PETROLOGY OF THE SODA-MINETTE DIKES FROM HÅÖYA, LANGESUNDSFJORD, S. NORWAY

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The soda-minette dikes from Håöya are dark porphyritic rocks essentially composed of plagioclase (An_{23} to An_{30}), orthoclase-antiperthite, aegirine-diopside, biotite, sphene, apatite, rutile and ore. Chemically, the soda-minettes contain a high percentage of soda in comparison with the minettes described elsewhere. The sequence of formation of feldspars in the phenocryst and groundmass is traced in the light of the optical and X-ray properties of the mineral and the chemistry of the environment. Emphasis is particularly put on the conditions necessary for the formation of ocellar structure in the rock. These dikes were emplaced mainly in the nepheline syenite pegmatites and were locally deformed while still semiconsolidated.

Dark porphyritic dike rocks (1 to 2 m thick) occurring in a part of the Langesundsfjord area have been described by Dons (1969). The dikes are mainly found inside the nepheline syenite pegmatite dikes and also occasionally inside the larvikite, which is the main country rock of the area Brögger (1879) has given an account of the petrology of one of these dark- coloured dikes which he called soda-minette, but he did not mention the rhomb-shaped sporadic felspar phenocrysts occurring in the dike.

Mineralogical and chemical characteristics of the dike described below justify the name soda-minette. Mineralogically, the rock is a lamprophyre of minette type (Johannsen 1938). The prefix 'soda' used by Brögger (1897) seems appropriate because of the exceptionally high soda content of the rock. The presence of the rhomb-shaped phenocrysts in the rock might indicate a relation to the Oslo rhomb-porphyries (dikes and lavas). The present account is based on the study of samples of the dike derived from the collection of the Håöya area made by Head Curator J. A. Dons.

MESOSCOPIC FEATURES

The dike rock is fine- to medium-grained, melanocratic and sprinkled with dark grey feldspar phenocrysts. The groundmass of the dike is a mixture of fine-grained clusters of biotite flakes meshed with sugary aggregates of greenish grey feldspar and other mineral grains. The phenocrysts are found irregularly distributed and show rhombic to subrhombic outlines varying in length from a few mm up to 3 cm. The distance between the phenocrysts can be more than 10 cm when measured on outcrop surfaces.

In places where this dike is found in contact with nepheline syenite pegmatite dikes, some amount of mixing of the two rocks is locally seen. At one such contact, studied here, the soda-minette contains medium-sized grains of dark minerals forming thin layers at the contact which is commonly sharp. From this sharp contact to the inside of the dike, the thin dark layer gives way to a thin zone of mixed light pink coloured material of the pegmatite and the groundmass of the dike. Apart from this mixing of the soda-minette with pegmatite material at the contacts, isolated elongate aggregates and single crystals of feldspar and nepheline (2 to 7 mm across) are also found as xenocrysts inside the soda-minette dike without any hybrid rock in between. In some places, small pieces of the soda-minette are found engulfed by the pegmatite. These inclusions are variously assimilated by the pegmatite to produce a medium to coarse-grained, mesocratic hybrid mass containing big crystals of pyroxene, feldspar and biotite.

A part of the area (Dons 1969) in Langesundsfjord has possibly suffered deformation during the emplacement of the soda-minette dikes involving also the pegmatite and the larvikite. The effects of this deformation are discernible in the dikes as directional alignment of mineral grains indicating movement of semiconsolidated material of the dike during deformation.

MICROSCOPIC FEATURES

The rock looks fresh under the microscope. The *feldspar phenocrysts* are subhedral to euhedral with rounded edges (Fig. 1). They consist of Carlsbad or Baveno twinned crystals. Bigger phenocrysts sometimes have irregularly packed grains in the outer parts. In outline the phenocrysts vary from rhombic to subrhombic, but prismatic laths with tapering ends measuring up to 3 cm in length are also found. The outlines are made up by (001), (110) and (100) faces of the feldspar crystal. The phenocrysts commonly have minute irregularities on the surface and are intergrown with the groundmass in such a way that the phenocryst is surrounded by a thin rim (a few mm) of clusters of dark minerals and small feldspar grains, the latter being perthitic showing a granophyric texture (Figs. 1 & 2).

Among the poikiloblastic inclusions in the phenocrysts, grains of pyroxene and sphene are most common, while biotite, apatite, rutile and ore are found in minor amounts. The pyroxene, rutile and apatite also occur as extremely fine needles distributed irregularly throughout the phenocrysts.

The *groundmass* of the dike is holocrystalline, hypidiomorphic, equigranular and composed of pyroxene, biotite, feldspar, sphene, apatite and ore.

Clusters of dark minerals occurring in the phenocrysts and in the ground-

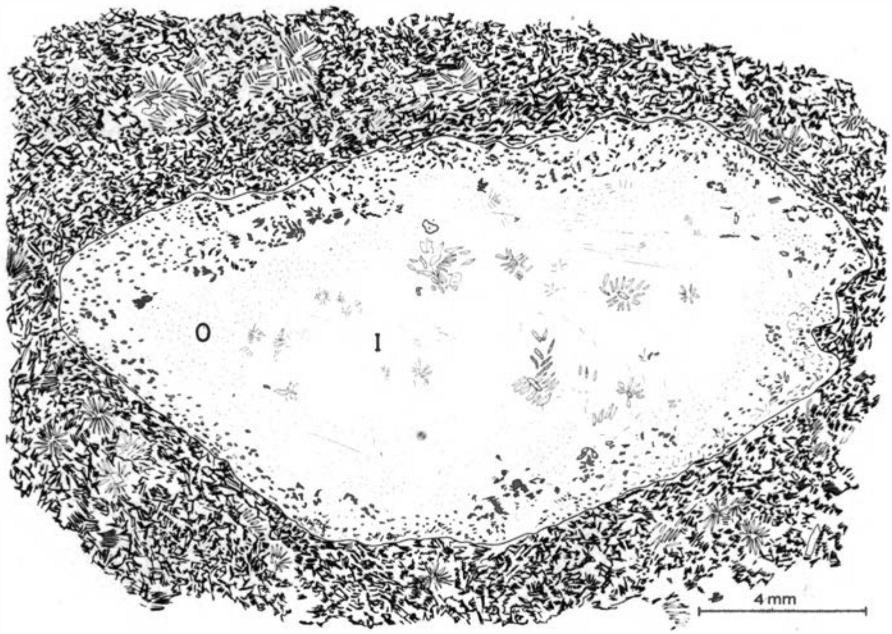

Fig. 1. Phenocryst in soda-minette. The surface is corroded and shows intergrowth with groundmass material. Ocelli are seen scattered both in phenocryst and in the groundmass. I — inner part, O — outer part of the phenocryst (see Table 1). Ordinary light.

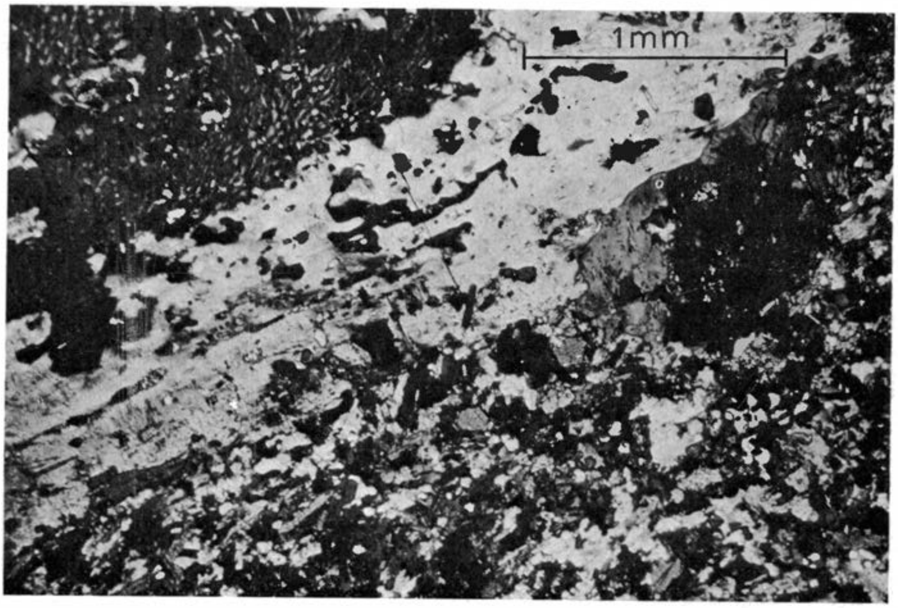

Fig. 2. The outer part of phenocryst with spindle-shaped antiperthitic lamellae (upper left), the groundmass (lower right), and the rim around the phenocryst with intergrown groundmass (centre oblique). Crossed nicols.

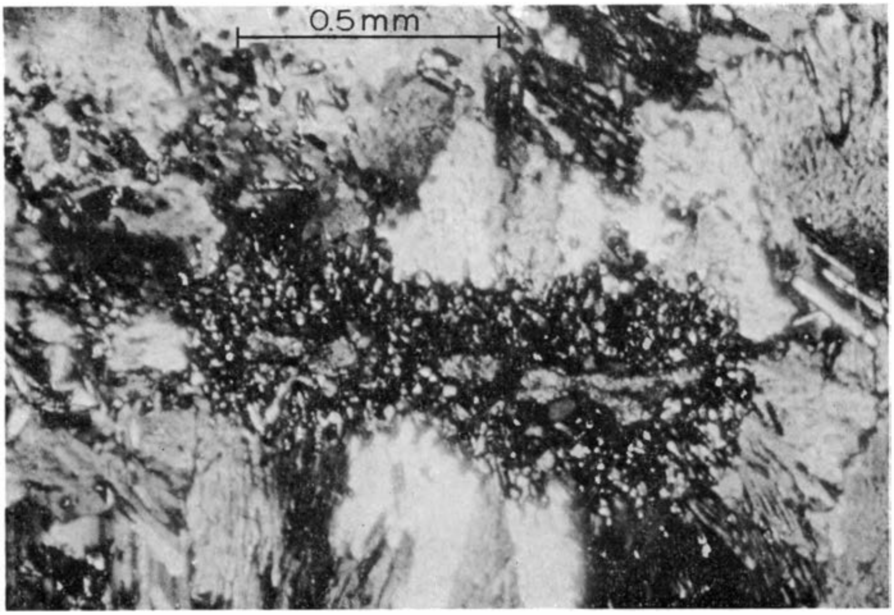

Fig. 3. An ocellus included in the phenocryst. The ocellus (centre of the Fig.) shows an elongated sphene grain surrounded outwards by radially arranged pyroxene needles and the granophyric antiperthitic feldspar grains. Crossed nicols.

mass show *ocellar* structure consisting of radially arranged mineral grains (Fig. 1). The *ocelli in the groundmass* have a core of ore surrounded by sphene or contain only short prismatic grains of sphene in the centre. Outwards follow slender, short, radially arranged laths of pyroxene intimately associated with biotite and interstitial feldspar. The amount of biotite increase at the periphery of the ocelli. Maximum diameter of an ocellus is about one mm.

The *ocelli enclosed in the phenocrysts* always contain an outermost rim

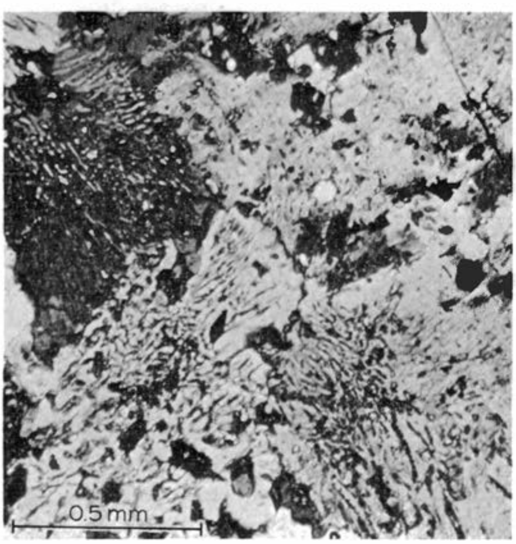

Fig. 4. Granophyric antiperthitic feldspars. Crossed nicols.

Table 1. Characteristics of feldspar in the inner (I) and the outer (II) part of the phenocryst, and in the groundmass (III)

	I	II	III
	PLAGIOCLASE		
An content	23-30	17-25	15-26
Structural state	medium—high	low	medium—high
$2\ V_z$	78°-82°	86°	80°
Twinning	albite, incipient pericline and carlsbad	albite and distinct pericline	albite and carlsbad
Zoning	normal and patchy	patchy	normal
	ANTIPERTHITIC POTASH FELDSPAR		
Shape and orientation	stringlets parallel to (010) & (100)	strings parallel to (010); elongated spindles parallel to (100)	strings parallel to (010)
$2\ V_x$	28°-40°	44°-46°	60°
Δ 131-1$\bar{3}$1	.12, .13	.19, .21	–

made up of short tablets of perthitic feldspars with well-developed granophyric texture (Fig. 3). The perthitic lamellae in these feldspars show subradial disposition to the centre of the ocelli.

The *feldspar of the phenocrysts* varies in composition and in its structural state in different parts of the crystals. Details are listed in Table 1, and shown in Figs. 1, 2, and 4.

The *feldspar of the groundmass* is mostly unaltered plagioclase occurring in anhedral to subhedral short prismatic grains exhibiting a range of composition from An_{15} to An_{26}. The larger anhedral grains contain poikiloblasts of dark minerals. See Table 1.

The *feldspars,* in the part of the groundmass that surrounds a xenocryst of nepheline (incorporated from the nepheline syenite pegmatite), are long subhedral grains (An_{14}-An_{21}, $2\ V_z = 88°$ and medium temperature optics) with broad and patchy antiperthite lamellae having irregular replacing contacts with the host plagioclase. These lamellae have $2\ V_x = 60°$ and show no twinning.

Pyroxene in the dike occurs in groundmass and also as poikiloblasts in the phenocrysts, making anhedral to subhedral short prismatic grains. The bigger grains show well-developed cleavages. Commonly the mineral is distinctly pleochroic, X — bright green, Y — green, Z — pale green, and has extinction $Z \wedge c$ varying from 46° to 60° (rarely up to 70°) with $2\ V_z = 60°$-68°. These optical data approximate to aegirine-diopside of Di_{80}-Aeg_{20} composition (Winchell 1933). This was also checked by X-ray powder pattern compared with the data of Nolan & Edgar (1963) indicating composition around Di_{80} -Aeg_{20}.

In the groundmass, pyroxene is intimately interwoven with biotite and sphene; it rarely contains inclusions of feldspar. Grains that occur as individual poikiloblasts in the phenocryst, and also those forming ocelli, are slender long

Table 2. Mode of soda-mines (volume percent)

	1	2	3	4
Plagioclase	61.27	39.50 (Plagioclase + Antiperthitic potash feldspar)	51.77*	53.41*
Antiperthitic potash feldspar	18.63			
Biotite	1.98	35.38	26.73	28.80
Pyroxene	13.62	15.22	16.47	12.63
Sphene	3.46	5.65	2.62	0.87
Apatite	1.04 (Apatite + Ore)	2.30	2.78	2.59
Ore		1.95	–	–
Calcite	–	–	–	1.34
Total	100.00	100.00	100.37	99.64

No. 1. Phenocryst, dike from Håöya.
No. 2. Groundmass, dike from Håöya.
No. 3. Groundmass, dike from Håöya, calculated mode after Brögger (1897).
No. 4. Whole rock, dike from Bratthagen, Lågendalen (Lougenthal), calculated mode after Brögger (1897).
* Soda-microcline and soda-orthoclase of Brögger.

laths of prismatic habit. Extremely thin needles of the mineral are plentiful as inclusions scattered in all directions in the phenocryst. The bigger well-developed grains are zoned and show darker shades of green and higher extinction ($Z \wedge c$) from centre outwards, indicating aegirine rich compositions at the margin.

Biotite is the major dark mineral in the groundmass of the dike rock and occurs as short subhedral laths intimately ingrown with the pyroxene. It commonly contains minute inclusions of plagioclase and pyroxene, and sometimes of sphene. The colour of biotite varies from brownish to greenish brown in different specimens. Commonly the pleochroism is X — pale brown, Y — greenish brown, Z — brown, $2V_x = 4° — 6°$, and $n\beta = 1{,}650 \pm .001$.

Sphene makes up the major accessory constituent of the dike rock and occurs as subhedral to anhedral grains of varying size. Bigger grains are poikiloblastic, containing rounded grains of biotite, pyroxene, plagioclase and often ore. Euhedral rhombic grains are occasionally found. Commonly, the grains occur in aggregates and show tentaculating margins. The colour of sphene varies as X — brownish pink, Y — yellowish pink, Z — pale, and extinction $X \wedge c$ is 42°. Most grains show high dispersion. Alteration of sphene into leucoxene and calcite is frequently observed when the mineral occurs in intimate association with ore. Sphene along with ore often occupies the centre of ocelli.

Apatite is found as euhedral to subhedral prismatic laths often bent and enclosed by sphene or feldspar. The grains have corroded margins. Often, very long needles of apatite occur in the marginal rim of the feldspar phenocrysts.

Rutile is mainly found as minute elongated grains included in feldspar, and shows extreme birefringence.

Ore mineral in the dike is chiefly ilmenite, which occurs as anhedral grains associated intimately with sphene, leucoxene and calcite. These are generally

Table 3. Chemical analysis and norm of soda-mieutte and other dike rocks

Weight percent	1	2	3	4	5	6
SiO_2	50.35	51.95	51.22	53.93	53.34	51.05
TiO_2	2.31	1.95	1.70	1.86	2.03	2.59
Al_2O_3	15.53	14.95	17.56	17.39	16.51	17.39
Fe_2O_3	1.87	4.09	3.51	4.68	5.67	4.77
FeO	7.36	5.70	4.34	4.79	6.14	6.99
MnO	0.21	0.30	0.20	0.30	0.13	0.11
MgO	3.35	3.54	3.22	1.36	2.25	4.36
CaO	5.53	6.10	4.52	4.36	3.76	5.35
Na_2O	6.66	5.43	5.72	5.71	3.99	3.07
K_2O	3.15	4.45	4.37	4.27	5.12	3.20
P_2O_5	1.58	1.15	1.08	0.90	1.03	1.09
H_2O^+	1.15	1.10	1.93	1.12	–	–
H_2O^-	0.05	–	–	–	–	–
CO_2	0.26	–	0.60	–	0.70	1.20
Cl	–	–	–	0.15	–	–
F	0.85	–	–	–	–	–
Total	100.21	100.71	99.97	100.82	100.67	101.17
Q	–	–	–	–	8.29	16.74
C	–	–	1.51	–	4.71	8.71
Or	3.75	17.40	14.75	18.30	20.57	2.51
Ab	47.27	35.89	46.08	49.05	36.37	28.02
An	3.62	4.37	5.65	9.27	0.43	2.86
Ne	7.27	6.28	3.49	1.45	–	–
Bi	23.92	14.17	18.17	11.20	16.22	26.73
Aeg-Di*	3.72	11.14	–	–	–	–
Di	–	–	–	0.04	–	–
Sph	4.86	4.08	3.60	3.90	4.31	5.50
Mt	1.96	4.27	3.70	4.90	6.02	5.07
Ap	3.32	2.40	2.29	1.89	2.19	2.32
Cc	0.33	–	0.77	–	0.90	1.54

No. 1. Groundmass of soda-minette, Håöya (anal. B. Bruun) by courtesy of J. A. Dons.
No. 2. Groundmass of soda-minette, Håöya (Brögger 1897).
No. 3. Soda-minette of Bratthagen, Lågendalen (Lougenthal) (Brögger 1897).
No. 4. Rhomb-porphyry dike, Tyveholmen, Oslo (Brögger 1933).
Nos. 5 & 6. Groundmass of rhomb-porphyry dike from Tyveholmen and Haugen respectively (recalculated to oxide weight percent from cation percent after Oftedahl 1946).
*Aeg-$NaFeSi_2O_6$; Aeg-Di is made in the proportion 20/80.

confined to the groundmass and occasionally occupy the centre of an ocellus.

Modal composition of the phenocryst and groundmass of the soda-minette dike from Håöya, along with other soda-minettes, is given in Table 2.

PETROCHEMISTRY

A chemical analysis, showing the norm of the groundmass of the soda-minette dike, is given in Table 3 along with the one reported by Brögger (1897) from Håöya. These two analyses are compared with that of another soda-minette

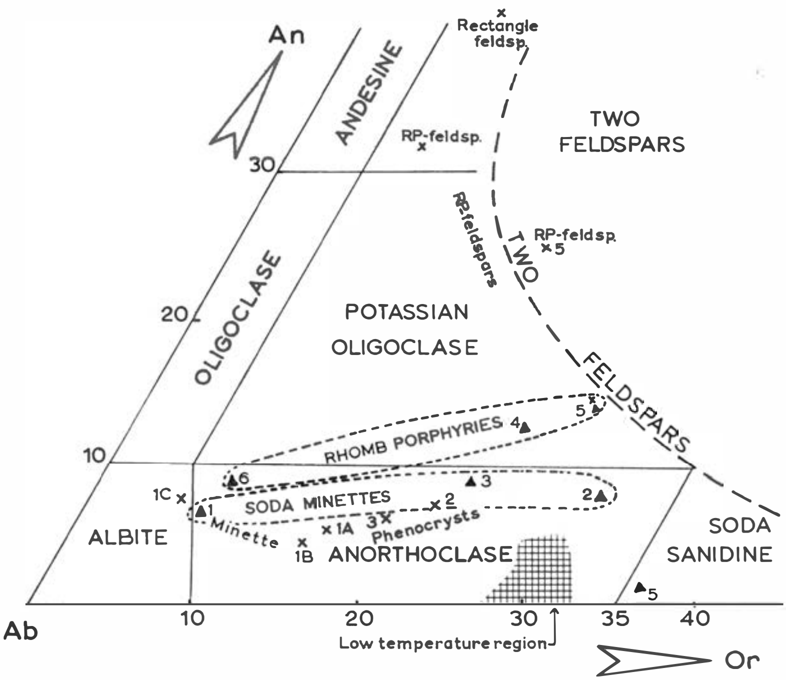

Fig. 5. Normative feldspar proportion of soda-minette and rhomb-porphyry plotted in the An-Ab-Or system. Solid triangles represent whole rock and groundmass analysis, and crosses represent feldspar analysis. Sample numbers correspond to those in Tables 3 and 4. It is seen that the rhomb-porphyries fall in the field of potassian oligoclase, whereas the soda-minettes lie in the anorthoclase field. The soda-minette phenocrysts lie in the high temperature region of the anorthoclase field and in most cases seem to be more sodic and less calcic than the bulk rock.

from Bratthagen, Lågendalen (Lougenthal) and of a fresh rhombporphyry dike from Tyveholmen, Oslo. Analyses of two more rhombporphyry dikes (after Oftedahl 1946) are given for comparison.

The two analyses of the soda-minette from Håöya contain higher amounts of CaO and FeO and lower Al_2O_3 than the one from Bratthagen. These rocks are higher in soda content than the normale minettes (Johannsen 1938) and contain much smaller amounts of MgO. The soda-minette of Håöya, as mentioned earlier, is characterized by rhomb-shaped feldspar phenocrysts. Dons (personal communication 1967) tentatively regarded them as dark varieties of rhomb-porphyry dikes during his field work. Brögger (1897) did not classify this dike under the rhomb-porphyries probably because he did not notice the presence of phenocrysts in the rock. The rhomb-porphyries are generally mesocratic (containing mainly biotite and chlorite). They are usually saturated in silica (norm in Table 3), whereas the present soda-minette is not.

Due to the presence of minerals like biotite and sphene in appreciable amounts in the soda-minette (Table 2), a modified norm has been derived

Table 4. Partial chemical analysis of feldspar and normative An-Ab-Or molecules (recalculated to 100)

	1A	1B	1C	2	3	5
SiO_2	61.65	62.53	62.85	65.89	66.29	55.12
TiO_2	0.39	0.26	0.24	–	–	0.43
Al_2O_3	20.37	20.62	21.00	20.53	20.39	20.70
ΣFe_2O_3	1.34	0.58	0.72	–	–	9.96
MgO	–	–	–	–	–	1.23
CaO	1.52	1.20	1.78	1.47	1.26	4.13
Na_2O	10.20	10.27	10.65	8.38	8.80	4.96
K_2O	3.00	2.73	1.05	3.73	3.26	4.47
Σ	98.47	98.19	98.29	100.00	100.00	100.00
K_2O/CaO	1.97	2.27	0.59	2.54	2.58	1.08
K_2O/Na_2O+CaO	0.25	0.24	0.08	0.37	0.32	0.49
An	5.35	4.47	7.30	6.97	5.99	24.30
Ab	79.27	81.29	87.06	71.93	75.56	56.70
Or	15.38	14.24	5.64	21.10	18.45	19.00

Nos. 1A, 1B and 1C are feldspars separated from phenocrysts (see text) in dikes from Håöya (present work).

Nos. 2 & 3 are calculated feldspar compositions of soda-minette dikes from Håöya and Bratthagen respectively (Brögger 1897).

No. 5 is the phenocryst with inclusions of other minerals from the rhomb-porphyry dike from Tyveholmen, Oslo (Oftedahl 1946), recalculated from cation percent.

from the analyses in Table 3. The basis for the calculation is the catanorm (Barth 1962), but the biotite and sphene are made instead of hypersthene and ilmenite. Another modification is attempted by adding an aegirine molecule to the normative diopside in the proportion Aeg_{20}/Di_{80}, as obtained by the petrographic observations. Calculation of biotite and sphene in the case of rhomb-porphyries is also commensurate with the mineralogy of the rocks. Normative feldspar compositions of the soda-minette and other dike rocks, when plotted in An-Ab-Or triangle (Fig. 5), fall in the field of ternary feldspar. This is discussed in more detail later in this account.

In Table 4 three partial analyses of phenocryst feldspar from soda-minette of Håöya are given and compared with those of feldspars from other soda-minettes and rhombporphyry dikes (Fig. 5). The feldspars were separated by crushing the hand-picked phenocrysts to 120 mesh size and putting the washed material in acetylene tetrabromide for the separation of heavy minerals. At this stage no attempt was made to separate antiperthitic potash feldspar from plagioclase. The material was finally run through an isodynamic magnetic separator at a high intensity.

Analyses of feldspars given by Brögger 1897 (Nos. 2 and 3 in Table 4) seem to include mainly the groundmass feldspar, since he does not mention the presence of phenocrysts in either case.

The feldspar phenocrysts of the soda-minette are soda-rich anorthoclases — one has an albitic composition — in contrast to the more calcic phenocrysts of the rhomb-porphyries (potassian oligoclase or potassian andesine).

The phenocryst feldspars of the rhomb-porphyry dikes and soda-minette are similar in that they contain a central plagioclase with antiperthitic lamellae increasing in amount outward, and in the presence of granophyric intergrowth of the two feldspar phases. But the phenocrysts in the soda-minette possess three very distinct features that are not noted in those of the rhomb-porphyry: (1) the central plagioclase is distinctly more sodic and fresh, (2) it contains clear antiperthitic lamellae along (100) and (010) and the albite twin lamellae are thin, clearly demarcated, and regular in shape, (3) the outer parts of the phenocryst are conspicuously fresh. The presence of two phases (a monoclinic K-feldspar phase and a triclinic plagioclase phase) is confirmed by X-ray powder patterns.

PETROGENESIS

Textural, mineralogical and chemical characters of the soda-minette suggest its crystallization from a hydrous alkaline basic magma under moderate depth conditions. The inequigranularity in texture, the comparative rarity of biotite as inclusions in the phenocrysts, and the presence of minute amounts of potash feldspar in the groundmass, indicate sudden changes in the physical conditions of crystallization during the consolidation of the rock. A melt of composition that may give rise to the soda-minette could possibly be derived from fractional crystallization of an alkali basalt magma.

Feldspar phenocrysts evidently crystallized in the early plutonic stages at relatively high temperature. The fractional crystallization of plagioclase produced normally zoned crystals. In the ocelli the formation of ilmenite in the centre is followed by sphene, aegirine-diopside and biotite. The individual pyroxene crystal inclusions in the phenocrysts likewise indicate zoning with outward enrichment of aegirine. The composition of the last-precipitated feldspars corresponds to soda-rich anorthoclases. On slow cooling, exsolution took place producing the granophyric implications of orthoclasic and albitic feldspars. The exsolved potash feldspar phase seems to have acquired a replacive attitude towards the host plagioclase resulting in the development of swells, at the ends of antiperthitic lamellae, into wart-like intergrowths.

Sudden change in the physical and chemical conditions of crystallization took place at this stage causing the residual liquid to separate from the crystal mesh and penetrate as dikes into higher levels. This liquid carried a small proportion of big crystals and numerous minute crystallizing centres where the formation of plagioclase (compare columns I and III of Table 2) and dark minerals had already progressed to some extent under conditions parallel to that of larger crystals. The consolidation of this partly crystalline mass eventually came to completion under the new environment. The corroded boundaries of the phenocrysts in the form of rims containing inclusions of groundmass material may be attributed to reaction between the intratelluric feldspar crystals and the alkaline liquid during the emplacement of the dike. Chemically the liquid was now deficient in Al, just saturated with silica, and rich in alkalis, partly Mg and water vapours. Under such chemical environment the soda was chiefly consumed in the formation of pyroxene, and the potash along with magnesium (and ferrous iron) gave rise to biotite instead of potash feldspar. Sphene and ore were constituted in amounts depending on the availability of the suitable elements.

The characteristic mineralogical structure of the ocelli in the rock also depicts the chemical changes that took place in the melt during the course of consolidation. It is noted that the formation of ocelli in the later stages had been influenced by the diverse chemical environments indicated by the difference in composition of the outer rims of the ocelli, namely, (1) those included in the phenocryst feldspar contain a zone of granophyric antiperthite surrounding the pyroxene grains whereas (2) those occurring in the groundmass have pyroxene surrounded by biotite grains. These features and associations clearly manifest the diverse physicochemical conditions controlling the consolidation of the soda-minette as discussed above.

The soda-minette dikes of Håöya are notably different from other members of the lamprophyre group. They are devoid of fugitives (except water vapours) and the late stage alteration of early formed minerals. Chemically the soda-minettes correspond to the groundmass of the rhomb-porphyries occurring so abundantly in the Oslo region.

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