Permian Rocks and Faulting in Sandsvær at the Western Margin of the Oslo Region

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In the Sandsvær area, a Permian quartz conglomerate and great thicknesses of both the B_1-basalt and the rhomb porphyry RP_2 are found above the Ringerike sandstone and the underlying Cambro-Silurian sediments. The younger Permian supracrustal units are engulfed by larvikite and ekerite. The larvikite is intersected by aplite, a granitic rock possibly formed by assimilation of Ringerike sandstone by the larvikite magma.

The area is cut by a number of dip-slip faults, most of which are connected to the subsidence of the Oslo graben. The steep dip of the supracrustals towards the intrusives at the contact was caused by sinking of the supracrustals into the melt, while dip-slip faults parallel to the contact possibly were formed by a later pushing upwards of the half-consolidated magma.

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Introduction

The area described is situated at the western margin of the Oslo region, just south of the town of Kongsberg, Southern Norway (Fig. 1). The northwestern part of the area consists of Precambrian Telemark– and Kongsberg–Bamble rocks (not dealt with in this report). Permian intrusives (larvikite and ekerite) make up the southern and eastern parts of the area. A belt of Cambro–Silurian and Permian supracrustal rocks is preserved between the Precambrian gneisses and the Permian intrusives. The area is cut by a number of faults, ranging in age from Precambrian to late Permian.

As early as 1824, Naumann described a section through the Cambro–Silurian sediments southwards to the igneous rocks in the mountain Skrim. Dahll (1861), in a corresponding section, gives the sediments a synclinal structure between the Telemark rocks and the Permian intrusives.

In 1877 Corneliussen investigated the area dealt with in this text. A detailed map and description were published in 1880. The map clearly shows the geological main features. One marked fault is treated in detail.

Kjerulf (1879) gives two sections through the Cambro–Silurian sediments. Both seem to rest on observations made by Corneliussen. The geological quadrangle map Kongsberg was published in 1926 by Brøgger & Schetelig. In spite of a more detailed stratigraphy within the Cambro–Silurian sediments, data concerning the area treated in this text seem to a large extent to rest on observations made by Corneliussen.

Strand's diary notes (1937) have been most useful during the present writer's fieldwork. Størmer (1953) describes the Middle Ordovician sediments

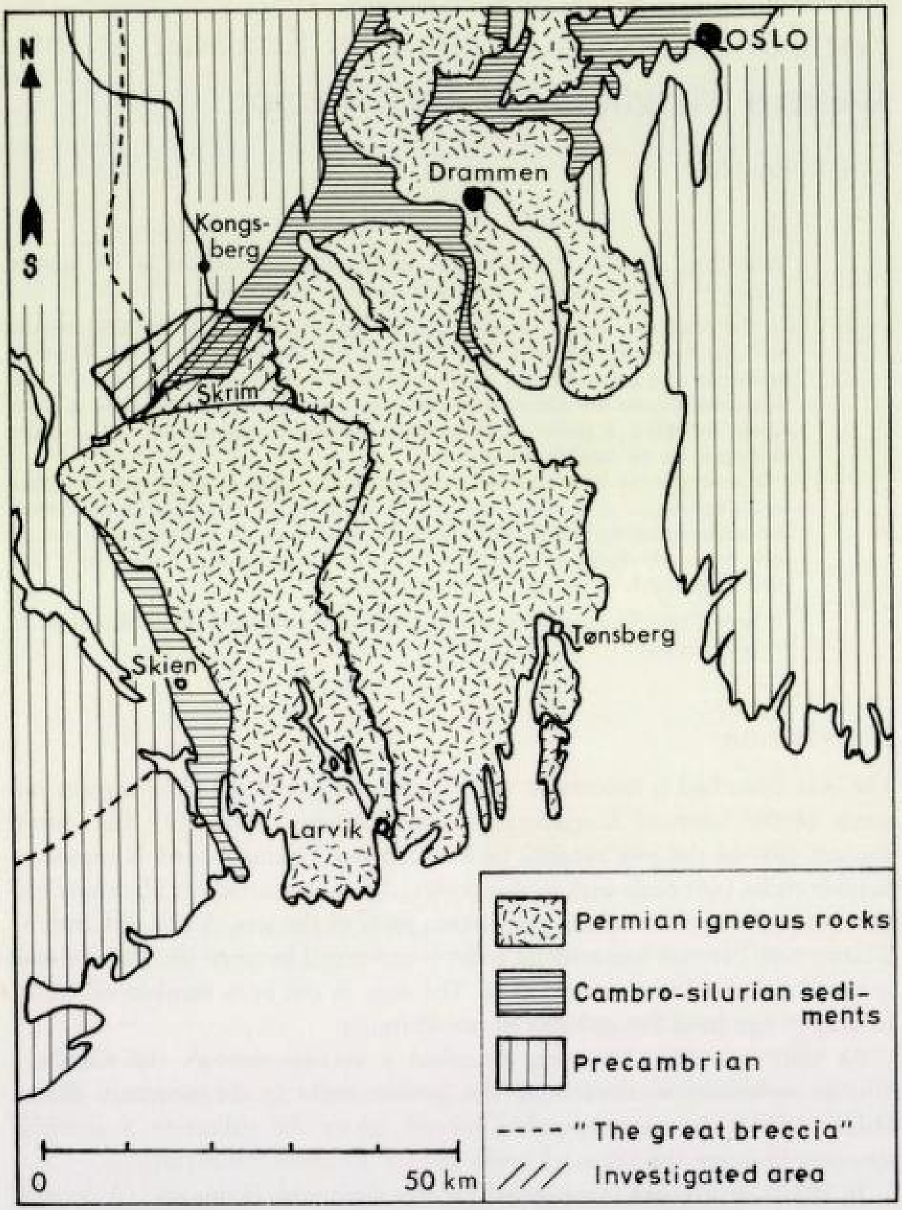

Fig. 1. The geographical and regional geological position of the investigated area.

from the Eiker–Sandsvær district. Heintz (1953) gives a detailed section from the Precambrian rocks in the north-west through the sediments to the larvikite in the mountain Evjuseterfjell. He has also made an unpublished excursion map of the area, which has been of great help to the present writer.

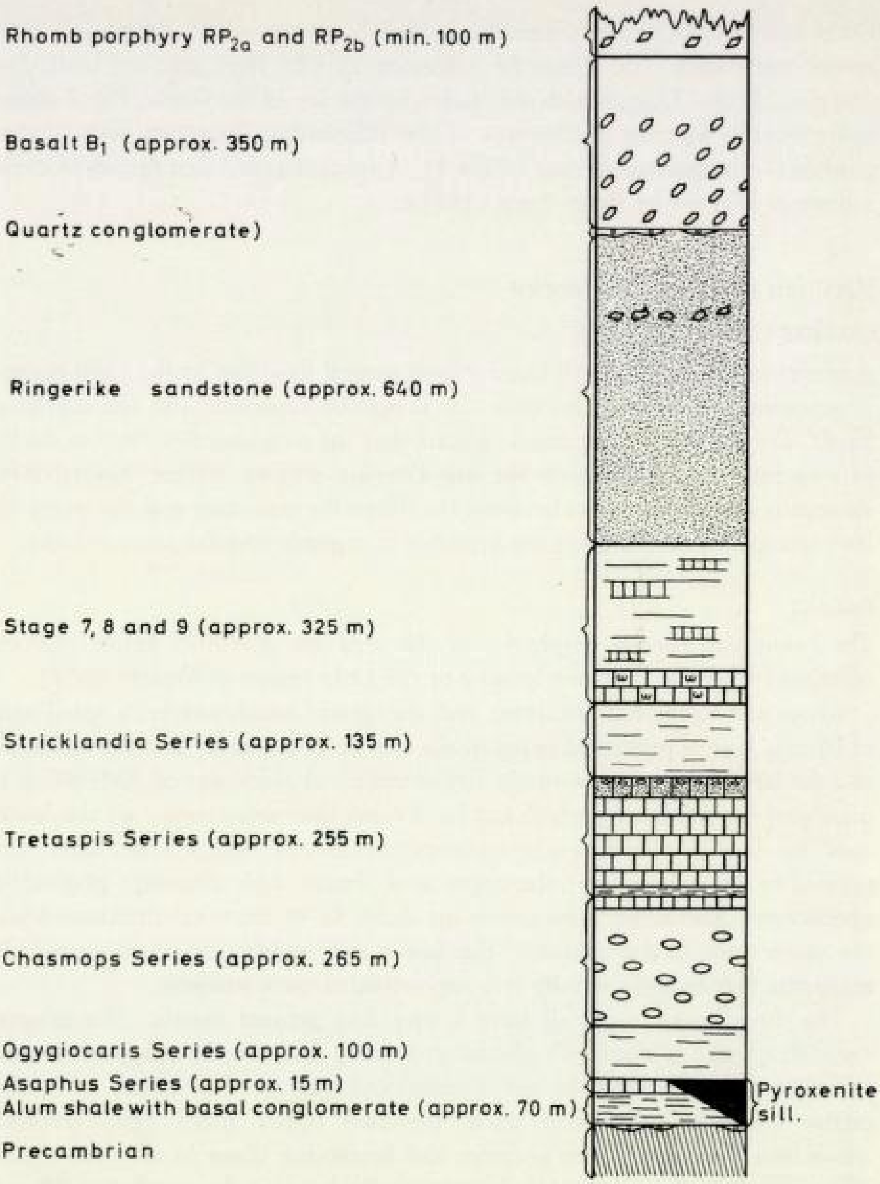

Fig. 2. The supracrustal rocks overlying the Precambrian in the investigated area.

Cambro-Silurian sedimentary rocks

The sediments of the described area rest with an angular unconformity upon the Precambrian gneisses. They have not been folded during the Caledonian orogeny. The dip is rather constant, 10–20° towards the south-east (the same as the dip of the Precambrian peneplain). Only in the vicinity of the Permian intrusives does the dip rapidly increase towards the intrusions, as will be discussed later. Locally the Precambrian border is controlled by faults.

A basal conglomerate is overlain by Cambrian alum shales. The marine

Ordovician and Silurian sediments are mainly composed of alternating limestones and shales. The Ringerike sandstone of Old Red type, of Ludlovian and possibly also Downtonian age, makes up the top of the strata. Fig. 2 shows some features and the thicknesses of the different sedimentary units distinguished on the geological map (Plate I). A more detailed description of these sediments is given by Rohr-Torp (1971).

Permian supracrustal rocks

QUARTZ CONGLOMERATE

A quartz conglomerate, well known from several localities in the Oslo region, is occasionally developed between the Ringerike sandstone and the overlying basalt. The scattered occurrences indicate that the conglomerate (0–3 m thick) fills up small irregularities in the sub-Permian erosion surface. Several measurements along the contact between the Ringerike sandstone and the overlying lava (conglomerate) suggest the presence of a gentle angular unconformity.

BASALT

The basalt and rhomb porphyries of the area are described below and are correlated with the lava stratigraphy of the Oslo region (Oftedahl 1952).

Above the Ringerike sandstone and the quartz conglomerate, a small area of basaltic lava is preserved between the ekerite of the mountain Hovdebøfjell and the larvikite of the mountain Evjuseterfjell. A thickness of 300–400 m is calculated for the basalt, which can be divided into three zones: a) the lower zone, basalt with abundant augite phenocrysts, b) the middle zone, more even grained to dense basalt, c) the upper zone, basalt with abundant plagioclase phenocrysts. The lower zone makes up about ⅔ of the total thickness while the upper zone is the thinnest. The lower and middle zones are so rich in magnetite that in their vicinity it is impossible to use a compass.

The three basalt types all have a very fine grained matrix. The mineral associations are: titanoaugite phenocrysts along with biotite, plagioclase ,and titanomagnetite. Accessories are titanite and apatite. The lower zone also carries common hornblende while the two upper zones carry chlorite. Amygdules filled mainly by prehnite and heulandite occur in all three zones. The plagioclase phenocrysts of the upper zone have an An-content of 53 and are not markedly zoned. The minute plagioclase grains of the two lower zones have not been determined.

According to Oftedahl (1952) the B_1-basalt of the Vestfold area has the same subdivision into three zones as described above. In Vestfold, east of the described area, the maximum thickness of B_1 is 120–150 m, B_2 approx. 10 m, and B_3 approx. 40 m.

The three divisions of the present basalt, its great thickness and the fact that it is overlain by RP_2 show that it must represent the B_1-basalt, the lowermost lava formation of the Oslo area sequence.

The expected thickness of B_1 in the described area is a little more than 100 m

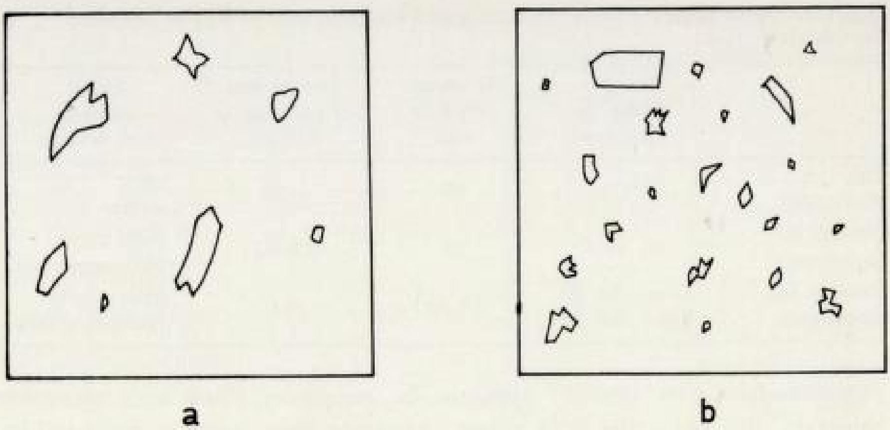

Fig. 3. a. Rhomb porphyry, lower part.
b. Rhomb porphyry, upper part. Natural size.

(Oftedahl 1952, p. 43). The calculated thickness of 300–400 m is not due to repetitions by faulting, and must be explained in another way. If the area described had represented a depression in the sub-Permian peneplain, one would have expected a greater thickness of Permian sediments below the lavas. The explanation must be that the area was situated in the vicinity of a volcanic vent (see p. 60).

RHOMB PORPHYRY

Above the basalt a small area of rhomb porphyry is preserved, dipping steeply towards the south-east. The thickness of the rhomb porphyry is at least 100 m. It can be divided into two zones (Fig. 3), both with fine-grained grey matrix. The lower zone carries a few small and a few medium grained pink plagioclase phenocrysts, making up approximately 10% of the rock volume. The upper zone carries more phenocrysts. They are nearly always small, often forming 'star-shaped' twins. The phenocrysts, which make up 10–20% of the rock volume, are pink or greyish white.

The phenocrysts of the lower zone are less than 1 cm across, usually rhomb-shaped and heavily altered. They are often broken apart and almost completely recrystallized into smaller plagioclase grains (An–30–31, low temperature), lath shaped along (010). The original plagioclase is not determinable. The matrix is composed of perthite, often mesoperthite, biotite, common hornblende, chlorite, apatite, titanite, white mica, and opacite. Grain size, 0.1–0.2 mm.

The upper zone often has a glomeroporphyritic texture. The phenocrysts are approx. 1.5 mm in size, often zoned (core: An–30, rim: An–25, high temperature). The matrix feldspar is not determinable. The other minerals are the same as for the lower zone, with a grain size of less than 0.1 mm.

Aggregates composed of biotite and hornblende with small amounts of apatite and opacite, which frequently occur in both zones, may represent either

Table 1. Rhomb porphyry from the investigated area compared to RP_2 as described by Oftedahl (1946)

	Comp. of plag. in phenocrysts	% phenocrysts in rock	Size in mm of groundmass feldspar	Other minerals than feldspar
RP_2 (Oftedahl)	An 20	10	0.02	chlo. quartz
Present RP lower part	An 30.5	10	0.1–0.2	chlo. amph. bio.opaque min.
Present RP upper part	Core: An 30 Rim: An 25	10–20	0.1	chlo. amph. bio.opaque min.

pseudomorphs after primary pyroxene or amygdules filled with secondary minerals, altered by the later contact metamorphism towards the larvikite. A complete lack of crystal outlines favours the latter hypothesis.

Mesoscopically the bottom of the present rhomb porphyry has the greatest resemblance to RP_{2a} and the top to RP_{2b} as compared to the different rhomb porphyries of the Oslo region.

Table 1 shows some features of the present rhomb porphyry compared to dates on RP_2 given by Oftedahl (1946).

Only RP_1–RP_5 and RP_9 have plagioclase phenocrysts in the range An 20–An 35, and except for RP_2 they all look quite different from the present rhomb porphyry (op. cit.).

Oftedahl (1946, Table 9) has not distinguished between RP_{2a} and RP_{2b}. The average of the phenocryst content from top and bottom of the present rhomb porphyry is close to 10%. Only RP_2, RP_{10} and RP_{12} have such a small amount of phenocrysts, whereas the others have 20% or more. RP_{10} looks quite different from RP_2, and RP_{12} has phenocrysts of An 45 composition.

The grain size of the matrix feldspar is quite different from the value given by Oftedahl, but as this value depends on local temperature conditions during the crystallisation process, it seems to be of little diagnostic value.

The differences between the other matrix minerals must be expected because of the later contact metamorphism of the present rhomb porphyry.

Except for RP_{17V}, which is quite different from the present rhomb porphyry, only RP_2 has a thickness greater than 100 m in Vestfold, east of the described area (Oftedahl 1952). Since the thickness of the present rhomb porphyry is at least 100 m, this argument also indicates that it represents RP_2.

In parts of Vestfold RP_1 is missing (Oftedahl 1952), giving the same picture as in the described area, where RP_2 lies directly above B_1.

Permian intrusive rocks

Larvikite and ekerite occupy the south-eastern and eastern part of the mapped area. As my investigations of these rocks brought little new, they are not treated in this text. Brøgger & Schetelig (1926) have mapped kjelsåsite east of the lake Ravalsjøen (G–13). In my cand. real. thesis I have shown that the

Table 2. Modal analyses of aplite

	8–19–A	11–A–2	11–A–3	11–A–13	J–27–2	J–27–3
Alkali feldspar	54.2	47.2	52.4	49.4	58.2	43.0
Quartz	25.6	28.1	18.2	31.4	18.8	24.4
Plagioclase	16.2	22.1	20.3	16.2	12.4	24.4
Biotite	x	2.4	3.5	2.2	2.4	3.2
Amphibole			4.4		2.4	0.2
Pyroxene	2.2					
Muscovite	x	x	x	x	0.2	0.4
Titanite	1.6	x	0.6	x	1.4	0.8
Zircon		x	x	x	0.2	0.2
Apatite		x			0.4	0.2
Allanite	x	x	x		x	x
Opaque minerals	0.2	0.2	0.6	0.8	3.6	3.2
Limonite				x		
Total	100.0	100.0	100.0	100.0	100.0	100.0
An cont. of plg.	30.0	28.0	28.5	29.0	30.0	28.0

area is composed of larvikite which is often hybrid in composition because of heavy assimilation of basalt.

APLITE

The larvikite massif is cut by a number of aplite dikes, the width of which varies from 1 to more than 100 m. The dikes always show sharp borders against the larvikite; they are cut by the younger ekerite. Chilled margins never occur, indicating that the larvikite was hot during intrusion of the aplite. Aplite is not separated from larvikite in Plate I.

The aplite is greyish- to brownish red, with a fine grained saccharoidal texture; 1–2 cm rhomb-shaped plagioclase phenocrysts, identical to the plagioclase of the larvikite, may occur.

Modal analyses of the aplite are given in Table 2. The composition is granitic (Streckeisen 1965). The An–content of the 'matrix plagioclase' is given at the bottom of the Table.

The alkali feldspar is an irregular patchy perthite, often 30 Ab, 70 Or, but variable within a single thin section. The amphibole is common hornblende and the pyroxene, which is often zoned, has core and rim composed of titanoaugite. The opaque mineral is titanomagnetite while the titanite is often keilhauite (yttrotitanite).

The intimate connection in space and time and the occurrence of the same characteristic plagioclase phenocrysts in larvikite and aplite, make it unlikely that the aplite evolved from a magma independent of the larvikite magma. Three theories for the formation of the aplite are possible:

1. Anatexis of consolidated larvikite gave a granitic neosome. A squeezing upwards of the neosome gave rise to the aplite dikes, while the paleosome was left in the deeper regions of the larvikite intrusion.

2. The aplite magma was formed by a special differentiation of the larvikite magma. Primarily the differentiation is characterized by an increase in silica. Thus the aplite has nearly the same amount of quartz as has the ekerite of the described area (ca. 25%). Also, the alkali content of the magma is slightly increased by the differentiation. This is seen by a higher alkali feldspar/plagioclase ratio in the aplite than in the larvikite. In the described area this ratio is 2.6 for the aplite and 0.6 for the larvikite. The increase of alkalis is much less than in ekerite, where alkali pyroxene and alkali amphiboles occur.
3. The alteration of larvikite magma to aplite magma may be explained by assimilation of quartz-rich country rocks (Ringerike sandstone). This last theory is favoured by the author.

The described area is not unique in having the larvikite cut by a number of aplite dikes. The same feature is mentioned by Sæther (1962) from Nordmarka, north of Oslo.

DIKE ROCKS

The Cambro–Silurian as well as the Precambrian rocks are cut by a number of different dike rocks. They have not been more closely examined, except for one approx. 50 m thick metapyroxenite sill between D–13 and I–7.

Mesoscopically the dike rock is identical to the bottom of the B_1–basalt. It is so rich in titanomagnetite that it makes the use of a compass difficult. The titanoaugite phenocrysts are nearly completely altered to a bluish green common hornblende containing rutile inclusions. The matrix is composed of calcite, titanite, titanomagnetite and apatite. Plagioclase is absent.

In mineral composition the sill corresponds to the pyroxenite from the central parts of the Vestby volcanic neck (Ramberg 1970).

A volcanic neck composed of Oslo essexite (Brøgger 1933) is situated at the lake Eiangsvann approx. 1 km south-west of the south-western corner of Plate I (A–14). The pyroxenite sill is possibly related to this neck.

The fact that the B_1–basalt is situated only some 15 km from a volcanic neck seems to be the explanation of the great thickness of this basalt in the described area.

Discussion of the increasing dip of the supracrustals towards the intrusive contacts

An increasing dip of the supracrustal rocks towards the intrusive contacts is well known from several localities in the Oslo region. A list of references is given by Oftedahl (1960).

In the Sandsvær area, the dip of the supracrustals is constant (10–20° south-east) from the Precambrian border and south-eastwards until approximately 1 km away from the intrusive contacts. Further on towards the contacts, the dip increases rapidly to 70–100° SE at the contact. The dip *does not* increase when crossing faults striking more or less parallel to the strike of the supracrustals

Table 3. Density of natural glasses compared to density of contact metamorphosed supracrustal rocks from the investigated area

Rock/glass	Density (g/cm^2)
Tretaspis Shale	2.79
Tretaspis Limestone	2.87
Calcareous sandstone	2.78
Stricklandia Shale	2.84
Pentamerus Limestone	2.77
Downtonian Sandstone	2.65
Augite porphyry (B_1)	3.21
Rhomb porphyry (RP_{7b})	2.72
Rhyolite obsidian	2.37
Trachyte obsidian	2.45

(faults of group 3, see later), as described from the Skien–Langesund area (Brøgger 1883).

To maintain a constant thickness of the different supracrustal units towards the intrusives, where the dip is so rapidly increasing, the supracrustals have to be folded down towards the contacts by a flexure around axes approximately parallel to the contacts. The simplest explanation of such a flexure is a gravity sinking of the supracrustals into the melt.

In Table 3, the densities of contact metamorphosed supracrustals from the investigated area are compared to the densities of natural rock glasses. Rhyolite obsidian corresponds approximately to an ekeritic melt, trachyte obsidian to a lavikitic melt. (Values for the rock glasses are given by Daly 1966.)

The densities given in Table 3 are determined at room temperature, but as rocks and their glasses all have a coefficient of linear thermal expansion very close to 10^{-5} centigrade^{-1} (Skinner 1966), the differences in density are also real at the actual intrusion temperature.

If the supracrustals are considered to have represented a comparatively thin cover above an overhead stoping intrusion, the differences in density between the rocks and the glasses are sufficient to allow a sinking of the supracrustals into the melts.

The increasing south-easterly dip of the supracrustals towards the intrusions can thus in a simple way be explained by the differences in density between the supracrustals and the melts. More complicated theories therefore seem unnecessary.

Faults

The area described is cut by a number of faults. They can be divided into three groups:

1. Those with fault planes striking close to north.
2. Those with fault planes striking north-east (or south-east), where the north-western (north-eastern) side is relatively lifted.
3. Those with fault planes striking north-east, where the south-eastern side is relatively lifted.

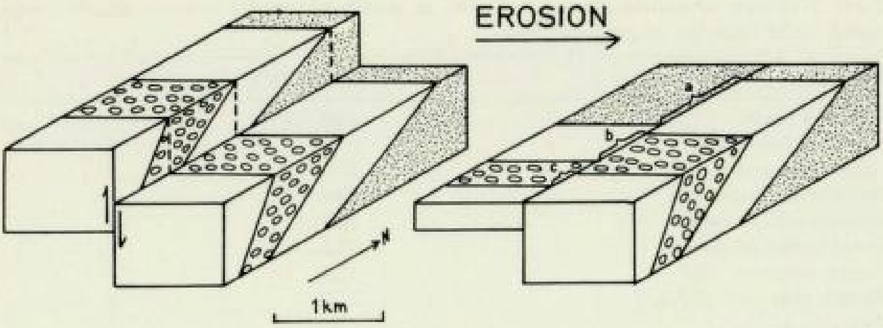

Fig. 4. Dip-slip fault crossing layered rocks with increasing dip towards the south. After erosion, note a>b>c.

FAULTS OF GROUP 1

The 'great breccia' in the Precambrian is described by Bugge (1928, 1936, 1937). It enters the described area from the north, south of the lake Kolsjø (E–5) and splits into several branches towards the south. Along two branches the Cambro–Silurian is disrupted.

Along the hill Kisgruveåsen (I–2) another breccia is described in the Precambrian by Bugge (1936). Later movements along this breccia have disrupted the Cambro–Silurian sediments to the south.

Less than 1 km east of the hill Kisgruveåsen is another, less prominent fault belonging to group 1.

These faults all form marked breccia zones in the Precambrian, while the younger sediments are sharply cut without brecciation.

Inside the Cambro–Silurian area the faults of group 1 are linear, independent of the topography, showing that they must have nearly vertical fault planes. The linear trace also shows that the faults must be younger than the downbending of the sediments towards the intrusions (p. 61). If the age relation were the opposite, the steeply dipping north striking fault planes would have curved traces on the map after having been bent along with the sediments around north-easterly directed fold axes.

The picture along the faults of group 1 may have been formed in two ways or a combination of both: 1. The western side is horizontally dislocated towards the south relative to the eastern side. 2. The western side is vertically lifted relative to the eastern side. Constant dip when crossing a fault shows that no rotation has taken place. From the map it is seen that the dislocation of rock-borders along the faults decreases towards the south. This decreasing dislocation as the dip increases towards the intrusions, indicates that the western block is vertically lifted relative to the eastern block. If the movement along one fault had been horizontal and constant, the dislocation of rock borders along this fault should also have been constant.

Fig. 4 shows to the left a block where the western part is vertically lifted. By erosion of the two sides down to the same level (right hand side of the

Table 4. Calculated dip-slip by the faults of group 1

Dislocated border	W. branch of 'great breccia'	E. branch of 'great breccia'	Fault S. of Kisgruveåsen	Fault W. of Muggerud
Precambrian – alum shale			105 m	40 m
Top of alum shale	75 m	160 m	95 "	30 "
Top of Ogygiocaris Series	75 "	165 "	100 "	
Top of Chasmops Series	70 "	175 "	100 "	
Top of Tretaspis Series			105 "	
Average dip-slip (approx.)	75 m	165 m	100 m	

Figure), the same picture will arise as is shown on the geological map along faults of group 1. Note: a>b>c.

In Table 4. is shown the dip-slip calculated at different rock borders dislocated by faults of group 1. Except for the eastern fault which 'dies' towards the south, the figures are quite constant along each individual fault. This also indicates that the group 1 faults are formed by a vertical relative dislocation of the western block.

One can see from Plate I (I–6, J–6) that a certain horizontal drag has taken place along the fault by the hill Kisgruveåsen. However, the constant dip-slip along this fault shows that any horizontal displacement must have been negligible. The drag may have been caused by horizontal forces acting along the old breccia zone at an early stage, giving a plastic deformation without disrupture of the overlying sediments.

The limestone enclosed in the larvikite (G–10) appears to have been dislocated by the western branch of the 'great breccia'. In that case, the dislocation of the limestone is the opposite of the dislocation of the sediments further towards the north (see Plate I). As a constant dip on either side of the fault shows that no rotation has taken place, the two limestone bands rather seem to represent two stratigraphically different limestones. This is supported by the fact that the limestone east of the fault has twice the thickness of the limestone west of the fault.

Faults of group 1 may also have been active at an early stage. A lifting above sea level of the western side of the 'great breccia' (same relative displacement as the later described movements), before or contemporaneously with the deposition of the alum shales, can explain the stratigraphic wedging out of the alum shales west of this fault.

Corresponding movements along the fault south of the hill Kisgruveåsen before or contemporaneously with the deposition of the Orthoceras Limestone (also here the same relative displacement as the later observed movements) can explain the stratigraphic wedging out of the Orthoceras Limestone west of this fault. If the theory is valid, the Orthoceras Limestone has to be a shallow water deposit as the vertical displacement which gave dry land in the west has to be small. If the displacement had not been small, it would have manifested itself in Table 4, by somewhat higher values for the dip-slips below the

Orthoceras Limestone than for the higher units which were not yet deposited at the time of this movement.

The conclusion is that within the Cambro–Silurian area the faults of group 1 are dip-slip faults on which the western side is relatively lifted. The latest movements are younger than the downfolding of the sediments towards the intrusions (see p. 61). The group 1 faults are mainly reactivated Precambrian fault zones.

FAULTS OF GROUP 2

Only two faults belong to this group. One is seen in Plate I between (M–2) and (L–3). The area has a thick drift cover so that the downfaulted south-eastern side is exposed only in the river Dalselv, which runs in a 30–40 m deep canyon composed of alum shales down to the bottom. Little is known about this fault. It is younger than the heavily tectonized alum shales. A determination of the relative vertical displacement is impossible as the alum shales are eroded away on the up-faulted side, but it must be more than approx. 40 m. From the topography the strike of the fault plane is calculated to approx. N–50^g, and the dip is unknown.

The other fault belonging to group 2 is seen in the river Dalselv (K–4) where the fault plane makes a sharp bend of almost 100^g. South-westwards and south-eastwards from this bend there is no continuation into the alum shales of the fault. The alum shales are markedly dragfolded, showing that the fault is younger than the deposition of the alum shale. Because of the sharp bend, this fault must be a dip-slip fault. In the river Dalselv the fault plane is seen to dip almost vertically. For the same reason as for the other fault of this group, only a minimum value of 25–30 m is calculated for the dip-slip.

FAULTS OF GROUP 3

One fault belonging to this group has been traced from Sørby (O–2) to Trengen (M–5). South-west of Trengen it continues as a joint-zone with no dislocation. The fault possibly splits into two branches south-west of Dalen (M–4) and one branch follows a marked depression between Dalen and Skumtjern (L–5).

Another fault of group 3 is traced from Lintveit (P–3) along Rosstjerndalen to Store Lauvarvann (M–6), where it splits into three branches as seen between the two lakes (L–7). A more detailed map of this area is shown in Fig. 5. South-westwards from Lille Lauvarvann (K–8) only the two south-eastern faults can be traced. The north-western one continues as a joint-zone with no perceptible dislocation.

A generalized map along faults of group 3 is shown in Fig. 6. At a glimpse the relative movements seem to be horizontal with the south-eastern side dislocated towards the south-west. It is, however, shown by slickensides that vertical movements also have taken place. Actually there are more arguments against the faults of group 3 being strike-slip faults:

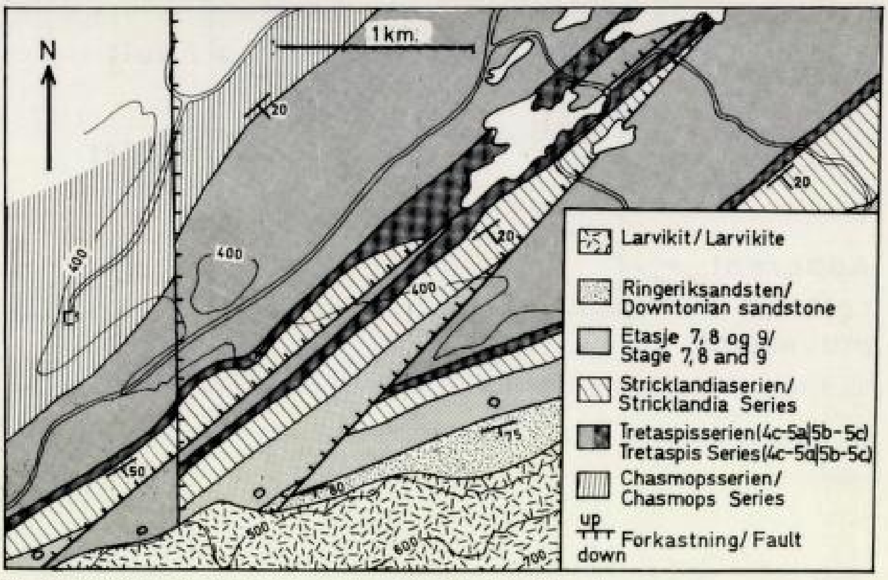

Fig. 5. Detailed map of the area south-west of the lake Store Lauvarvann.

1. Between P–3 and M–6, the strike of the fault plane makes a bend of some 10ᵍ (not clearly seen from the map). By horizontal movements, the rocks along the fault in this area should have been brecciated, not undeformed as they are.
2. The bedding dip changes from the usual 10–20ᵍ SE to almost horizontal near the faults of group 3. This effect on the bedding must have been caused by vertical drag along the fault planes by a relative lifting of the south-eastern side.

If the bedding, as in the described area, is dipping south-east, the dislocations shown on the generalized map (Fig. 6), will also develop if the south-eastern side of the fault is relatively lifted vertically. This is illustrated in Fig. 7.

By accepting the group 3 faults to be dip-slip faults, the above described dislocations of the borders near the intrusive contact, show that these faults are younger than the flexure towards the intrusions, which gave the supracrustals their increasing south-easterly dip.

This age relation can also be shown in another way. The fault north-east of Store Lauvarvann in the area O–3, as seen from aerial photographs, passes linearly through a canyon and a marked ridge. The terrain is here elevated some 50 m per 200 m. In this area, outside the flexure towards the contacts, the fault plane thus must be quite steep. (A dip of 70° would give a deflection of some 6°.)

If the faults of group 3 had been older than the downbending of the supracrustals towards the contacts, the fault planes near the intrusions would have been folded along with the supracrustals. The result would have been that for the last kilometre towards the contact, where the dip of the bedding changes

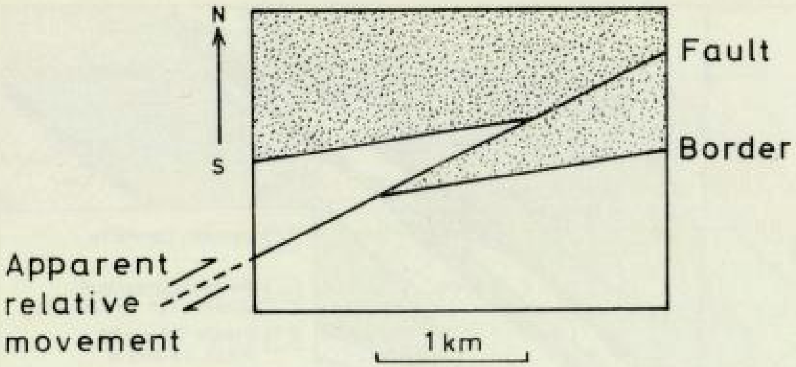

Fig. 6. Generalized map along faults of group 3.

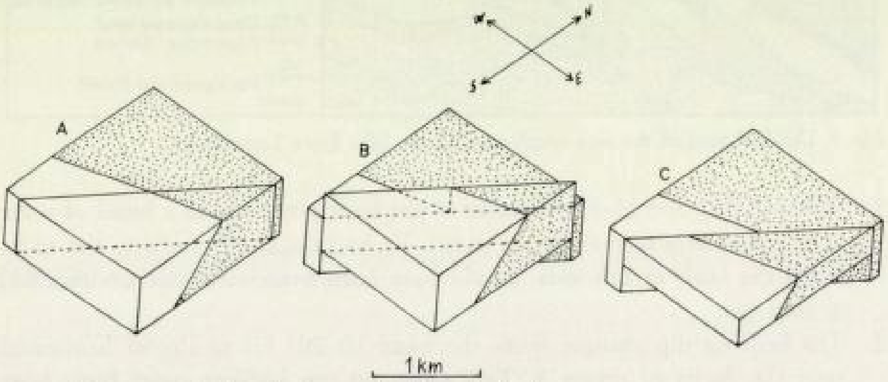

Fig. 7. Disrupture of a border by a vertical dip-slip fault.
A. Before faulting, the fault plane and a border are seen.
B. The south-eastern block is lifted relatively.
C. After erosion. The map is similar to that in Fig. 6.

from approximately 15^{g} SE to 80^{g} SE, the dip of the fault planes would have changed from nearly vertical (as by O–3) to some 35^{g} NW at the contact.

South-westwards from the lakes Store- and Lille Lauvarvann, however, the two faults of this group continue linearly to the contact, although the terrain is elevated some 100 m per kilometre along the faults. This shows that the faults must be *younger* than the downbending of the supracrustals, as the fault planes are nearly vertical all the way to the contact.

The conclusion is that the faults of group 3 are almost vertical dip-slip faults on which the south-eastern side is relatively lifted. The faults are younger than the downbending of the supracrustals towards the intrusive contacts. The total displacement along the subparallel group 3 faults is estimated to some 400 m throughout the faulted area.

AGE RELATIONS BETWEEN FAULTS OF GROUPS 1 AND 3

The formation of group 3 faults and the latest movements along group 1 faults took place after the downbending of the supracrustals towards the intrusives.

The age relations between the two groups of faults are difficult to solve, since both groups, inside the Cambro–Silurian area, are dip-slip faults with almost vertical dipping fault planes.

However, marked valleys along swarms of aplite dykes continue southwards into the larvikite along the extension of faults of group 1. This indicates that the latest movements took place after the larvikite was to a large extent consolidated. The somewhat younger aplite (see p. 59), found its way along the weak zones represented by the faults in the larvikite. Accordingly the aplite is not brecciated or mylonitized along the fault lines.

The faults of group 3 cannot be traced into the larvikite. This could be explained by the larvikite at this stage still being a melt. However, the faults are younger than the downfolding of the supracrustals, which most probably took place after the intrusion of larvikite, while it was still a melt (see below). My opinion is that the faults of group 3 were formed after the larvikite was partly consolidated, so that the supracrustals were no longer sinking into it. At this stage the core of the intrusion was still a melt, able to merge along weak zones in the outer shell, thus 'healing' the faults and blotting out the traces of them. If this is the case, the faults of group 3 must be somewhat older than the latest movement along faults of group 1.

TECTONIC HISTORY

1. Precambrian: Large movements along the 'great breccia' (E–5) and the breccia along the hill Kisgruveåsen (J–2); possible movements also along the fault by Heistadmoen (M–2).
2. Before or contemporaneously with depositon of the alum shales: possible minor relative lifting of the western block along the 'great breccia'.
3. Before or contemporaneously with deposition of the Orthoceras Limestone: possible minor relative lifting of the western block along the fault by the hill Kisgruveåsen.
4. After deposition of the alum shales: formation of the fault in the river Dalselv (K–4) by a relative sinking of the south-eastern block. Movements also along the fault by Heistadmoen (M–2). Both faults belong to group 2.
5. After deposition of the Asaphus Series: formation of the fault (group 1) west of Muggerud (J–5), probably by a relative lifting of the western block.
6. Contemporaneously with the intrusion of larvikite: downfolding of the supracrustals into the melt.
7. After intrusion of the larvikite, before complete consolidation: formation of faults of group 3 by a relative lifting of the south-eastern blocks.
8. Larvikite just consolidated, before or contemporaneously with intrusion of aplite: new relative lifting of the western blocks along the 'great breccia' and the fault by the hill Kisgruveåsen. The less prominent group 1 fault west of Muggerud was possibly formed at this stage.

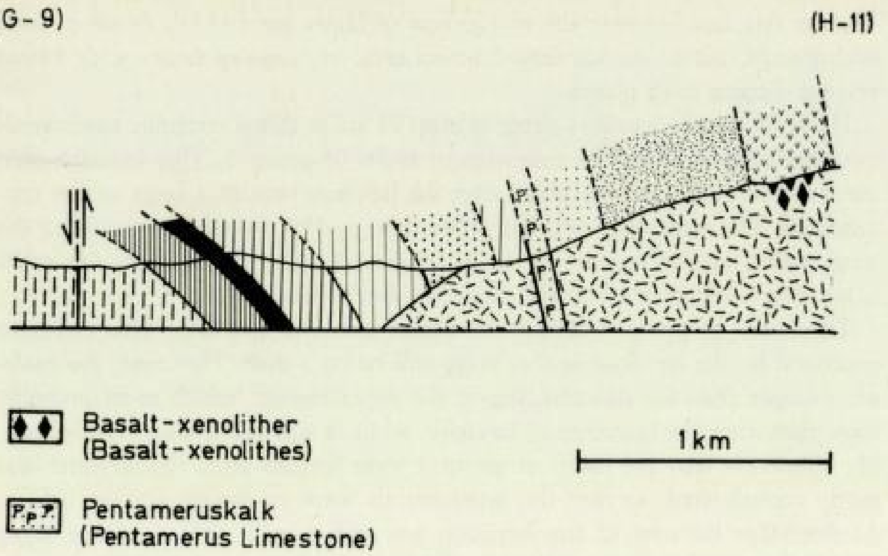

Fig. 8. Section from the Precambrian rocks in the north-west (G–9) to the mountain Skrimtoppen (H–11). Legend is given on the geological map (Plate I).

ORIGIN OF THE FAULTS, DISCUSSION OF THE BORDER RELATIONS TOWARDS THE INTRUSIONS

All the faults described, except those of group 3, have in post-Cambrian time caused a relative sinking of the land mass east and south-east of the faults. Together they may represent a system of faults, activated at different times, connected to the downfaulting of the Oslo Graben. If the latest movements along the 'great breccia' and the fault along the hill Kisgruveåsen are parts of the Oslo region subsidence, this subsidence must have lasted until after the intrusion of larvikite.

The faults of group 3, which have caused a relative lifting of the south-eastern land mass, must be explained in another way. In the area described these faults are considered younger than the downfolding of the supracrustals towards the intrusions.

The same general picture is seen at different places in the Oslo region near the big intrusions; only the age relations between downfolding and upfaulting towards the intrusions are not yet straightened out.

Some mechanisms which might have given these border relations are discussed below.

1) In the area described the downfolding of the supracrustals may have been connected to the intrusion of larvikite, while the upfaulting towards the intrusions could have been a result of the later intrusion of more viscous ekerite (see Plate I). This theory, however, does not seem valid, as elsewhere in the Oslo region similar border relations exist towards only one intrusive body.
2) The intrusive contact may represent an old fault zone, along which the south-eastern land mass has sunk, either as part of the Oslo region

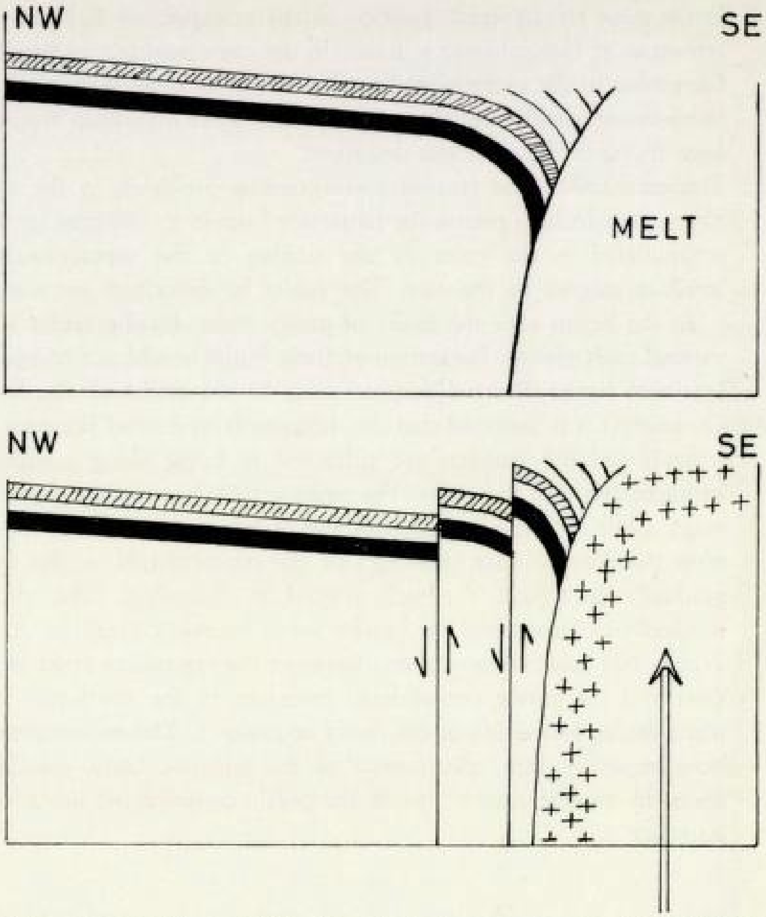

Fig. 9. Top: The supracrustals are sinking into the hot magma because of their higher density.
Bottom: A late upward movement of the partly crystallized magma leads to formation of the faults of group 3.

subsidence, or as a cauldron subsidence. The steep dip of the supracrustals towards the contact is caused by a drag along the old fault plane. Later the intrusives have forced their way up to their present position during formation of the group 3 faults.

A couple of hundred metres north-west of the mountain Skrimtoppen (H–11), huge xenoliths of augite porphyry are found within the larvikite. At the summer farm Grønnliseter (H–10) a limestone bed, approx. 50 m thick, is enclosed in the larvikite. In Fig. 8 is shown a section from the Precambrian border (G–9), through the limestone at Grønnliseter and further towards the south-east through the basalt xenoliths to the mountain Skrimtoppen. The bedded sequence is extrapolated south-eastwards from the contact. The different sedimentary units are drawn with correct thicknesses and the same steep dip as measured by the contact.

As seen from the section, the augite porphyry–xenoliths are found exactly in the same stratigraphic position as the extrapolated B_1-basalt, while the limestone at Grønnliseter is found in the same position as the Pentamerus Limestone in the extrapolated section. With an older down-faulting of the south-eastern land mass along the contact, these inclusions would not have been found in the positions described.

3) Brøgger (1883) has treated corresponding problems in the Langesund–Skien area. In his opinion the faults are formed to compensate the tension accumulated in the crust by the sinking of the supracrustals into the larvikite magma in the east. The faults he described are normal faults.

   In the Skrim area the faults of group 3 are dip-slip faults with almost vertical fault planes. Formation of these faults would not compensate such tensional forces directed perpendicular to the strike of the fault planes.

4) On page 61 it is assumed that the differences in density between the supracrustals and the magmas are sufficient to bring along a sinking of the supracrustals into the melts. The sinking must have taken place at an early stage, while the melt was still hot and of low viscosity (Fig. 9, top). Later, after the downfolding (sinking) of the supracrustals, as the temperature gradually decreased, the melt started to crystallize. The viscosity was markedly increased and the border zones became crystalline. At this stage (see p. 67) relative movements between the crystalline crust in the north-west and the partly consolidated intrusion in the south-east have taken place during formation of the faults of group 3. The movements may have been caused by late 'adjustments' of the intrusive body, possibly brought about by vapour activity inside the partly consolidated intrusion (Fig. 9, bottom).

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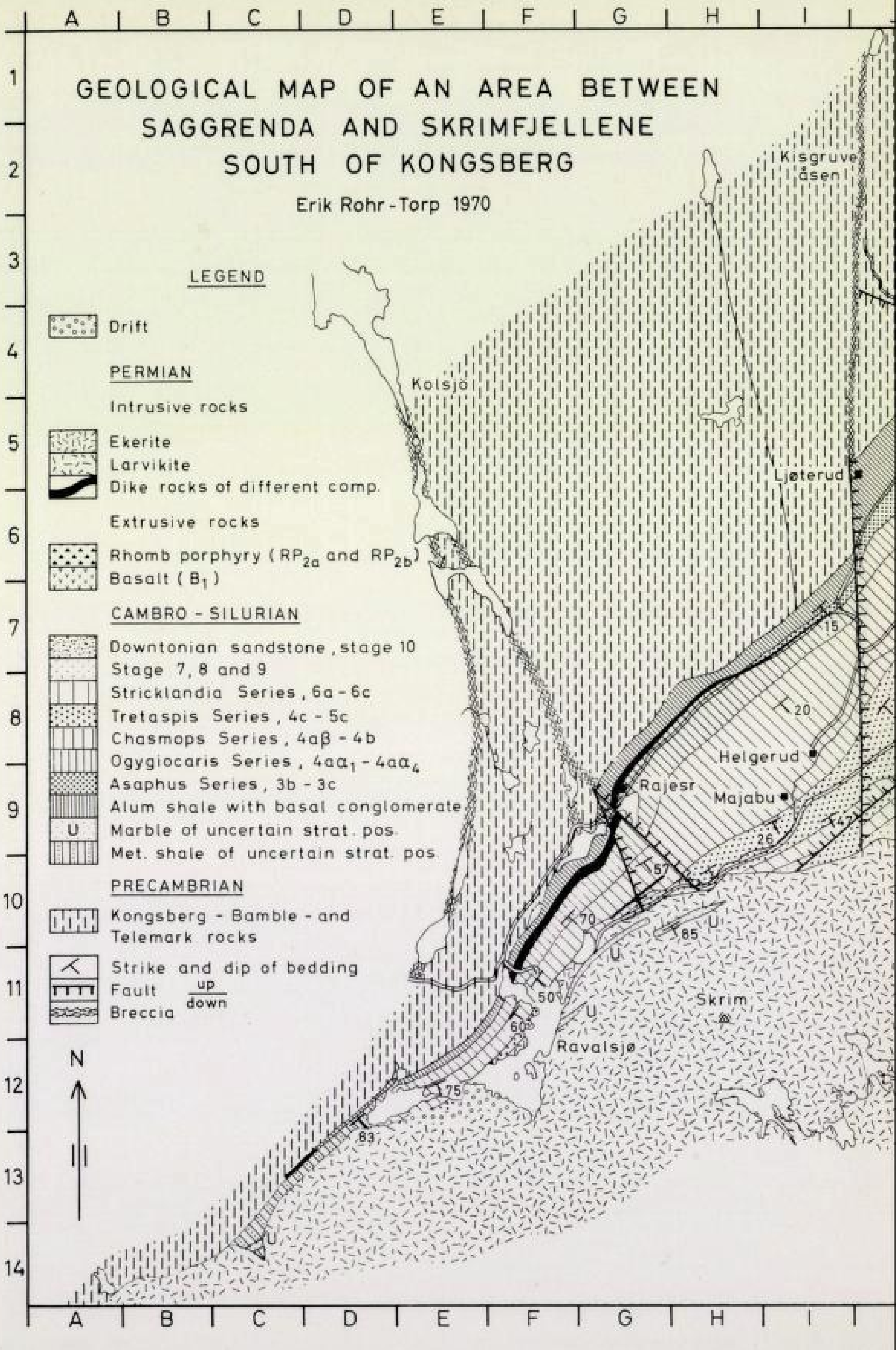
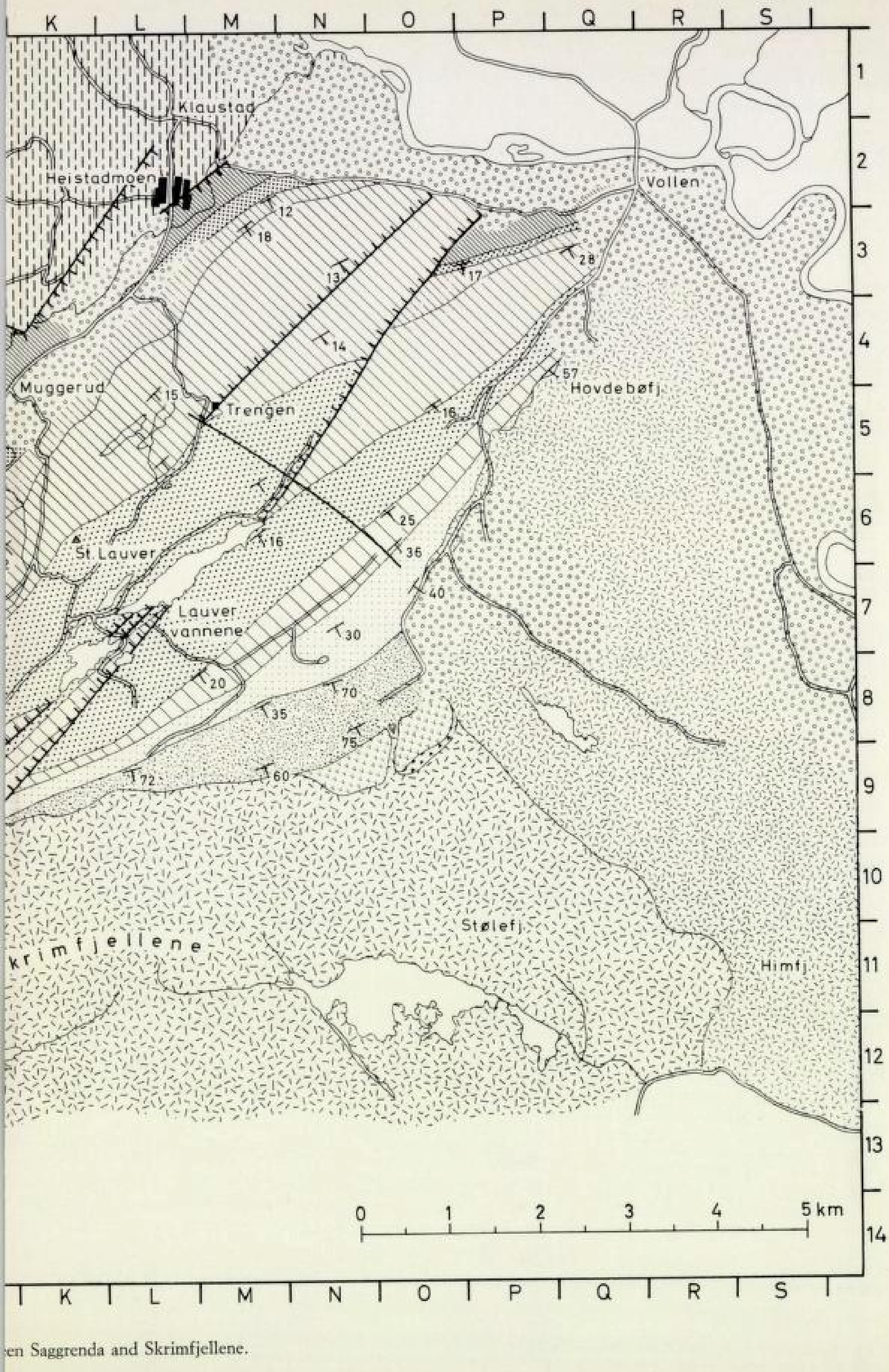


Plate I. Geological map of an area b



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