Excursion 6

Southern Part of the Oslo Rift

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First day — the Vestfold volcanic area
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The Vestfold volcanic area lies on the western side of the Oslofjord and west of the towns Holmestrand and Horten. It consists of a lava plateau cut by two cauldrons, the *Hillestad cauldron* to the north and the *Ramnes cauldron* to the south (Oftedahl 1967). Especially between the two cauldrons the lava plateau shows a well developed and very comprehensive lava stratigraphy (Fig. 1). In this area it is possible to follow the succession of lava flows underlain by Carboniferous/Permian sedimentary strata (the Asker group) to the uppermost volcanics, supposedly younger than any others in the Oslo region. The Hillestad cauldron will not be visited. This consists essentially of a subsided caldera block of ignimbrite flows, cut by later intrusions of nordmarkite and ekerite. South of the Ramnes cauldron and west of a line through the western margins of the two, intrusions of monzonitic and syenitic plutons disturb the lava stratigraphy and produce contact metamorphic volcanics whose stratigraphy is difficult or impossible to unravel.

THE VESTFOLD LAVA PLATEAU

The Vestfold lava sequence is divided into a lower and an upper part, with the level of the basalt B_3 separating the two. The lower part corresponds to the total development of the lava flows in the Krokskogen area, west of Oslo, which contains the basalts B_1, B_2, and B_3, and the rhomb porphyries $RP_1 - RP_{12}$. In Vestfold the lava-stratigraphy starts with B_1, here consisting of some 20 basalt flows, making up a unit of 120 – 150 m thickness. The Krokskogen types RP_1, RP_2 and RP_4 follow B_1 in the Vestfold area, whereas most of the overlying flows seem to be local flows for this area (Oftedahl 1952a). Only RP_5 and RP_6 have been found.

The upper half of the Vestfold lava sequence which has a stratigraphy that runs from B_3 and RP_{13} to RP_{26}, is very interesting for the reason that it contains not only basalt flows B_4 and B_5 but also four trachyte members, T_1 to T_4. The uppermost grade into a rhyolite, in part ignimbritic. The complete stratigraphy is shown in Table 1. The trachyte unit T_1 which wedges out to the south is thickest in the north, close to the Hillestad cauldron. It seems reasonable to assume that it flowed out of the Hillestad volcano before or during the caldera

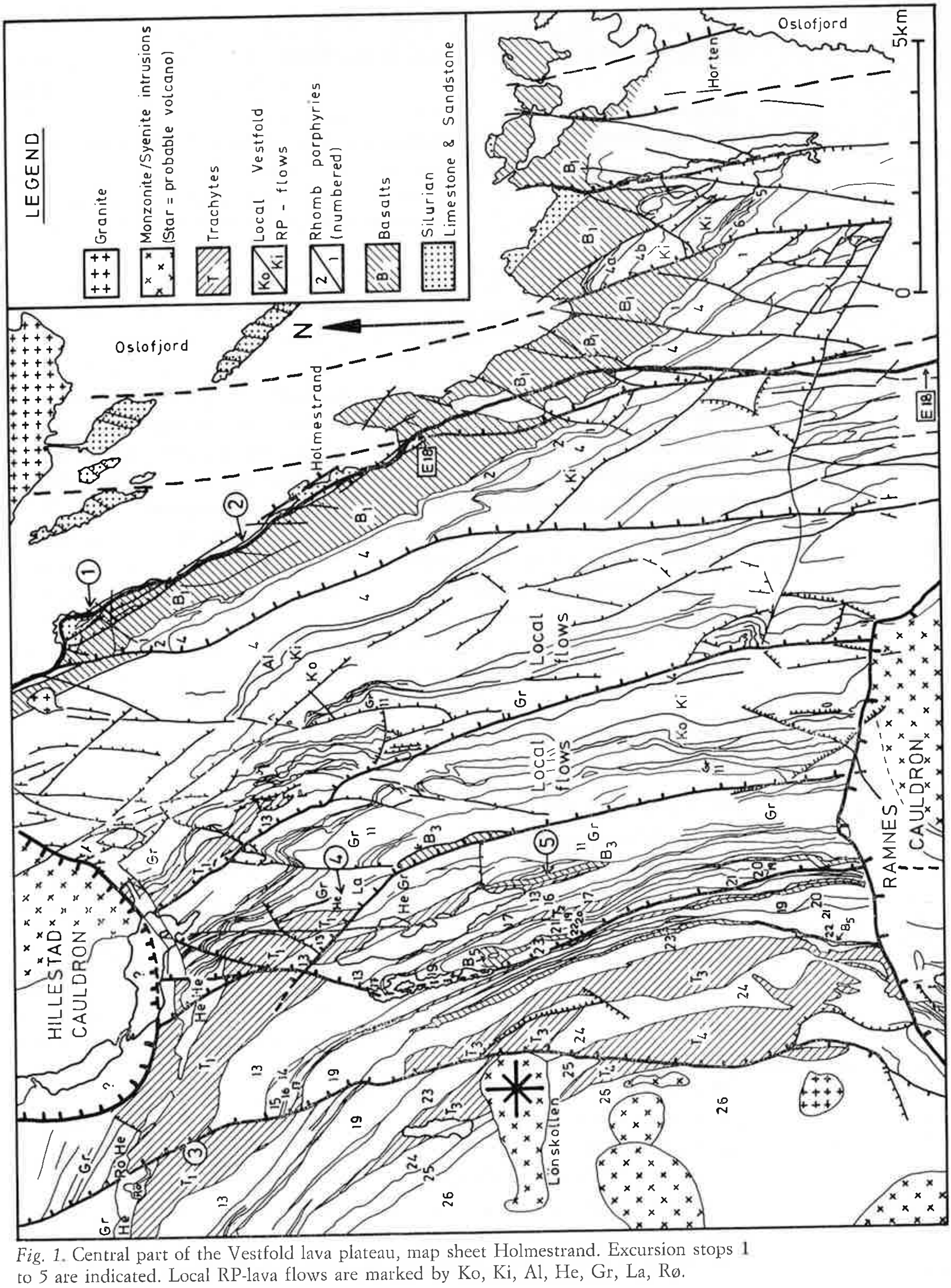

Fig. 1. Central part of the Vestfold lava plateau, map sheet Holmestrand. Excursion stops 1 to 5 are indicated. Local RP-lava flows are marked by Ko, Ki, Al, He, Gr, La, Rø.

Table 1. Volcanic stratigraphy of the Ramnes cauldron and the Vestfold lava plateau

Ramnes cauldron	R_9, R_{10}, R_{11}
	Tuff, cald.-lake sed.
	A_7 megabreccia
	R_7, R_8. Major ignimbrites, 100 and 300 m
	R_5. 450 m ign. with breccias and R_6
	R_1–R_4. Thin ign. R_3 rheo-ign. or obsidian?
	RP_{27}+B
	Sønset trachyte with ign. on top, first ignimbrite eruption
	Hosken basalt
	RP_{26} flows; trachytes and basalt intercalated
Vestfold lava plateau	Ig_1. Up to 250 m ignimbrite
	RP_{26}. Many RP flows, near Kolsås type
	T_4. Trachyte flows, from Ramnes volcano(?)
	$RP_{24/25}$. Kolsås types
	T_3. Trachyte flows, most likely from Ramnes
	RP_{23}. Typical RP_1 type, 50 m
	B_5. Aphyric basalt, 20 m
	RP_{18b}–RP_{22}. RP_2 types, only RP_{19} ca. Kolsås
	T_2/B_4. Trachyte in the N, basalt in the S
	RP_{14}–RP_{17}. 14 and 17 are beautiful Kolsås types
	RP_{13}. Rectangle porphyry
	T_1. Complex unit of latite and trachyte lavas
	Many local RP lava flows, e.g. Hegg type
	RP_1, RP_2, RP_4. Krokskogen type flows
	B_1. Up to 150 m basaltic lava flows

B = basalt, RP = rhomb porphyry lava, T = trachyte lava, A = 'agglomerate', breccia, R = rheoignimbrite, ignimbrite, Ig = ignimbrite.

formation. The uppermost part is a latite porphyry that looks exactly like the trachyte porphyries, possibly derived from the lower part of the magma chamber at the end of the T_1 effusive activity. The source of T_2 is also most likely in the north (Hillestad?) since it wedges out to the south. T_3 may have come from the Ramnes volcano, but is thickest around the Lønskollen monzonite–syenite intrusion which may be considered as the root of a volcano, marked by a star in Fig. 1. This volcano could therefore be the T_3 source. Later it developed into an intrusion. The T_4 unit most likely flowed from the Ramnes volcano. Finally, all geologists who have studied the rhomb porphyry lavas agree that they represent fissure eruptions, as postulated by W. C. Brøgger in the last century. A limited number of rhomb porphyry dikes found in the area could easily be feeders.

THE RAMNES CAULDRON (Fig. 2)

The history of the Ramnes volcano started at the time of the T_3 activity. Within the T_3 unit and against the Ramnes ring fault to the south occurs a formation of lapilli tuff and volcanic breccia. Both are most coarse-grained to the south against the ring fault and fining northwards. They also wedge out to the north and are thickest to the south against the cauldron. A beautiful load impression

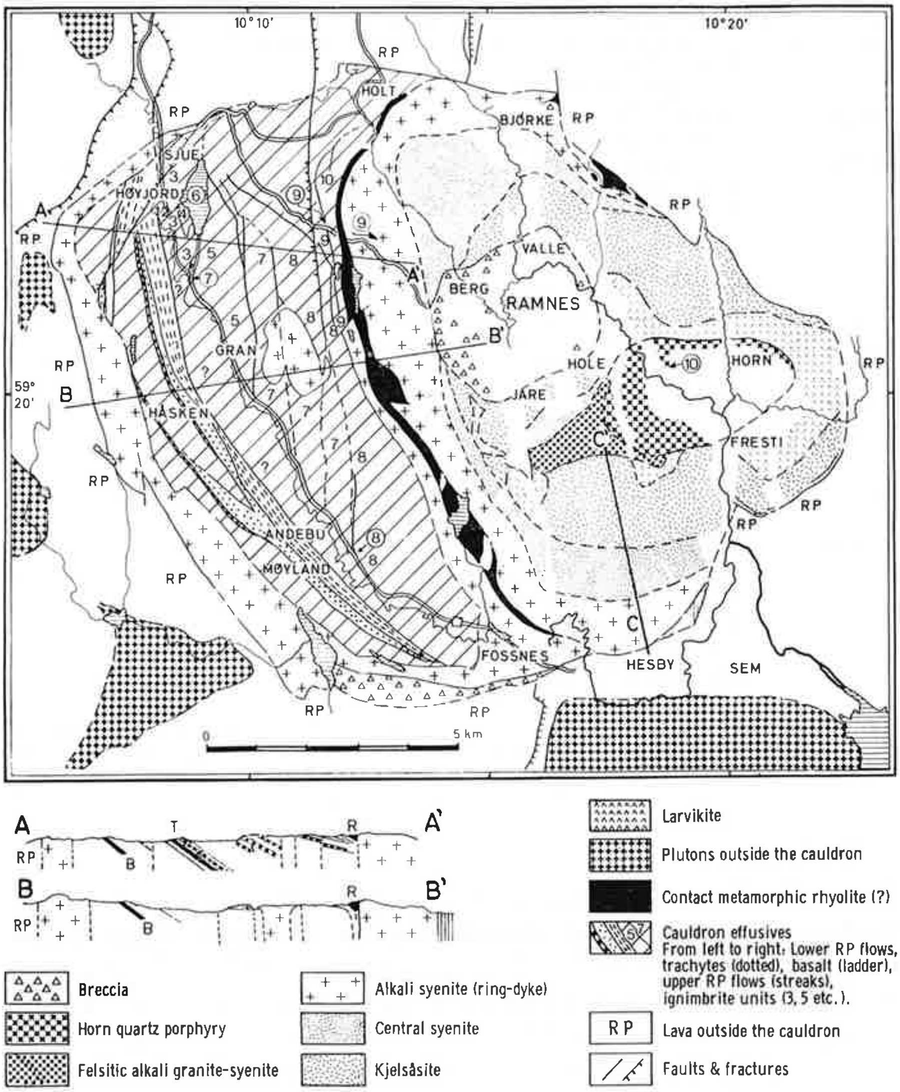

Fig. 2. The Ramnes cauldron according to map by Sørensen (1975), based on mapping by R. Sørensen, Chr. Oftedahl and E. Schou Jensen. Excursion stops 6–10 are indicated.

was produced by a head-size boulder testifying that the formation was formed by air-fall ash with the addition of bombs. Thus, this explosive activity must be considered as representing the birth of the Ramnes volcano, which also could have produced the T_3 trachytes. The first subsidence may have started with the T_3 eruption or, more certainly, with the bigger eruptions producing the trachyte/rhyolite and the ignimbrite of T_4.

The Ramnes cauldron now consists of three different rock groups: A western crescent-shaped area of volcanic rocks, a central intrusive complex (syenite to monzonite, breccia and aplitic granite), and a syenitic ring dike.

In most of the well-preserved cauldrons of the Oslo region it has been possible to establish the connection between the stratigraphy of the subsided caldera block and the volcanics outside it. This proves difficult for the Ramnes cauldron, even if its volcanics are relatively easy to map because of a constant inward dip within the crescent-shaped area. The lower half of the exposed sequence (see Table 1) contains many rhomb porphyry flows, most of which could well be RP_{26} flows. In addition a number of trachyte flows and some basaltic flows have been discovered. Therefore the most likely connection is that the uppermost RP_{26} flows may correspond to the lowermost rhomb porphyry flows within the subsided caldera block. Towards the end of the rhomb porphyry effusions ignimbrites start to appear. A typical trachyte lava flow also appears after the first typical ignimbrites (see Table 1).

The ignimbrite volcanics contain 11 units according to mapping by E. Schou Jensen and R. Sørensen. The total thickness must be over 1000 m and may easily be as much as 1400 m. This is the only area of thick typical ignimbrites preserved in the Oslo region. Most likely the thickness of 1400 m represents caldera infill deposit, but a much thinner ignimbrite sheet may have covered the uppermost rhomb porphyry lavas of the Vestfold lava plateau, in the way described by Elston et al. (1976) for New Mexico.

The central intrusion of the Ramnes cauldron has been described by Sørensen (1975). It forms a stock with vertical contacts against the inward-dipping volcanics. In hand-specimen the rock grades from a volcanic-looking trachyte porphyry through fine-grained to coarse-grained syenite, with later intrusion of monzonite (kjelsåsite). This massif again is penetrated by younger larvikite, by a volcanic breccia in the center of the cauldron (the original effusive center?) and by an aplitic granite.

The most probable development of the Ramnes volcano is as follows:

1. The explosive activity started at T_3 time. A weak caldera subsidence may have started.
2. Trachyte T_4 flowed from the Ramnes volcano and the uppermost part of it formed from ignimbrite explosions. More subsidence occurred along the ring-fault.
3. The RP_{26} lava flows may have spilled into a caldera depression which also could have sucked up other flows, trachyte and basalt. The Sønset trachyte flows and ignimbrite issued from the Ramnes volcano, succeeded by the last rhomb porphyries.
4. Filling of the caldera basin, which gradually subsided, by the ignimbrite units $R_1 - R_{11}$.
5. Resurgence? The uppermost rhyolitic portion of the magma chamber underlying the Ramnes volcano had been completely emptied, and the underlying porphyritic trachyte magma formed a big viscous dome with a vertical fault-bounded contact. It consolidated to a syenite in the interior, followed by more and deeper magma, now monzonitic of composition. The ring dike invaded the western half of the ring-fault.
6. The central intrusion or dome was penetrated by the last volcanic explosions

producing the central volcanic breccia and by the last viscous rhyolite magma, extruded as a Mt. Pelée-type cigar-shaped body. The deeper part crystallized to an aplitic granite.

This history deviates in a number of points from that recently proposed by Sørensen (1975, p. 84–85), but it does not conflict to any great extent with the preliminary gravity interpretation of the cauldron (Ramberg 1976).

Road log (Excursion 6, first day)

1. *Upper Silurian (Ringerike) sandstone*, at Smørstein, in highway E 76.
North of Holmestrand the sandstone which underlies the Permian sediments and volcanics can be studied in a road-cut and a quarry. Due to the rise of the Caledonian mountains in the north-west, the shallow-water limestone deposition changed to sand deposition in large deltas with meandering rivers, largely from the west. Beautiful current ripples and cross-bedding may be seen here.

2. *Basalt flows of B_1, north of Holmestrand.*
Some 8 successive lava flows may be seen in the 0.5 km-long basalt escarpment just north of the railroad station. Solid rock and boulders from above demonstrate the B_1 flow types: from ankaramitic flows rich in phenocrysts of black 1 cm Ti–augite and 0.5 cm red olivine pseudomorphs ± white plagioclase tablets, to augite–plagioclase phenobasalt, plagioclase basalt, and to aphyric andesitic basalt, all mildly alkaline. Selected analyses, norms and modes are presented in Table 2. One flow only exhibits columnar jointing. Two basalt conglomerate horizons suggest that we are at the foot of a B_1 shield volcano.

3. *Trachyte T_1*, at Dokka intersection, W of Holmestrand.
The T_1 unit consists of several trachyte lava flows, amounting to over 100 m in thickness and each of 10–20 m. A large road-cut shows a typical flow 2/3 up, porphyritic with microperthite phenocrysts, and with a planar flow-banding. For composition, etc., see Table 2.

4. *Rhomb porphyry of Hegg type* at Gutu, just west of road R. 312.
This RP-flow which belongs to the uppermost of the local flows below the B_3 basalt, contains one of the most well crystallized rhomb porphyries in the Oslo region. The rhomb feldspar is coarse antiperthite, and the groundmass contains augite, biotite, chlorite and a little quartz.

5. *B_3 basalt* at Rød. From Rød farm with Rød-type RP (Kolsås type) past the Ende type (nearly a 'rectangle' porphyry) and Rønneberg type (again similar to Kolsås) to the overlying B_3 formation. This aphyric rock, andesitic basalt, contains a volume of quartz porphyry, with a charp contact. The basalt also contains fragments of the quartz porphyry and vice versa. This quartz porphyry shows abundant phenocrysts of altered plagioclase up to 1 cm in size and quartz up to 0.5 cm. No doubt the two rocks were liquid simultaneously at the time

Table 2. Chemical and approximate modal compositions of Vestfold volcanic

	1 B_1	2 B_1	3 T_1	4 La	5 RP–H	6 RP_{16}	7 RP_{19}	8 B_3	9 B_3	10 R_1	11 R_4	12 R_5	13 R_{10}	14 R_{11}
SiO_2	46.2	48.2	64.30	56.05	52.83	58.93	60.04	50.20	44.83	73.84	75.00	75.94	75.35	75.40
TiO_2	3.48	3.03	1.10	1.84	1.95	1.72	0.87	2.61	3.08	0.38	0.20	0.27	0.57	0.50
Al_2O_3	13.7	14.9	14.17	15.99	16.47	16.95	19.12	15.70	15.00	14.28	12.90	13.43	12.70	11.55
Fe_2O_3	8.0	7.4	3.79	5.82	9.06	7.40	6.17	4.87	5.41	1.07	0.92	0.02	2.29	2.99
FeO	5.6	6.3	1.00	2.07	n.d.	0.46	1.21	5.74	6.16	0.77	0.88	1.03	0.51	0.28
MnO	0.21	0.24	0.12	0.25	n.d.	0.25	0.14	0.09	0.10	0.18	0.09	0.21	0.04	0.23
MgO	6.56	5.42	1.30	3.14	2.84	1.47	0.79	4.96	6.17	0.00	0.14	0.00	1.08	0.08
CaO	10.07	9.06	1.40	4.27	4.55	2.25	0.91	6.95	6.85	0.00	0.33	0.00	0.04	0.24
Na_2O	3.51	3.37	5.68	5.68	4.99	5.50	5.82	3.78	3.75	3.78	3.80	3.58	5.43	4.39
K_2O	1.64	1.88	3.60	3.23	3.55	3.67	4.49	2.65	1.02	5.38	4.60	4.81	3.70	4.45
H_2O+	–		0.55	0.89	1.93	1.89	0.00	0.91	3.58	0.38	0.44	0.79	–	–
$H_2O\div$	–		0.09	0.10	0.34	n.d.	0.15	0.13	0.39	0.02	0.12	0.00	–	–
CO_2	–		1.17	0.00	n.d.	0.00	0.00	1.26	3.72	0.05	0.21	0.13	0.0+	0.0+
P_2O_5	0.44	0.45	n.d.	0.53	0.99	n.d.	0.30	n.d.	n.d.	0.00	0.02	0.00	–	–
	99.41	100.25	98.27	99.86	99.50	100.49	100.01	99.85	100.06	100.13	100.04	100.21	100.71	100.10
Q	–	–	12.40	–	–	3.00	9.37	–	–	29.3	32.6	33.9	25.7	30.6
San	12.0	14.0	–	22.98	35.09	36.09	70.38	23.55	2.48	–	–			
Ano	–	–	77.90	–	–	–	–	–	–	66.4	63.0	61.5	70.8	65.5
Pla	47.0	49.0	–	58.72	47.76	49.21	12.84	48.18	64.53	–	–			
Nep	–		–	–	0.04	–	–	0.45	–					
Cli	24.0	24.7	8.32	9.38	3.77	8.70	5.35	15.54	22.70		0.8	1.4	1.0	1.0
Oli	3.6	–		5.12	7.16		–	8.23	5.26					
Apa	0.8	0.8		1.09	2.06		0.46	–	–	–	–			
Mag	7.6	7.9	0.70	1.19	1.31	1.15	0.73	1.67	1.84	1.2	1.2	0.2	1.7	2.1
Ilm	5.0	4.4	0.68	1.52	2.03	1.85	0.86	2.39	3.19	0.6	0.4	0.4	0.8	0.8

1. B_1 basalt, with plag, and augite phenocrysts, S in Holmestrand. Weigand 1975, anal. No. 58. 2. B_1 aphyric basalt, N in Holmestrand, Weigand 1975, anal. No. 59. 3. T_1 trachyte lava. Gjerstad, 15 km W of Hillestad, map sheet Drammen. (7, 6611). 4. Latite porphyry, top T_1. East side Revovann, map sheet Holmestrand. (14,6374). 5. RP, Hegg type. Gutu, east of Holmsvann. Holmestrand. (3, 6101). 6. RP_{16}. Breimyr, 3 km SE of Dokka, Holmestrand. (18, 6522). 7. RP_{19}. Solberg, 2.5 km SSW of Dokka, Holmestrand. (27, 6622). 8. B_3. Road to Haugtuft, 1.5 km W of Hillestad, map sheet Drammen. (4, 6602). 9. B_3. Haugtuft, 1.5 km W of Hillestad, map sheet Drammen. (5, 6603). 10. R_1. Heimdal, Holmestrand. (89, 6404). 11. R_4. Sjue, R. 306, Holmestrand. (90). 12. R_5. Myresaga, Holmestrand. (91, 6410). 13. R_{10}. Gislerød, Holmestrand. (102, 71–66). 14. R_{11}. Holt, Holmestrand. (103, 63–66).

Nos. 3–10, 12–14, unpublished anal., Chr. Oftedahl. Analyst: I. Rømme. (7, 6611) etc.: Anal. No. and sample No. No. 11: Dr. Jack Green. Samples 71–66 and 63–66 from R. Sørensen.

of extrusion. At other places in Vestfold the B_3 unit is represented by nearly aphyric rocks ranging in composition from basaltic to latitic (Table 2). At Rød and further north the basalt has a sharp contact against the overlying T_1 formation which ranges from trachytic upwards into latitic composition without a visible break.

6. *Contact, ignimbrites R_1/R_2* south of Heimdal road intersection at R. 35 in the Ramnes cauldron. The contact between the two lowermost big rhyolite formations R_1 and R_2 is exposed in a long road-cut. It is knife-sharp and suggests that the two ignimbrite eruptions followed very soon after each other and made up one cooling unit. The stratigraphy of the subsided caldera block

is presented in Table 1. For chemical composition etc., see Table 2. The exposure is also very fine for a study of the fiamme problem (McBirney 1968).

7. *R_3 and R_4* at Myresaga, road to Illestad. At once off R. 35, we see long exposures of the unit R_3. This unit is exceptional among the Ramnes rhyolite units in showing intense turbulent flow structure with big lithophysae. It has earlier been interpreted as an obsidian flow (Oftedahl 1967) but is now considered as a rheo–ignimbrite: a very hot ignimbrite deposit can develop abundant and large lithophysae and start flowing due to an internal heating up. Eastwards along the road and upwards in the section the turbulent flow structure gradually disappears and is replaced in part by brecciation. Around the turn of the road the rock grades into typical R_4, a rhyolite which contains very small feldspar phenocrysts and nearly no eutaxitic structure. It seems possible to interpret R_3 and R_4 as belonging either to the same flow unit or to two flow units, the later following immediately after the earlier one, only being not quite so hot as the first one.

8. *Mega-breccia* at Gravdal, just south of road intersection R. 35/R. 307. A small quarry on the east side of R. 35, 600 m south of the intersection, permits the inspection of the contact between the explosion breccia A_6(?) and the underlying ignimbrite R_7. The fragments of the breccia are mostly made up by RP-types found within the caldera block and underlying the ignimbrites. The breccia debris flow formed by collapse in the caldera wall obviously landed on a hot ignimbrite because the ignimbrite top layer is deformed.

9. *R_{10} and R_{11}*, the central dome, at Gislerød between intersections Kjønnerød on R. 306 and Ramnes church. The R_{10} unit is quite different from the ignimbrites already inspected. It shows a marked plane-parallel flow structure with small spherulites. It occurs only in the northern part of the Ramnes volcanics and seems to be a local lava flow. In the road slope to the southwest the overlying unit crops out. R_{11} is a flinty felsite without phenocrysts or structures. A few small flames have been discovered in the rock. Thus it may be a very strongly welded tuff with no trace of pumice remaining. On the hill top follows a felsitic porphyry which constitutes the margin of the central intrusion. Because of its seemingly gradual transition from a felsite porphyry to a coarse-grained syenite, the intrusion was first interpreted as a lava dome with marked cooling against adjacent volcanics (Oftedahl 1960a, 1967). Sørensen (1975) prefers an interpretation as a composite pluton with a peripheral syenite and a central kjelsåsite, again cut by larvikite and the last granitic plug (Horn quartz porphyry). If weather and time permit, this gradual transition may be checked by the excursion party walking the road one km.

10. *The Horn quartz porphyry* at R. 312 at Horn. Road-cuts show the central part of the intrusion to be intermediate between a quartz porphyry and an aplitic granite. This intrusion is considered the youngest (Sørensen 1975), supposedly a Mt. Pelée-type granitic plug.

Second day — the larvikite/lardalite complex

Jon S. Petersen

THE LARVIKITE COMPLEX

Larvikite (= monzonite) is the most voluminous plutonic rock-type in the Oslo Region, and is particularly abundant in the southernmost part of the region where it constitutes a batholitic occurrence of more than 1000 km^2. Another important occurrence is in the Skrimheia north of Skien (Segalstad 1975). The Nordmarka district north of Oslo (Sæther 1962) and the Ramnes cauldron (Sørensen 1975) contain rocks that are just a little less alkali-rich than larvikite and form the related rock kjelsåsite. The distinction between larvikite and kjelsåsite is essentially a geochemical one (Barth 1945) and in hand-specimen the rock appears roughly the same.

The term larvikite actually covers a range of monzonitic rocks which include Qz- and Ne-bearing types, as well as types that contain neither of these phases, and occasionally they form a transition to rhomb-porphyry lava (latite) which constitutes the major extrusive rocks in the region (Oftedahl 1967). The larvikites show spatial relations to kjelsåsite and sørkedalite (Ol–diorite) (Brøgger 1933, Bose 1969) and to the basic rocks of the region (essexite, etc.). Petrographic and field evidence suggests a complex pattern of geochemical evolution that involves crystal accumulation as well as magmatic fractionation.

Gravimetric investigations of the southern part of the Oslo rift structure revealed the presence of a deep, large, dense mass, which was interpreted as a gabbroid pluton underlying the larvikite field (Ramberg & Smithson 1971). These gabbros may have a common origin with the voluminous monzonitic rocks found in the region.

A regional study of Th–U distribution in plutonic rocks of the Oslo province (Raade 1973) revealed a marked contrast in the Th/U ratio between rocks of the kjelsåsite–larvikite–lardalite series and the plutonic rocks of the nordmarkite–ekerite–granite series. The former have a constant and low Th/U ratio of approx. 4, whereas the latter show variable and significantly higher ratios of 5–6. The low and constant Th/U ratio of the larvikite series conforms with an origin by mantle derivation, a conclusion supported by Sr-isotope studies (Heier & Compston 1969) that reveal low initial Sr^{87}/Sr^{86}-ratios on the order 0.704–0.705. However, the overlap of Sr-initial ratios from lower crustal and upper mantle materials makes this latter observation perhaps less significant.

The larvikites commonly display a type of orientational fabric caused by the parallel or subparallel alignment of the often characteristically rhomb-shaped feldspars. Mafic minerals form interstitial and poikilitic grains of essentially biotite and augite. Zones and bands of 5–50 m width are found locally to show rhythmic and often graded, igneous lamination (Fig. 3). These zones are surrounded by more homogeneous or weakly orientated larvikite.

A number of curvilinear topographic features in the area follow the orientation of the planar larvikite structures and form a pattern of circular arcs which

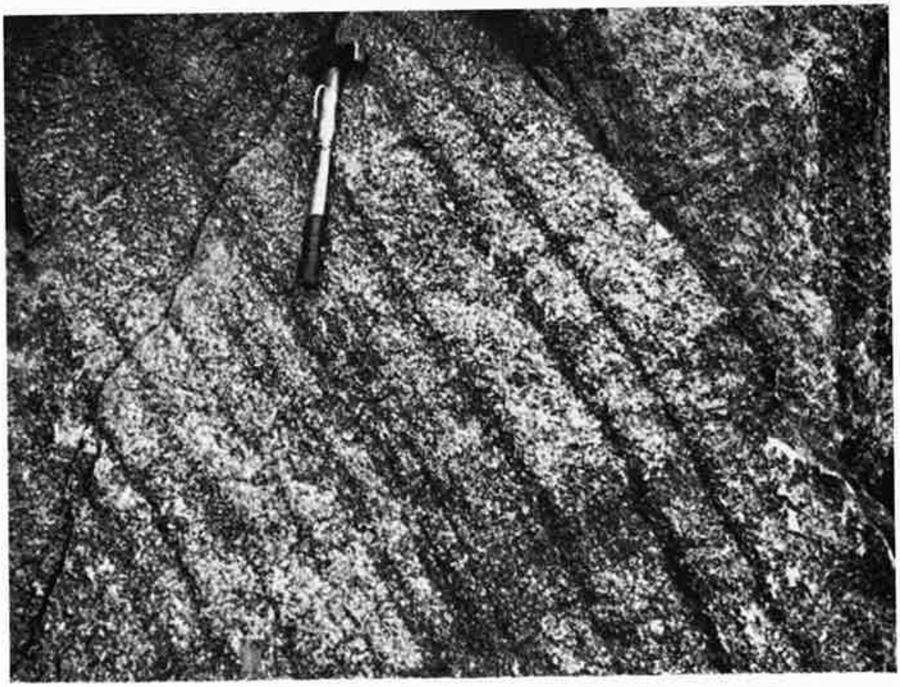

Fig. 3. Rhythmic, igneous lamination in larvikite, formed by the downwards concentration of mafic minerals in successive layers. From Vassvik, NW of Larvik.

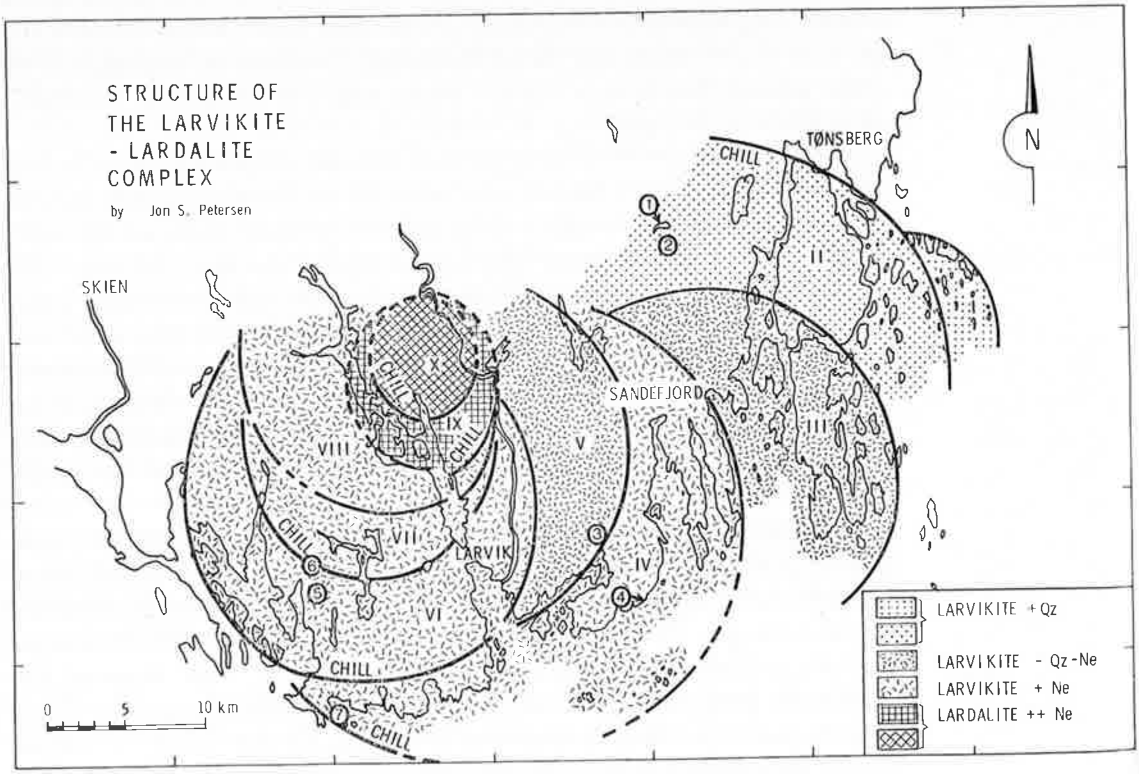

Fig. 4. The compositional and structural geometry of the larvikite-lardalite complex suggests a systematic shift of centers of activity toward the west.

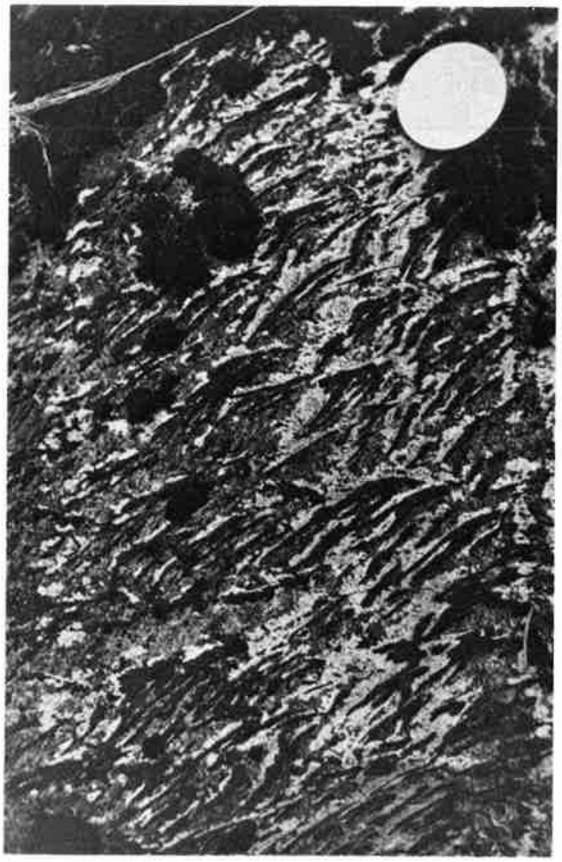

Fig. 5. Mesoscopic dendritic growth of pyroxene and nepheline (white) in a fine-grained matrix of the border zone between lardalite–1 and lardalite–2, near Lauvesetra. Similar textures, occurring along the boundary between lardalite–1 and larvikite, suggest the development of substantial supercooling of lardalite magma at two different periods. The crystals grow inwards (towards left) at right-angles to the boundary and curve slightly downwards (photo shows vertical view). Coin diameter 2.4 cm.

are cut repeatedly by others, suggesting a structural younging towards the west. The topographic elements are narrow depressions, small streams, elongate hills and lakes, among others, and they clearly relate to the orientational fabric of the larvikite and thereby form primary structural elements that are significant in the interpretation of the evolution of the larvikite complex.

A structural analysis of the southern larvikite area (Petersen 1977) revealed that this large batholith actually consists of several circular sections which cut each other in a manner that suggests a general shift in the center of activity towards the west. These cusp-shaped sections divide the larvikite massif into a number of individual fractions whose mutual relations are complex (Fig. 4). The formation of this pattern can be viewed either as the result of complex cauldron subsidence, implying a systematic displacement of the zone of collapse, or indicate a central-type intrusion of the larvikites which shifted sequentailly towards the WSW. In both cases the periodic evolution might be related to extrusive episodes in the region.

During geological mapping of the lardalites (foyaite-monzonite) which constitute the core of the larvikite massif, conspicuous contact zones were discovered along the lardalite-larvikite boundary (Fig. 5). These zones show mesoscopic development of dendritic crystals of feldspar, pyroxene and nepheline in successive zones of a porphyritic, fine-grained matrix. The metastable crystal growth is evidence of substantial supercooling along the boundary and suggest an origin by multiple intrusion of the lardalites. Furthermore, the local occurrence of fine-grained, porphyritic variants along internal boundaries in the larvikite, some of which contain dendritic feldspars, supports an origin of the entire larvikite complex by multiple injection (see stops 6 and 10).

Different magnetic properties of the larvikite sections produce a pattern of moon-shaped anomaly arcs on aeromagnetic maps of the region and clearly support the impression of systematic structural and intrusive younging towards the west. Furthermore a gradational, regional increase in magnetic field intensity with evolution of the complex is apparent, suggesting systematic variation in the oxide composition and content of the different larvikite members.

Compositional variations in the larvikite complex follow this pattern of structural younging towards the west. Different larvikite variants are confined to individual cusp-shaped sections. The two easternmost cusps near Tønsberg contain quartz, generally as a late interstitial mineral. Between Sandefjord and Larvik, the larvikite sections are of intermediate composition, as they contain neither Qz nor Ne. West of Larvik, the larvikites are essentially Ne-bearing, where the nepheline forms both interstitial grains and exsolved drops within the feldspars. Finally, the two latest circular plutonic masses of this structural sequence are composed of lardalite which contains modal nepheline in amounts of 10–40%. Thus the distribution of rock-types in the larvikite complex, roughly stated, is towards a higher degree of undersaturation with evolution from east to west.

THE LARDALITE COMPLEX

The lardalite complex is the major occurrence of undersaturated plutonic rocks in the Oslo region, and therefore constitutes an important end member of the magmatic activity in this region. The large number of rock-types occurring in this area were thoroughly studied by Brøgger and described in his monograph: «Die Ganggefolge des Laurdalits», appearing in 1898. Chemical data was later compiled by Brøgger (1933) and a preliminary geological map was presented by Oftedahl (1960).

Recent detailed geological mapping in southern Vestfold (Petersen 1977) showed that the lardalite forms a composite ring-complex which was later transgressed and partly assimilated by syenites, forming a large variety of rock-types in a limited area (Fig. 6). Subcircular boundaries limit the lardalite complex, except where destroyed by later intrusives and indicate an origin by multiple, central-type, igneous activity. The centers show slight displacement with time, a situation similar to that discovered in the larvikite complex. The position of the lardalite in the central core of the larvikite complex suggests that the lardalite intrusion was the youngest event in the evolution of the

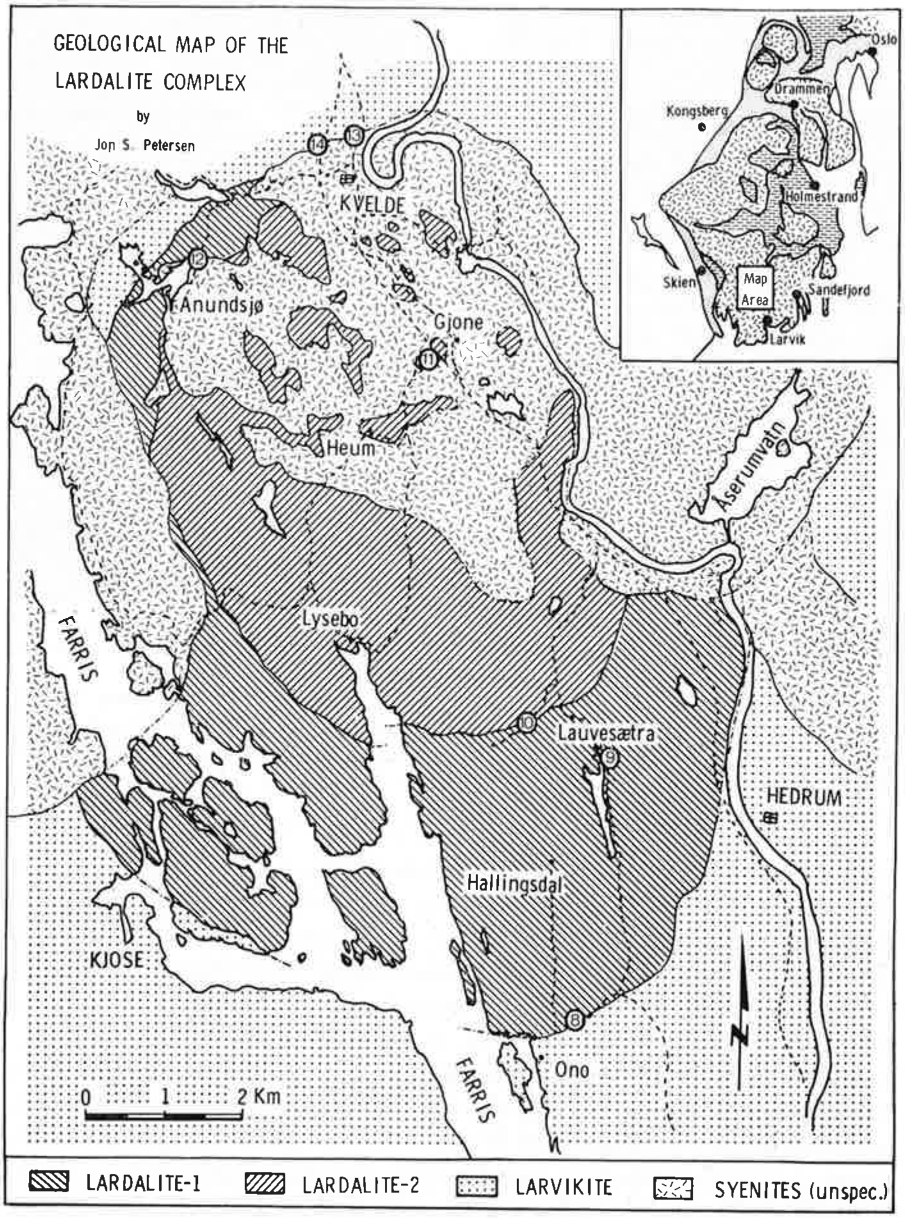

Fig. 6. Generalized geological map of the lardalite complex that constitutes the core of the larvikite massif. Younger intrusions of syenite-foyaite partly dissect the multiple, off-centered, plutonic ring-complex of larvikite and lardalite. Excursion stops 8–14 are indicated.

monzonitic rocks of the Oslo Graben. Two individual sections, here referred to as lardalite–1 and lardalite–2, can be distinguished on the basis of super-cooled contact zones (see stop 10). Both sections show a remarkable compositional zonation.

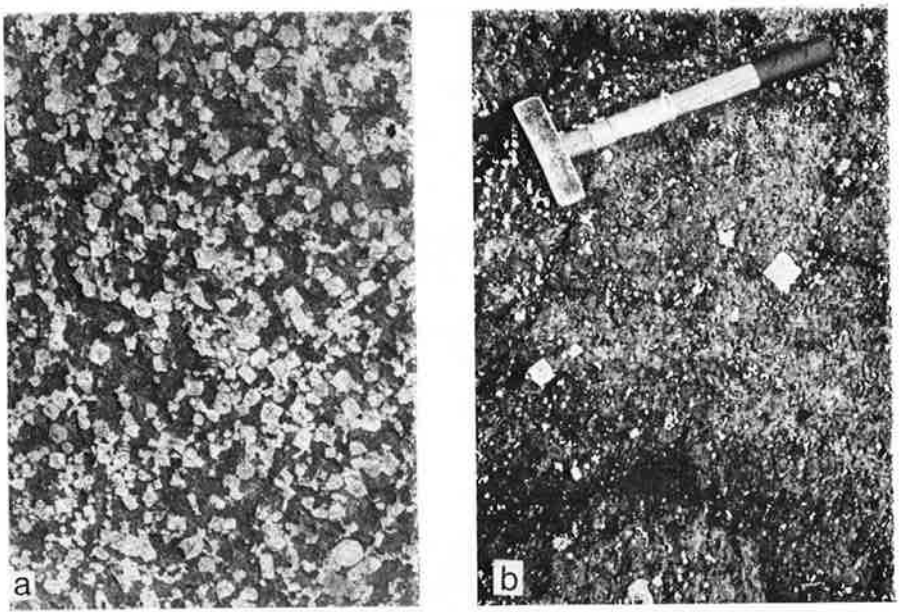

Fig. 7 (a). Nepheline-rich lardalite showing abundant, euhedral nepheline grains of 1–2 cm size, easily recognized as white crystals, due to weathering. This type forms the outermost zones of the lardalite–1 massif. Coin diameter 2.4 cm.
(b). Porphyritic lardalite, where euhedral nepheline grains constitute only about 1–10%, and where the bulk of the nepheline occurs as interstitial grains. This type forms an intermediate variant, and completely gradational transition between this type and the nepheline rich-variant (Fig. 7a) exists.

Lardalite–1, which constitutes the outher ring complex, shows inverse zoning: the rock at the southern boundary is an extremely coarse-grained lardalite containing about 30% nepheline, found as 2–3 cm euhedral crystals evenly distributed between 3–4 cm, often lense-shaped alkali-feldspars (Fig. 7a). Very large poikilitic biotite occurs sporadically. The content of euhedral nepheline gradually decreases inwards and, about 1–2 km from the southern contact, Ne-porphyritic lardalite constitutes a characteristic variant where euhedral nepheline makes up only about 2–10% and an interstitially developed nepheline forms the greater part (Fig. 7b). Along Lauvebuvann (near Lauvesætra), 2–3 km from the boundary, the large euhedral Ne-crystals have almost disappeared. The rock here forms a coarse-grained lardalite with lense-shaped feldspars and interstitial nepheline in decreasing amounts. At the northern part of Lauvebuvann, about 3 km from the southern boundary, the lardalite is porphyritic again, now because a medium-grained matrix developed and surrounded the large feldspar megacrysts. Finally, within the last 300 m of the lardalite–1 massif, the feldspar megacrysts also disappear, and the rock appears as homogeneous medium-grained olivine-lardalite with only limited amounts of nepheline, easily identified on moderately weathered surfaces as small, interstitial, white grains.

The content of mafic minerals gradually increases from the margin to the

Table 3. Chemical zonation of the lardalite complex. Analytical data from Brøgger (1933) and Neumann (1976)

		1 Pollen	2 Ono	3 Løvemoen	4 Lauve	5 Lysebo S.		6 Lysebo N.	7 Lien
SiO_2	CHILL	56.35	55.55	54.55	54.51	45.16	CHILL	52.38	55.25
TiO_2		1.00	1.12	1.40	1.49	6.98		1.41	1.05
Al_2O_3		19.85	20.38	19.07	19.69	15.26		18.81	19.07
Fe_2O_3		1.91	2.06	2.41	2.16	9.57		2.62	1.82
FeO		2.03	2.42	3.12	3.42	4.99		3.67	2.93
MnO		.20	.16	.17	.18	.63		.21	.20
MgO		1.17	1.46	1.98	2.02	3.18		2.04	1.26
CaO		2.60	2.32	3.15	2.68	2.87		3.30	2.31
Na_2O		8.89	8.15	7.67	7.93	6.57		7.55	8.80
K_2O		5.31	5.04	4.84	4.93	3.87		4.32	5.05
P_2O_5		.67	.64	.74	.94	1.54		1.11	.66
	MARGIN			→				CENTER	

core. This inverse zoning is also reflected in the chemical composition of the complex. The lardalite becomes richer in Ti, Fe, Mg and P towards the center, whereas the alkalies decrease in amount (Table 3).

The compositional variation may have developed as the result of a partial melting process. The first fraction to develop during melting would be the nepheline-rich, interstitial melt fraction of a Ne-normative source rock, e.g. larvikite in accordance with its minimum melting composition. This material forms the outer ring of the complex. Towards the central part of the complex one finds evidence of a progressively greater degree of fusion of the parental rock. The melt becomes increasingly more mafic and finally reaches the composition of olivine-lardalite which contains ultramafic Ol-Px-Oxid-rich restites as schlieren. A detailed geochemical and petrographic study with this model in view is currently being carried out.

The lardalite–2 section, in contrast to lardalite–1, shows an apparently normal zonation. A nepheline-poor coarse-grained lardalite forms the outher part of the complex which gradually becomes more Ne-rich inwards. A medium-grained variety, referred to as Lien-type lardalite, forms the central part of the intrusion and locally seems to cross-cut earlier parts of the lardalite–2 complex. This cross-cutting relationship is seen along the western boundary, where the Lien-type is in contact with olivine-lardalite of the lardalite–1 section. These relations suggest that the Lien-type lardalite in the lardalite–2 plug possiblv forms a separate unit.

The lardalite–2 pluton has been seriously dissected by the intrusion of younger syenites that essentially leave the Lien-type lardalite over as roof-pendant and erosional remnants 'swimming' in syenite (Fig. 6). The syenite itself makes up a large variety of rock-types ranging from syenite-aplite in the central part (between Gjone and Kvelde) through sphene-syenite (around Heum) and nepheline-syenite (between Heum and Anundsjø) to foyaite

(Anundsjø) and sodalite-foyaite (NW-Kvelde). Near Åserumvann the syenite forms a sphene- and nepheline-free unit. Finally along the eastern coast of Farris, the rock is a pulaskite (= Qz-free nordmarkite) that contains xenoliths of larvikite and syenite. These relations suggest a younger age for the pulaskite.

The time relationship between the different rock-types in the area appears to be as follows: *larvikite - lardalite–1 - lardalite–2 - syenite - pulaskite.* Since the larvikite-lardalite massifs described here occupy almost the total width of the Oslo graben, their structural and compositional relationships give important information regarding the development of the rift structure. It has not yet been possible to determine the time interval of evolution in the larvikite complex. However, the systematic displacement of the centers of activity possibly relate to the process of crustal rifting and thus suggest a unilateral, dilational opening towards WSW in this part of the Oslo graben.

Road log (Excursion 6, second day)

1. *Larvikite transition to rhomb porphyry.* Road-section at Gjennestadvann, 1 km W of Skjee church. Fig. 4.

Along the northeastern boundary of the larvikite massif, the larvikite often displays a subvolcanic texture with rhomb-shaped feldspar grains evenly distributed in a medium-grained matrix. A selective colouring of the 'matrix' occasionally reveals a porphyritic appearance, even of the equigranular rocks in this region. Completely gradational transition between larvikite and rhomb porphyry is found in this part of the complex indicating a possible relationship between the extrusive rhomb porphyry series and the multiple, central-type plutonic complex.

2. *Red quartz-bearing larvikite.* Quarry 1.5 km west of Stokke.

Red larvikite ('tønsbergite', Brøgger 1933) constitutes an essential part of the quartz-bearing larvikites. However, dark grey, 'normal' coloured Qz-larvikite is found in central Nøtterø island, and the colouring is considered to be of late magmatic origin. The selective colouring sometimes produce an attractive ornamental rock, which was once quarried on Bolærne islands, east of Tønsberg. This rock consists of deep red-brown feldspar cores surrounded by light pink-coloured rims and interstitial parts, forming a delicate structure which resembles the rapakivi texture. Careful examination of the rocks shows quartz as small transparent grains of a characteristic interstitial appearance. The quartz is often triangular shaped and is surrounded by larger subhedral feldspars. Quartz, easily identified on weathered surfaces, constitutes about 2–5% of the rock and is commonly rather heterogeneously distributed. The rock shows well-developed feldspar lamination and displays features of feldspar accumulation due to selective colouring.

3. *Dark intermediate larvikite (schillerizing).* Klåstad quarry, 7 km east of Larvik.

Dark larvikite is known from several places in the larvikite complex. The

Klåstad variant belongs to the outer part of a circular larvikite section which constitutes the major occurrences of dark larvikite in the region. An unusually developed schiller effect, caused by light refraction in the cryptoperthitic feldspars, makes the dark larvikite a beautiful ornamental stone, known throughout the world as 'black labrador'. Numerous quarries, along the line Viksfjord–inner Sandefjord, clearly define the distribution of the precious variant, which makes up a single unit of the larvikite complex. An orientational fabric is poorly developed at Klåstad; however, it becomes increasingly better developed towards the central parts of the section. Near Lauve, 1 km north of Klåstad, road-cuts reveal a strongly orientated variant. The dark larvikite is free of quartz and nepheline, but commonly contains olivine pseudomorphs.

4. *Layered larvikite.* Kjerringvik. Follow path to Fornet, the small peninsula east of Kjerringvik.
The dark larvikite at Klåstad cuts a series of grey larvikites, which in turn form the characteristic curved peninsulas of Tinvik, Østerøya and Vesterøya south of Sandefjord. These larvikites consist of partly layered varieties. Only a few hundred metres SE of the Klåstad quarry, rhythmic layering can be seen in road-cuts and similar layering is found throughout the unit. At Kjerringvik where the banding appears nicely exposed on glaciated cliffs, the zones of layering are from 5 m to more than 50 m thick and are surrounded by more homogeneous larvikite. The layering is often of the graded type with concentration of mafic phases and oxides at the base of each layer and gradually increasing amounts of feldspars upwards; this is particularly well developed at stop 14.

5. *Light Ne-bearing larvikite (schillerizing).* Quarry at Tvedalen, north of Helgeroa, 17 km from Larvik.
The light type of larvikite found here makes up another important ornamental stone known as 'blue pearl' or 'light labrador' rocks. This variant, which belongs to a single cusp-shaped larvikite section, is a nepheline-bearing type that also contains olivine. The nepheline forms interstitial grains and exolution drops in feldspars. It is not usually observed in hand-specimen although some can be observable on weathered surfaces. Large pegmatites often found in this rock contain many beautiful crystals of accessory as well as major minerals.

6. *Contact relations between internal larvikite sections.* Road exposures near Saga, 6 km north of Helgeroa.
The boundary between the light 'blue' larvikite known from the Tvedalen quarries and a younger, dark 'green' larvikite is exposed along road-cuts near Saga. The contact is sharp against a fine-grained larvikite showing conspicuous dendritic feldspar morphology. The light larvikite shows signs of recrystallization in the vicinity of the boundary. Northwards the fine-grained variety gradually becomes porphyritic with large feldspar phenocrysts in a matrix that still contains the fine-grained dendritic phases. Finally the dendritic crystals

disappear, and the rock grades from the porphyritic variety into the normal, coarse and dark green larvikite. The boundary relations indicate a thermal contrast between the two types of larvikite and therefore suggest an origin by multiple injection.

7. *External borders of the larvikite complex.* Coast sections near the harbour of Nevlunghavn.

The borders of the larvikite massif display complicated contact features that suggest considerable thermal contrasts. Strong magma – country rock interactions led to the development of brecciated and sheared border-zones as well as to the formation of large Ne-pegmatites unusually rich in rare minerals (cf. Brøgger 1890). At Nevlunghavn the larvikite becomes strongly oriented and gradually more fine-grained towards the boundary. The border zone is essentially a pegmatite-aplite hybrid. Porphyritic patches are found in increasing amounts outwards, and finally constitute most of the outer rim of the complex. This marginal rhomb porphyry may represent either an early chilled shell, which was later partly assimilated by the ascending magma, or the remnants of overlying lava-flows which were engulfed by stoping along the contact of the magma.

8. *Lardalite and its contact relations.* Small hill at road-cut 500 m east of Ono, at the Hallingsdal road. Follow path to Ono bay. Fig. 6.

The slightly discordant boundary between ordinary, oriented larvikite, and the most nepheline-rich lardalite variant, almost follows the road from this point westwards to the bay of Ono. At Ono, glaciated cliffs expose beautifully the mesoscopic appearance of Ne-lardalite which shows euhedral nepheline crystals of 1–2 cm homogeneously distributed in a very coarse-grained rock. The readily weathered nepheline appears as white spots on the grey rock surface. A strongly weathered surface of the locality displays the euhedral appearance of feldspar and nepheline megacrysts in a more mafic matrix. This area marks the nepheline-rich, feldspar-porphyritic boundary-layer of the complex. The lardalite found immediately north of this locality (left of the branch to the Lauvesætra-road) contains 20–30% nepheline, developed as short euhedral crystals.

9. *Porphyritic olivine–lardalite.* Road-cut 200 m south of Lauvesætra.

The feldspar-porphyritic Ol-lardalite found here forms a transition into homogeneous medium-grained, dark, olivine-lardalite which makes up the end member of a gradational change from the Ne-rich variety seen at stop 8. The Ol-lardalite contains interstitial nepheline together with 1–5% olivine. Inclusions and schlieren of ultramafic rocks rich in olivine, pyroxene, apatite and oxides occur sporadically within the mafic part of Ol-lardalite. These schlieren suggest restite formation and imply a development of inverse zonation in the lardalite complex by partial melting of, e.g., larvikite.

10. *Contact layer between lardalite–1 and lardalite–2.* Road exposures approx. 500 m west of Lauvesætra along the westerly-trending forest-road north of the cottages. Fig. 5.

Immediately north of Lauvesætra, a very coarse-grained, well orientated lardalite variant appears which resembles the peripheral parts of the lardalite complex but are less nepheline-rich. The boundary between homogeneous, non-porphyritic Ol–lardalite and this coarse-grained variety appears as a 3 m-wide zone of dark layered rock. Close inspection shows that this contact-zone consists of curved dendritic pyroxenes which grow inwards towards the center of the pluton and which are separated by layers of pure 'comb-textured' nepheline, which, in places, are up to 40 cm thick. The contact-zone is heterogeneous and consists of layers with pyroxene–nepheline–feldspar, pyroxene–nepheline and nepheline alone, in this order from the periphery inwards. The sequence is repeated three times before the coarse lardalite appears and this stratification is maintained all along the contact. The metastable dendritic growth of pyroxene and nepheline is most likely the result of considerable magma super-cooling reflecting extrusive events and related gas-pressure release.

11. *Lien-type lardalite and Ne-syenite.* Road-cut 200 m W of Gjone along the road to Lysebo.

The Lien-type lardalite constitutes the central part of the lardalite complex and is a medium-grained variety dominated by rectangular rather than rhomb-shaped feldspars. The occurrence here is an irregular erosional remnant under-lain by more easily weathered Ne-syenite, which can be seen in the small stream opposite the road. The Ne-syenite is a member of a syenite suite that cross-cuts the lardalite complex. It ranges from a fine-grained syenite aplite without nepheline through sphene–syenite and Ne–syenite (hedrumite; Brøgger 1898, p. 183) to foyaite which contains more than 30% feldspathoids. The texture is trachytoid and consists of tabular microperthite with interstitial nepheline, biotite, aegirine and oxides.

12. *Foyaite/Ol–lardalite contact.* Road-cut along Anundsjø 2 km west of Kvelde.

The trachytoid Ne–syenite seen at stop 11 grades into granular foyaite in the northwestern part of the syenite massif, where it transgresses the lardalite ring complex. From about 100 m northeast of the lake and southwards along the lake, coarse lardalite passes into Ol–lardalite with oxide-rich ultramafic schlieren. Near the lake, this series is cut by homogeneous white foyaite with approximately 30% interstitial nepheline, minor sodalite and only a few per-cent mafic constituents. Pegmatitic patches occasionally contain large aegirine needles.

13. *Sodalite foyaite.* Road-cut at the southeastern corner of the Kveldeåsen, north of Kvelde.

The sodalite foyaite is the highest differentiate of the syenite complex and forms a lense-shaped body along the northern boundary. In this rock, large poikilitic, sky-blue, sodalite grains and interstitial reddish nepheline makes up about 40% of the rock. The red colour of the nepheline is due to small hematite inclusions in contrast to the foyaite seen in stop 12 where minute magnetite inclusions cause the nepheline to have a grey, smoky appearance. This difference in oxide composition, together with the presence of sodalite, suggests that the sodalite foyaite represent a residual, fluid-rich pocket of the syenite massif.

14. *Chilled foyaite against layered larvikite.* Road-cut west of Kveldeåsen by main road (R–8).

Granular foyaite becomes fine-grained and strongly sheared near its margin, which here is a sharp and discordant contact against larvikite. The fine-grained foyaite borders upon a 10 cm-wide zone of recrystallized larvikite. This recrystallization suggests that any considerable thermal contrast between foyaite and lardalite (stops 11 & 12) must be limited. In the road-cut 50 m further north, rhythmic lamination is seen in the larvikite, striking roughly east-west.