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On the Precambrian bedrock and its structure in the Pellinge region, South Finland

by Matti Laitala

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ON THE PRECAMBRIAN BEDROCK AND ITS STRUCTURE IN THE PELLINGE REGION, SOUTH FINLAND

BY

MATTI LAITALA

WITH 41 FIGURES AND NINE TABLES IN THE TEXT
AND FIVE APPENDICES

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The Pellinge region belongs to the Svecofennian mountain system. In the north and south, the district is bounded by late-orogenic granites and in the east and west by anorogenic granites of the rapakivi class.

The rocks of the area are for the most part sedimentogeneous, with pyroclastic sediments contributing a goodly share to their composition. The rocks situated at the bottom of the supracrustal formation, which has a thickness of about 6 500 m, are quartz-feldspar schists and gneisses. Occurring among them as intercalations are mica- and hornblende-bearing schists and gneisses. In mineral composition, these rocks correspond to arkoses, graywackes and subgraywackes. Associated with them are minor conglomerate and limestone layers. Overlying them are pyroclastic sediments, tuffites and agglomerates, with intercalations composed of uralite- and plagioclase-porphyritic metabasalts and pillow lavas. Uppermost, the uralite porphyrites make up larger continuous basalt formations. In addition, there occur in the region many separate formations of plutonic rocks, varying in composition from gabbro to granite.

Deviating from the rocks of southern Finland in general, those found in the Pellinge district are exceedingly well preserved. Plenty of observations of primary structural features have been made of the pyroclastic sediments in particular and also of the basalts, and this has made it possible to put together a picture of the large-scale folding that has taken place in the region. The mode of folding is isoclinal, and the area as a whole forms a synclinorium. In the light of the diagrams drawn of the planar and linear structures, the relation of these structural elements to the folding has been clarified and an interpretation made of the main features of the development of the overall geological structure of the study area caused by the folding.

A brief description of the local plutonic rocks, is included and their connection with the structure and folding of the region is discussed.

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INTRODUCTION

The Pellinge area, which is the subject of the present paper, is situated in the coastal region of southern Finland. It comprises the southeastern section of the rural commune of Porvoo and the southwestern section of the district of Pernaja. It is situated about 60 kilometers east of Helsinki and roughly 25 km southeast of the nearest town, Porvoo. The situation of the area is shown in Figure 1. Its length, measured along an east-west line, is about 25 km and its breadth, extending north-south, about 10 km. For the most part, the area consists of islands, of which there are many and which vary in size from 15 sq. km to — in the case of skerries — only a few sq. meters. In the mapping work, maps of the separate rural districts (= communes) and aerial photographic maps on the scale of 1:20 000 were utilized as reference maps, in addition to which stereoscopic photographs on a scale of approximately 1:37 000 were examined.

The area emerged for the first time as an exploration target of the Geological Survey of Finland at the end of the 1870s in connection with mapping operations. As a result of the mapping program, a map of a general nature on the scale of 1:200 000 was published, together with an explanatory text (Moberg 1881).

Early in the second decade of the century, J. J. Sederholm explored the area more thoroughly (Fig. 1, Area 1) and the results were published in 1923. Many investigations have subsequently been made in the near vicinity — on the western side (Fig. 1, Area 2) by C. E. Wegmann and E. H. Kranck (1931) as well as by L. H. Borgström (1931) (Fig. 1, Area 3), and on the eastern side, in the rapakivi belt, by Wahl (1925), Simonen and Vorma (1969) and Vorma (1971). Having a close bearing on the area is Vaasjoki's study (1953) on the Pernaja district (Fig. 1, Area 4). The area dealt with in the present work is the same one investigated by Sederholm (Fig. 1, Area 1 and Appendix 1).

In his earlier research in southern Finland, Sederholm (1907) had paid particular attention to the description and interpretation of various granitization phenomena as well as to stratigraphic classification. In pursuing his objectives, Sederholm (1923) also put chief emphasis on the Pellinge area, where he divided the supracrustal rocks into two age groups, separated by a distinct hiatus. The conspicuously metamorphosed rocks occurring at the northern margin of the area, which include, besides the rocks of mainly sedimentogeneous origin, tuffites and basic basalts as well as plutonic rocks, make up, in this classification, the oldest category, the so-called Svionian group.

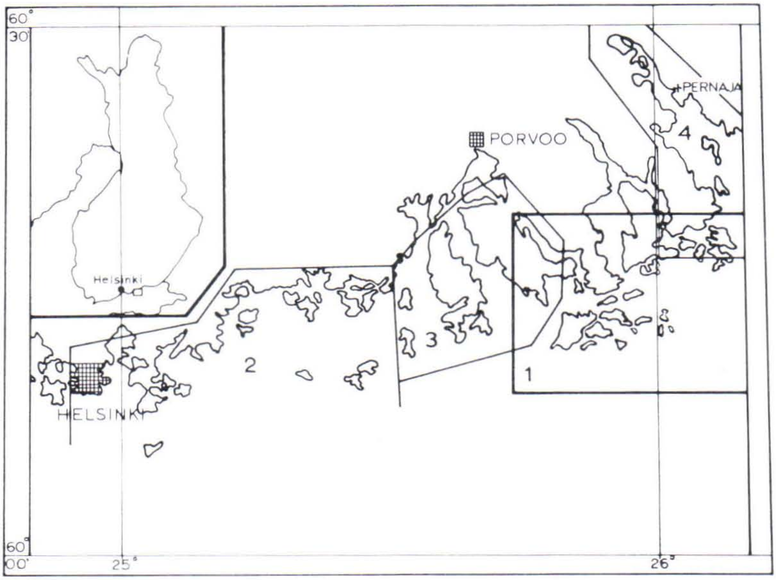

FIG. 1. Location of areas investigated and mapped in detail in the southern Finnish coastal region to the east of Helsinki. 1- The Pellinge district, investigated by Sederholm (1923). This is the same region dealt with in the present work. 2- The coastal stretch between Helsinki and Onas (Wegmann and Kranck 1931). 3- The granite area of Onas (Borgström 1931). 4- The Pernaja district (Vaasjoki 1953).

The more weakly metamorphosed supracrustal rocks, occurring in the middle of the area, belong to a younger class than the former to make up the so-called Bothnian group. The rocks of this group are mainly tuffites as well as lava rocks (uralite and plagioclase porphyrites), which he breaks down further into two subdivisions, representing different ages. In addition, the group includes the plutonic rock separating the foregoing sub-classes as well as the migmatitic granites met with in the northern and southern sections of the area.

The very youngest class comprises the granites of the rapakivi group occurring in the western and eastern parts of the area.

With the exception of the last-mentioned, youngest age group, this age classification arrived at by Sederholm for the rocks of the area caused a lively exchange of differing views, the participants being Mäkinen (1924, p. 361—366), Sederholm (1924, p. 542—548) and Eskola (1924, in a newspaper article commenting on Mäkinen's critical sally). Later, Sederholm (1933, p. 20) changed his opinion of the Bothnian in Pellinge: ». . . dass er jetzt alle Metabasalte (Uralitporphyrite) zu einer Formation rechnet.» This change evidently involved only the two subdivisions of the so-called Bothnian group, which he combined into a single class of the same age. The major divisions, involving the Svionian and Bothnian groups, separated by a hiatus, remained steadfast in his age classification (Sederholm 1926, 1932, 1934).

On the basis of the stratigraphic classification of the supracrustal rocks, Sederholm (1923, 1931, 1932, 1934) also divided the plutonic rocks into four groups. The plutonic rocks of the first category are associated with the folding of the Svionian supracrustal rocks; those of the second group are associated with the diastrophism of the Bothnian formation; those of the third group are involved in the Karelian orogeny; and, finally, the plutonic rocks of the fourth group have not been involved in any orogenic movements.

In the view of several researchers (Mäkinen 1915, Eskola 1936, Wahl 1936, Simonen 1948), there exist no valid grounds for dividing supracrustal rocks into Svionian and Bothnian categories. Nowadays, they are regarded as belonging to the same Svecofennian orogenic formation. In the classification of plutonic rocks, too, the prevailing points of view have undergone change since Sederholm. With their study, Wegmann and Kranck (1931) introduced the idea of a magmatectonic classification of the Svecofennian plutonic rocks. Wahl (1936) drew attention to the close relationship prevailing between the intrusion and orogeny of plutonic rocks, and he divided them into »prim-orogenic» and »ser-orogenic» categories. Later, the terms applied by Eskola (1930) to these categories began to be used, namely, »synkinematic» and »late-kinematic» plutonic rocks. At present, plutonic rocks are divided, according to their situation and orogenic folding, into preorogenic, synorogenic, late-orogenic, postorogenic and anorogenic groups (Simonen 1969), of which the synorogenic and late-orogenic groups correspond to the ones proposed by Eskola (1930) and Wahl (1936).

In Sederholm's (1923) study dealing with the Pellinge area, no attention whatsoever is paid to the structural features. The present study is planned to cast light on this aspect of the matter. At the beginning, a brief description will be given of the supracrustal rocks and the primary structures observed in them. By reference to these structures, an attempt will be made to work out the overall structure of the area, and by means of diagrams made of the structural elements, the main outlines of the structural development. In conclusion, a brief description will be offered of the infracrustal rocks and their place in the structural picture.

MORPHOLOGY AND THE MAIN FEATURES OF THE BEDROCK

As far as its character is concerned, the area runs true to the southern Finnish coastal type, with its myriad islands. In the western section, the closely bunched islands form a typical inner archipelago. In the eastern section, excepting the immediate proximity of the coastline, the islands are small and scattered, forming a typical outer archipelago.

The elevations to some extent depend on the kinds of rock present in the various places. Thus the fine-grained and erosion-resistant basalts occurring in the middle of the area form ridges that rise above the surrounding country. Taken as a whole, however, the relief of the area is low. The highest point above sea level is about 20 m, and the greatest depth of the water in the eastern section marked on the marine chart is about 60 m.

The forms of the islands and their relative positions reflect in many places the features of the geological structure of the area. On the nearly vertical flanks of the folds, where the schistosity and bedding planes join, the longitudinal axes of the islands and the rock exposures run parallel to them. At the core of the folds and especially at their crests, the longitudinal trend lines of the islands adhere to the bedding planes. The shores of such islands also slope more gently in the direction of the dip of the beds.

The most conspicuous fracturing of the bedrock has taken place in line with the schistosity and along the plane perpendicular to the axis of the main folding. As they exist at present, they afford good channels for the water traffic, which, especially in the summertime, is quite lively.

The study area (Appendix 1) belongs to the formation known as the Svecofennian mountain range. It is bounded on the east and the west by younger granites belonging to the rapakivi group. In the north and the south (not visible on the map), there occurs migmatitic granite, which is characteristic of the coastal region of southern Finland. At the northern margin of the area, there are sedimentogeneous schists and gneisses of varying composition, conglomerates and minor occurrences of limestone and skarn. The largest part of the area consists, however, of lava rocks and sediments of volcanic origin, which vary in composition from basic to intermediary. Inside the area are numerous rather small, separate gabbro, quartz-diorite and granodiorite intrusions, to the last-mentioned of which are also connected small granite occurrences in the eastern section of the area.

The primary structures preserved in the sediments have made it possible to work out the folding pattern and stratigraphic sequence of the area. In the area there occur sizable arching synclines and anticlines, the axes of which plunge at angles ranging from 15° to 40° toward the northeast or the east. On the flanks of these larger folds, there appears folding on a small scale with axial directions varying from slight westerly to sharp southwesterly. The style of the folding is isoclinal. The area as a whole is a synclinorium, with the volcanic rocks overlying the sedimentogeneous rocks occurring at the northern margin of the area.

SUPRACRUSTAL ROCKS

Metasediments

At the northern margin of the study area, supracrustal rocks form a zone trending approximately east-west. In the western section, this zone is about 4 km broad and continues eastward in a breadth of about 0.5 km to the north side of Risholm all the way to the rapakivi contact. The zone corresponds to the area that Sederholm (1923) termed the formations of Sundarö and Rabbasö. Corresponding rocks are met with separated from this continuous zone also on the north shore of Stor Pellinge and on a single islet in the sea at the south end of the area, about 1 km south of Långö.

The predominant rocks in this zone are quartz-feldspar schists and gneisses with intercalations of mica schists and gneisses, amphibolite and hornblende gneisses. In addition, there are minor occurrences of conglomerate, limestone and skarn.

Quartz-feldspar schists and gneisses

At the north margin of the afore-mentioned zone, which runs on the north side of Risholm across the southern part of Sundarö and Sarvsalö to Kardrag, the quartz-feldspar schists are generally fine-grained. The grain size is less than 0.2 mm. The bedded structure of the rock is clear-cut and well preserved. Intercalations mica schist and amphibolite occur in the rock in moderate abundance.

The principal minerals of the quartz-feldspar schists are quartz, plagioclase (An_{10-25}) and biotite. The relative amounts of quartz and plagioclase vary. Additional minerals are potash feldspar, hornblende, chlorite, epidote, muscovite, sillimanite and, in a few instances, also diopside. The hornblende content varies greatly and in places is apt to be so high as to place the rock in the amphibolite or hornblende-gneiss class. The hornblende is evidently a product of volcanic activity. Accessory minerals are magnetite, apatite, sphene, calcite and — present in a couple of the thin sections examined — also tourmaline.

To the south of Kardrag, on the south side, approximately, of the Tirmo-Granö line, the rock gradually turns coarser, becoming a quartz-feldspar gneiss, the grain size of which is less than 1.5 mm. Owing to metamorphism and strong folding on a small scale, the clear bedded structure characteristic of the fine-grained type has disappeared. The quantity of intercalations rich in amphibole is smaller than in the rocks of the northern margin; but, on the other hand, there is a more abudant occurence of intercalations rich in mica. The locality is further marked by the occurrence of small conglomerate and limestone intercalations.

The chief minerals of the gneiss are quartz and either oligoclase or potash feldspar. Present, in addition, are biotite, muscovite or sericite. Quartz occurs not only in the fine-grained ground mass, especially in the southern part of the area, but also as rounded phenocrysts, measuring between 3 and 4 mm in diameter, or as grain clusters, frequently possessing a faintly bluish color. Both the plagioclase and the potash feldspar are in places conspicuously sericitized.

In addition to the principal minerals, the rock contains in places — mainly in the zone running from Sundö past the north side of Rabbasö to Byttholm —

strongly pinitized cordierite. The accessory minerals are sphene, apatite, epidote and calcite.

Mica schists and mica gneisses

Mica schists and mica gneisses occur as narrow zones or intercalations among the quartz-feldspar schists and quartz-feldspar gneisses described in the foregoing. In places the bedding of the mica schists is quite clear-cut, but in other places, owing to the effect of metamorphism, it has disappeared at the same time as a growth in the grain size has occurred. The grain size of the mica schists is less than 0.2 mm and that of the mica gneisses less than 1 mm. In both cases, the mineral composition is the same. The principal minerals are quartz, biotite and, in varying amounts, both potash feldspar and plagioclase (An_{20-25}). In addition, the rock contains garnet, cordierite and sillimanite. Accessory minerals are sphene, magnetite, apatite, epidote, zircon and, in a few instances, tourmaline.

Amphibolites and hornblende gneisses

Among the quartz-feldspar schists there also occur intercalations of amphibolites, the chief minerals of which are plagioclase, hornblende, quartz and, in places, potash feldspar. At the northern margin of the area, in the Kardrag-Risholm zone, they are a common occurrence; and in places their original bedded structure, notably in the eastern section, is well preserved. The transition into quartz-feldspar schist is frequently observed to take place gradually as the hornblende content decreases.

On the south side of the Tirmo-Granö line, these schists have metamorphosed most conspicuously with the result that the original stratified structures have disappeared. Simultaneously, an increase in the grain size has taken place, and the rocks are at present hornblende gneisses.

The grain size of the amphibolites is less than 0.2 mm and that of the hornblende gneisses less than 1.5 mm. The composition of the plagioclase is generally oligoclase, but in places it is apt to rise up to An_{35}. Additional components are cummingtonite, biotite, chlorite, epidote and, in the more basic types, also diopside.

Conglomerates

On the south side of the Tirmo-Granö line, there are also conglomerates among the quartz-feldspar gneisses. At Tirmo they occur only as minor intercalations, whereas farther south, in the Sundö-Viasholm zone, they occur as longish and continuous belts.

The conglomerate layers vary from 1 to 20 m, the widest of them being in the southern part of the zone. One of the best occurrences is to be seen on the east shore of Sundö, where a decrease in both the size and number of the conglomerate pebbles is to be observed towards the southern margin of the bed.

The pebbles in the conglomerate are light-colored. In mineral composition and structure, they resemble the surrounding quartz-feldspar gneisses.

The mass in between the pebbles is of a darker color. The principal minerals are quartz, plagioclase, biotite, hornblende, and microcline. In addition, cummingtonite, epidote and, in one instance, also some diopside are present. Quartz occurs not only as a fine-grained mass but also as larger, rounded phenocrysts, or as clusters of many grains. Similarly, the plagioclase is apt to occur in the form of larger phenocrysts corroded around the edges. The composition of the plagioclase is An_{20-25}. The amount of amphibole varies considerably. It increases consistently, however, in the direction of the volcanic area occurring on the southern side.

Limestones and skarns

On the north shore of Sundö, on the little island situated to the east of it and on the island of Stor Byttholm, limestone and skarn occur along with the quartz-feldspar gneiss as intercalations about one meter thick and a few meters long. The limestone is generally impure, containing in addition to calcite also dolomite and wollastonite as well as skarn minerals, such as garnet, diopside, hornblende and epidote.

Mineralogical and chemical character of the metasediments

The microtextures of the rocks of the north margin are granoblastic or blastoclastic. Table 1 gives the mineral compositions of the rocks of the area, which have been determined, like the mineral composition of all the rocks reported on in this paper, by the point counting method (Chayes, 1949). Analyses 1—6 represent the compositions of the quartz-feldspar gneisses occurring south of the Tirmo-Granö line. In the making of the determinations, staining with potassium-rodizionate (Bailey and Stevens, 1960) was done in a few instances to differentiate between the quartz and the plagioclase on account of their close similarity. Sederholm (1923, p. 69) reported that a sample taken from Stor Byttholm contained (as determined by the so-called Rosiwal method) quartz 76% and muscovite 24%. No quartz content as high as that has been met with, however, in thin sections of samples taken from the same sites and stained by the foregoing method (Table 1, Nos. 2, 4 and 5). Analyses 7—9 represent the mineral compositions of the quartz-feldspar schists occurring on the north side of the afore-mentioned line. Noteworthy in these is their relatively high biotite content, and on the basis of their composition the rocks are intermediary forms between the afore-mentioned quartz-feldspar gneisses and mica schists. The composition of the mica schists is represented in Table 1 by analysis No. 10. The composition of the amphibolite intercalations is represented by analysis No. 11. These are probably products of volcanic activity that took place during the sedimentation stage.

TABLE 1

Mineral compositions of sedimentogeneous rocks at the northern margin.

	1	2	3	4	5	6	7	8	9	10	11
Quartz	60.1	53.9	51.4	48.8	48.2	47.2	45.0	41.5	31.4	30.1	19.0
Potash feldspar		9.0	21.9		35.6			4.2	0.6		
Plagioclase	6.6	0.6	13.6			40.1	25.5	27.3	46.1	29.1	58.4
Biotite	5.2	1.1	13.0			5.6	19.0	25.8	19.0	40.5	
Muscovite	13.0	35.4			16.1						
Sericite				51.2							
Cordierite	14.8					7.1					
Hornblende							5.3		2.2		20.1
Calcite							4.0				
Epidote											1.3
Accessories	0.3		0.1		0.1		1.2	1.2	0.7	0.3	1.2
	100	100	100	100	100	100	100	100	100	100	100

1. Quartz-feldspar gneiss. Hallonholm, rural commune of Porvoo
2. Quartz-feldspar gneiss. Stor Byttholm, Pernaja.
3. Quartz-feldspar gneiss. Rabbasö, Pernaja.
4. Quartz-feldspar gneiss. Stor Byttholm, Pernaja.
5. Quartz-feldspar gneiss. Stor Byttholm, Pernaja.
6. Quartz-feldspar gneiss. Bockholm, rural commune of Porvoo.
7. Quartz-feldspar schist. Brändholm, Pernaja.
8. Quartz-feldspar schist. Aparnäsudd, rural commune of Porvoo.
9. Quartz-feldspar schist. Kardrag, rural commune of Porvoo.
10. Mica schist. Kardrag, rural commune of Porvoo.
11. Hornblende gneiss. Stora Andholmen, Pernaja.

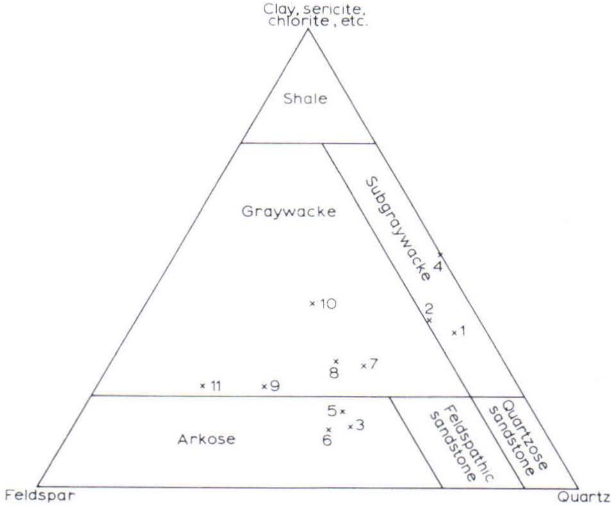

FIG. 2. Mineral compositions of sedimentogeneous rocks of the north margin, marked in triangular diagram.

TABLE 2

Chemical compositions of sedimentogeneous rocks at the northern margin.

	1	2	3	4
SiO_2	76.76	79.90	75.34	76.37
TiO_2	0.91	0.45	0.32	0.41
Al_2O_3	11.55	10.38	12.59	10.63
Fe_2O_3	0.34	1.48	0.48	2.12
FeO	0.70	0.60	1.42	1.22
MnO	—	—	0.05	0.25
MgO	1.05	0.83	0.79	0.23
CaO	0.82	1.90	1.87	1.30
Na_2O	2.27	3.25	3.32	1.84
K_2O	5.40	0.99	2.90	4.99
H_2O+	0.01	0.06	0.92	} 0,83
H_2O-	0.50	0.60	0.04	
P_2O_5	—	—	0.06	0.21
CO_2	—	—	—	0.54
	100.31	100.44	100.10	100.94

1. Quartz-feldspar gneiss. Hönsholm, rural commune of Porvoo. Anal. Åge Renvall, 1934.
2. Quartz-feldspar schist pebble of conglomerate. Sundö, rural commune of Porvoo. Anal. Åge Renvall, 1934.
3. Quartz-feldspar schist. Hästö, Pernaja. Anal. Aulis Heikkinen.
4. Arkose, average analysis. Pettijohn 1957, p. 324.

To clarify the origin of the rocks present in the north margin, analyses 1—11 in Table 1 are marked (Fig. 2) by a triangular diagram (Krumbein and Sloss 1951, p. 130). Accordingly, Nos. 1, 2 and 4 are subgraywackes, Nos. 3, 5 and 6 arkoses and Nos. 7—11 graywackes.

Analyses 1 and 3 in Table 2 give the chemical composition of the quartz-feldspar gneiss and quartz-feldspar schist occurring in the north margin. When these compositions are compared with the mean-value analysis for arkose (Pettijohn 1957, p. 324) reported in analysis 4 of Table 2, they are found to correspond to each other and thus to be arkoses by origin.

Likewise, analysis 2 of Table 2, which represents the chemical composition of a fragment embedded in the conglomerate, corresponds in the main to the composition of the feldspar gneisses of the area. These conglomerates are to be regarded as intraformational deposits *sensu* Pettijohn (1957, p. 276).

Metapyroclasts

A substantial proportion of the volcanic rocks of the area are pyroclastic. By origin, they had been tuffs varying in grain size from fine to coarse as well as agglomerates, which in connection with later folding had undergone metamorphism. In the following discussion, the metamorphosed tuffs will be termed tuffites.

The tuffites and agglomerates occur numerously as beds varying in thickness from less than a meter to several tens of meters. Most commonly, these beds consist of numerous easily differentiated layers, though in some places no layered structure can be detected. This is the case especially with the agglomerate beds. The thicknesses of the separate layers composing the tuffite beds vary from less than a centimeter to a few dozen centimeters.

Fine-grained basic tuffites

Basic tuffites prevail in the area. Their mineral composition is similar to that of the basalts, uralite porphyrites and plagioclase porphyrites of the area. As for color, they are dark. The principal minerals are green hornblende of varying dark shades and andesine. In addition, there generally occur differing amounts of epidote, chlorite, biotite and quartz. Accessory minerals are sphene, magnetite and zircon.

Among the commonly occurring dark tuffites, there are present in places (e.g., on the south shore of Stor Pellinge, the west shore of the northern section of Älskholm and the west shore of Gåsholm) layers that stand out clearly from their surroundings by virtue of the lighter color of their weathering surface (Fig. 3). The

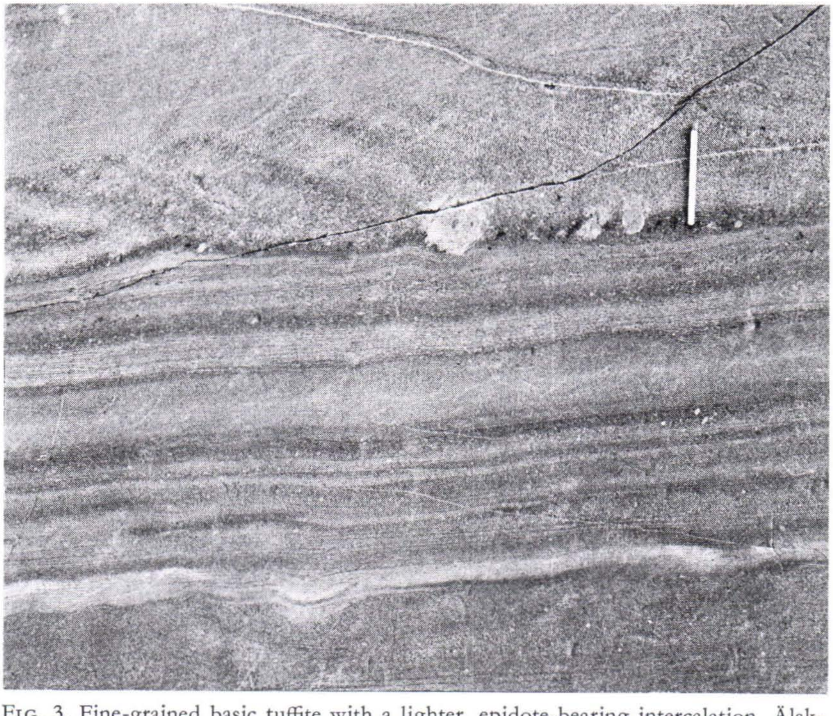

FIG. 3. Fine-grained basic tuffite with a lighter, epidote-bearing intercalation. Älskholm, N section, rural commune of Porvoo.

light color of these layers is due to the presence of epidote, which occurs in abundance in addition to the light green hornblende and andesine. Moreover, the layers also contain larger amounts of quartz.

The grain size of the basic tuffites varies. In the fine-grained types, the grain size is less than 0.1 mm, and in the coarser types less than 0.4 mm. The commonest types are the ones with a grain size of under 0.2 mm. Both the fine-grained and, especially, the coarser tuffites are also apt to contain uralite and plagioclase phenocrysts and fragments of a larger size, that is, around 1 mm in diameter. The plagioclase in such instances is conspicuously sericitized.

Along the northern edge and in the western part of the volcanic area, changes have taken place in the basic tuffites in places through the effect of stronger metamorphism. The original layered structure has disappeared and the grain size grown. The grain size of the amphibolitic rocks is under 2 mm. The mineral composition is the same as in the preserved tuffites.

Coarse-grained basic tuffites and agglomerates

Besides the afore-described fine-grained tuffites, there also occurs in the area an abundance of coarser pyroclastic sediments varying in grain size, which likewise contain fragments of varying size. With respect to their grade of coarseness, these compose a continuous series ranging from fine tuffites to agglomerates and volcanic breccias. They are closely associated with the fine tuffites and likewise occur as alternating beds stretching several meters in breadth.

The grain size of the ground mass of the coarse-grained pyroclastic sediments varies from 0.5 mm to 4 mm. The chief minerals are hornblende and andesine, which usually has sericitized. In addition, the groundmass is apt to contain epidote, biotite, quartz and chlorite.

The size of the fragments present in these rocks varies considerably, too (Fig. 4). The diameter of the smallest is ca. 1 cm, and the largest of the fragments observed are ca. 2 m in diameter. Most common, however, are fragments with a diameter of from 2 cm to 20 cm. In highly deformed areas (e.g., east of Julö) the fragments are likely to be so greatly lengthened that at present they occur as stripes 1—3 cm wide and 1—2 m long.

In different parts of the area, differences are likely to be observed in the composition of the fragments of agglomerates. Throughout the area, uralite-porphyritic and plagioclase-porphyritic fragments are predominantly present. In addition, also quartz-feldspar schist fragments occur at the north margin of the western part of the area. They are once more met with in the southern part of the same area, but not quite so abundantly as at the northern margin. Around Fobistholmarna, fine-grained feldspar-porphyric fragments occur in abundance among the fragments. In the southeastern half of the Furuholmarna area, the fragments are likewise fine-grained, feldspar-porphyric rocks and plagioclase-porphyritic rocks. In addition,

FIG. 4. Agglomerate. Island situated about 200 m west of Utterholm, rural commune of Porvoo.

the fragments include amygdaloid lava, stratified tuffite and, in places, very fine-grained pieces consisting of quartz, plagioclase and potash feldspar, the grain size of which runs under 0.01 mm. In association with the acid tuffite occurring at Furuholmarna, the agglomerates also contain an acid groundmass, in which the fragments are of basic tuffite and lava material. The areal division made on the basis of the agglomerate fragments just described is quite general in character.

Quantitatively, the fragments present in the agglomerates vary. In places, only a few occur here and there, whereas in other places they are present in such abundance that they account for an estimated 90% of the total material. This is true of, for example, the agglomerate (Fig. 5) situated in the reef to the southeast of Furuholmarna. Most commonly, the fragments account for an estimated 20%—40% of the total.

There are different types of agglomerates, the differences being probably due both to the degree of deformation and, possibly, a different mode of origin. The type most commonly met with in the area is represented by beds containing numerous fragments stretched out in line with the schistosity, fragments of different sizes being evenly distributed throughout each bed. However, there are beds clearly revealing a transition in the size of the fragments from one edge of the bed to the opposite side. The thickness of such beds is apt to be several dozen meters, as is the case on the northernmost island of Fobistholmarna and the island situated to the west of Utterholm.

Fig. 5. Agglomerate. Island situated about 400 m south of Furuholmarna, Pernaja. The label used in the field photos is 12 cm.

Fig. 6. Agglomerate. South shore of Stor Pellinge, rural commune of Porvoo.

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Deviating from the foregoing type are those agglomerates in the stratified tuffitic material in which there are angular or only slightly rounded fragments. On the western margin of Revvikudden, on the south shore of Stor Pellinge, there is an agglomerate the fragments contained in the stratified tuffitic material of which are angular and sharp-edged (Fig. 6). The shapes of the fragments give a clear picture of how, during the genesis of the agglomerate, the erosive forces were unable to affect them very greatly, for the fragments have retained nearly their original appearance.

In Pernaja, on the eastern and southern sides of the Furuholmarna islands, there occur agglomerates that likewise deviate from the prevailing types in the area. There, the fragments, which occur in exceptional abundance (see p. 16, and Fig. 5), are angular in form. No kind of stratification can be detected. The mass in between the fragments consists of a fine-grained tuff material, and close inspection reveals it to be breccia-like agglomerate.

Intermediary and acid tuffites

Compared to the abundance of basic tuffites, there is a sparse occurrence, considering the area as a whole, of acid and intermediary tuffites. They occur most abundantly in the eastern section of the area, in the locality of Hästö, Hamnholm and Furuholmarna, where they appear as rather narrow layered beds a few meters thick among basic tuffites and basalts. Only in the northwestern part of Furuholmarna is there to be seen a larger occurrence of them, one some 200 m thick, which also includes acid lavas. Elsewhere, mainly at the northern margin of the volcanic area, they occur only as slight, isolated layers among basic tuffites.

The color of these rocks is reddish or reddish gray. Their structure is granoblastic. They vary in grain size. In the fine-grained types, the grains are less than 0.01 mm in diameter, and in the coarser types the corresponding diameter is less than 0.5 mm. In them there also occur fairly regularly larger quartz and plagioclase phenocrysts measuring between 0.5 mm and 1 mm in diameter. The composition of the plagioclase is An_{10-15}.

The chief minerals of the groundmass are plagioclase (An_{10-15}), quartz and potash feldspar. These minerals vary in their proportions in the different types. In addition, the rocks contain likewise varying amounts of epidote, hornblende, chlorite, muscovite and magnetite.

The intermediary and acid tuffites are closely associated in their mode of occurrence, and therefore differentiating them in nature often proves difficult — being based in the main only on the detection of different hues.

Metalavas

Among the pyroclastic sediments, there is also a profusion of lava rocks. In general, they occur as numerous beds in association with tuffites and agglomerates, but in the central portions of the area they are also apt to form larger continuous areas. In the vicinity of Hasselö, such an area has been observed to be composed of numerous different basic lava beds. The thickness of the lava beds varies from 1 to 50 meters. Beds with a thickness of less than 10 meters are the most common, however, in the area.

Both basic and intermediary lavas are present in the area. The basic types are uralite porphyrites, pillow lavas, amygdaloid lavas and so-called fragmentary lavas. Various primary structures are abundantly preserved in these types. The intermediary type is represented by fine- and coarse-grained feldspar porphyry.

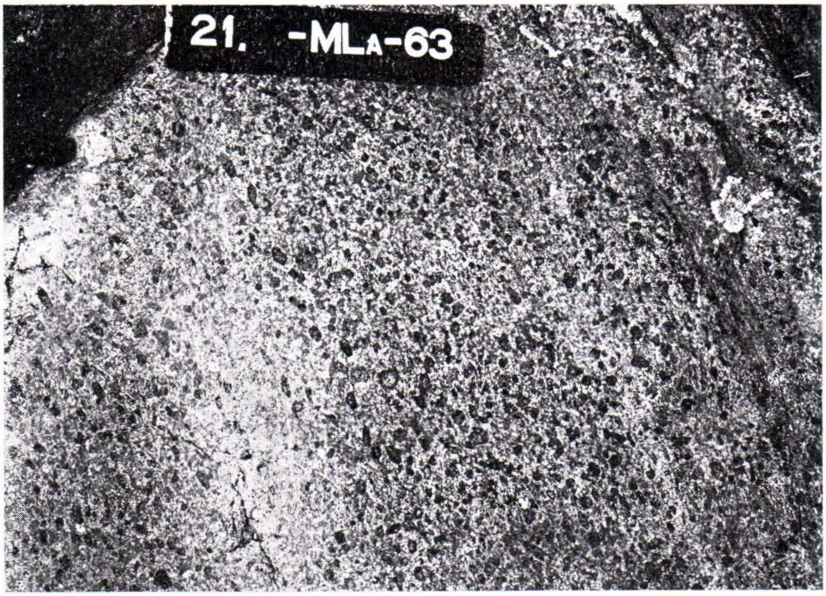

FIG. 7. Uralite porphyrite. Sandö, rural commune of Porvoo.

Basic lava rocks

Uralite porphyrites

The uralite porphyrites (Figs. 7 and 8) of the different sections of the area are of the same description. The fine-grained (grain size under 0.2 mm), granoblastic groundmass contains hornblende phenocrysts (grain size: 0.5—12 mm) in varying amounts. In places, the groundmass exhibits the original flow structure of the lava.

FIG. 8. Uralite porphyrite. Sandö, rural commune of Porvoo. Microphotograph, magnification c. 8×, nicols / /. Photo by Erkki Halme.

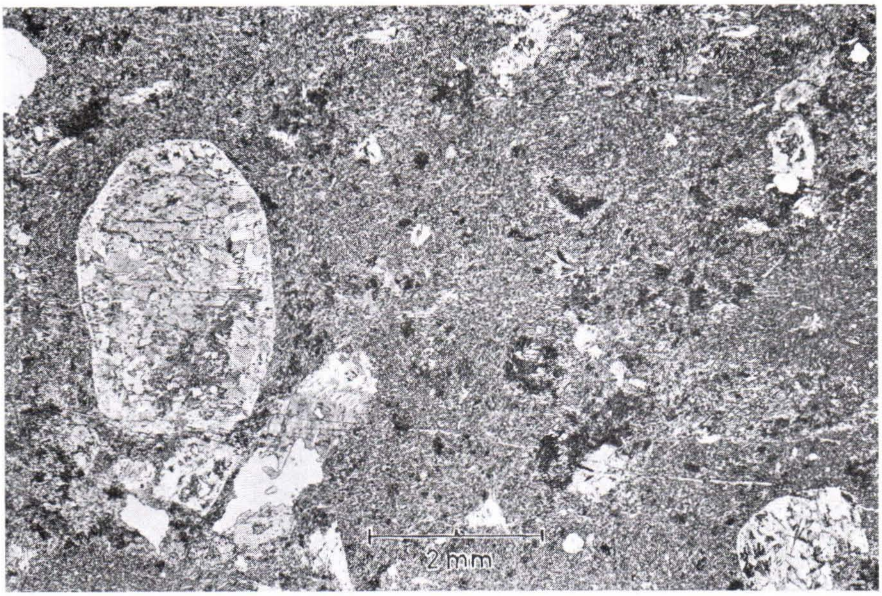

FIG. 9. Uralite porphyrite in which the crystal form of the uralitized pyroxene is preserved. Korshäll, Pernaja. Microphotograph, magnification c. 11×, nicols / /. Photo by Erkki Halme.

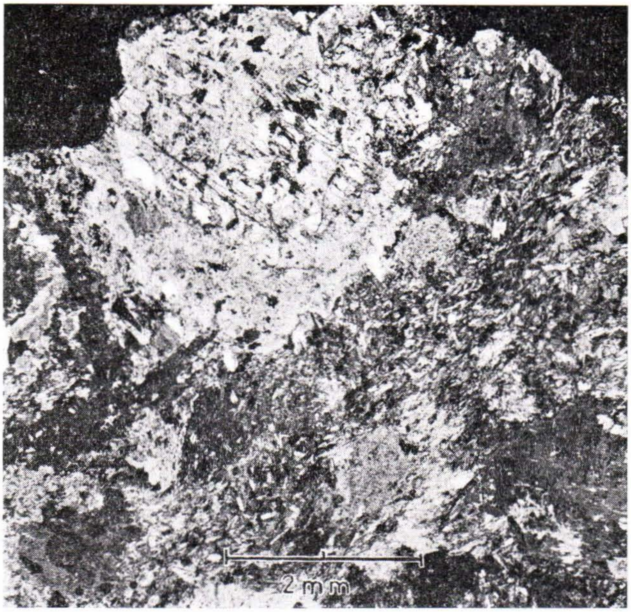

FIG. 10. Uralite porphyrite. Core of uralite contains ragged augite whose crystal form is partly preserved. Rocky islet on south side of Ölandet, rural commune of Porvoo. Microphotograph, magnification c. 13×, nicols / /. Photo by Erkki Halme.

The hornblende occurring as phenocrysts is green or light green of color. In places, the original augite crystal form of the hornblende phenocrysts is to be seen (Fig. 9). In a few rare cases, corroded augite still persists as a relict in the middle of the grain (Fig. 10).

The granoblastic groundmass consists of hornblende similar to the phenocrysts and plagioclase (An_{40-45}). Biotite occurs sparsely as tiny flakes, but it is apt exceptionally also to form largish clusters, in which case the grain size, too, is larger. In the groundmass there also occurs a slight amount of quartz and, as accessories, apatite, sphene, magnetite and epidote.

In the typical fine-grained uralite-porphyrite beds, there occur types resembling coarse plutonic rocks. On the small rocky islet south of Ölandet, the uralite porphyrite contains coarse-grained ($\varnothing < 5$ mm) gabbroic segregations composed of hornblende, plagioclase (An_{40}) and biotite with a diameter of between 0.2 m and 1 meter, the boundaries of which against the surrounding uralite porphyrite are quite gradual. These features are probably early segregations crystallized out of lava. Similarly, also at the western margin of the area, on the island of Nyttisholm, the uralite porphyrite contains a variant resembling a plutonic rock.

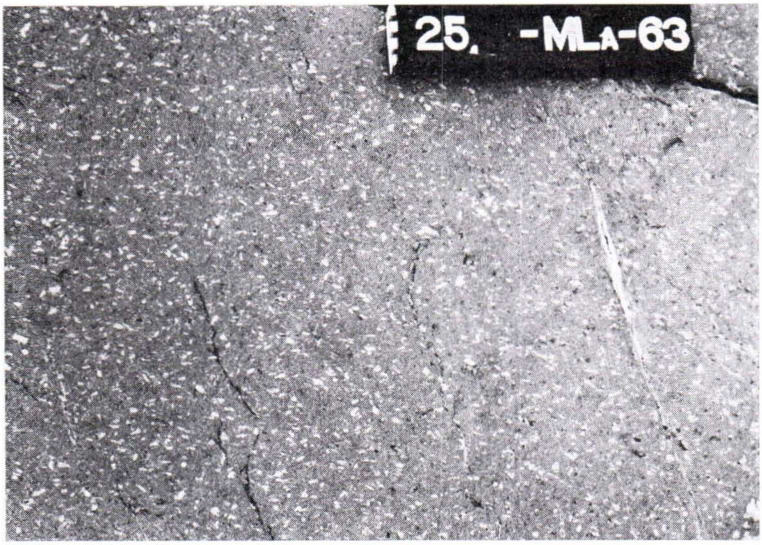

FIG. 11. Plagioclase porphyrite. Korsholmsör, situated about 150 m to the east from Korsholmen, rural commune of Porvoo.

Plagioclase porphyrites

The plagioclase porphyrites occur as beds like the uralite porphyrites. They have not been observed to form any large continuous areas, although their occurrence in the marginal portions of the area composed of volcanics is perhaps more abundant than in the middle portions.

The fine-grained (grain size under 0.2 mm) groundmass of the most common type of plagioclase porphyrite (Fig. 11) contains plagioclase phenocrysts varying in size from 0.5 to 4 mm and the composition of which is An_{35-40}. In places, preserved in them one can observe original crystal forms.

The groundmass consists mainly of plagioclase and hornblende. The composition of the plagioclase is the same as in the phenocrysts. The hornblende is generally green, but it also occurs in light green and faintly bluish varieties. There are sporadic occurrences of quartz and biotite. Accessory minerals are magnetite, sphene, apatite and epidote. In places, the groundmass exhibits the orginal flow structure of the lava very well preserved (Fig. 12).

Deviating from this general type is a plagioclase porphyrite that occurs at the northern margin of the eastern section of the area in a belt about 300 m broad running west from Risholm across Hästö. There, plagioclase phenocrysts occur more abundantly; in general they are larger, with a diameter ranging from 4 to 10 mm. The groundmass is fine-grained (grain size < 0.5 mm) and consists of plagioclase, hornblende and biotite. On the islands to the west of Risholm, this »coarse-

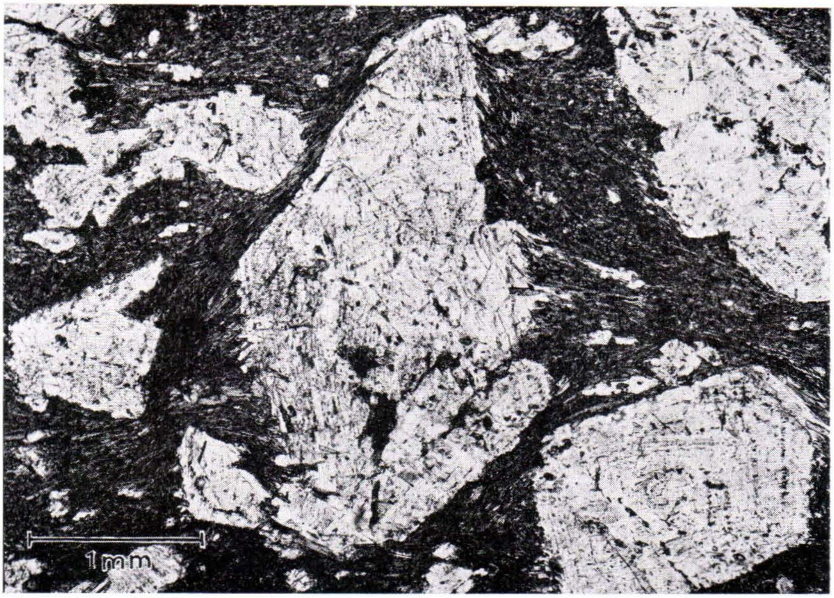

FIG. 12. Plagioclase porphyrite with idiomorphic plagioclase crystals and flow structure preserved in groundmass. Ölandet, rural commune of Porvoo. Microphotograph, magnification c. 23×, nicols / /. Photo by Erkki Halme.

grained» plagioclase porphyrite occurs as separate patches in fine-grained material resembling the groundmass. Further, as it runs westward, the belt turns into a gabbroic rock resembling plutonic rock, which, however, exhibits structural features characteristic of porphyrite. In the southern part of Öster Ryssholm, the plagioclase-porphyrite phenocrysts are still larger; they are likely to be as much as 2 cm in length.

Uralite-plagioclase porphyrites

Similar in their mode of occurrence to the foregoing lava rocks are the uralite-plagioclase porphyrites, which evidently represent an intermediary form between these two rocks. Present in the fine-grained groundmass as phenocrysts are both hornblende and plagioclase. The three porphyrites pass over into each other quite gradually.

Pillow lavas

Pillow lavas occur in association with uralite porphyrites, uralite-plagioclase porphyrites and, more rarely, also plagioclase porphyrites. They are present in the zone composed of volcanic rocks along the northern margin of the area, a zone that runs westward via the northern section of Lill Pellinge to the north shore of

Stor Pellinge. In this zone, the lavas occur as narrow beds among stratified pyroclastic sediments. They further occur at the margins of the larger areas composed of lava rocks situated in the central part of the area, also in the proximity of pyroclastic sediments. In addition, they have been met with well preserved on the isolated island of Digskär situated about 24 km from the area toward the east-southeast. Also among the metasediments of the northern section of the area, there occurs a basalt bed. Along its northern margin there are patterns resembling pillow lava.

According to several investigators, the pillow-lavalike structure is the result of rapid cooling of the lava, caused either by the air or the water (Lewis 1914; Shrock 1948, p. 359—363). The occurrence of pillow lavas in the studied area among pyroclastic sediments as intercalations or in association with lava beds situated in the immediate proximity of pyroclastic sediments gives grounds for assuming that the lava eruptions took place in water. In the zone running from Lill Pellinge to and along the north shore of Stor Pellinge, it has been possible to determine the faces of the layers from the primary structures of the tuffite layers. Thereby it has further been possible to note that a pillow-lavalike structure occurs in the surface portions of the lava beds (Fig. 13). The grading over from homogeneous lava to a surface portion resembling pillow lava proceeds little by little without any sharp lines of demarcation. The lava consists of fragments that give pillow lavas forms characteristic of »pillows» (Shrock 1948, p. 359—366). Such pillow-lavalike zones vary generally in width from 1—10 m.

FIG. 13. Pillow-lavalike surface portion of plagioclase porphyrite. Rocky islet situated about 400 m south of Bånholm, on north side of Stor Pellinge, rural commune of Porvoo.

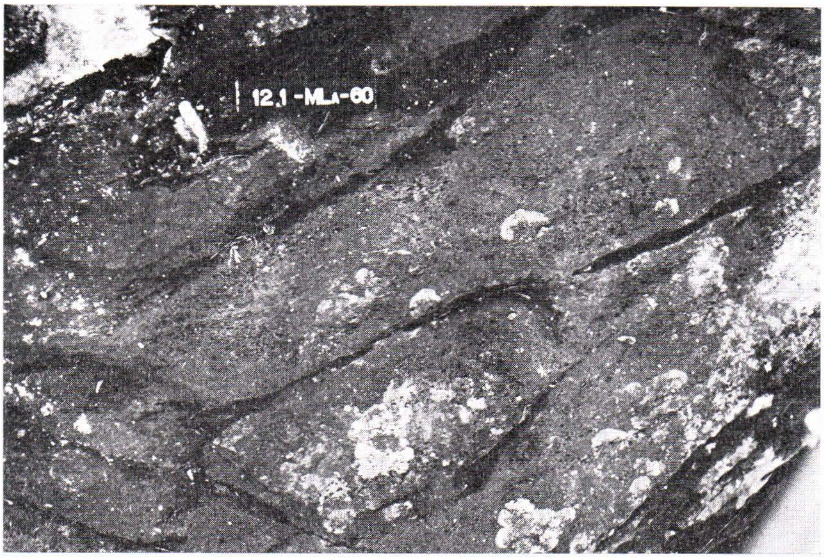

FIG. 14. Pillow lava in which calcite amygdalae are concentrated along margins of pillows. Northern part of Delholm, rural commune of Porvoo.

The pillows vary between 0.5—2 m in length. As for color, they are apt to be dark, like the underlying basalts. In places, owing to their abundant epidote content, they are light of color. Concentrated in their marginal portions, they are likely to have quartz or calcite amygdaloids, which generally have worn down into hollows on their weathering surface (Fig. 14).

The spaces between the pillows consist of a fine-grained mass, the mineral composition of which is likely to vary considerably. The chief minerals are epidote, hornblende, plagioclase, chlorite, quartz and calcite. Depending on the amount of epidote present, the color of this matrix is either dark or light. The mass containing calcite in abundance had generally worn away on its weathered surface and in place of the matrix there are hollows conforming to the outlines of the pillows (Fig. 15).

Fragmentary lavas

In their mode of occurrence, the fragmentary lavas (Fig. 16) resemble pillow lavas. They most commonly occur in the surficial portions of uralite-porphyrite as well as plagioclase-porphyrite beds, but the impression is gained in certain places that the entire lava bed is fragmented. Compared to those in the pillow lavas, the fragments are generally smaller, their diameter varying from 5—40 cm. In deformed rocks, they are slightly rounded and elongated in shape. In better preserved rocks, they are angular or irregularly shaped. The color of the mass between the fragments

FIG. 15. Pillow lava. Calcite-bearing mass filling space between pillows has been worn down. Northern part of Delholm, rural commune of Porvoo.

FIG. 16. Fragmentary lava. Flottaskär, rural commune of Porvoo.

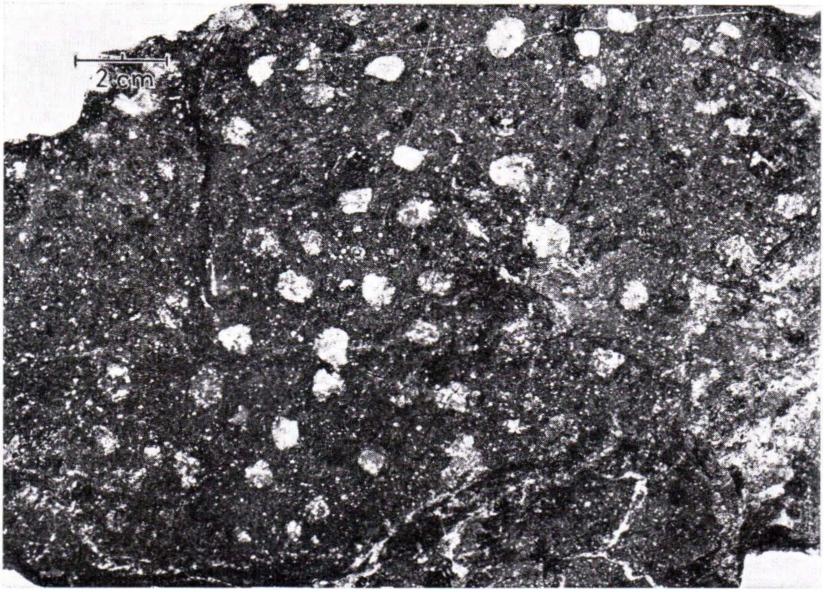

FIG. 17. Amygdaloid lava. Uralite porphyrite with quartz amygdalae. Island situated about 50 m to the east from the east end of Sandholmen, rural commune of Porvoo.

varies. The dark, interstitial mass consists of the same minerals as do the fragments; the shade of color is due only to the fine grain of the material. The color of the light interstitial mass is in many cases due to a higher epidote content.

Amygdaloid lavas

Notably in uralite-porphyrites as well as plagioclase-porphyrites, there occur in places in the study area (Fig. 17) amygdaloids, which in individual beds are likely to be evenly distributed throughout. In general, however, they are concentrated in different parts of a single bed in different ways, which may be explained in greater detail in connection with the primary structure (p. 38).

The amygdaloids vary generally in size between 0.2 and 3 cm, but larger ones have also been seen. Depending on the degree of deformation, the amygdaloids are generally more or less elongated. In particularly highly deformed lavas, the amygdaloids have become stretched out into long and narrow streaks. Most commonly, the amygdaloids have formed exclusively out of quartz, but in addition plagioclase (ca. An_{60}), calcite, epidote, hornblende and tiny magnetite grains are also met with as amygdaloid minerals.

TABLE 3

Chemical compositions of basic lava rocks.

	1	2	3	4
SiO_2	50.18	56.06	50.78	52.28
TiO_2	0.70	0.92	0.75	0.87
Al_2O_3	14.58	13.97	18.08	20.75
Fe_2O_3	1.27	1.41	2.80	2.35
FeO	9.14	7.59	5.33	5.20
MnO	0.12	0.09	0.11	0.10
MgO	9.90	6.95	5.72	2.70
CaO	9.60	9.48	10.80	8.18
Na_2O	1.98	2.06	3.12	3.82
K_2O	0.49	0.63	1.00	1.55
H_2O+ / H_2O-	1.70	0.56	1.06	1.66
	99.66	99.72	99.55	99.46

1. Uralite porphyrite. Båtviken, Stor Pellinge, rural commune of Porvoo. Anal. Eero Mäkinen. (Sederholm, 1923, p. 34.)
2. Uralite porphyrite. Sådholm, rural commune of Porvoo. Anal. Eero Mäkinen. (Sederholm, 1923, p. 28.)
3. Plagioclase porphyrite. Öster Ryssholm, Pernaja. Anal. Eero Mäkinen. (Sederholm, 1923, p. 36.)
4. Plagioclase porphyrite. Ägghällan, Pernaja. Anal. Eero Mäkinen. (Sederholm, 1923, p. 74.)

The basic lava rocks, uralite-porphyrites and plagioclase-porphyrites of the study area described in the foregoing are similar to the corresponding basic lava rocks described from different localities in southern Finland previously by a number of researchers (Sederholm 1891; Simonen 1948; Seitsaari 1951). Analyses 1 and 2 of Table 3 represent the chemical compositions of the uraliteporphyrites of the area. The high SiO_2 content reported in analysis 2 is probably due to the quartz amygdaloids contained in the rock. Analyses 3 and 4 represent the chemical composition of the plagioclase-porphyrites. These compositions correspond to those of normal basalts, and the changes occurring in conjunction with the metamorphism have been isochemical in nature.

Intermediary lava rocks

Fine-grained feldspar porphyry

On the island of Furuholmarna, in the eastern section of the area, and in the vicinity of Bastuö, about 5 km to the southeast of it, there occurs a fine-grained feldspar porphyry in a zone 100—300 m broad. In outward appearance, the rock is reddish gray and in the dense groundmass feldspar can be observed as phenocrysts. Inspected microscopically, the grain size of the groundmass is under 0.2 mm and the size of the plagioclase phenocrysts varies between 0.5 and 1.5 mm.

The groundmass consists mainly of plagioclase, the composition of which, its refraction compared to that of Canada balsam, proved to be oligoclase. In addition the groundmass contains an abundance of biotite, quartz, potash feldspar interstices between the grains as well as scant amount of hornblende, chlorite, calcite, and muscovite. Accessory minerals are apatite, epidote, appearing in cross section as beautiful hexagons, ilmenite grains, around which in many instances occurs a sphene border about 0.1 mm wide. In places, the groundmass also exhibits the original flow structure of the lava.

The plagioclase phenocrysts are oligoclase in composition. In general, they are markedly epidotized.

Coarse-grained feldspar porphyry

Coarse-grained feldspar porphyry occurs in the central part of the region in a zone that runs from Lill Måsholm to Bastuö. In addition, it is met with in narrow zones at Skvättan, Korsholm, Gåsholm and Måsholm.

This rock contains an abundance of plagioclase phenocrysts. This creates the impression that the rock, taken as a whole, might be coarse-grained. Microscopic examination, however, proves that the rock is very much like the afore-described fine-grained feldspar porphyry. The plagioclase phenocrysts measure less than 3 mm. In composition they vary: An_{25-35}. In places, the phenocrysts exhibit a highly developed zoned structure, signifying that the middle of the plagioclase is richer in An than the borders.

The grain size and the mineral composition of the groundmass is similar to what they are in the foregoing fine-grained type. An exception is the hornblende, which occurs in greater abundance in the coarse type, forming in places uralite phenocrysts.

In the comparison between the fine- and coarse-grained feldspar porphyries, the similarity of their respective mineral composition has already been noted in connection with the rock description. The similarity extends also to their chemical composition. Analysis 1 in Table 4 represents the chemical composition of the fine-grained feldspar porphyry, and analysis 2 that of the coarser-grained variety. When these are compared with the mean chemical compositions of dacite (analysis 3) and andesite (analysis 4) calculated by Daly (1933, p. 456 and p. 447), the composition of the fine-grained feldspar porphyry is seen to correspond with dacite and the composition of the coarse-grained feldspar porphyry to andesite.

Moreover the modes of occurrence of these two rocks are similar. They are situated by and large in the same zone, in the western part of which occurs the coarse-grained and in the eastern part the fine-grained type. In the middle of the zone, to the east of Bastuö, they occur side-by-side. According to the observations made in the region of the bedding sequence, the fine-grained feldspar porphyry

TABLE 4

Chemical compositions of intermediary lava rocks.

	1	2	3	4
SiO_2	66.57	63.68	66.68	63.20
TiO_2	0.58	0.92	0.58	1.67
Al_2O_3	14.56	15.84	16.50	16.35
Fe_2O_3	3.46	1.80	2.41	3.67
FeO	2.51	4.55	1.93	2.23
MnO	0.10	0.08	0.06	0.21
MgO	1.42	1.99	1.44	2.06
CaO	4.57	5.93	3.51	4.11
Na_2O	3.40	3.42	4.03	3.61
K_2O	2.30	2.02	2.71	2.48
P_2O_5	0.18	—	0.15	0.41
H_2O+	0.75	0.50		
H_2O-	0.05			
	100.45	100.73	100.00	100.00

1. Fine-grained feldspar porphyry. Island situated about 1 km to the east of Bredholm, Pernaja. Anal. Aulis Heikkinen.
2. Coarse-grained feldspar porphyry. Island situated about 400 m to the east of Måsholm, rural commune of Porvoo. Anal. Eero Mäkinen. (Sederholm, 1923, p. 51.)
3. Average dacite, 90 analyses. (Daly, 1933, p. 457, Table 55, Anal. No 6.)
4. Average andesite, 10 analyses. (Daly, 1933, p. 447, Table 52, Anal. No 9.)

overlies the coarse-grained variety. Evidently, the same lava produced both the hypabyssal type that crystallized deeper down, represented by the coarse-grained andesitic feldspar porphyry, and the type that crystallized on the surface as the finegrained dacitic feldspar porphyry.

Primary structures

In the tuffites, agglomerates and lavas of the region, structures dating back to the time of formation of the original rocks can still be recognized. They have been preserved in special abundance in the tuffites. By means of these surviving primary structures, it has been possible to determine a large number of the directions of the bottom or top of layers, on the basis of which a picture could be drawn of the structure of the region.

Tuffites and agglomerates

One of the commonest and useful structural features used in determining the direction of the bottom and top of layers is the variation in the degree of coarseness of the tuff material occurring in individual layers of stratified tuffites (Shrock 1948, p. 330—331). Generally speaking, it is the coarser mineral matter and fragments that have collected in the lower part of the layers (Fig. 18). In the direction of the upper part of the layers, the grain-size decreases. This sorting has also brought about variation in the mineral composition of the lower and upper parts of the layers (Fig. 19). In the coarse lower part, hornblende generally is present abundantly

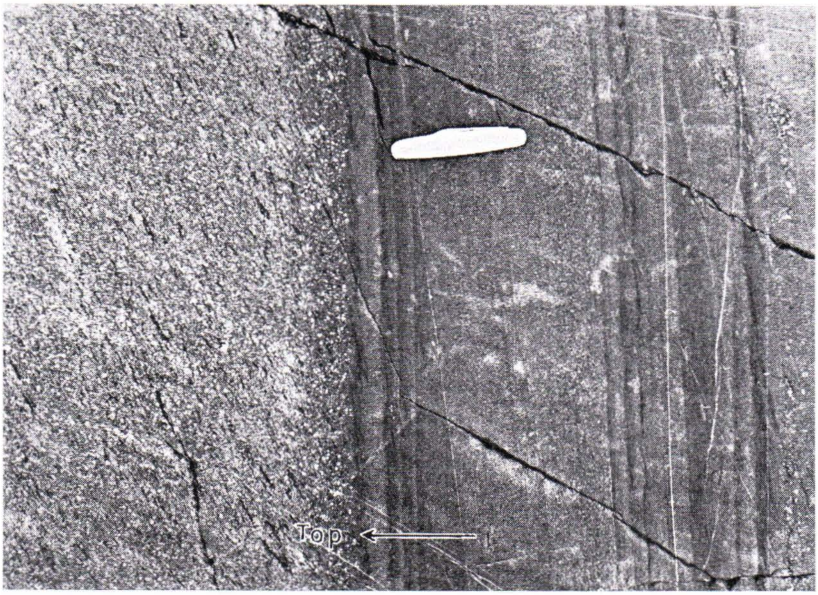

FIG. 18. Variation in the degree of coarseness of the mineral constituents of the tuffite layers. The rock also exhibits schistosity intersecting the stratification. South shore of Stor Pellinge, rural commune of Porvoo.

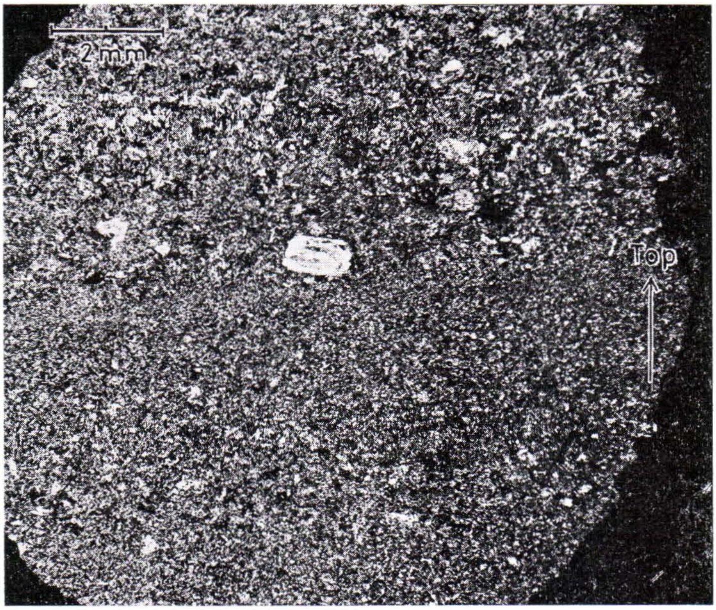

FIG. 19. Microphotograph of tuffite layers. The picture shows the diminishing size of the grains in the direction of the layer surface. The large grain contained in the lower part of the upper layer is hornblende, the lighter grains being plagioclase. Korshäll, Pernaja. Nicols / /, magnification c. 9×. Photo Erkki Halme.

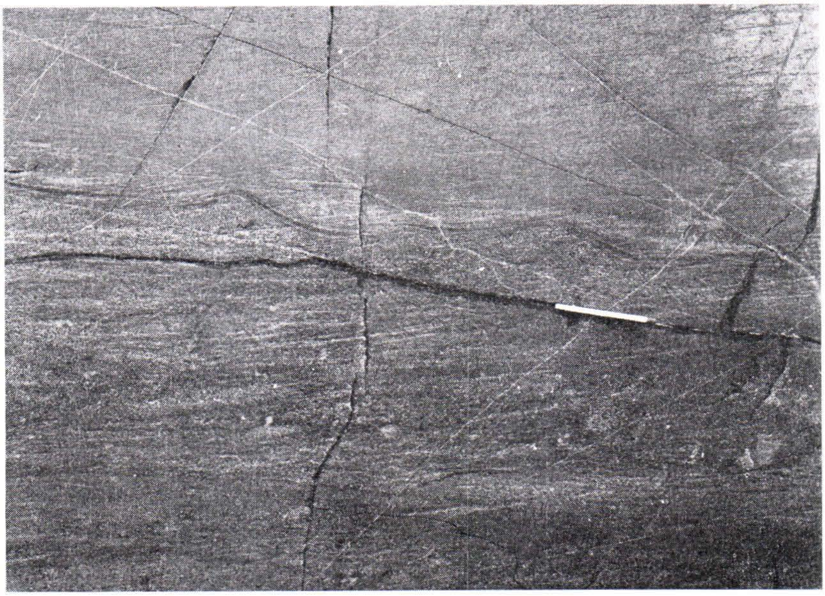

FIG. 20. Current ripple marks in tuffite. Northern part of Älskholm, rural commune of Porvoo.

along with large plagioclase grains. In the direction of the upper part of the layers, the proportion of plagioclase increases as the grain size decreases. As the layers include quartz and biotite, the quartz is also situated in the upper part of the layers and the biotite forms the top surface. At the bottom of the layers, magnetite and sphene grains are present as accessory minerals.

Besides the foregoing inner structural features of the layers, primary structures have survived in the area also on the boundary surfaces between layers, along with structures characteristic of stratified rocks.

On the west shore of the northern part of Älskholm, there is a cut through the bedrock nearly at right angles to the layer surfaces of the tuffites, which dip at a gentle angle of about 20° toward the east. In this locality, between the fine-grained tuffite layers, there is a coarser-grained layer about 15 cm thick containing plagioclase and hornblende. On the upper surface of this layer, one can observe a wavy pattern, which greatly resembles ripple marks, (Fig. 20). The length of the waves varies from 8 to 11 cm and the amplitude is from 1 to 1.5 cm, so that the index of the waves is ca. 8. The crests of the waves are rounded. On the upper surface of the waves there is an exceedingly fine-grained (Ø < 0.02 mm) layer consisting mainly of a tuffite material that contains hornblende; this layer is either entirely lacking or very thin on the crest of each wave but becomes stronger toward the trough, where it gains a thickness of some 3—4 mm. At the trough of each wave, there is also usually a larger amount of magnetite.

FIG. 21. »Scour and fill» in tuffite. Northern part of Älskholm, rural commune of Porvoo.

This structure fully corresponds to the ripple marks described by Shrock (1948, p. 109—111). The asymmetric forms of the ripple marks and the index value of 8 suggest their having been produced through the action of flowing water (Shrock 1948, p. 94), the direction of flow in this case having been from the north southward. To a high degree of certainty these features are to be regarded as ripple marks. It is hardly likely that any tectonic structure is in question, for the surrounding layers as well as the one under consideration are very well preserved and undisturbed.

In the same place, about 6 meters to the south from the preceding ripple marks, there occur a couple of forms in the stratified tuffite that were possibly produced by flowing water. It may be seen from the currents that during the stage of their origin, there developed in the horizontal layers (Fig. 21) a hollow about 30 cm long and 20 cm deep, the northern wall of which has been cut very sharply and the southern side a gentle slope, making the form conspicuously asymmetric. Later on, tuffite was deposited in this place. Its stratification conforms to the shape of the hollow. After the hollow was filled, horizontal layers were laid over it.

This formation structurally corresponds fully to the structures created by the erosive action of flowing water, as described in the literature (Shrock 1948, p. 230—231). A whirlpool developing in the flowing water had produced a hole in the sediments, which at the time were still in a loose state; subsequently this hole filled up (»scour and fill»). The steeper wall of the hollow represents the direction from which

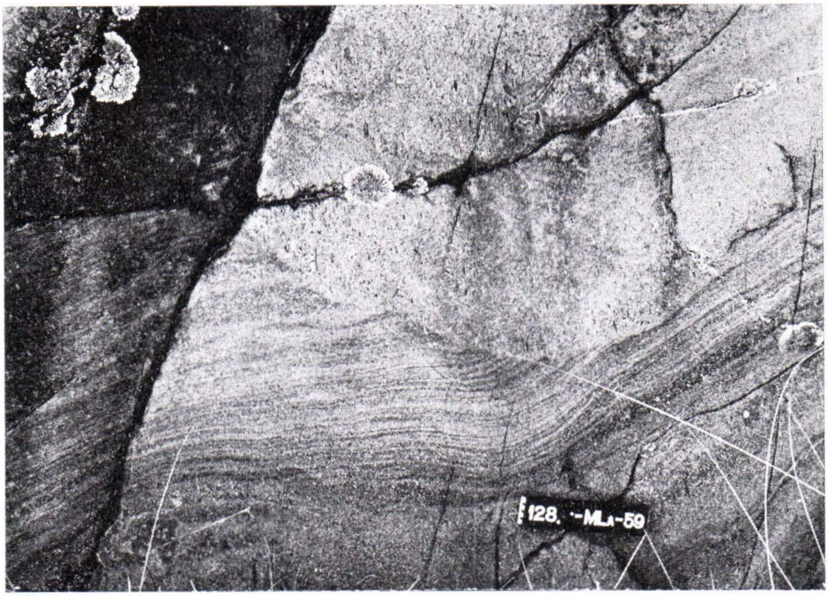

FIG. 22. Cavity caused by erosion in tuffite. Cavity later filled with new ash material, the layers of which conform to the edges of the cavity. South shore of Stor Pellinge, rural commune of Porvoo.

the flow had come. In the case described, the flow had been from north to south. This supports the observations made previously, on page 33, regarding the direction of flow in connection with ripple marks. The same direction was also obtained in connection with the current bedding occurring in the vicinity (Fig. 3, p. 14).

On the south shore of the Stor Pellinge, there is another, corresponding hollow caused by erosion; in type, it slightly differs from the one just described. A hollow was scoured into the stratified tuffite bed; the hollow cuts through the strata(Fig. 22). The tuffitic layers at the base vary in thickness from 0.5—1 cm. The hollow scoured out later became filled with a coarser tuffite material, which forms layers from 5 to 20 cm thick. In these layers one can observe sorting according to grain size. In this case, too, the layers conform the shape of the hollow.

One sedimentary feature useful in the determination of the orientation of the bottom or top of layers is a crossbedding structure met with in stratified tuffites; it occurs abundantly in the area. Structures of this kind occur in both thin tuffite layers and also as larger bodies several meters long. The upper parts of current beds have usually been worn away, with the result that a marked discordance with the overlying horizontal layers is to be observed (Figs. 23 and 3, p. 14).

Also to be seen in tuffites are features varying in size that were produced by the sliding of loose sediments. One smallish such occurrence is on the west shore of the northern part of Älskholm, where in a fine-grained tuffite layer situated be-

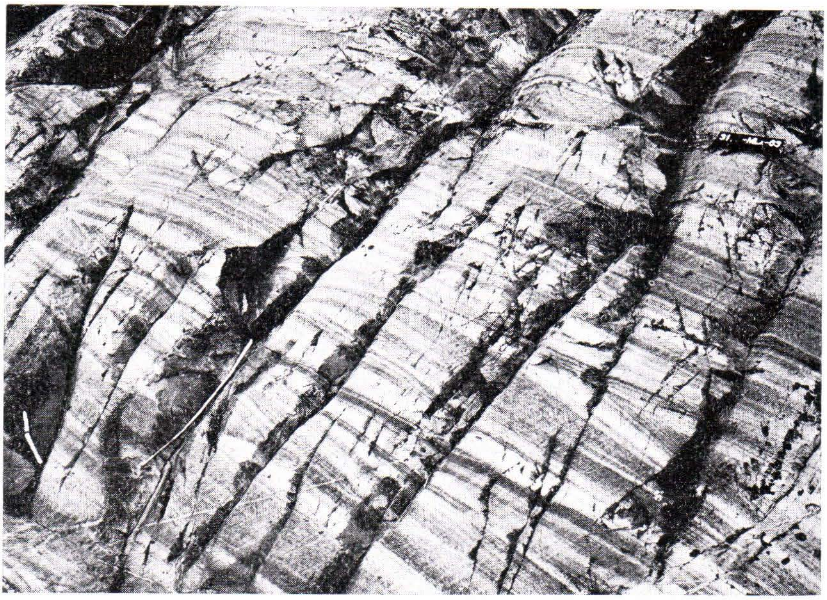

FIG. 23. Cross bedding in tuffite. West shore of Gåsholm, rural commune of Porvoo.

tween two coarse-grained horizontal layers, there can be observed foldlike, partly overthrust structures (Fig. 24). The direction of the overthrusts is from north to south.

In unhardened tuffites, deformation took place also from the weight of the lava bed discharged over them. An example of this is the occurrence situated in the eastern section of Risholm. The fragments present at the bottom of the lava bed caused the deformation of the underlying loose tuffite, which to some extent forced a way between the fragments. (Fig. 25). On Flottaskär, the lava discharged over the tuffites caused shattering and small faults in the tuffites. Such faults do not extend to the overlying lava (Fig. 26).

Also in the agglomerates there are structural features whereby the directions of the bottom and the top of the layers can be determined. It has already been mentioned (p. 16) that in the thick agglomerate beds variation in the size of the fragments can be observed at the different margins of each bed. The portion of the bed containing the large fragments probably represents the original basal portion of the bed, from which the size of the fragments diminishes toward the surface. This same phenomenon is to be noticed in places also in narrower agglomerate layers, an instructive example being the agglomerate occurring at Korshäll in the Pernaja group of islands (Fig. 27). The occurrence contains several agglomerate layers from 1 m to 1.5 m thick, in which the largest fragments are in the basal and the smaller ones in the surface portion. The fragments are somewhat rounded.

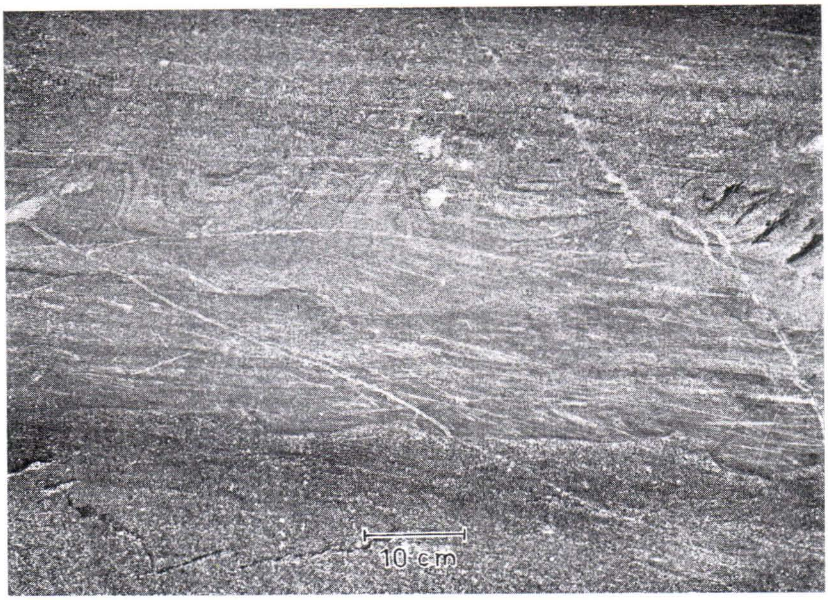

FIG. 24. Penecontemporaneous folding in tuffite. Ripple marks in lower part of picture (cf., Fig. 20). Northern part of Älskholm, rural commune of Porvoo.

FIG. 25. Fragments in lower part of lava bed have deformed tuffite layers below. Risholm, Pernaja.

FIG. 26. Lava discharged on top of tuffites has caused displacements in underlying tuffite, which do not extend to the lava on top. Flottaskär, rural commune of Porvoo.

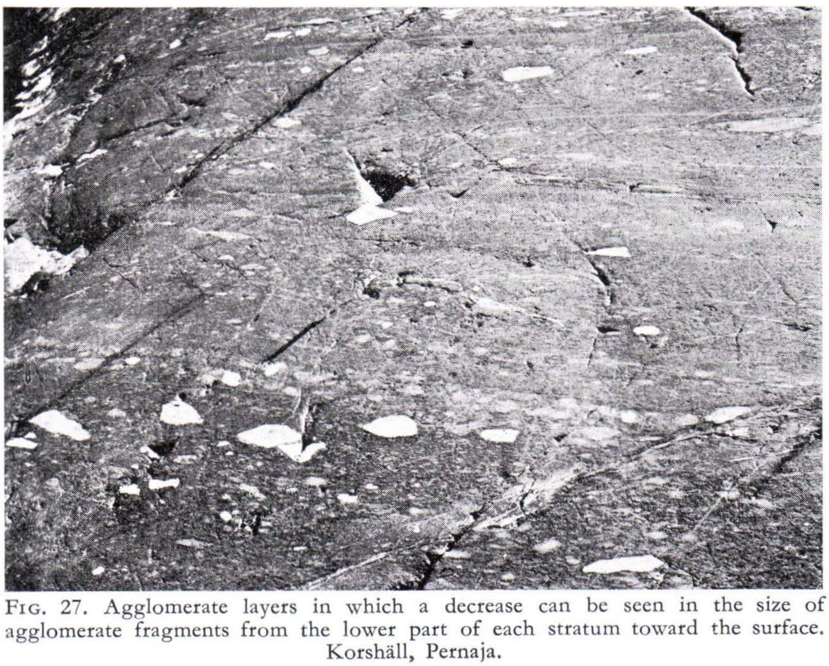

FIG. 27. Agglomerate layers in which a decrease can be seen in the size of agglomerate fragments from the lower part of each stratum toward the surface. Korshäll, Pernaja.

Lava rocks

In the lava rocks, the primary structures appear either as structural variations occurring within the beds or as different phenomena in the upper and lower portions of the beds.

In many places where observations could be made throughout the cross section of the entire uralite-porphyrite bed, the different parts of the bed were seen to vary with respect to the size and number of uralite phenocrysts. In the lower portion of the bed, there are tiny phenocrysts sparsely distributed, and they form a narrow zone there. Toward the center, the phenocrysts show an increase in size and number. Toward the surface, the phenocrysts again diminish in size and number. The breadth of such a surface zone is greater than that of the zone at the bottom.

Associated with the lower margin of the coarse-grained central portion of the lava bed, there also occur the previously mentioned (p. 21) varieties of segregation of a plutonic character. They apparently crystallized from the lava after having become separated at an early stage.

When the lavas contain amygdalae, these have been observed in the study region to be very often concentrated at the different margins of the beds in different ways. The zone along one edge is narrow and contains amygdalae sparsely whereas the zone along the other edge is broader and contains an abundance of amygdalae. The latter zone in that case represents the upper portion of the lava bed (see Shrock 1948, p. 348—349).

FIG. 28. Flow structure in the lava, revealed in the arrangement of the quartz amygdalae into arciform patterns. From an island c. 1 km east of Bastuö, rural commune of Porvoo.

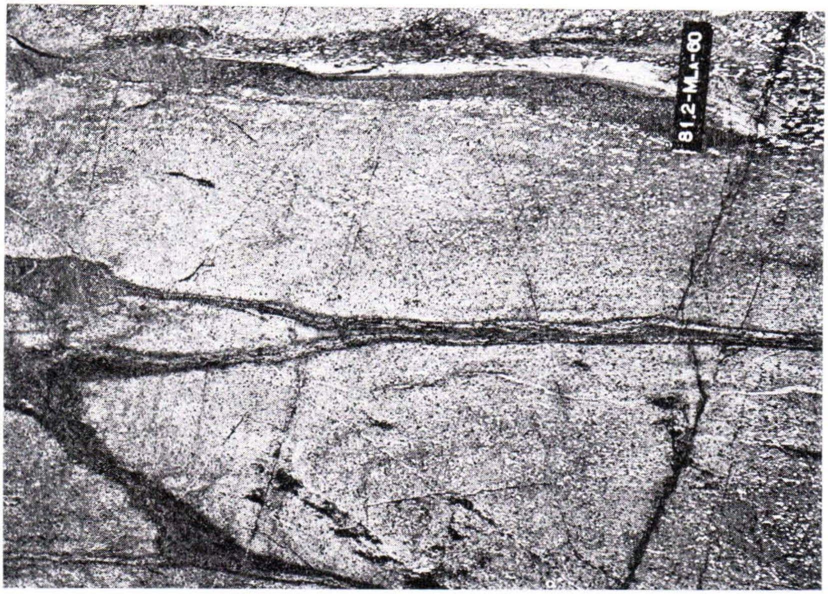

FIG. 29. Quartz amygdalae concentrated in the upper part of the pillow of a pillow-lava formation. West part of Lill Pellinge, rural commune of Porvoo.

The lavas further exhibit structures that probably represent the original flow structure. On the island about 1 km to the east of Bastuö, there are a couple of nearly vertical uralite-porphyrite beds containing quartz amygdalae; these beds trend roughly northeast — southwest. Within the beds, the amygdalae are arranged so as to form arches, which are convex lengthwise to the beds, in this case toward the southwest (Fig. 28). The structure probably originated in such a way that, as the lava was discharged, solidification took place at the edges of each bed on account of more rapid cooling, whereas in the center, on account of the higher temperature, the substance remained more mobile and continued to move in the direction of advance. In this instance, the direction of flow of the lava would have had to be from the northeast to the southwest.

In spite of deformation, the forms of the pillows in the pillow lavas have in many places preserved their original form (p. 24, Fig. 13). On the basis of these forms, it was possible to determine the orientation of the upper surfaces of the lava beds (see, Wilson 1942, p. 62—64; Shrock 1948, p. 364—366). In many instances too, particularly as far as the uralite porphyrite is concerned, on such a pillow-lavalike upper surface, there occurs a concentration of amygdalae both in the pillows and the fine-grained mass betweem them and in the uralite porphyrite underneath the pillow lava. In the pillows, the amygdalae are apt to appear in their marginal portions, forming a zone adhering to the contours (see, p. 25, Fig. 14) or then have become concentrated in the upper portion of the pillow (Fig. 29). In one case, the longitudinal direction of the amygdalae in the lower portion of a pillow is at right angles to the lower edge, whereas in the upper part the longitudinal trend of the amygdalae runs parallel to the upper edge.

On the upper and lower margins of the lava beds, there also occurs quite generally compact chilled zones, which vary in width from a few cm to between 10 and 20 cm. Where both margins could be observed, the chilled zone of the upper margin appeared to be broader than that of the lower margin.

The fragmented upper portions of the lava beds have in many places afforded an excellent opportunity for making determinations of the top. Exceedingly well preserved lava structures are to be seen on the eastern shore of Älskholm. It is therefore described in the following in greater detail. The stratified structures of the layers of the extremely well preserved tuffite bed overlying the lava bed has made it possible to verify the fact that the upper margin of the lava is actually in question.

The fragmented lava bed is uralite porphyrite, and the thickness of the zone containing the fragments on the upper portion of the bed is ca. 2.5 m. The fragmentation begins quite gradually: in the uralite porphyrite (Fig. 30) there is first to be noticed the appearance of fine-grained, indefinitely shaped detached patches a few sq. cm in size. Upwards, their color gradually lightens at the same time as the fragments take on a more definite shape, whereupon this pale, fine-grained material fills up the interstices. Further, the fragments increase in size toward the top surface, and they develop an existence distinctly separate from each other. A pale, fine-grained mass surrounds them all over. In the uppermost portion on the lava bed, the fragments, the long axes of which run at right angles to the bed, are apt to be about 40 cm across. The surface of the bed is very uneven (Fig. 31), resembling the surface of present-day boulder or aa-lava beds (see Macdonald 1953). The irregularities of the surface are covered by the overlying layered tuffite.

In outward appearance, these fragments are of the same rock material as the underlying uralite porphyrite. Also examined microscopically, this material proves to resemble uralite porphyrite. In the fine-grained ground mass, the grains of which are less than 0.02 mm in size, the phenocrysts consist of both plagioclase (An_{55}) and hornblende, varying in size between 1.5 and 2 mm. The hornblende is also likely to occur radially arranged into fans. Under the microscope, the fine-grained mass reveals the presence of plagioclase and hornblende laminae as well as disseminated magnetite. In the middle of the fragments, the ground mass has slightly larger grains. At their margins, the fragments contain abundant concentrations of quartz amygdalae measuring about 3 mm across.

The mass in between the fragments is exceedingly fine-grained and conceivably glass by origin. Close to the edge of a fragment, this matrix is finer of grain than in the middle. Under the microscope, it could be observed to contain epidote, hornblende, quartz, plagioclase and a dissemination of fine magnetite. In addition, there occur some sparse plagioclase phenocrysts, which are less than 0.5 mm across. The matrix further contains small amygdalae with the following compositions: 1. quartz,

FIG. 30. Incipient fragmentation in the upper part of a uralite porphyrite bed. East shore of Älskholm, rural commune of Porvoo.

FIG. 31. Fragmented upper surface of uralite porphyrite bed. Visible in upper right corner are the overlying tuffite layers. East shore of Älskholm, rural commune of Porvoo.

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2. epidote, 3. epidote and plagioclase, 4. epidote, hornblende and plagioclase, 5. hornblende and quartz. Around the latter amygdalae, magnetite is profusely disseminated. Also likely to occur in the matrix are little pieces broken loose from the nearest fragment.

In Table 5, Analysis 1 gives the chemical composition of the fragments and Analysis 2 that of the mass between them. The fragments resemble in outward appearance and mineral composition the intact uralite porphyrite underlying the fragmented zone. Also the chemical composition of the fragments (Analysis 1) corresponds to the chemical compositions of the uralite porphyrites of the region (see, p. 28, Table 3, Anal. 1 and 2). A comparison between the fragments and the intermediary mass reveals differences in their chemical composition (Table 5, Anal. 2). The total iron content of both the fragments and the mass is the same, but the latter contains substantially more ferric iron than do the fragments. This situation corresponds to the observations made of the degree of oxidation of the iron contained in the upper surfaces of lava beds (Butler and Burbank 1929, p. 35—37). Moreover, the mass contains more SiO_2 and CaO, whereas its MgO content has appreciably diminished compared to that of the fragments. This gives reason to assume that partial differentiation has taken place.

There are differing opinions about the causes and modes of occurrence of fragmentation in the upper suface of lava beds. According to one view, it was caused by gases discharged upward by solidifying lava (Butler and Burbank 1929, xi; Shrock 1948, p. 348—349). Considering the process involved in the fragmentation — which in the foregoing instance worked gradually upward from below in the fragmented zone —, this view seems to have validity here, too. This would mean that as the gases increased in volume upon rising from the already partly solidified lava and broke through the solid surface, the still molten lava below, after becoming differentiated to a more acid state, penetrated into the cracks that had appeared.

TABLE 5

Chemical compositions of fragments and surrounding mass of fragmented lava.

	1	2
SiO_2	47.25	53.97
TiO_2	0.62	1.00
Al_2O_3	18.84	15.23
Fe_2O_3	4.74	8.47
FeO	7.06	3.44
MnO	0.13	0.13
MgO	6.86	2.52
CaO	7.92	13.12
Na_2O	1.72	1.05
K_2O	1.92	0.25
P_2O_5	0.16	0.22
H_2O+	2.68	0.93
H_2O-	0.23	0.05
	100.13	100.38

1. Fragment of the fragmentary lava. Älskholm, rural commune of Porvoo. Anal. Aulis Heikkinen.
2. Mass in between the fragments of the fragmentary lava. Älskholm, rural commune of Porvoo. Anal. Aulis Heikkinen.

STRUCTURE OF THE REGION AND ITS EVOLUTION

The following elucidation of the structure of the region is based mainly on observations made of minor structural features occurring in individual exposures. Of these smallscale structures, the most important are planar and linear structures, minor folds and preserved primary structures. An attempt was made by combining such observations to work out a picture of the broad regional structures and their evolution.

Planar structures

The planar structures appearing in the rocks and exhibiting varying modes of origin are termed in this paper, after Sander (1948, p. 105), »s-surfaces». The most important of these is the bedding formed by the sediments before deformation (S_0-surfaces) and the schistosity caused by the deformation (S_1-surfaces).

Bedding (S_0)

The degree of metamorphism undergone by the rocks in the region investigated varies. At the northern and southern margins, it has been exceedingly intense, with the result that the original structures of the sediments have been destroyed. The original stratification, however, remains in the rocks as a banding in which the individual bands varying in composition are of even thickness and continuous.

In the central zone of the region, on the other hand, the primary structural features have been abundantly preserved in the layered tuffites and the lava beds occurring in conjunction with them. Judging by their depositional features, it is easy to decide that the determination made of the S_0-surface truly is a bedding plane. The strikes and dips of these planes are represented in Appendix 2.

Schistosity (S_1)

Compared to the bedding of the sediments, the s-surfaces created by the movements set off by the deformation that occurred in conjunction with the folding are secondary with respect to their mode of origin (Whitten 1966, p. 216). In the area investigated, the intensity of the deformation varies from place to place. In general, it exhibits greater intensity along the northern and southern margins as well as in the eastern and western sections. Variation in intensity was also observed on a smaller scale. As an example, mention might be made of the granitic vein about 3 cm wide and 10 m long running between tuffitic strata on the southwestern shore of Stor Pellinge. The eastern end of the vein is slightly folded along with the clearly observable tuffitic layers (Fig. 32). At its western end, this vein is broken up into numerous branches a few millimeters thick and from 5 to 20 cm

FIG. 32. Slightly folded granitic dike situated between tuffite layers. South shore of Stor Pellinge, rural commune of Porvoo.

long, which are situated about 1 or 2 cm apart. These branch veins run parallel to the local schistosity and at right angles to the original vein (Fig. 33). The determinations of the S_1-surfaces were made from the parallel structures of the flaky and laminar minerals as well as of the deformed, elongated fragments of the conglomerates and agglomerates. These planar structures are illustrated in Appendix 3.

The strikes of the S_1-surfaces generally vary between southwest-northeast and west-east. A more conspicuous deviation from the afore-mentioned directions occurs in the southwestern part of the region, where the S_1-surfaces run nearly north-south. The dips vary between 70° and 90°. The dips follow a consistent pattern in relation to the line running from the eastern part of the south shore of Stor Pellinge at first northward and later across the northern part of Ölandet, arching toward the east, and Delholm. On the north side of this line the dips have a southerly and on the south side a northerly direction. Vertical dips are concentrated on the line.

With respect to the relation of the S_0- and S_1-surfaces to each other, it may be noted that at the northern and southern margins of the region, they generally run parallel. Elsewhere they intersect each other at varying angles (Fig. 34). Considered as a whole, the mode of occurrence of the S_1-surfaces is consistent in both schist and plutonic rock areas, and there is full reason to assume that they evolved in conjunction with the folding into axialsurface schistosity conforming to the axis surface (see Mead 1940, p. 1010).

FIG. 33. The same granitic dike as in Fig. 32, conspicuously deformed. South shore of Stor Pellinge, rural commune of Porvoo.

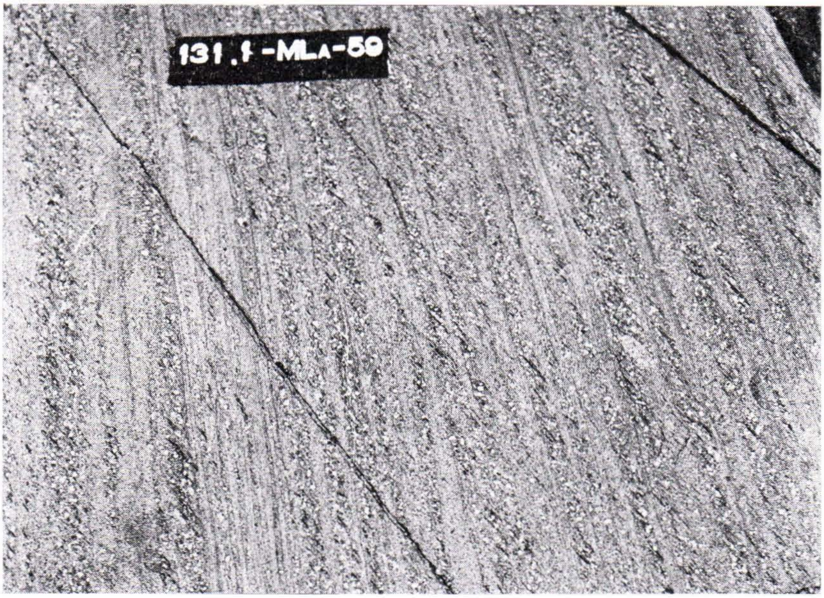

FIG. 34. Schistosity intersecting stratification of tuffites. South shore of Stor Pellinge, rural commune of Porvoo.

Linear structures

Lineations and the axes of the minor folds

Lineation observations were made from many different line directions resulting from deformation. Of these, the most important are the longitudinal directions of the hornblende and the biotite on the S_0- or S_1-surfaces, the extended longitudinal directions of the fragments of the agglomerates, the pebbles of the conglomerates, the pillows of the pillow lavas and the amygdalae of the lava rocks. The line of intersection of the S_0- and S_1-surfaces is likewise viewed as an lineation (Cloos 1946; Turner and Weiss 1963, p. 101 and p. 54—55).

The lineations vary in the region in prominence. They are particularly conspicuous at Aparnäs and its surroundings in the northwestern part of Stor Pellinge, where the ratio obtained for the diameter of the fragments of the extended agglomerate was 1 : 1.5 : 10. The lineation is so marked that the amphibolite occurring there — which was probably originally gabbro — has been quarried in the direction of the lineation.

The axes of the minor folds run in line with the local lineation. In the southwestern part of Stor Pellinge there occurs in the tuffites and lava rocks miniature folding, on the order of a few millimeters, the axes of which have been interpreted to represent lineations (see Billings 1954, p. 359; Turner and Weiss 1963, p. 101; Whitten 1966, p. 265). In this study the attitude of these rectilinear structures is related to geographic axes in terms of trend and plunge (see Clark and McIntyre 1951; Turner and Weiss 1963, p. 47; Whitten 1966, p. 38).

Local variations, shown on Appendix 4, occur in the trends of the lineations and axes of the minor folds. These will be described in more detail in connection with the structural diagrams.

Folding

The principal folding in the region emerges in the picture projected by the map as major folds constructed out of various structural elements with their axes running toward the northeast or nearly due east. On the limbs of the main folds, there occur minor folds, which can be observed on rock exposures and the axes of which run both parallel to those of the main folds and in deviating directions (see p. 50—53). Furthermore, there occurs in the region transverse folding, which will be described later along with the structural evolution.

Major folds

It was possible to determine a large number of top directions in the layers by means of the primary structures preserved in the metasediments and metalavas as well as by means of drag folds and intersections of S_0- and S_1-surfaces (see, Shrock 1948, p. 437—440; Billings 1954, p. 78—82 and 345—350). These directions are represented on Appendix 2. They made it possible also to determine the largest synclines and anticlines, the axial traces of which are marked on Appendix 2. The major folds have been designated after local place names.

Delholm syncline. From the southwestern part of Stor Pellinge, the syncline reaches all the way to the vicinity of Delholm. In the western section, it at first follows a NNE line, but in the middle of Stor Pellinge it turns ENE. On the eastern side of Delholm, the syncline descends underneath a rather broad uralite porphyrite bed and evidently widens and, on the basis of the top directions worked out, joins the syncline of Långhäll.

In the southwestern part of Stor Pellinge, the fold is closed in shape and, on account of the overthrust having taken place toward the northwest, both of its limbs dip toward the southeast. In the middle of Stor Pellinge, the shape of the fold is more open and nearly symmetrical; and that is the way it runs all the way to Delholm.

Älskholm anticline. The anticline extends from the eastern part of the south shore of Stor Pellinge to the vicinity of Älskholm. In the western section, its trend is also NNE, but more to the ENE it turns eastward. In the western section, on account of the overthrust that had taken place toward the northwest, its limbs dip ESE. In the east, on the south side of Ölandet, the northern limb of the anticline dips gently (ca. 40°) and the southern limb more steeply (ca. 75°—80°) toward the north. So the asymmetric shape and the southward-dipping character of the fold is clear enough. In the east, close to Älskholm, the shape of the fold is more open, but its southward-dipping character remains clearly apparent.

Sundö anticline. An anticline occurs in the vicinity of Sundö. Owing to the higher degree of metamorphism undergone by the sedimentogeneous schists of the area, no primary structures have been found there; but in structure the area is similar to the Älskholm anticline and the Delholm syncline. In the light of the structural similarity, the feature in this locality may be judged to be an anticline. It has a closed form and it tilts slightly toward the north.

Långhäll syncline. East of Älskholm, in the area of Korsholm-Långhäll, there is an open syncline, which, situated on the northern side of the Älskholm anticline, dips slightly toward the south. This syncline likewise extends possibly northeastward to the vicinity of Ormskär, closed in form and dipping gently toward the south.

Julö syncline. In the Julö area, on the southeast side of Stor Pellinge, there is a syncline with an east-west trend in its eastern part but which in its western end turns toward the southwest. The limbs of the syncline dip in its eastern part toward the north. In the western part, the shape of the fold is nearly symmetrical.

Nyttisholm syncline. Judging by the primary structures, there is a syncline on the west side of the southwest shore of Stor Pellinge. Its position and trend are uncertain, for the open sea ahead of it prevents accurate determination. In the light of observations made from on shore, it structurally resembles the afore-mentioned Julö syncline. See, structural diagrams of subareas II and III in Appendix 5.

The large folds referred to here are likely to be several kilometers long. Between these major folds, there occur smaller ones, which are connected with them and vary in length from a few dozen to hundreds of meters. These could be observed by means of their primary structures. As they are situated on the limbs of the major folds, in which steeply dipping layers run parallel for long distances, such folds must be quite closed and isoclinal in style. Folds of this kind occur in particular abundance on the south shore of Stor Pellinge as well as in the eastern section of the area.

Minor folds

The minor folds to be seen on rock exposures vary in size from tiny wrinkles to forms a few meters across. Isoclinal folds with the closed shape occur in greatest abundance on the limbs of large folds, notably in the schist zone of the north margin, whereas the open folds are characteristic of the middle portions and ends of the major folds. In many instances, beautifully developed drag folding is associated with last-mentioned folds (Fig. 35).

There is local variation in the intensity of the minor folding. Conspicuously folded in the eastern section of the area are the surroundings of Ormskär and Mysscholm as well as the tract from Risholm to the west. Corresponding tracts in the western section are the surroundings of Julö and the southwestern section of Stor Pellinge, where overthrusts have occurred, too (Fig. 36). In the last-mentioned locality, both in the tuffites and the lava rocks there occurs crenulations.

Examined as a whole, the folding of the region gives the impression of its being a syncline, or rather a synclinorium, composed of several folds, the central portion of which lies in the vicinity of the Delholm syncline.

Structural diagrams

The trends of the lineations and axes of the minor folds vary locally. When such localities are separated from each other, several subareas emerge (see, Turner and Weiss 1963, p. 175) in the western section of the region investigated in which these trends are the same or nearly the same (Appendices 4 and 5). In the eastern section of the region, with the exception of the northern margin, no such division can be made, for the islands belonging to the archipelago proper are sparse and consist largely of plutonic rocks. The eastern section is therefore regarded as a single entity. In the western section, the homogeneous subareas form alternating and parallel zones, which are folded along slightly curved lines running east and west, with their boundaries generally following the direction of the schistosity of the rocks but in places also apparently intersecting it. In aerial photographs, these boundaries are distinguishable by the fractures and, in places, where no fractures

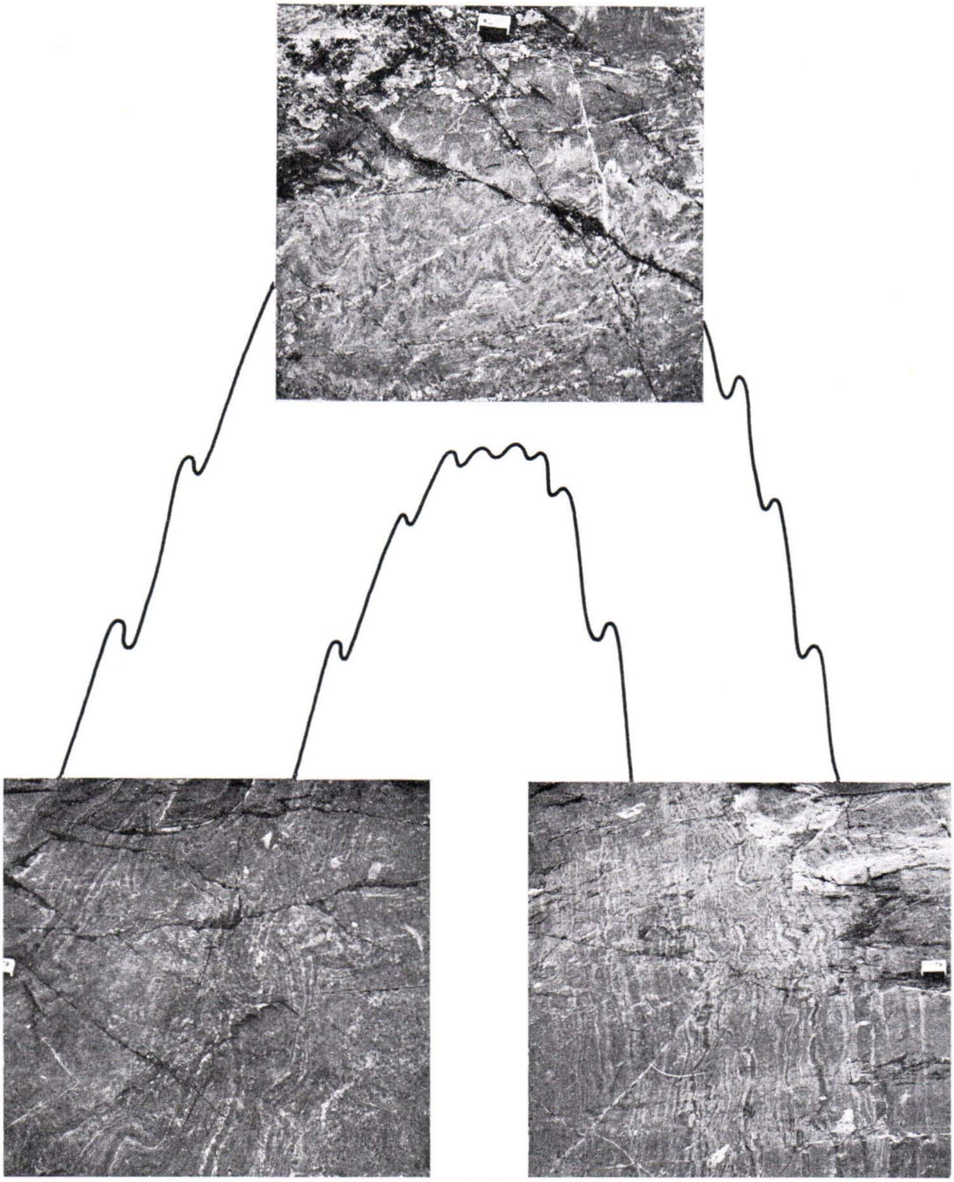

FIG. 35. »Drag folding» on flanks of minor folds. Islet located about 1 000 m east of Byttholmen, Pernaja.

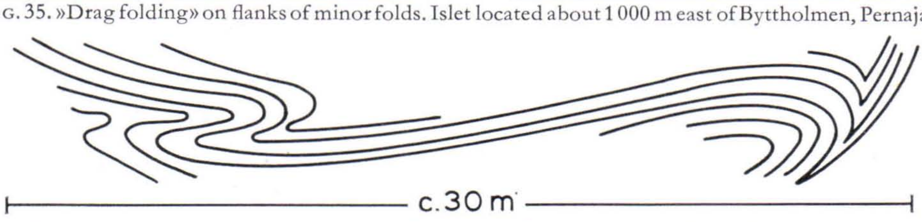

FIG. 36. Schematic drawing of overthrust minor folds. Southwest part of Stor Pellinge, rural commune of Porvoo.

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can be seen owing to, for example, the soil cover, by the differences in the level of the ground. To make possible a comparison of the structural differences between these subareas, the structural elements from each subarea have been plotted separately on the lower hemisphere of Schmidt's equal area net to construct the diagrams (Billings 1954, p. 112—114). Although only sparse observations are available from some of the subareas, they nevertheless probably provide an overall picture of each of them, considering that the areas are relatively small and homogeneous. The directions and dips of the structural elements were measured within a margin of error of 5°, which, in my opinion, is wholly adequate in clarifying the structural differences and interpreting the reasons for them by means of a statistical study of this kind. In the following exposition, the diagrams made of the strata will be termed S_0-diagrams, the ones made of the schistosities S_1-diagrams and those of the lineations and axes of the minor folds L-diagrams. An S_0-diagram enables one to determine the trend and plunge of axis B of the major folds in a given area (Wegmann 1929, p. 104—105). The diagrams of the subareas are presented in Appendix 5.

The subareas marked off on the basis of the directions of the lineations and axes of the minor folds are divided into three groups:

1. Areas in which the directions are to the northeast or east. This category includes subareas I, IV and VI.
2. Areas in which the directions are to the southwest or west. Belonging to this group are subareas II, III, V and VII.
3. Eastern subarea VIII, in which the directions are to the west, southwest and northeast.

Group 1

Subarea I is located in the southern part of Stor Pellinge and includes the ends of the Delholm syncline and Älskholm anticline bent toward the southwest.

On the S_0-diagram, the poles of the normals of the strata form a great circle, the B direction of the axis of which, ca. N 40°E 35°, is the trend of the axis of the main folding in the area.

On the L-diagram, the strongest maximum of the lineations, L_1, is in approximately the same place. In addition, there occur in nearly the same direction two weaker maxima, L_2 and L_3. Such an occurrence of several maxima in approximately the same direction is apparently due to the marked bending of the major folds in this area. Besides the foregoing, there occurs in the diagram still a fourth weak maximum, L_4, in the direction S 15°E 55°. It deviates appreciably from the preceding directions. Reference will be made again to this direction later (p. 55).

The same bending appears in the S_1-diagram as three maxima of the foliation plane, according to which the schistosity varies from the north-south line to the direction N 30°E. The magnitude of the dips varies from 70° to 80° toward the east.

Subarea IV is the extension of the preceding area toward the east, comprising the middle portions of the Delholm syncline and the Älskholm anticline. In the light of the diagrams, the area is clearly delineated.

On the S_0-diagram, there occur two prevalent trends of the principal folding, B_1 (N 50°E 25°) and B_2 (N 75°E 15°). The B_1 direction of the fold axis occurs in the western and eastern parts of the subarea. Direction B_2 occurs in the central portion of the area, marked on the map (Appendices 4 and 5) as IV:a. In this area, there is a profusion of well-preserved primary structures; accordingly, the metamorphism there was probably weaker than in the surroundings.

On the L-diagram, there are likewise two maxima, L_1 and L_2, the trends and plunges of which correspond roughly to the trends of the fold axes.

On the S_1-diagram, the maximum areas are broad, reflecting variation also in the strikes and dips of the schistosity.

According to the S_0- and L-diagrams, there takes place in the area a turning of the axis trend and that of the lineation from the northeast line in the western section to the east line in the central section and, once again, to the northeast line in the eastern section at the same time as the plunge of the axis in the central section becomes slightly less steep.

Subarea VI is separate from the preceding ones, comprising the central portion of the Sundö anticline. Compared with the preceding ones, it also reveals differences of structural style.

The S_0-diagram is somewhat unclear, with weak maximum points on the outer circle of the diagram. This is apparently due to the conspicuous minor folding that occurs in the area and would have required a larger amount of observations.

In the L-diagram, on the other hand, there is similarity. It has a distinct maximum, L, the trend of which is the same as the trends B_2 and L_2 of central portion IV:a of subarea IV. The plunge, however, is steeper, ca. 40°.

From the S_1-diagram, the strike of the schistosity plane obtained is approximately N 65°E 70°S.

Group 2

Subarea II is located at the west end of the formation, and it comprises the Nyttisholm syncline.

On the S_0-diagram, the poles of the strata form two great circles, the corresponding trends B_1 and B_2 of the fold axis being parallel to them but a difference of about 35° occurring in the plunges. The gentler B_1 (S 80°W 35°) prevails, as may be observed from the maxima of the corresponding great circle.

On the L-diagram, there occur the corresponding lineations L_1 and L_2. In addition, there occurs still a third lineation trend, L_3, which plunges straight south at a 65° angle. This trend coincides approximately with the lineation L_4 of subarea I. This direction will be reconsidered later (p. 55).

From the S_1-diagram, the strike of the schistosity is ca. N 85°E 85°S.

Subarea III is situated at the south margin of the western part of the formation and comparises the Julö syncline, which opens toward the southwest.

The trend of the fold axis B, obtained from the S_0-diagram, is ca. S 80°W 70°.

In the L-diagram, there occur three maxima, which indicate changes in the lineation trend from the east end of the fold to the western part. Of these, the gentle southwestern trend, L_1, occurs in the eastern part of the fold, the more steeper western trend, L_2, around the middle of the fold and the steep southwestern trend, L_3, in the western part of the fold. The L_3 trend is approximately the same as the fold axis B.

The S_1-diagram also reveals the changes that had taken place in the strike of the schistosity from the N 85° E line to the N 75° E line, the dips being 70° to 80° toward the north.

Subarea V is situated in the center of the area as a zone about a kilometer broad bent nearly to an east-west line; it lies on the limb of the fold between the Delholm syncline and the Sundö anticline.

The direction of the limb of the fold obtained from the S_0-diagram is approximately east-west and the dip ca. 70°S. The area surrounding the point of the maximum is broad, indicating the variation in the orientation of the layers.

On the L-diagram, there occur three maxima, L_1, L_2 and L_3. The lineations corresponding to the maximum L_1 fall into the eastern part of the zone. The maximum L_2 has stretched to quite a length on roughly a plane striking northwest-southeast with a dip of about 60° SW. The corresponding lineations fall into the vicinity of the bend in the western part of the zone, where also field observations ascertained the lineation to have developed quite markedly. A lineation plunging steeply southward occurs at the western end of the zone, coinciding with trend L_4 of subarea I. This trend will be dealt with later (p. 55).

The S_1-diagram reveals the lineations to run along the schistosity plane, which strikes ca. N 85°E 85°S.

Subarea VII is situated at the north margin of the region, occurring as a curving zone about 2.5 km wide, which, at least in its western portion, lies on the north limb of the Sundö anticline.

Variation in the orientation of the strata is to be observed on the S_0-diagram, being due to the curving of the zone. In the eastern part of the zone, the strikes are ca. N 80°W and in the western part N 70°E. The dips are steep.

On the L-diagram, the trend of the lineations varies. A weak maximum, L_1, occurs at the east end of the zone. The lineations corresponding to the likewise weak maximum L_2 fall in the vicinity of the curve made by the zone in the eastern section, while the lineations corresponding to the stronger maximum L_3 fall in the zone running toward the west. L_1, L_2 and L_3 are situated on a plane striking approximately northwest-southeast with a dip of ca. 60°SW (*cf.*, subarea V, L_2). Likewise characteristic of this zone is a turning of the lineation from the western direction of the eastern section to a nearly due south one at the western section at the same time as its dip steepens.

The S_1-diagram reveals that the schistosity partly has taken the same strike as the strata. Also lineation L_3 falls on the schistosity plane.

Group 3

Subarea VIII embraces the eastern section of the area investigated with the exception of the north margin, which is dealt with in conjunction with subarea VII. This area differs from the other areas in that it consists for the most part of plutonic rocks. More schists occur in the southwestern and northeastern sections. Also structurally, the area stands apart from the other ones, for which reason the clear-cut zones described in the foregoing could not be distinguished and the area is treated as a single entity.

On the S_0-diagram, the poles of the normals of the strata bring about a number of weak maxima on the outer circle of the projection, this apparently being due to the conspicuous minor folding that occurs in the region.

On the L-diagram, there are three maxima, of which the L_1 evidently represents the axis of the main folding. At right angles to this is L_2. The deviating trend L_3 occurs in a small, confined area in the southwestern part of the subarea.

On the S_1-diagram, considerable variation is to be observed in the strike of the schistosity plane: this appears as a dispersion of the normal poles of the planes over an extensive area. In the diagram, there occur two maxima, the corresponding strikes of which, N 70°E 75°N, occur mainly in the southwestern part of the region and the strike N 80°W 80°N in the northeastern section.

Structural evolution

The foregoing S_0- and L-diagrams make evident that in the cores of the major folds, observed to vary in orientation in the region from the northeast to nearly due east, the trends followed by the axes of the minor folds as well as by the lineations run nearly parallel with the main axes of the major folds. On the limbs of the main folds, the lineations and the axes of the minor folds likewise coincide but run, by contrast, west and southwest. Consequently, in the following interpretation of the structural evolution of the region, use was made of the trends of the lineations and axes of the minor folds represented in the L-diagrams. They seem to reflect the development undergone by the total structure quite faithfully.

The diagrams also reveal the changes that have taken place in the region in the L-directions. In the areas of the main folds (subareas I, IV, VI and VIII, Appendix 5), one will note how in the southwestern section, in subarea I, the NNE-trending axis gradually turns so that in subarea IV:a it runs nearly due east and from here, further, back to a northeasterly direction (subareas IV, eastern part, and VIII).

In subarea VI, the trend of the axis is ENE. The change in direction, as compared to that of subarea IV:a, is of the order of ca. 30° to 40° and in the southwestern section, in subarea I, it is nearly 50°. In the axis trends, there accordingly had taken place a rotation, the center of which is approximately in the vicinity of subareas IV:a and VI and the direction had been counter-clockwise. Simultaneously, changes had taken place also in the plunges of the axes, which in the southwestern section are ca. 30°, in the middle of subarea IV:a ca. 15° and in the northeastern section again ca. 30°.

The same rotation appears also in the L-diagrams of subareas V made from the limb of the main folds and VII as well as in subareas II and III of the L-diagrams of the folds opening toward the west. Common to all, proceeding from east to west, is a turning of the L-trends from a gentle westerly one to a steeper southwesterly one. It may be noted from the L-diagram of subarea V that the most marked change of trend happens around the arch opening south in the western part of the subarea, where the maximum L_2 composes a zone trending SE-NW. The same phenomenon may be noted also by examining the L-diagram of subarea III. In subareas III, V and VII, the change in the L-trend is ca. 35°—45°. The plunges steepen at the same time.

In subarea II, changes appear only in the plunges of the lineations. It has not been possible to determine how these directions fall into the various parts of the area because evidently they represent only part of a larger whole.

The last diagram of Appendix 5 summarize the data included in the diagrams of subareas I—VIII. On the basis of these and the diagrams of the subareas, an attempt was made in the following to elucidate the main features of the folding.

The main folding was caused by horizontal compression, the direction of which was approximately SSE—NNW. This is revealed by Appendix 5 of the L-diagram (see Sander 1948, p. 132) and the S_1-diagram (see Billings 1954, p. 343) comprising the whole region. During folding, however, there takes place a division of this one-direction compression into differential stresses, the directions and magnitudes of which change the whole time — having done so as early as the sedimentation stage or as the strength of the strata, the resistance of the formations and other physical properties varied (Bhattacharji 1958, p. 627). The changes in the direction of the forces at work naturally also cause changes in the directions of the fold axes and axial surfaces. This is what evidently happened around the middle of the region in the southward-thrusting area of acid gneisses and its extension to the south characterized by the occurrence of volcanic rocks (subareas IV:a and VI). This area, apparently owing to the rigidity of the originally arkosic sediments, constituted a resistant block (Appendix 5). Here, the folding was caused by differential stress, the direction of which was almost north-south and which, owing to its nature, was smaller. To this probably may be attributed the more open folding style of the area, the weaker metamorphism in comparison with the surroundings and the turning of the axis direction east (subareas IV:a and VI) and the gentler plunge in subarea IV:a.

On both the western and eastern sides of the afore-mentioned block, the force working from the south was able to make itself felt freely so that the yielding sediments gave way to form gently arching folds. Such large, arching folds opening southward occur on both the eastern and western sides of the rigid block.

By virtue of the greater density of observations afforded by a homogeneous archipelago, it was possible to elucidata more clearly the structure of the arched transverse fold opening south in the western section. The crest of the fold occurs in the northwestern part of Stor Pellinge and the inner curve in the Julö area. As this arched fold developed, the limbs of the main folds acted as yielding slide surfaces, whereas the central portions of the folds, thanks apparently to the strength of the structure, were preserved. The sliding that occurred on the limbs of the main folds is revealed by the development of the L-trends as shown in the L-diagrams of subareas II, III, V and VIII. The steeply plunging lineation L_3, which occurs at the western end of the subareas, varying from southwest to south, and the lineation L_4 of subarea I fall onto the »axial surface» of this transverse fold and thus represent the developing axis trend of the fold. On the west shore of Julö, foliation directions were measured from the quartz diorite — this was done also on the south shore of Stor Pellinge — and the figure obtained of ca. N 20°W 70°W seems to correspond to the »axial surface foliation» of this folding.

The radius of the outer curve of this fold, located in the northwestern part of Stor Pellinge, is larger than the radius of the inner curve, located in the vicinity of Julö. In type, it is a flexure fold. On the outer curve of the fold in the northwestern part of Stor Pellinge, there are several long bays oriented toward the southeast, the directions of which deviate from the general style of the bays in the archipelago. These might be fractures formed in the tension zone at the crest of the fold (see, Billings 1954, p. 89). Analogously, in the compression area of the fold in the vicinity of Julö, where the compression had been great, there is a syncline opening toward the southwest, one in an en echelon position in relation to the principal folding. A similar phenomenon is to be observed in the eastern section, in the vicinity of Ugglasö-Korsholm, where the compression produced minor folding oriented northwestward in the inner part of the arched fold opening toward the northwest.

The slight overthrusts of the strata occurring in the southwestern and southeastern parts of the region are also associated with this folding, dating from a late stage.

With the whole taken into account, the summary of the L-diagrams constructed of the region (Appendix 5) reveals that the L-trends of the main folds (the directions of the b-axes) and the ones situated on the limbs of the main folds (those of the a-axes) developed synchronously and roughly at right angles to each other. Many researchers have previously had their attention drawn to the relation between such directions. Van Hise (1894) was the first to refer to the minor folding of a folded formation as »cross-folding» — he regarded the main folding and the associated minor folding as representing two different stages in the evolution of a structure. At present, the view prevails that both foldings are synchronous (Newhouse 1955; Rast and Platt 1957; Whitten 1959).

The inter-relations of folding have also been studied experimentally (Hungerer 1922). The synchronousness of foldings is further supported by the latest experimental studies (Bhattacharji 1958).

In studies carried out in southern and southwestern Finland, the lineation has been observed to be both at right angles to the fold axis (Neuvonen and Matisto 1948; Simonen 1949, 1952, 1953) and parallel to it (Salli 1955). Also the magma has been found to have caused a conspicuous lineation in the direction of its movement (Härme and Seitsaari 1950). The lineation has further been observed to run in different directions but not perpendicular to the b-axis of the general folding (Härme 1955).

In the area of Orijärvi (Tuominen 1957), two general lineations trending eastward have been observed; the more gently plunging of the two (15°—20°) runs parallel to the fold axis and the steeper (with a plunge of 45°) is assumed to be connected with the overthrust directed westward.

PLUTONIC ROCKS

In the following presentation, mention will first be briefly made of the plutonic rocks that bound the region under investigation. The plutonic rocks actually associated with the region itself will be dealt with somewhat more thoroughly.

Plutonic rocks skirting the study region

Microcline granites

In the north, the region borders on an extensive area of microcline granite. Granite of the same kind has also been met with on the south side of the region, on a few rocky islets (not shown on the map) out at sea about 10 km from Stor Pellinge. This granite composes migmatites with older rocks and it is a rock typical of the southern coastal region of Finland. Such migmatites have been described by quite a number of investigators, but special mention should be made of Sederholm's studies, which have become classics by now (1907, 1923, 1926, 1934). A petrological summary of these rocks has been published by Simonen (1960, p. 64—72).

At Kardrag, at the northern margin of the region, observations have been made of the contact between the granite and the schists dipping southward at an angle of approximately 80°. The contact proper is not visible. In the area of the contact, there is a deeply eroded zone a few dozen meters wide, wich is covered with soil. At the southern edge of this contact zone, granite has abundantly penetrated the schists. At the same time, strong fracturing of the rocks has taken place, along with metamorphic changes, the most striking of which is a marked epidotization of the minerals of both rocks.

Elsewhere, the contacts are covered with either loose deposits or water.

Granite of Onas

On the west side of the region, there occurs a granite massif, which takes up an area of nearly 300 sq. km. It is composed of potash feldspar forming grains 2—3 cm in size and plagioclase, quartz, biotite and hornblende. The composition of the rock is fairly homogeneous. Only at its western margin do diverse varieties occur.

The contact between this granite and the schists of the study region lies under the sea, so no observations of it have been made. Detailed descriptions of the rock have been published by Sederholm (1923, p. 95—97) and Borgström (1931).

Rapakivi

In the east, the region is bounded by the great Wiborg (Viipuri) rapakivi massif. The most prevalent type of this rock contains potash feldspar ovoids which are generally mantled by plagioclase. In addition to the potash feldspar and plagioclase, the rock contains quartz, biotite and hornblende as the principal minerals. The rapakivi has been described closely by Sederholm (1923, p. 75—92), Wahl (1925), Vaasjoki (1953, p. 49—50), Savolahti (1956), Simonen and Vorma (1969) and Vorma (1971).

In the eastern part of the region, also the contact between the rapakivi and the schists has been met with. The rapakivi has been observed to intersect the schists intrusively. The contact and the contact phenomena have been described in detail by Sederholm (1923, p. 75—92) and Vaasjoki (1953, p. 49—50).

Plutonic rocks occurring in the region

The plutonic rocks occurring within the region investigated composed separate intrusions, which are identified by the place names.

Haverholm quartz diorite

On the north side of Stor Pellinge, there is an area of plutonic rock, the longitudinal direction of which is the same as the direction of the local foliation, ca. N70°E. It is located at the core of the northward-tilting Sundö anticline. The western margin lies under the sea, and in the east it borders on arkose gneisses. The rock varies in composition from gabbro to granodiorite. The predominant type, however, is quartz diorite. It generally contains volcanic fragments. The granodioritic types contain less fragments; but, on the other hand, they have amphibolitic and arkose gneiss intercalations running parallel to the foliation. There is a greater abundance of granodiorites at the northern margin of the area. The arkose gneiss on the eastern side is especially rich in quartz-dioritic and granodioritic veins, which, running parallel to the foliation, can be traced to this massif.

The principal minerals of the rocks are plagioclase (An_{28-33}), which in some instance is present as phenocrysts, hornblende, quartz and chlorite. Diopside has also been met with in the gabbros. At the western margin of the area, the plagioclase is conspicuously sericitized. Accessory constituents are epidote, magnetite, apatite and — in some places occurring abundantly — sphene. No potash feldspar has been detected in any of the thin sections examined.

The gneissose structure of the rock is well developed, as observed both in the field and under the microscope.

The mineral composition of the rock is given in Table 6, Nos. 1 and 2.

Kummelskär quartz diorite

The same kind of quartz-dioritic rock, which in places is porphyritic, has been met with on the outermost islands of the group on the south side of Stor Pellinge as well as on the skerries located some 13 kilometers to the east from them. Here, too, the gneissose structure is marked, and the rock contains volcanic fragments as well as amphibolitic intercalations running parallel with the foliation.

The chief minerals in the rock are plagioclase (An_{27-32}), quartz, hornblende and biotite.

Våtskär granodiorite

At the eastern end of the region, west of Våtskär, there is a body of plutonic rock similar in mode of occurrence to the foregoing ones. In composition it is granodiorite. It likewise forms an elongated massif parallel to the foliation, and the gneissose structure of the rock is well developed. It also contains basic inclusions. The plagioclase (An_{27}) composes phenocrysts, which are arranged parallel to the foliation. Present, in addition, as major mineral constituents are quartz, biotite and hornblende. A detailed description of the rock was published by Sederholm (1923, p. 137—146) as well as by Vaasjoki (1953, p. 17—18).

This rock, too, occurs in the schists of the southern margin, in the form of veins running parallel to the foliation.

The mineralogical composition of the Våtskär granodiorite is given in Table 6, Nos. 3 and 4.

TABLE 6

Mineral compositions of plutonic rocks. 1—2 Quartz diorite of Haverholm, 3—4 Våtskär granodiorite, 5—7 quartz diorite of Julö.

	1	2	3	4	5	6	7
Quartz	5.0	11.5	25.7	21.0	29.6	27.5	5.4
Potash feldspar			13.0	13.6		10.5	6.4
Plagioclase	58.6	53.3	50.5	46.9	28.0	42.7	37.1
Biotite			1.2	8.3	10.0	12.5	1.1
Chlorite	6.4	7.4	4.7				
Hornblende	27.4	25.9	4.5	9.9	28.0	2.7	48.3
Epidote						2.3	
Accessories	2.6	1.9	0.4	0.3	4.4	1.8	1.7
	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Quartz diorite. Island situated about 200 m to the west from Brudholm, rural commune of Porvoo.
2. Quartz diorite. Brudholm, rural commune of Porvoo.
3. Granodiorite. Vadholm, Pernaja.
4. Granodiorite. Bergholmen, Pernaja.
5. Quartz diorite. Långö, rural commune of Porvoo.
6. Granodiorite dike. Björnholm, rural commune of Porvoo.
7. Quartz diorite dike. Glosholm, rural commune of Porvoo.

Julö quartz diorite

In the western part of Långö and in Julö, there occurs a small, independent body of plutonic rock, the predominant variety of which is quartz diorite. Its chief minerals are plagioclase (An_{30-33}), quartz, hornblende and biotite. The plagioclase occurs to some extent as long, idiomorphic laminae, with the result that the structure is ophitic in appearance. In places, the plagioclase exhibits a well-developed zoned structure. To some extent, the hornblende is green, to some extent, pale bluish. The accessory minerals are sphene, magnetite, calcite and apatite. The mineralogical composition of the rock is given in Table 6, No. 5.

Also occurring in the intrusion are granodioritic varieties, whereupon potash feldspar is present in addition to the afore-mentioned minerals and the composition of the plagioclase is An_{25}. Myrmekite generally occurs in the plagioclase.

This plutonic rock is situated in the Julö syncline, which had formed in the inner arch of the great transverse fold opening southward (see, p. 55). Its eastern margin lies on top of volcanics and runs at an angle of about 20° toward the west in conformity with the lineations and the axes of the minor folds in the eastern part of the syncline. The northern border dips at an angle of about 80° to the north and the western border at one of about 70° to the east.

At the northern and southern margins, the plutonic rock brecciates the surrounding volcanics. The center of the plutonic rock is homogeneous, and there one can notice a weak schistosity in the direction N20°—45°W, the dip being ca. 70°W. This schistosity direction intersects nearly at right angles the foliation directions measured from the surrounding volcanics. This direction apparently came about during the time of transverse folding. Also situated on this level are the steep south-westerly and southerly L-directions (see, p. 55).

On the southern and southwestern sides of the intrusion, there occur an abundance of quartz-diorite and granodiorite dikes (Table 6, Nos. 6 and 7) deriving from this intrusion and that discordantly intersect the surrounding volcanics.

Plutonic rocks of the vicinity of Ryssholm

These plutonic rocks are situated in the eastern section of the region, in the vicinity of the island of Ryssholm, and they comprise the rocks designated by Sederholm (1923, p. 113—128 and 146—148) as Rysskär granite and Stadslandet gabbro. The area, measured east and west, is approximately 6 km long and 3.5 km broad. The plutonic rocks extend southward on the eastern side of the archipelago proper as a zone about 1.5 km broad. This body of plutonic rock also includes a narrow, veinlike occurrence running from the south shore of Byö and curving westward on the eastern side of Stor Byttholmen to reach as far as the north shore of Lill Pellinge. The same kind of narrow zone of plutonic rock has further been met with on the north shore of Stor Pellinge; in all likelihood, it is an extension of the one just mentioned. It is not, however, possible to decide this for sure because the areas in between are covered with surficial deposits.

The rocks of the area vary a great deal. In mineral composition, they are gabbros, quartz gabbros, diorites, quartz diorites, granodiorites and granites, which grade over into each other. No contacts have been detected. On the basis of the abundance in the occurrence of given varieties of rock, it is possible to distinguish different roughly bound areas. At the northern margin of the area, in the southern part of Byö and Stadslandet, and in the islands fronting it, the predominant variety of rock is gabbro. In the middle of the area, there are a couple of small stretches of granite. The rest of the area contains a mixture of all the varieties of rock mentioned, and it would be virtually impossible to draw the boundaries between occurrences on a map.

The plutonic rocks of the area vary in mineral composition. The principal minerals contained in the gabbros are plagioclase (An_{33-37}), green hornblende and biotite. In places, there is a scanty amount of quartz in addition. Besides the hornblende and biotite, the diorites and quartz diorites contain a greater amount of quartz, and the composition of the plagioclase varies between oligoclase and andesine (An_{25-33}). The granodiorites contain plagioclase (An_{18-27}), a slight amount of hornblende or, in its place, chlorite, potash feldspar, biotite, quartz and, in many instances, epidote. Compared to granodiorites, the granites contain more potash feldspar, and the composition of the plagioclase is An_{15-25}. The mineral compositions of the different plutonic rocks of the area are given in Table 7.

In the basic types, the gabbros and diorites, plagioclase is frequently observed to form lamallae, which are apt to be 4 mm long and 1 mm wide. The spaces between the crystals are filled with dark minerals. For this reason, the rock is ophitic in structure (Fig. 37). Such types occur abundantly in marginal parts of the plutonic rock area. The plagioclase grains in very many instances exhibit beautifully developed, zoned crystallization.

TABLE 7

Mineral compositions of plutonic rocks in vicinity of Ryssholm.

	1	2	3	4	5	6	7	8	9	10	11
Quartz	1.9	1.2	11.9	14.2	16.8	19.2	27.0	27.8	40.0	27.8	43.6
Potash feldspar ..				0.5	7.8	12.4	4.3	11.9	13.4	25.2	29.7
Plagioclase ..	51.6	58.0	39.5	53.4	48.0	50.8	56.1	43.8	42.3	41.8	25.2
Biotite		7.0	10.3	12.4	12.2	9 5	8.5	9.9	2.2	2.0	1.5
Chlorite	2.1		0.9				1.1		1.4	2.2	
Hornblende	43.3	32.2	34.8	17.9	13.9	7.4	2.3	5.3			
Epidote								0.5			
Sphene		0.6		1.0		0.2					
Calcite				0.2				0.2			
Apatite	0.5	0.4	1.4	0.3		0.2	0.3	0.2			
Accessories	0.6	0.6	1.2	0.1	1.3	0.3	0.4	0.4	0.7	1.0	
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Gabbro. Kråkskär, Pernaja.
2. Gabbro. Tärneshäll, Pernaja.
3. Quartz gabbro. Hägglandet, Pernaja.
4. Quartz gabbro. Stora Klacken, Pernaja.
5. Quartz diorite. Måshäll, Pernaja.
6. Granodiorite. Sundarö, Pernaja.
7. Granodiorite. Kråkskär, Pernaja.
8. Granodiorite. Äggörarna, Pernaja.
9. Granodiorite. Ryssholm, Pernaja.
10. Granite. Sundarö, Pernaja.
11. Granite. Ryssholm, Pernaja.

FIG. 37. Ophitic textural features in gabbro. Brändholm, Pernaja. Microphotograph, magnification c. 12×, nicols+. Photo Erkki Halme.

In a few places in the plutonic rock area proper, but, especially, also in the dike running from the south shore of Byö and turning westward at Byttholm, the gabbro in places contains hornblende phenocrysts about 5—7 mm across with the matrix ordinarily being finer of grain. These types are variants of the even-grained gabbro and very closely resemble the uralite porphyrites of the region.

Also other varieties deviating in structure from the plutonic rocks proper occur. On the west shore of Stor Finnholm, the observation may be made at the western margin of the plutonic rock how the quartz-dioritic rock possessing an ophitic texture gradually changes into a finer-grained porphyric rock, which in texture closely resembles the hypabyssal feldspar porphyry occurring on Lill Måsholm-Bastuö (see, p. 29).

The plutonic rocks contain tuffitic as well as uralite- and plagioclase-porphyritic fragments, which vary in abundance from area to area. They occur in especial profusion close to the contacts of the plutonic rocks as well as at the center of the area, where the fragments give the rock its dominant character. On the other hand, in the district located to the southeast and east from Byö, there are fewer of the fragments and in some places the plutonic rock is homogeneous. Through the effects of the molten magma that penetrated them, the fragments have altered in many ways. These phenomena have been described in detail by Sederholm (1923, p. 116—128) and Vaasjoki (1953, p. 28—39). In addition, more acid plutonic rocks brecciate basic plutonic rocks that crystallized earlier.

In the southern part of Måsholm, there is to be seen the contact between the granodiorite of the Ryssholm rocks and an earlier volcanic rock. The granodiorite penetrates the country rock as veins, forming a zone of veined gneiss some 2 m broad. In general, direct contacts between the plutonic rock and older volcanics are rare.

The country rock surrounding the intrusion abounds in dikes that cut across it. In mineral composition and structure, these dikes correspond to the country rock of the locality itself and derive from this massif. In places, they brecciate the country rock and, in other places, they have penetrated the country rock along the foliation planes, composing veined gneissose migmatite. One example is to be observed on the west shore of Viasholm. A description of it is given by Sederholm (1923, p. 128—137, Fig. 59, p. 132), according to whom the conglomerate occurring on the island became homogenized by palingenesis during the penetration of the plutonic rock and then recrystallized into a material appearing to be plutonic rock. The case might also be interpreted as migmatite. Material penetrated along the foliation plane from the vein of plutonic rock cutting the conglomerate to produce a veined gneiss. Similar phenomena have been described by Härme (1958, p. 46, and plate I, Fig. 1).

Tunnholm gabbro

The Tunnholm gabbro is situated in the southwestern part of the region on the island of Tunnholm and the islands in its vicinity. On account of the surrounding sea, no contacts between the gabbro and the country rocks are to be seen. The longitudinal direction of the formation is evidently southwest-northeast. A detailed description of the gabbro has been given by Sederholm (1923, p. 42—49). The predominant type of rock is a medium-grained (grain size: 1—5 mm), somewhat brownish gabbro, which contains slightly pleochroic augite, brown hornblende and plagioclase (An_{38-43}). In places, the rock exhibits an ophitic structure.

Deviating from the prevailing type, the gabbro contains in spots phenocrysts about 1 cm in diameter as well as coarser-grained and darker-colored patches of rock resembling fragments. The phenocrysts are diopside, which in some places have undergone uralitization. The phenocrysts are likely to occur in quite some abundance, in which case the rock strongly brings to mind uralite porphyrite. The boundaries of the dark fragments against the surrounding gabbro are gradual and also the transition from one variety of rock to another takes place gradually. In composition, the fragments are more basic than the gabbro and they contain diopside, hornblende and plagioclase (An_{57-63}) as well as olivine. In their mode of occurrence and appearance, these fragments closely resemble the ones that occur in the uralite porphyrite on the small rocky islets of Stensundsviken, on the southern side of Ölandet (p. 21). These fragments should probably be regarded as basic segregations of magma that became separated from the main mass at an early stage.

In places, the gabbro is also distinctly banded, bringing to mind the streaky appearance of the uralite porphyry met with at Edisudden, in the southwestern corner of Stor Pellinge, and, to some extent, also on the island of Nyttisholm (p. 21). The width of the bands varies from 20 cm down and in cross section they display differences in both mineral composition and grain size. One edge of a band is likely to be coarse-grained and contain a profusion of dark minerals while the other edge may be of a lighter shade and finer of grain. The structure of such individual bands is not, however, always even nearly regular but marked by inhomogeneous features. This banding can probably be attributed to movements that took place during the crystallization of the magma, and it may be regarded as representing an original flow structure.

Among the gabbro occurrences, especially in the marginal portions of the massif, there are also to be found dioritic rocks, the principal minerals of which are plagioclase (An_{28-32}) and hornblende. In addition, apt to be present are secondary potash feldspar, epidote and chlorite.

Further present in these types of rocks are coarse gabbro-pegmatitic dikes, the chief mineral constituents of which are oligoclase and hornblende. These dikes brecciate the gabbro in places, and they have been described in detail by Sederholm (1923, p. 46—49).

The mineral compositions of the different types of Tunnholm gabbro are tabulated in Table 8.

TABLE 8

Mineral compositions of different rock varieties of Tunnholm gabbro.

	1	2	3	4	5
Plagioclase	10.9	17.0	39.4	54.2	81.9
Hornblende	8.6	26.4	10.2	9.0	13.9
Diopside	75.5	55.3	44.2	26.0	
Olivine				8.8	
Potash feldspar					3.8
Chlorite			5.8		
Serpentine	4.5				
Accessories	0.5	1.3	0.4	2.0	0.4
	100.0	100.0	100.0	100.0	100.0

1. Pyroxenite. Halskär, rural commune of Porvoo.
2. Gabbro. Måsholm, rural commune of Porvoo.
3. Gabbro. Halskär, rural commune of Porvoo.
4. Olivine gabbro. Island situated to the southeast from Tunnholm, rural commune of Porvoo.
5. Diorite. Bredskär, rural commune of Porvoo.

Virskär gabbro

The Virskär gabbro is located in the southeastern section of the district, forming in the vicinity of Virskär an area that in the south is divided into branches running toward the southwest and the southeast. In view of the uniformity of the area, it has been regarded as a single formation, even though it does contain highly diverse types of gabbro (Table 9, Nos. 1—9).

Common to these types is their ophitic structure. The plagioclase forms lamellae, the interstices of which are filled with dark minerals. The most basic type is represented by the diabase-like rock met with on Virskär and on the islands on its northern side. This rock is brownish in color, and in places it displays a weak banding. The chief minerals are plagioclase (An_{40-45}), both brown and green hornblende and diopside (Fig. 38). In the eastern part of Virskär, there are olivine-bearing varieties with a lower content of hornblende. Around the olivine are to be seen various reaction rims, which have been described by Sederholm (1916, p. 37—38). The mineral compositions of the different types of Virskär gabbro are tabulated in Table 9, Nos. 1—5.

The rocks in the branch running southeastward from the area are less homogeneous than the Virskär type depicted in the foregoing. In the Morumshällar area, the rock is smaller of grain (Ø ~ 1 mm). In places, the hornblende composes phenocrysts, to a certain extent, and otherwise hornblenditic bands and larger accumulations. The principal minerals are plagioclase (An_{35-40}), hornblende and scapolite. The plagioclase forms lamellae, the interstices of which are filled with hornblende and scapolite. Accessory constituents are sphene, magnetite, epidote and apatite — the last-mentioned mineral abounds in spots in the scapolite areas (Table 9, No. 7). Granodiorite also occurs in the rock.

FIG. 38. Pyroxene-bearing gabbro. Virskär, rural commune of Porvoo. Microphotograph, magnification 12×, nicols+. Photo Erkki Halme.

TABLE 9

Mineral compositions of varieties of Virskär gabbro.

	1	2	3	4	5	6	7	8	9
Plagioclase	63.7	65.4	51.5	56.5	39.7	57.3	24.4	44.7	44.3
Hornblende		6.3	17.6	41.5	57.7	36.7	54.6	43.1	31.7
Diopside	16.3	15.5	30.5						
Olivine	10.5	8.6							
Biotite	7.1	2.6		1.6		4.7		4.9	8.0
Scapolite							18.5		
Chlorite					2.4				
Quartz								3.5	10.1
Accessories	2.4	1.6	0.4	0.4	0.2	1.3	2.5	3.8	5.9
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Gabbro. The east shore of Virskär, rural commune of Porvoo.
2. Gabbro. The east shore of Virskär, rural commune of Porvoo.
3. Gabbro. Central part of Virskär, rural commune of Porvoo.
4. Gabbro. The western shore of Virskär, rural commune of Porvoo.
5. Gabbro. The western shore of Virskär, rural commune of Porvoo.
6. Gabbro. Strömmingsgrund, rural commune of Porvoo.
7. Gabbro. Morumshällarna, rural commune of Porvoo.
8. Gabbro. Stångskär, rural commune of Porvoo.
9. Quartz gabbro. Sandö, rural commune of Porvoo.

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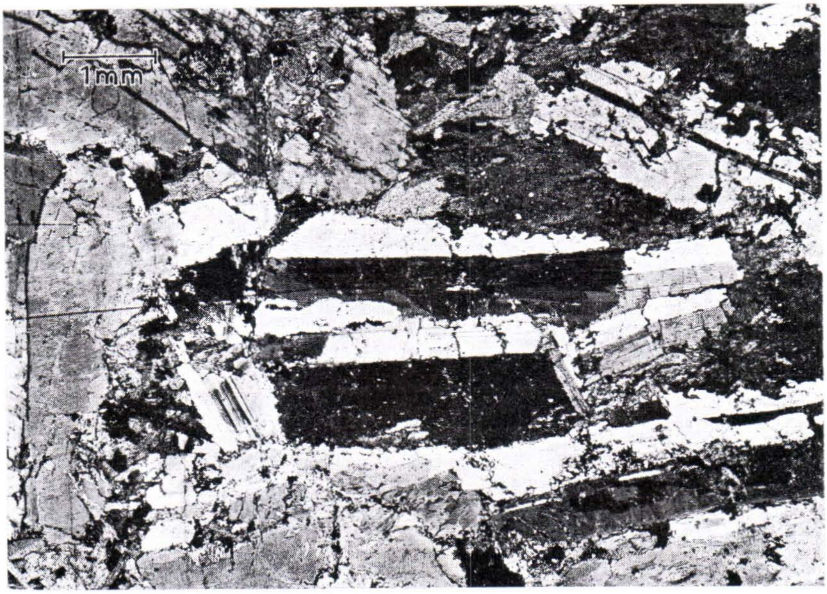

FIG. 39. Gabbro. Strömmingsgrund, rural commune of Porvoo. Microphotograph, magnification c. 13×, nicols+. Photo Erkki Halme.

In the locality of Strömmingsgrund, situated likewise in the same zone in a southeasterly direction, the rock is coarser and the plagioclase (An_{35}) occurs as phenocrysts about 5 mm long and 1—2 mm wide (Fig. 39). The groundmass consists of green hornblende and biotite (Table 9, No. 6).

The branch of the formation running southwest is more homogeneous than the foregoing in mineral composition. The chief mineral constituents are plagioclase (An_{33-37}), green hornblende and biotite. In addition, the rocks contain scanty amounts of quartz (Table 9, Nos. 8—9). In this locality, too, the plagioclase forms distinct lamellae and is in places zoned. Hornblende, biotite and quartz fill the interstices between the plagioclase lamellae. In places, the rock also displays weak banding.

At the southern tip of Virskär and on Strömmingsflada, which is located northwest of Virskär, the contact between the gabbro and the surrounding rock can be seen. In the southern part of Virskär, it can be clearly observed how the gabbro brecciates the agglomerate. On Strömmingsflada, the contact is more poorly visible, but here, too, the gabbro brecciates the older tuffite and in places forms with it a kind of rock comparable to veined gneiss. The evidence provided by the contact makes the intrusive nature of the gabbro unmistakable.

Pegmatites

In general, the pegmatites occur as numerous dikes, in the abundance of occurrence of which variation can be observed from area to area. In the middle of the area, they occur less numerously, and in the marginal portions more abundantly as veins either parallel to the schistosity and the bedding or intersecting them. They are met with in particular profusion in the plutonic rock area on the southern side of Stadslandet. The dikes vary in width from a few centimeters to several meters. On the west shore of Glosholm, there is a dike about 60 m wide.

In addition to the numerous dikes, pegmatite also occurs as broader areas in the northwestern part of Stor Pellinge and on the islands in the vicinity, in the northern part of Haverholm and the southwestern part of Korssundsholm. In these localities, the grain size of the pegmatite is substantially larger than that of the dikes.

The principal mineral constituents of the pegmatites are potash feldspar, quartz and biotite. In addition, muscovite and plagioclase are apt to be present.

The relation of the plutonic rocks to the structure and the folding of the region

All the plutonic rocks of the region investigated are younger than the supracrustal rocks. On the basis of their mode of occurrence, however, they can be divided into two categories.

The first category contains the quartz diorites of Haverholm and Kummelskär, situated in the marginal parts of the region, as well as the granodiorite of Våtskär. Common to all of them is an elongated occurrence parallel to the strike of the schistosity in the gneiss areas, where the S_0 and S_1 planes join together. Similarly, the gneissose, to some extent cataclastic, structure of these plutonic rocks represents an advanced stage of development. The quartz diorite of Haverholm lies in the core of Sundö anticline. The relation of the quartz diorite of Kummelskär and of the granodiorite of Våtskär to the regional structure cannot, owing to the lack of reliable observations, be determined confidently. Nevertheless, the similarity of these occurrences to the quartz diorite of Haverholm gives a reason for assuming that they likewise are located in the area of the anticline.

The second category contains the quartz diorite of Julö, the plutonic rocks of the vicinity of Ryssholm and the gabbros of Tunnholm and Virskär. The two varieties of rocks mentioned first share a number of features in common. The dominant rock of both is a quartz diorite, which has both more basic and more acid variants and, in the vicinity of Ryssholm, even one with a granitic character. The texture of the rocks has an ophitic appearance, and the plagioclase in many instances has crystallized in zones. In them, there also occur varieties that resemble the supracrustal basalts of the region. Furthermore, both formations contain an abundance of fragments from the surrounding country rock.

All these features give the impression that the intrusions are rather thin sheets. Their ophitic texture strongly suggests that the depth of crystallization was not very great. It has already been noted that the quartz diorite of Julö is located in a syncline (p. 59); hence the rock forms a phacolith at the bottom of the syncline.

A similar mode of occurrence is to be observed in the plutonic rocks of the Ryssholm vicinity, too. According to the determinations made of the directions of the faces of the strata in the country rock, in the north, west and south, this plutonic rock lies on top of schists. In the eastern section, the determinations are less sure; but it is probable that the plutonic rock here underlies the schists. This, too, may be regarded as a phacolithic sheet, which crystallized near the surface of the ground. The same thought was previously expressed by Sederholm (1923, p. 147) with reference to the gabbroic varieties occurring at the northern margin of the Ryssholm intrusion.

Common to the occurrence of these rocks, further, is the fact that both types are located in the compression area of the transverse fold opening out toward the south.

An extension of the Ryssholm plutonic rock area in the south is the Virskär gabbro. Its mode of occurrence resembles that of the former. In the northern section, it overlies the supracrustal schists that have been overthrust toward the south. In the southwestern section it likewise overlies the schists. Here, too, the structure of the rock, which in places is distinctly ophitic, indicates that it crystallized under hypabyssal conditions, either as a sheet or, possibly, at least in the southern section, as a fissure eruption running from the southeast toward the northwest. On account of the sparsity of islands, the density of the observations is poor, so the matter could not be completely verified.

Similarly, the Tunnholm gabbro shares features in common with all the rocks mentioned in the foregoing. It is located in the vicinity of the southwestern parts of the Älskholm anticline and the Delholm syncline. Nevertheless, owing to its isolated position bordering on the sea, its relation to the general structure of the region is difficult to determine reliably.

The afore-mentioned plutonic rocks are synorogenic in relation to the folding. During the orogenic stage, they had become situated in the anticline and syncline areas of the folds. Their differences in composition are due to the differentiation that took place during the crystallization. The differences in degree of deformation occurring in the rock structures can apparently be attributed to their varying positions in relation to the folding.

The migmatitic granite located on the north side of the region is associated with the extensive granite occurrence composing migmatites on the south coast and represents the diastrophism that took place during the orogenic stage. It took its place late in the orogenic process (see Simonen 1960, p. 64—65). The same state of affairs prevails also out at sea, as in the case of the migmatitic granite met with on the skerries situated about 10 km from the region investigated and from the southern margin of the map.

In Sederholm's view (1926, p. 112—116), the so-called Onas granite, located on the west side of the region, is younger than the migmatitic granite just referred to but slightly older than the rapakivi occurring on the east side of the region. According to later age determinations (Kouvo 1958), the rapakivi and the granite of Onas have proved to be contemporaneous, and nowadays both are regarded as anorogenic granites (Simonen 1969, p. 487).

BASIC DIKES

Several investigators (Sederholm 1907, 1923, 1926, 1934; Wegmann 1931; Kranck 1933; Edelman 1949) have described younger basic dikes intersecting the country rock in the southern Finnish coastal region. The relationship of such intersecting dikes to the country rock was studied closely and discussed in detail by Sederholm (1923) in many connections involving individual exposures in the region. In the following, the occurrence of these dikes will be dealt with as a regional phenomenon.

The dikes vary in width. The narrowest dike to be observed is about 5 cm wide and the broadest 8 m; the most common are between 10 and 50 cm. They are similar in composition to the basaltic lavas of the region. The chief minerals are plagioclase (An_{35-40}) and hornblende, in connection with which biotite occurs in spots as an alteration product. In general, the dikes are even-grained, the grain size being less than 1 mm. However, they are apt to contain as phenocrysts hornblende or plagioclase, or both together, in which case the veins resemble corresponding porphyrites. At the contact of the dikes with the country rock, fine-grained chilled margins are sometimes observed.

Excepting the migmatitic granites in the northern and southern sections and the younger granites belonging to the rapakivi group, basic dikes generally occur everywhere else in the region in varying measure. The largest number of observations has been made in the central area composed of volcanic rocks, but veins also intersect the arkosic gneisses at the northern margin and the plutonic rocks of the region.

A comparison of the directions in which the dikes run with the directions of the structural features reveals that in only rare instances do these directions coincide with the bedding of the surroundings. Somewhat more commonly do these directions run parallel to the schistosity of the country rock. Most commonly, the dikes form angles of between 10° and 20° or even more with the direction of the schistosity. In the case of some of the intersecting dikes, the same schistosity prevails as in relation to the surrounding country rock. There further occur dikes that had folded synchronously with the country rock. There are also displacements in the dikes that took place in line with the schistosity. The dikes are apt, moreover, to intersect each other. Basic dikes are in certain places intersected by pegmatitic dikes.

In the light of the observations told in the foregoing, the age relations of the dikes and their relation to the folding vary. The probability is that they penetrated the fractures that developed in the bedrock during the intra-orogenic phase (Edelman 1949, p. 23—24). The precondition must have been that the supracrustal formations had gained a firm space and the plutonic rocks crystallized through the metamorphism that took place during the orogeny.

Sederholm assumed that the genesis of the veins was connected with the younger volcanic activity belonging to the Bothnian (Sederholm 1907, 1923, 1926, 1932) formation. Eskola (1914, p. 15) on the other hand, regarded the veins as hypabyssal; and his view was shared by Edelman (1949, p. 24). In the area in question, that the dikes were associated with the volcanic activity that took place at the end of the synorogenic phase seems highly likely.

Deviating in type from the afore-mentioned dikes, which are present all over the region, are the ones that in their mode of occurrence are closely associated with the intermediary lavas of the region, specifically the coarse-grained feldspar porphyries. These veins either penetrate this coarse-grained feldspar porphyry (Skvättan, Västaholm, the islands on the south side of Bastuö, Gåsholm, Måsholm) or occur in the country rock in its immediate proximity (Korsholmsör). In addition, they have been met with, deviating from their usual mode of occurrence, in the immediate vicinity of the southern border of the quartz diorite in the Julö area as well as on the island located about 2 km to the northwest from Furuholm in the eastern section of the region, likewise in association with quartz diorite.

The dikes run parallel to the local foliation. They vary between 2 and 8 m in width. The grain size is less than 1 mm and the principal mineral constituents are plagioclase (An_{25-30}) and hornblende, with sphene, epidote, chlorite, quartz and magnetite present in accessory amounts. In this fine-grained mass, there are both isolated plagioclase phenocrysts 0.5—2 cm long as well as segregations measuring from 5 cm all the way to a full meter across and consisting almost exclusively of larger plagioclase grains (Fig. 40). The plagioclase has undergone marked alteration and was possibly highly basic originally, for chlorite and epidote occur in abundance along with sericite as alteration products. The interstices between the large plagioclase grains are made up of hornblende, chlorite, epidote and, in scanty amounts, sphene.

The segregations resemble plutonic rock, specifically anorthosite, and they must be regarded as having become isolated from the magma at any early stage.

DISCUSSION

Several Finnish investigators have concluded that the bedrock of southern Finland represents a very deep section of the root area of the Svecofennian mountain chain in which the effect on the rocks of the deformation accompanying the orogeny has been exceedingly great. It is for this reason that the rocks of volcanic origin are inhomogeneous and, in many instances, shattered by plutonic rocks, mainly late-orogenic granites, besides which the primary structures of the sediments have

FIG. 40. Basic dike. Gåsholm, rural commune of Porvoo.

been completely destroyed. On the other hand, the geological appearance of the region under investigation represents a type deviating markedly from the general style along the southern Finnish seaboard. The volcanics compose quite a uniform and well-preserved area, in the rocks of which primary structures have survived in abundance. The region as a whole gives the impression that possibly a level higher than the general level is in question. This difference in level might be due to the possibility that the entire complex was originally a deeper depression. This view is supported by the circumstance that even at present the land uplift in this locality is slower than it is in the areas to the east and the west of it (Fig. 41).

It has been already pointed out that the region as a whole represents a synclinorium composed of several folds. Southward from the northern margin, it is possible to work out a sequence of strata composed of supracrustal rocks to a thickness of approximately 6 500 m. Reading from the bottom to the top, the sequence is as follows:

1. Quartz-feldspar schists and gneisses, among which there occur mica and hornblende schists and gneisses as intercalations (corresponding in mineral composition to arkoses and graywackes). In the upper part of this formation, at its south margin, there occur the more acid types (subgraywackes in min-

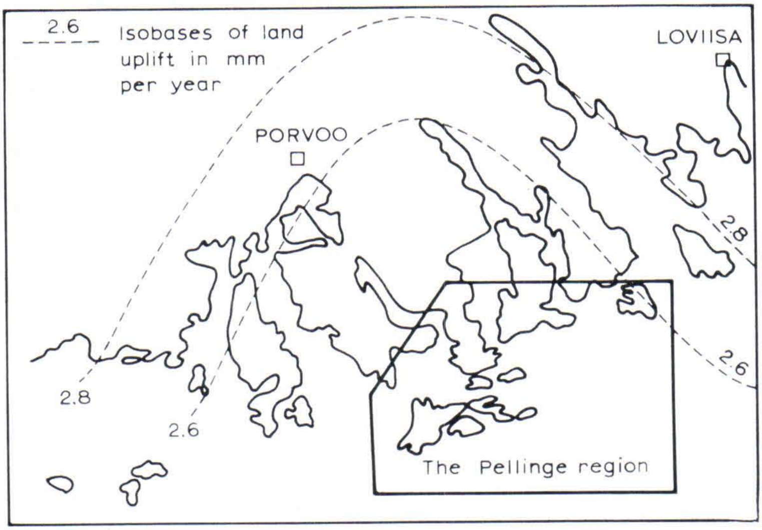

FIG. 41. Isobases of land uplift (mm per year) in Porvoo area (marked with a broken line). Map drawn after Kääriäinen (1969, pp. 69—76). Bounded area represents the Pellinge district, the subject of the present paper.

eral composition) as well as small limestone and intraformational conglomerate deposits.

2. Stratified tuffites and agglomerates, including uralite- and plagioclase-porphyritic lavas as intercalations. Narrow pillow lava layers occur at the lower margin of the pyroclasts.
3. More extensive uniform uralite-porphyrite formations.

With respect to their mode of formation, the supracrustal rocks of the Pellinge region, taken as a whole, show a similarity to the geosyncline features of later times. The quartz-feldspar schists and gneisses of the graywacke and arkose type along the northern margin show that, during the stage of their formation, erosion, transportation and sedimentation had been rapid. The consequence was imcomplete chemical weathering of the material (see, Pettijohn 1943, p. 956—957). Substantial arkose occurrences indicate the rapid accumalation of sediments on a rapidly sinking formational base under conditions typical of geosyncline areas (Krumbein and Sloss 1951, p. 131 and 351). Directly on top of these sediments without any appreciable transitional zone, there is a sizable formation containing volcanics. This is evidence of powerful volcanic activity, which started abruptly. Such a developmental geosyncline stage is characteristic of so-called eugeosyncline zones (Still 1941; Kay 1951).

Owing to the mode of genesis, deep-water sediments characterized by a layered structure generally prevail in geosyncline areas. In the region studied, it may be stated, on the strength of the evidence provided by the sedimentary primary structures occurring in the tuffites, in particular, that the sedimentation took place in both deep and shallow water. Besides the commonly occurring graded bedding, one also meets with the cross bedding that evolves in shallow water. These structures do not belong to the same sedimentation stage (Bailey 1936, p. 1716; Pettijohn 1943, p. 967). In addition, there occur other shallow-water structures, such as current bedding, ripple marks and »scour and fill». Variation of this kind in the sedimentation facies occurs in geosyncline areas (Pettijohn 1943, p. 968); and, with respect to the reasons for it, Kay (1951, p. 85) has observed: ». . . Areas of great subsidence retain shallow marine or nonmarine environments if deposition of sediments balances or exceeds the sinking. Thus shallow-laid sediments are not distinctive of areas outside geosynclines.» As pointed out by Ruchin (1958), varying local elevations and depressions are also possible in geosynclines..

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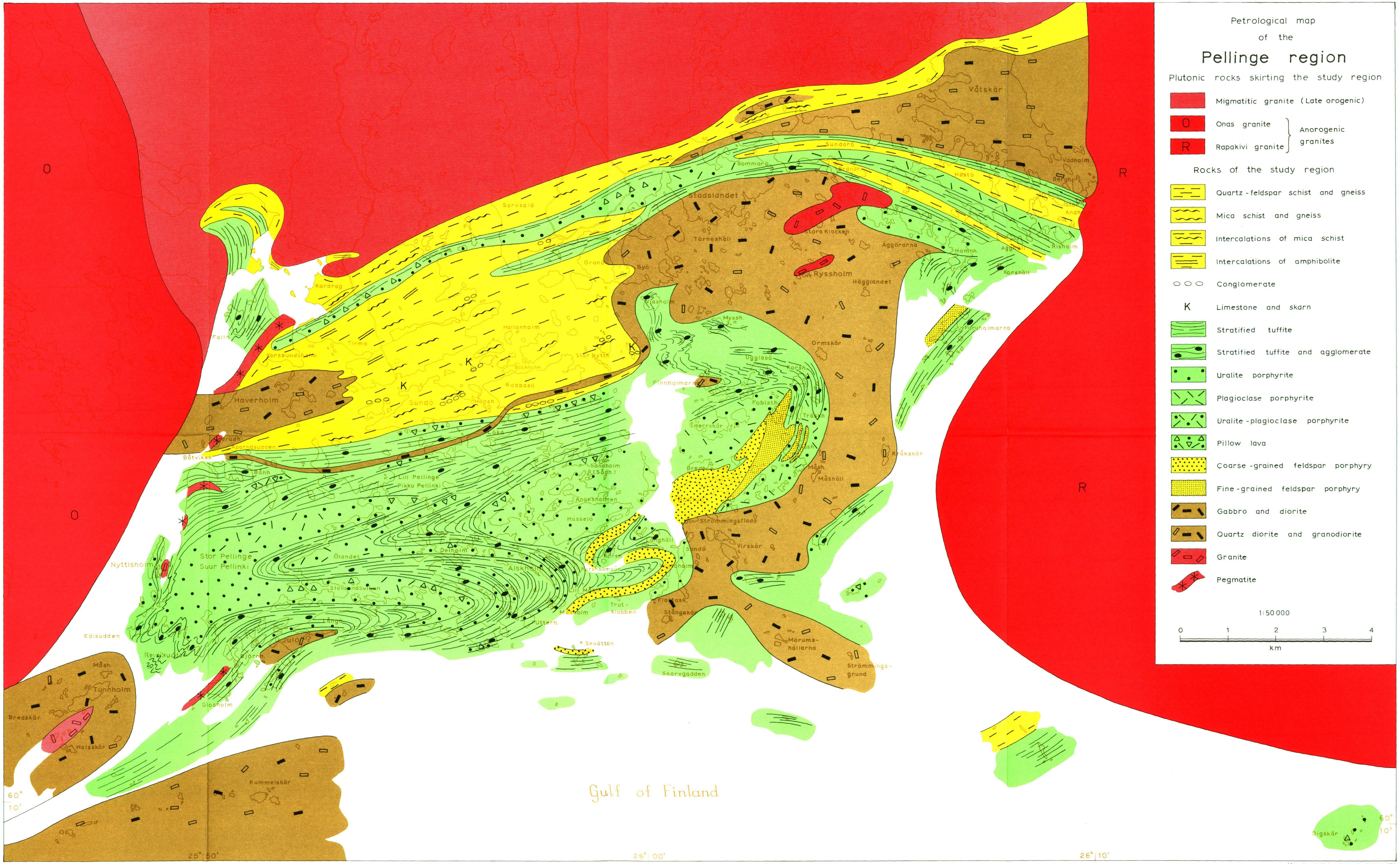

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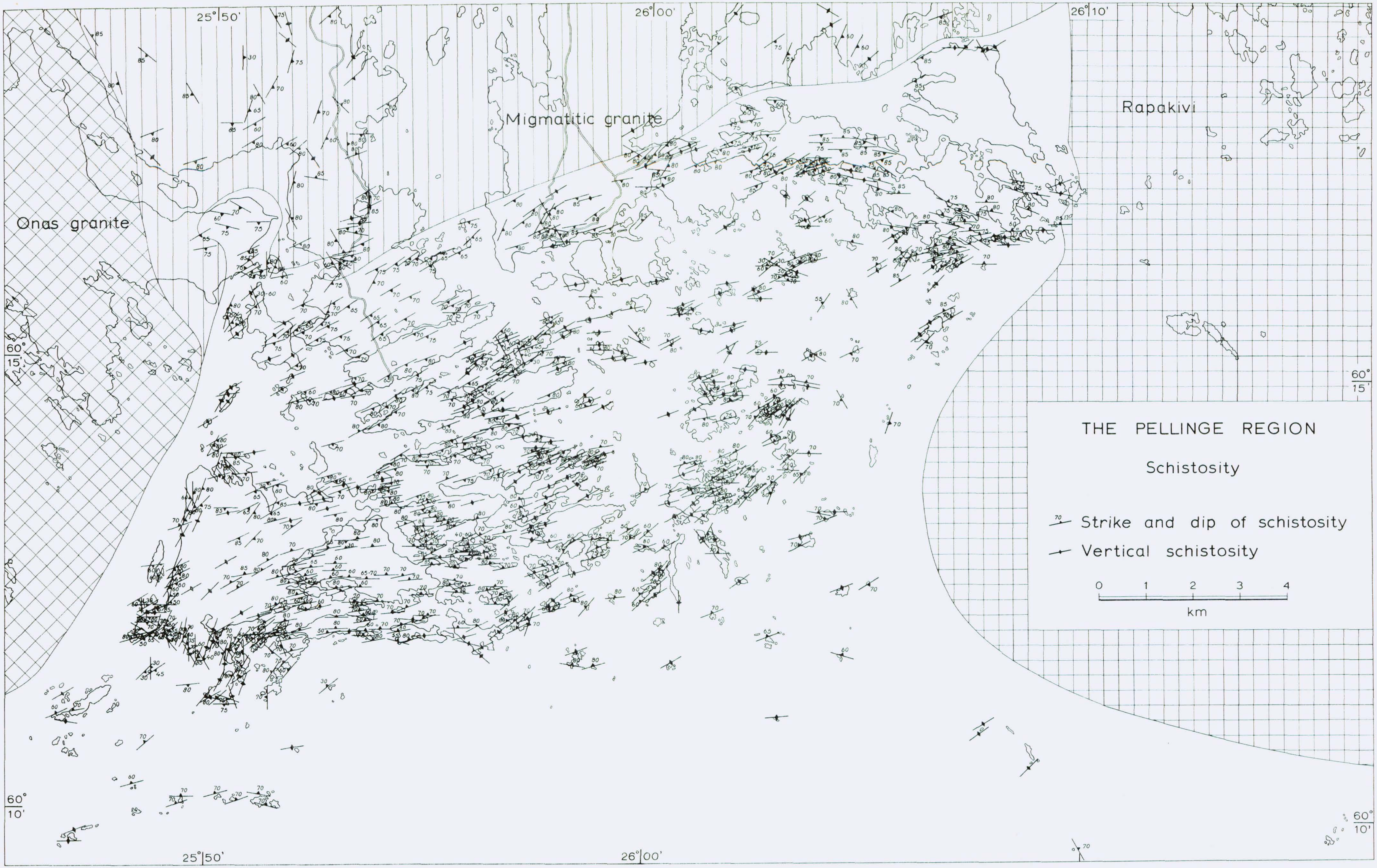

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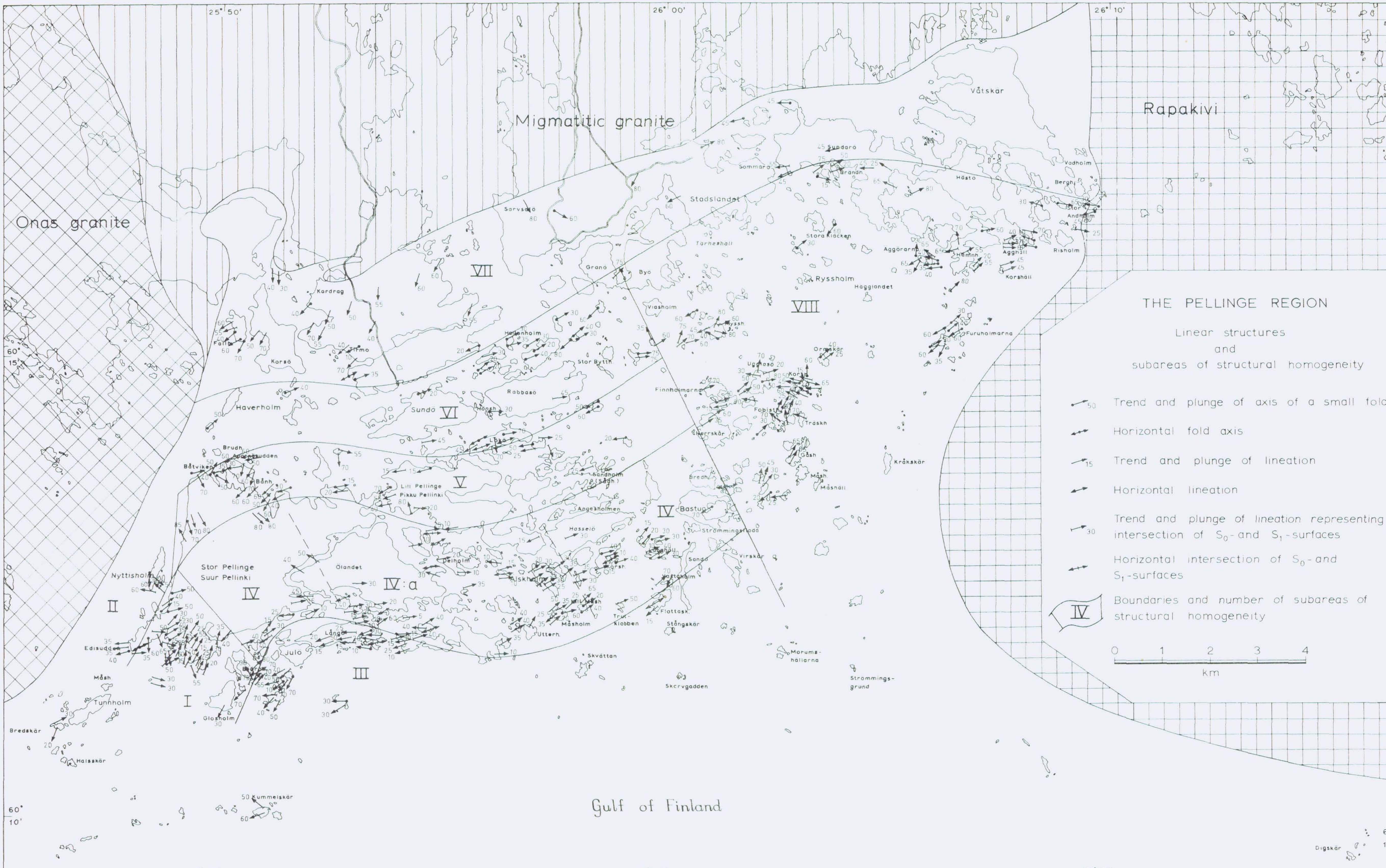

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