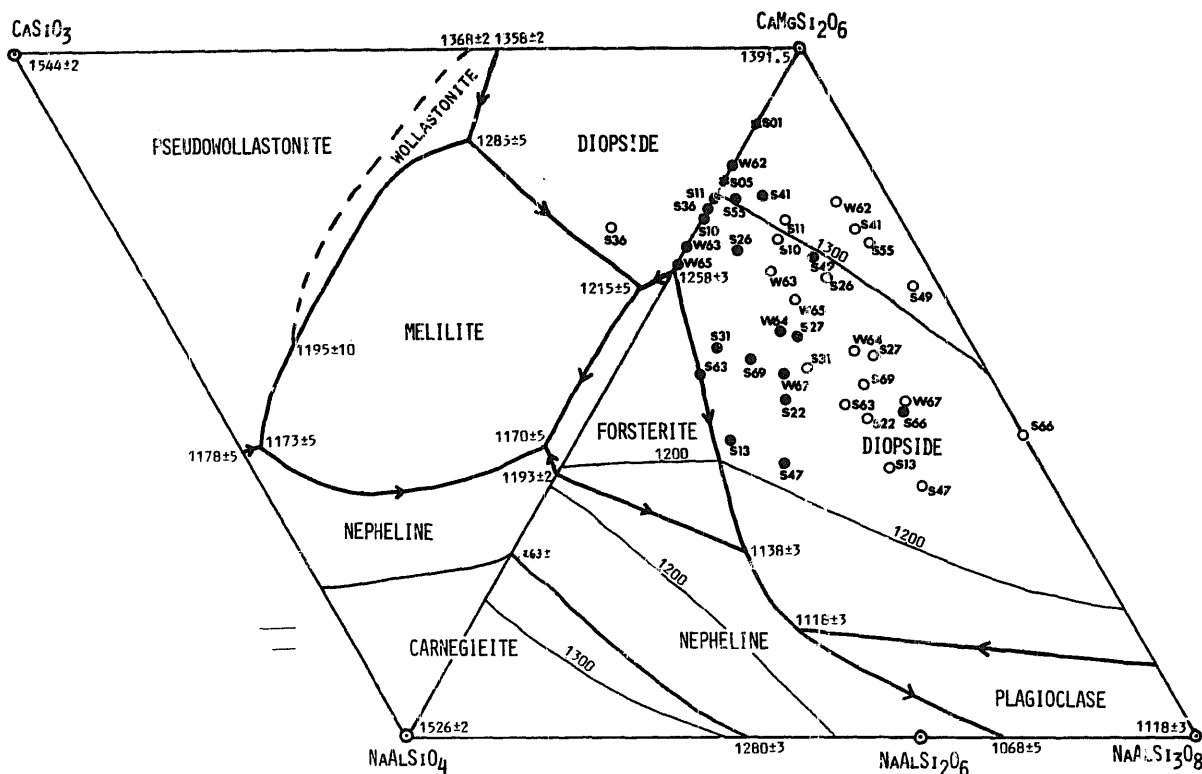
Fig. 9. Two 'coupled' diagrams: DI – NE – AB (right) as a redrawn part of the DI – NE – Q diagram by Schairer & Yoder (1960), and PWO/WO – NE – DI (left) by Schairer (1967), both found experimentally at 1 atmosphere pressure. Figures indicate temperatures in °C. Analyses of the Skien basaltic rocks are plotted as open circles; analyses where all iron is recalculated as FeO are plotted as filled circles. Asterisks are plotted when original and recalculated plots are located at the same point.

As a basis for a possible model for the genesis of the Skien basalts, the degree of differentiation, compiled from information in the MgO variation diagrams and the three different types of diagrams presented above, is qualitatively shown as a function of the crystallization order or 'stratigraphy' in Fig. 10. Both axes are therefore also time-dependent. The minerals present in the rocks, and the rock names, are also shown in the same diagram. Principally the main differentiation trend with stratigraphy is from ankaramites with pyroxene + olivine, towards basanite with plagioclase + pyroxene. There are, however, exceptions to the principal trend, where it seems that differentiation has occurred rather quickly.

From these facts the following model was constructed: A magma has differentiated by fractional crystallization, but smaller portions of magma have separated in subsidiary reservoirs, which also underwent fractional crystallization. The various extrusions of basalts have probably come at irregular intervals from different minor

magma chambers and from the major magma mass, all of which were differentiating, but at different rates; the magma in the smaller magma chambers at a high rate, and the major magma mass at a lower rate. This seems to be consistent with the actual zoning of the pyroxenes.

Numerical testing of crystal fractionation

To test the hypothesis presented above a linear programming least squares computer mixing programme was used. This kind of fractionation calculation has been employed, for example, on the Columbia River basalt by Wright et al. (1973), and following their model the rock with highest MgO content has been taken as the parent rock in each calculation.

A total of 235 model runs have been executed on the computer. Some examples from the runs are shown in Table 7. The ideal mixing model is composed of a limited number of minerals to be fractionated. Another important factor is that the compositions of the minerals used in the calcula-
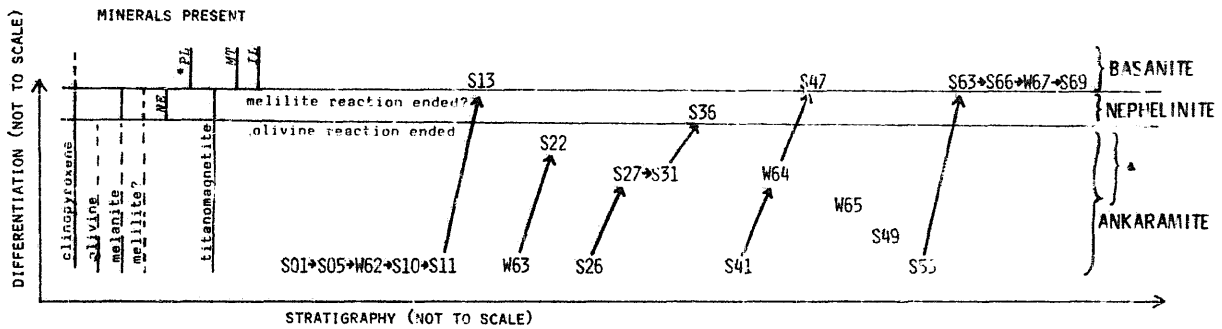
Fig. 10. Qualitative diagram showing increasing differentiation of samples from the Skien basaltic rocks against crystallization order ('stratigraphy' not to scale). Minerals principally present are shown to the left, phenocrysts indicated with asterisks: rock name to the right. *NE* = nepheline, *PL* = plagioclase, *MT* = magnetite, *IL* = ilmenite. ▲ = Altered ankaramite with chlorite and calcite.

Table 7. Mineral values in % of differentiated crystals (crystals removed) to arrive at daughter from parent, tested by means of a computer.

Rocks		Run	Minerals					Diff.
Parent	Daughter	No.	Diopside	Salite	Olivine	Magnetite	Ilmenite	Sum of squares
S05C, Am	S11, Am	41	2.4		0.4			1.189
S10C, Am	S13, Bn	54		34.0	0.3	1.7	0.9	4.404
S11, Am	S13, Bn	141		37.3	5.3	0.7	0.7	0.867
S41, Am	S49, Am	30	20.0		0.4	2.0	0.7	1.375
S41, Am	S55, Am	28	15.1		0.2		1.4	1.987
S41, Am	S66, Bn	134	39.7			3.5	1.4	4.742

Am = ankaramite. Bn = basanite.

tion ought to be chosen within the compositional range of the observed phenocryst minerals. The only observed phenocrysts to be accounted for in the fractional crystallization of the Skien basalts are clinopyroxene (Ti-poor diopside and titaniferous salite), olivine, plagioclase, and kaersutite, while apatite, magnetite + ilmenite (as titanomagnetite) sometimes occur as microphenocrysts up to 0.5 mm size. Magnetite and ilmenite in minor amounts (as titanomagnetite) had to be present during fractionation to control the iron and titanium contents of the rocks.

To decide what was a good fit the sums of squares of all differences of all elements between observed and estimated daughter rocks were examined. Comparing the observed and the estimated analyses, the analyses were taken to be practically equal (representing a good fit) when sum of squares of the differences was less than 2. When the sum of squares of the differences was 2–5, the fit was characterized as less good; while

the fit was not accepted when sum of squares was greater than 5.

Calculations among the different ankaramite lava flows seemed to be simple. The same was the case for calculations from ankaramite to basanite, though the fit was not always as good. Calculations from ankaramite to nephelinite, and among the basanites, however, seemed to be very difficult, and gave no satisfactory results. This is assumed to be a consequence of the many different phases present in the rocks. The number of phases increases with differentiation, and the number of reaction relationships among them also increases.

It must also be noted that the proportions of minerals involved in the calculations fit with observed mineral proportions in the rocks, and this can also be taken as a confirmation of the data obtained from the calculations.

From the computer runs the fractionation from ankaramite to basanite was calculated to

generally involve 30–40% clinopyroxene fractionation. Crystal fractionation from one ankaramite to another would involve less clinopyroxene fractionation, generally 15–20% for lava flows with nearly equal compositions.

The mixing calculations confirm that all Skien basaltic rocks *could* principally be produced through clinopyroxene fractionation from the more primitive members of the series. Olivine, together with titanomagnetite, has played only a minor role in the crystal fractionation. Clinopyroxene fractionation seems to be a dominant feature of the early differentiation history of the Skien basalts, but clinopyroxene is later accompanied by more phases with possible reactions occurring among the phases, making problems for the computer fits.

Comparisons with experimental work

Studies in the system nepheline-diopside by Bowen (1922, 1928) showed that this system is not binary. Forsterite appears on the liquidus surface, and melilite appears as a solid phase at subliquidus temperatures. For instance, a mixture of 30% NE and 70% DI begins to crystallize at 1270°C with separation of forsterite. This continues to separate until a temperature of 1240° is reached, when diopside begins to separate and forsterite to dissolve. The resorption of forsterite continues until the temperature has fallen to 1180°, and at about the same temperature melilite begins to separate. At temperatures below this the mass consists of diopside, melilite, and liquid.

The 'basalt tetrahedron' of Yoder & Tilley (1962) is inadequate to describe melilite-bearing lavas, which must be referred to an enlarged system forsterite-larnite-nepheline-silica, taking into account the Ca-rich composition of most melilites. This system is called the 'expanded basalt tetrahedron' and was introduced by Schairer & Yoder (1964). A crystallization 'flowchart' was deduced from their first studies, but this has been modified by later experiments. Modifications were found when anorthite was added to the system (Schairer et al. 1968) where it seemed that one important crystallization pattern led to a single eutectic at which nepheline-plagioclase-diopside-melilite crystallize simultaneously. The crystallization sequences are such that diopside and nepheline are never seen to crystallize together without either meli-

lite or plagioclase. This end point may be reached by two different paths:

1. The *nepheline basanites* would be represented by a quaternary invariant point with NE, DI, AN, FO. With loss of olivine the liquid moves to *nepheline tephrite* with NE, DI, AN, and further to *melilite olivine nephelinite* represented at a quaternary invariant point with NE, DI, MEL, FO. With further loss of olivine the liquid moves to *olivine nephelinite* with NE, DI, FO. A liquid crystallizing at this point will carry anorthite or melilite. The incompatibility of plagioclase and melilite in igneous rocks is pointed out by several authors (e.g. Yoder & Schairer 1969) and is supported by field observations on volcanic rocks in eastern Uganda (e.g. Nixon & Clark 1967).

2. Schairer & Yoder (1964) and Schairer (1967) describe another possible path of crystallization from an *olivine nephelinite* with NE, DI, OL or an *olivine melilitite* with DI, OL, MEL. Through olivine fractionation these liquids will move towards *olivine melilite nephelinite*.

Olivine reaction with the liquid will give rise to *melilite nephelinite*. When olivine is completely consumed by the liquid, wollastonite will occur in a composition called *wollastonite melilite nephelinite* by Schairer & Yoder (1964). At this point in the fractionation sequence the reaction of melilite with liquid takes place, precipitating a sodic plagioclase.

Schairer (1967:590) and Yoder (1973:165) point out that there is as yet no petrographic evidence for this latter process. Schairer expects that wollastonite may combine with nepheline to form soda-melilite molecules in the melilites, or may be found as perovskite or sphene in Ti-rich rocks. Yoder (1969, 1973) states that melilite and anorthite react to form a clinopyroxene and garnet at low temperatures, and aluminous clinopyroxene and wollastonite at high pressures. The occurrence of melanite and aluminous clinopyroxene with melilite would be expected in the presence of iron and titanium.

There are, however, complications in fitting the simplified experimental models to the rocks. For instance olivine-free nephelinites without melilite cannot be fitted to the experimental models at all according to Bailey (1974). In the natural system TiO_2, K_2O, Fe, CO_2, and H_2O are evidently important. To end up with an experimental model fitted to the Skien basalts is not an

easy task, but it seems that the second crystallization path above describes a possible course of evolution for the magma. From the studies quoted above the olivine reaction clearly plays a very significant role in the early stage of these fractionation processes. Schairer et al. (1968) expect olivine .resorption to be seen in natural nepheline-bearing suites, appearing as olivine mantled by fine aggregates of clinopyroxene. This is in fact observed very clearly in the lowermost Skien lava flows, as described above. The late crystallizing minerals are obviously melanite, nepheline, and ore in the lower 2/3 of the Skien basalt pile; sphene also occurs occasionally and melilite may be present. The upper parts of the Skien basalts are characterized by a sodic plagioclase (An 20–30) without melilite. Clinopyroxene is the dominant mineral throughout the whole sequence of basalts, though it diminishes when plagioclase appears.

Conclusions

The experimental work by Schairer & Yoder (1964) and Schairer (1967) quoted above apparently give melts of compositions similar to that of the Skien basalts when starting with a melt of olivine nephelinite or olivine melilitite magma composition. From these experiments the whole series of Skien basalts are believed to represent differentiation from an initial magma with a composition possibly represented by olivine + nepheline, called *olivine nephelinite*. Clinopyroxene fractionation is thought to have played the most important role in the magmatic evolution of the Skien basalts, and the early olivine-reaction and perhaps the late melilite-reaction have taken place to a lesser degree. The principal petrological evolution of the Skien basalts may be summarized as a flow diagram (Fig. 11).

In conclusion, it seems likely that there has been an olivine nephelinite magma intrusion which at moderate depths has separated smaller portions of magma into minor reservoirs. The various extrusions of basalts have come at irregular intervals from the different minor magma chambers and from the major magma mass, all of which were differentiating at moderate pressures, but at different rates. The nature of the more undersaturated basaltic magmas (nephelinites and melilitites) have been discussed by Green (e.g. 1969, 1970a, 1970b). From his works there is reason to believe that the Skien basalts
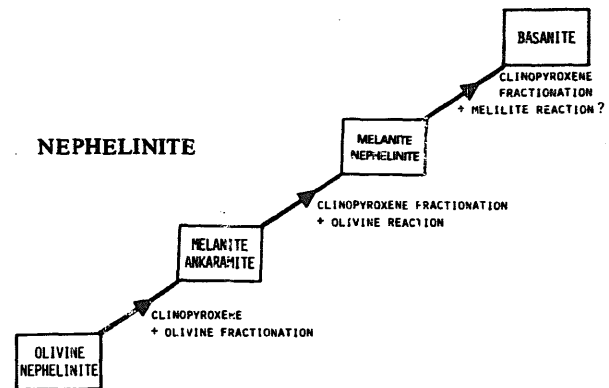

Fig. 11. Flow diagram for the magmatic evolution of the Skien basaltic rocks from a possible olivine nephelinitic parental magma.

have originated at great depths. The petrogenetic grid for mantle-derived basaltic magmas by Green (1970b) puts the origin of the olivine-nephelinites to ~ 30 kbar pressure with 1–5% H_2O in the melt; less than 10% melting of a pyrolite mantle may be involved. This depth (~ 100 km) corresponds to the low velocity zone. The low velocity zone of the upper mantle is interpreted by Green (1970b, 1971) as a region in which, due to the instability of amphibole in pyrolite containing 0 1–0.2% H_2O at depths in excess of 80–100 km, there is a very small (less than 5%) degree of partial melting. This liquid fraction is highly undersaturated olivine nephelinite or olivine melilitite. Ascent and extrusion of basaltic magmas may occur when the low velocity zone is tapped rather directly by major rift of fault systems, like the ones which might have initiated the formation of the continental Oslo rift.

Silica undersaturated lavas are most often accompanied by explosive extrusion of pyroclastic material, and contain ultramafic nodules implying a deep origin. The Skien nephelinite lava shows affinities with Fen damkjernite compositions, and the ankaramites show affinities with melteigite and ijolite compcsitions. The Fen alkaline complex is situated only 20 km away in the western direction. Here Griffin (1973) and Griffin & Taylor (1975) reported lherzolite nodules in the kimberlite-like damkjernite. A camptonite-dike is reported from Venstøp, Gjerpen, by Brøgger (1933b:33), and its composition is quite similar to that of the Skien basalts.

The Skien basalts are accompanied by rather few pyroclastic extrusions, and no ultramafic

nodules have been found. Carmichael et al. (1974:599) also report that ultramafic nodules seem to be lacking, curiously enough, in the basanites of the whole East African province, the most extensive known region of nephelinite volcanism. Other nephelinitic-melilititic magmas come rather directly from the upper mantle to the surface (O'Hara 1965). Such magmas have differentiated mainly by olivine fractionation. It seems a possibility that their temporary residence and differentiation in magma chambers at intermediate pressure have caused the peculiar petrography of the Skien basalts. Clinopyroxene fractionation was thus the dominant process of evolution, followed by an olivine reaction, in contrast to the lower-pressure olivine fractionation more common in basalts. Any ultramafic nodules would sink during the shallow-level differentiation; if they remained the olivine-rich nodules would react with the melt. This may explain the absence of ultramafic nodules in these rocks.

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