GEOLOGINEN TUTKIMUSLAITOS

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COMMISSION GÉOLOGIQUE

DE FINLANDE

N:o 187

THE GULLKRONA REGION, SW FINLAND

BY

NILS EDELMAN

WITH 44 FIGURES AND 4 TABLES N THE TEXT AND 2 MAPS ON PLATES

HELSINKI 1960

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Helsinki 1960. Valtioneuvoston kirjapaino

PREFACE

The present paper is the result of the mapping for the geological map sheet B 1, Turku, of the Geological Survey of Finland. The work in the archipelago was done during the years 1944—1953. The sea is in general left uncolored in the geological maps. Such a map of the archipelago becomes more or less illegible because the islands in many parts are so small that in the scale 1: 400 000 they are smaller than the printed dots. Therefore it was necessary to make a separate map of the archipelago and this map is accompanied by the present paper, which, however, is no ordinary explanation to a map. It is a report of the observations and of the opinions arrived at during the work. Many of the thoughts presented here are more in the nature of hypotheses than well-founded results, but I believe that they will nevertheless be useful in the future for students of the region as working hypotheses even if wrong.

I want here to express my sincere appreciation to Mr. Adolf A. Th. Metzger, professor at Åbo Akademi, Mr. B. Andersson, Mag. phil., Mr. B. Öhman, Mag. phil., and Mr. T. Stolpe, Mag. phil., who have given me permission to use their maps from different parts of the region for the map in this paper. I also want to thank all my co-workers in the Geological Survey of Finland. The parts mapped by different persons are seen in Fig. 2. I further wish to express my gratitude to Nordenskiöldsamfundet in Finland and to Svenska Vetenskapliga Centralrådet for the grants I have received from them. They have helped me, i.a., to obtain a seaworthy motorboat, without which the mapping would have been much more difficult and time-consuming. Furthermore I should like to point out the many fruitful discussions I have had with other geologists and especially with my teacher, Mr. E. H. Kranck, professor at Mc Gill university, Montreal, Mr. A. Simonen, Ph. D., state geologist of the Geological Survey of Finland, and Mr. M. Härme, Ph. D., my former room-mate at the Geological Survey. I want to thank Miss Thyra Åberg for drawing the maps and figures, Mr. Paul Sjöblom, M. A., for correcting the language, and all the others who have helped me in any way in this work.

Finishing this manuscript took many years because other duties consumed almost all my time. The lack of time also made the work in many respects more difficult. Because in recent years I have lived in the country, far from any geological library, it has been very difficult to study sufficiently related problems reported in the literature from other regions. I hope that, in spite of all its defects, this paper will give a general idea of the geology of this region.

Boliden, April 1959

Nils Edelman

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ABSTRACT

The present paper deals with the pre-Pleistocene geology of the archipelago of SW Finland excluding the Åland area. The main part of the rocks are Archean metamorphic and igneous rocks. Diabase dikes and two rapakivi granites of Algonkian, sub-Jotnian, age occur. Remnants of unmetamorphosed sandstone are met with in two places, but sandstones are likely to occur elsewhere, too, in the present region.

The petrographic descriptions are short; only a few problems have been discussed somewhat more in detail. The origin of the ultrabasic rocks, common in the SE part of the region, is obscure but their microscopic character indicates a long and complicated evolution. They are probably basic igneous rocks, either volcanic rocks or intrusive sills, metamorphosed to ultrabasites. Another example of basification owing to metamorphism is met with in the hornblenditic borders of some pegmatites. The most common rock of the region is migmatic granite. Four principal types of migmatites may be distinguished. Schistose rocks are commonly granitized to veined gneisses, whereas brittle and isotropic rocks form migmatites of the breccia-type, agmatites. In some cases microcline porphyroblasts have grown in older rocks, now »porphyritic granites». The fourth type is the nebulitic granite, where granitization has given the rock a granitic composition although the primary structure is left intact.

It is shown by examples that many tectonic rules, valid in the upper parts of the earth's crust, are not applicable in migmatic areas. When studying the structural geology of areas where migmatites are met with, it is best to begin from the major structural elements, e.g., bedding, banding, and schistosity. The structure of the present region is characterized by large domes of migmatic granites and basins of gneisses and amphibolites. Large granite domes are often composed of minor domes separated by cross synclines of gneisses. The domes are in general tilted to the W.

The stratigraphy of the Svionian supracrustal rocks of the region is established in local gneiss basins. The general sequence of rocks seems to be as follows:

upper mica gneiss formation
basic horizon
leptite formation
lower mica gneiss formation

Comparing this result to the stratigraphy of other parts of the Svecofennides, great similarities are observed.

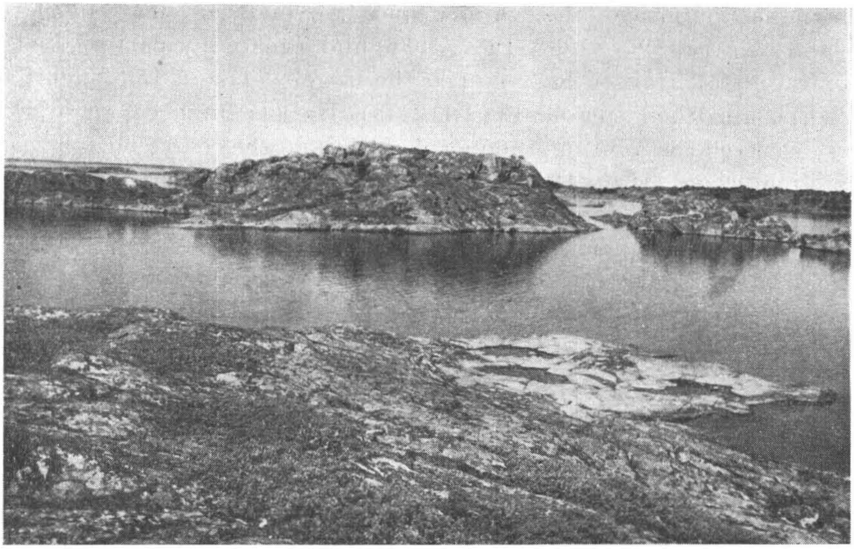

Fig. 1. A special type of archipelago with steep shores owing to jointing. A remnant of sandstone probably lies on the bottom of the sea to the right. Island of Borgön N of Örö. View from W.

INTRODUCTION

The region under study belongs to the archipelago of SW Finland, and the map presented here covers about 6 300 square kilometres. The relation between land and sea varies much within the region. In the N part the islands are large and comparatively high and the sea fills the mostly rather narrow channels between them. In the S part, on the other hand, the sea forms large open stretches of water, whereas the islands are in general small. The breakers washed away the loose deposits from the hills when the earth's crust slowly rose above the sea level during the post-Glacial time. Therefore the glacially polished bedrock is commonly well exposed, especially on the shores, where the breakers keep it clean and prevent the growth of lichens.

The region was previously mapped by the Geological Survey of Finland during the last decades of the 19th century, but the maps are nowadays antiquated (Moberg 1879, 1885, 1887a & b, 1888, 1890, Berghell 1892, Frosterus 1894). Later Sederholm published some observations from this region (1924), from the Hangö region farther E (1907), and from its continuation in the region around the Barösundsfjärd (1926), and the map of the Åland area just W of the present one (1934). Eskola's map of the leptite belt of Kisko—Kimito (1914) overlaps the present map in its E part.

Pehrman has published observations and two maps of different parts of the island of Attu (1927, 1931, 1932, 1936) and a map of a part of the island of Kimito (1945). Hausen has mapped the large islands of Lill-Nagu, Nagu, and Korpo and their surroundings (1944a). He has furthermore in several papers discussed the jointing, the morphology, and the coarse potash granites of this archipelago (1940, 1942, 1944b, 1947, 1948). Metzger has thoroughly studied the area of Ålö and Kyrklandet in the NE part of the region (1945) and he has prepared a map sheet — No. 1043 — of the surrounding area. Hackman has investigated the granodiorite of Kakskerta (1923). Anna Hietanen has published two maps of other areas farther N (1943, 1947). Her map of the Turku district overlaps the present map in its NE corner and it has been used by Metzger for preparing map sheet 1043. Metzger's map has later been simplified by me for the present map. Laitakari has studied limestone occurrences in the archipelago (1916, 1921) and B. Öhman has made an unpublished map of the limestone of Ovensor. Kanerva has mapped the rapakivi massif of Vehmaa (1928). Lehijärvi has recently published a map from a neighbouring area (1957). I have earlier published two maps and some observations from the present region (1949a, b & c, 1951, 1956). Some parts have been mapped by students for their theses in geology but their descriptions exist only as manuscripts (Andersson 1951, Edelman 1945, Stolpe 1952, Öhman 1952). The following persons have also taken part in the mapping: R. Lauerma, P. Similä, T. Stolpe, H. Wennervirta, and H.B. Wiik (Fig. 2).

The present region hence lies between areas mapped from different points of view. My interest has principally been concentrated upon the structural, stratigraphical, and some petrogenetical problems, whereas many petrological questions have been overlooked when not closely connected with the first-mentioned problems. Solving the problems of evolution, or geological history, is the ultimate purpose of geological investigations. Therefore the present map differs in many respects from many of the maps from the adjacent regions. The text differs too from the usual style in our country, e.g., in the respect that I have arranged the rocks more from a stratigraphical point of view than according to a pure petrographical classification. Some inconsequences can in neither case be avoided because a classification is only a means to help us understand nature, only a fabrication of the brain and not a law of nature. Especially in ultrametamorphic and migmatic regions every classification of the rocks will fail in some respect. Furthermore there are some inconsequences in the map because different parts of it have been made by different persons with varying exactitude. Also the parts mapped by me myself show many inconsequences because the point of view on many problems has changed quite considerably during the period of ten summers I have worked in this region.

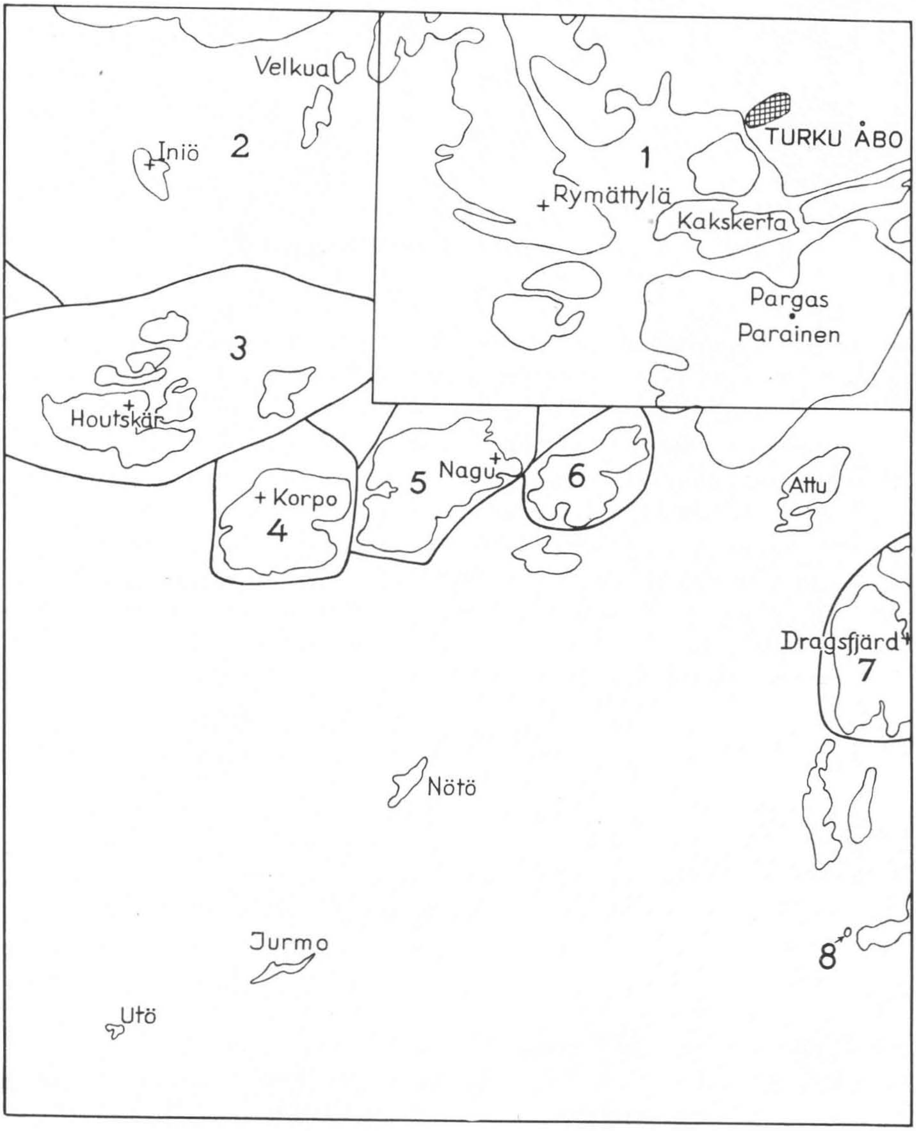

Fig. 2. The areas mapped by different persons. 1. geological map of Finland, sheet 1043, by A. Metzger, simplified and modified for the present purpose, 2. R. Lauerma and P. Similä 1951, 3. H. Wennervirta 1952, 4. B. Öhman (1952), 5. T. Stolpe (1950), 6. B. Andersson (1951), 7. H. B. Wiik 1947, 8. T. Stolpe (1952), and the remaining parts by me.

OUTLINE OF THE GEOLOGY

The region belongs to the Svecofennidic zone, a peneplained archean mountain chain striking E through central Sweden and southern Finland. The bedrock consists of hard rocks with the exception of minute remnants of non-metamorphic sediments. The oldest rocks are supracrustal (i.e., formed upon the earth's surface as sediments or volcanic rocks) and belong to the Svionian group. They form sequences mainly with arkoses, graywackes, and shales, nowadays transformed into different gneisses. Basic volcanic rocks, limestones, and different basic and ultrabasic rocks of obscure origin occur as a key horizon within the sedimentary sequence. In the S part of the region amphibolitic layers, probably metamorphic tuffites, alternate with the gneiss layers in the upper parts. The sequence seems to be from top to bottom in general as follows:

clays
limestones, marls, basic volcanic rocks
silts
clays

The total thickness of the supracrustal sequence is unknown and it seems to be impossible to determine it in this region, because the basement as well as the top of the supracrustal rocks has not been found. Metzger (1945) has estimated the minimum thickness of the sequence in the Pargas basin at 420—1750 metres.

Younger than the supracrustal rocks are the alkali-calcic infracrustal rocks. Infracrustal are rocks which have been formed within the earth's crust. Some of these alkali-calcic rocks are true magmatic rocks, some are metamorphosed supracrustal rocks, but the greatest part of them have a doubtful origin. They range in composition from aplites poor in mafic minerals to hornblendites. The most common members are the gneissose granodiorites and hornblende gabbros. They have commonly the shape of concordant sheets or lenses. Cutting contacts are exceptions.

Amphibolitic dikes occur mostly in the S part of the region. Many of them are with certainty younger than the alkali-calcic rocks, but there may be several generations of basic dikes.

The microcline granite, which as a rule is more or less migmatic, is younger than all the above-mentioned rocks. It seems to be principally palingenic in origin. Also the most homogeneous types of this granite show gradual transitions to migmatites of different kinds. The microcline granite commonly forms domes tilted westward.

All the said rocks have been affected by the Svecofennidic orogeny, and therefore they are more or less metamorphic. Quite unaffected by the orogenic metamorphism are the diabase dikes, which are most common in the NW part of the region, and the young granites belonging to the rapakivi group. The Fjälskär granite forms a rounded area in NW, whereas the large rapakivi massif of Vehmaa borders on the region in N.

Furthermore small remnants of unmetamorphic sandstone probably occur in many depressions at the bottom of the sea, as indicated by the locally numerous erratic blocks of sandstone. One sandstone dike has been met with in the region, and in the limestone quarries of Pargas a rather large sandstone occurrence has been found.

Already during the deposition of the sandstones the region was a peneplain, and the geologic history since then seems to have been comparatively uneventful judging from the fact that the peneplain still dominates the morphology of the region. Dislocations have taken place during some periods, causing, e.g., grabens. Periods of deposition and erosion have alternated and finally during the Pleistocene period the glacier ice cleaned the old peneplain of all weathering products and deposited them on the bedrock as glacial drift. The shapes and directions of the islands and the straits distinctly show the old structures, folding as well as jointing (Kranck 1937b, Edelman 1956).

PETROGRAPHY

MICA GNEISS

Gneisses rich in mica, and often also in garnet, or cordierite are most common in the N part of the region as well as farther N (Pehrman 1932, 1936, Hietanen 1943, Metzger 1945, Hausen 1944a). A gneiss with alternating mica-poor and mica-rich bands is a transitional type between the mica gneiss and the leptite (Fig. 5). It may originally have been a varved schist (Sederholm 1899, Simonen 1953). Unfortunately it has not been possible to separate this as a particular formation on the map because of the inhomogeneity of the field observations. Therefore it has been combined partly with the mica gneiss, partly with the leptite under the name of banded gneiss. Amphibolitic intercalations are locally common in the mica gneiss. An easily weathering type containing small amounts of graphite and sulphide minerals occurs as rather thin rusty bands in the gneiss. Sometimes they are thicker, in exceptional cases tens of metres thick.

The mica gneisses are apparently less resistant to metamorphism and granitization than the other rocks of the region. Therefore one rather seldom observes relic structures in them. The bedding is as a rule confused by secondary foliation and granitic veins. In a small island about 100 metres E of the NE point of Nagu Sandö the mica gneiss is well preserved, however, but even there the schistosity has locally nearly destroyed the primary bedding (Fig. 3). In the same island hornblende porphyroblasts have grown within certain gneiss layers, measuring tens of centimetres in breadth, transforming them to gabbro-looking rocks, although the adjacent layers seem to be very weakly metamorphosed (Fig. 4). In some cases one can follow a bed from a part without any hornblende porphyroblast to a part where the porphyroblasts comprise more than half of the rock. Pyroxene-bearing types have been found in some places (Hausen 1944a) but they do not form such large areas as in the regions farther E (Parras 1946, 1958, Härme 1954a, Lehijärvi 1957). Some of the pyroxene-gneisses could as well be connected with the leptites. The pyroxene probably originated by dewatering of hornblende or biotite, caused, e.g., by increased temperature or decreased pressure (Edelman 1948).

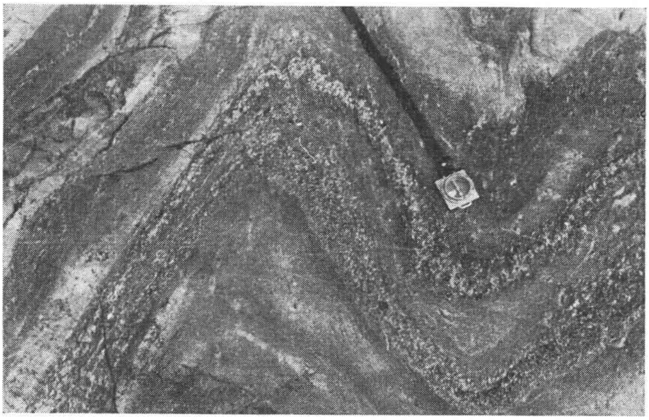

Fig. 3. Schistosity cutting primary bedding in mica gneisses or schists. At a short distance from here the bedding is almost entirely destroyed. SW shore, island 100 metres E of the NE point of Nagu Sandö. Foto M. Härme.

The mica gneisses are commonly medium-grained, schistose, and veined. The texture is granoblastic or porphyroblastic. The main minerals are feldspars, quartz and biotite. Garnet, cordierite and, exceptionally, hornblende occur in some zones as porphyroblasts, often in considerable amounts. Plagioclase seems to be the principal feldspar, but microcline occurs too, partly, however, as a result of the granitization. The pyroxene is generally a hypersthene. The weathered layers contain sulphides and graphite too. Sericite, chlorite, and pinite are alteration products.

There seems to be reason to describe the questionable conglomerate of Linnskär in this connection. On the SW cape of the island of Linnskär a diorite is divided along its S contact into rounded fragments. The breadth of this fragmented zone is 3 metres. The interspace between the fragments is filled with a gray, somewhat lighter matrix containing small fragments of amphibolite. A brownish ortho-pyroxene-bearing zone about one meter broad follows to the S. The rock of this zone seems to be connected with the matrix between the diorite fragments. S of the brownish zone there follows a 5-metres-broad layer of a rock rich in flattened fragments of amphibolite, diorite, different gneisses, and granite. The matrix is a garnet-bearing gneiss. A garnet- and cordierite-bearing gneiss then follows southwards. This sequence could be interpreted as an unconformity, an old weathered land surface buried under a conglomerate and a clay formation. The observed facts agree with such an explanation but it has by no means been definitely proved. The deformation has in general been so strong in this region that a tectonic origin is quite conceivable.

Fig. 4. Well-preserved schists or fine-grained gneisses. Hornblende porphyroblasts have grown in the layer situated to the right of the hammer head and some tens of metres from this place porphyroblasts dominate the layer. NW shore of the same island as in Fig. 3.

The gneisses rich in mica, and garnet, or cordierite have in the last few decades been called kinzigites in the Finnish literature. They have in general been apparently correctly interpreted as metamorphic clays. The high degree of metamorphism and granitization makes it impossible in the present region to determine most of the primary characteristics of these clays. The high content of feldspars indicates, however, that the original clay probably belonged to the graywacke or subgraywacke suite according to the terminology of Pettijohn (1949; Simonen & Kouvo 1951, Simonen 1953). The graphite- and sulphide-bearing types were originally intercalations of black shales.

LEPTITE

The leptites form a long broken zone with some protrusions to the S. This is a continuation of the leptite belt of Kisko-Kimito. Some minor leptite areas are also met with in other parts of the region.

The leptites are fine- to medium-grained acid gneisses poor in mica. The coarser types are often called leptite gneisses and another name used for the leptites is quartz-feldspar-schist. Intercalations of amphibolite, cordierite-antophyllite schist, garnet-mica gneiss, graphite-sulphide-bearing gneiss, and many other rocks occur, but they are in general subordinate. The banded gneiss with alternating mica-poor and mica-rich bands is mentioned in connection with the mica-gneisses (p. 12, Fig. 5). Amphibolite

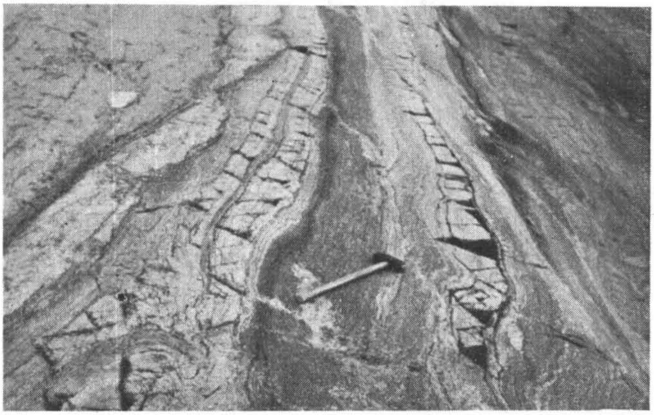

Fig. 5. Banded gneiss with alternating layers of mica gneiss and leptite. The mica gneiss layers are folded plastically, whereas the leptite layers have broken. Island of Gråbåten, parish of Nagu.

intercalations are sometimes rather numerous and then the assemblage resembles the banded formation (p. 16).

The colour of the leptites ranges from grey, or yellowish to pale reddish. In some cases it is rather dark. The bedding, or banding is often not conspicuous because of the small differences in colour, structure, and composition between adjacent layers.

The schistosity is also often rather indistinct owing to the poor mica content. In the gneiss with alternating bands of leptite and mica gneiss the leptite bands have as a rule evenly spaced cross joints, which do not continue in the schistose mica gneiss bands (Fig. 5).

Primary features other than bedding have generally not been preserved. The texture is granoblastic. In a layer on the island of Viggarholm porphyritic plagioclase grains in flattened fragments indicate a volcanic origin. Layers that could be interpreted as acid volcanic rocks are, however, rare and therefore the majority of the leptites seem to be sedimentary, especially as volcanic structures in general seem to be more resistant to metamorphism than sedimentary ones. Furthermore, similar leptites in other parts of S Finland have recently been interpreted as metamorphic sediments (Simonen 1953, Härme 1954b).

The mineral composition is simple. Feldspar and quartz are the main constituents. Biotite occurs in nearly all types in minor amounts. Garnet, hornblende, diopside, hypersthene, and sillimanite have been found in some types. Chlorite, epidote and sericite are the principal alteration products. Plagioclase seems to be the predominant feldspar, but microcline is common in some leptites. The dark minerals constitute only a minor part of the rock; in some types they are practically lacking.

On the N shore of the island of Tammo S of Attu there lies a little remnant of quartzite in a gneissose granite close to the contact against garnet-mica gneiss. The quartzite is thin-bedded with apatite bands between the beds. Some quartzite bands on the island of Stortervo are dealt with in connection with the basic zone (p. 23).

The leptites seem in the main to be metamorphic sediments with subordinate acid volcanic layers. Their high content of feldspars and relative poorness in minerals with an excess of alumina indicate that they were originally arkoses, commonly with the grain size of silts (Simonen 1953). The well-developed bedding indicates deposition in water, probably principally below the wave base, as cross-bedding has not been observed. The material had probably to a considerable extent been transported by wind, because no vegetation sheltered the land against deflation during the Archean age (Väyrynen 1954). The gneiss, with alternating leptite and mica gneiss bands, had been either a sediment with alternating silty and shaly beds or a coarsely varved graywacke.

THE BANDED FORMATIOS

The banded formation is a very inhomogeneous association of rocks. The main type is a banded gneiss-amphibolite with alternating bands or layers of leptite, or leptite gneiss and amphibolite (Figs. 6 & 7). Often, however, it contains intercalations of many other rocks, e.g., bands or lenses of brecciated ultrabasic rocks (Figs. 8 & 9), limestone layers or lenses, and

Fig. 6. Banded formation with alternating bands of leptite gneiss and amphibolite. Island 0.5 kilometres SW of the island of Ådgrundet, S part of the parish of Nagu.

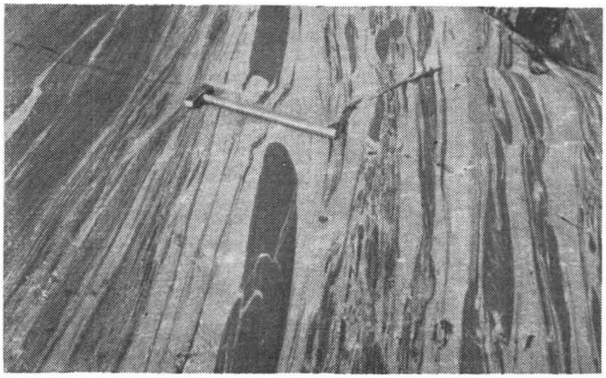

Fig. 7. Banded formation with broken and deformed basic layers. Island two kilometres ENE of the island of Kalvholm, parish of Hitis.

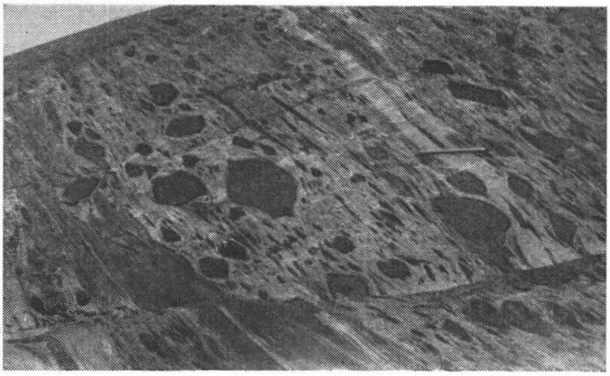

Fig. 8. Breccia zone with ultrabasic fragments deformed to eye like shapes in the banded formation. Island 1.2 kilometres ENE of the island of Kalvholm, parish of Hitis.

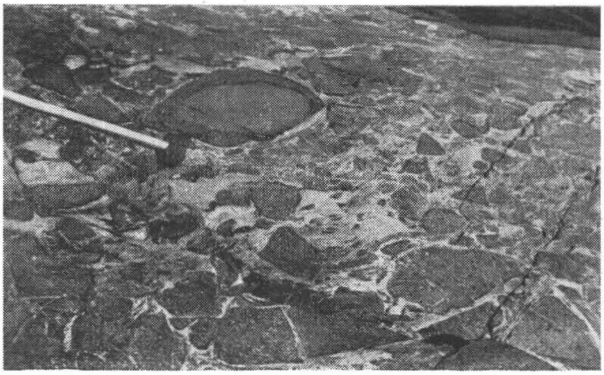

Fig. 9. Ultrabasic breccia. The large fragment close to the hammer head has a brownish nucleus rich in hypersthene surrounded by a greenish zone rich in clino-pyroxene, which again is surrounded by a thin black rim rich in hornblende (not visible in the picture). E shore, island of Djupplåten, parish of Hitis.

bands with gabbroic, dioritic, or plagioclase granitic composition. The ratio gneiss-amphibolite, the grain size, and the degree of metamorphism vary locally very much. Furthermore some parts have been more or less granitized. All these facts make the investigation as well as the description of this formation quite difficult.

The banded formation forms a long narrow zone striking E about 20 kilometres S of the leptite zone, and it continues eastwards at least to the region around Barösundsfjärd (Sederholm 1926). In the SW and S part of the present region it is separated into zones, lenses, and irregular areas; in the SE part again it widens in the shape of a fan to a broader basin. In this part it is most typical and least metamorphosed with the greatest differences in composition between the separate bands. Lenses of the banded formation occur outside this main zone.

The principal rocks of this formation are gneisses and amphibolites. They occur as bands or layers of varying thickness. The strong deformation has destroyed almost all of the minor and most of the major primary structures. The banding seems in many cases to be a primary bedding, although it has been affected and modified by movements. Often the banding, however, is a result of the deformation as well as metamorphism. This banded formation closely resembles the banded rocks and associated rocks of the island of Ornö in Sweden (Högbom 1910).

In the zone of the banded formation S of the Gullkrona fjärd, the amphibolites grow coarser in a westerly direction as a result of stronger deformation and recrystallization. In the same direction the banding becomes more indistinct and the rock takes on the appearance of metamorphosed diorites or hornblende gabbros.

Microscopic textures which could be primary and offer a possibility for interpretation of the origin are as a rule indistinct and problematic. A rather easily recognizable uralite porphyritic texture is met with in an amphibolitic zone SE of the island of Örö. The grain size often grows in accordance with the degree of metamorphism. In some cases one can follow in certain layers on the exposures the gradual transition from a fine-grained leptite to a medium-grained rock resembling a gneissose granite, or from an amphibolite to a rock resembling a diorite or a gabbro. The texture of the rocks belonging to the banded formation is granoblastic, but hornblende and plagioclase occur in some types as porphyroblasts.

The mineral composition of the gneisses and amphibolites is monotonous notwithstanding the variations in chemical composition. The mineralogical variations are more quantitative than qualitative. The acid bands consist principally of plagioclase, quartz, and more or less biotite, or hornblende, the basic bands again of hornblende and different amounts of plagioclase.

Also rather pure hornblenditic layers have been found. Sericite, epidote and chlorite are common alteration products. The hornblende is in general pale green with weak pleochroism. The biotite is pale brown and it often occurs as inclusions in the hornblende. The plagioclase commonly has inclusions of the alteration products sericite, and epidote. Its anorthite content varies in accordance with the basicity of the rock.

The ultrabasic breccias, the gabbros, the limestones and the skarns of the banded series will be described in connection with the basic zone.

The banded formation is not quite similar in all parts. Intercalations of ultrabasic breccias are common only in the area around the island of Rosala. Farther W the banding becomes generally less distinct, the rocks coarser, and the degree of metamorphism higher. It is in many cases very difficult, particularly in the W part of the zone, to draw any borderline between the rocks of the banded formation and the rocks of the alkali-calcic series. The leptite or gneiss layers of the banded series closely resemble in structure and composition the purer leptites farther N, though the grain size is as a rule coarser. Accordingly, it may be assumed that originally they were similar arkosic silts. The origin of the amphibolitic layers is somewhat more obscure. The composition points to a volcanic origin, but the general lack of preserved volcanic structures makes a sedimentary origin more probable. Therefore one is inclined to interpret the amphibolite layers as pyroclastic beds with varying amounts of weathering products. Mixing of volcanic and sedimentary material then produced the amphibolites with compositions between volcanic and sedimentary rocks.

THE BASIC ZONE

GENERAL FEATURES

Basic rocks of different kinds seem to form a stratigraphic key horizon in the region. This is best developed in the synclines or basins of Korpo, Nagu, Lill-Nagu, and Ålö—Kyrklandet, where it forms nearly continuous outer zones. Fig. 10 gives a conception of the complexity of a part of this zone in the island of Attu. A more basic zone occurs also in the banded formation around the island of Rosala. The basic zone consists principally of the following rocks: porphyrites, amphibolites, pyroxene amphibolites, limestones with skarns, ultrabasites, and gabbros. Similar rocks, especially the typical supracrustal ones, are with the exception of the basic banded formation rarely met with in greater amounts elsewhere, and then the stratigraphic position is as a rule unknown. They will, however, be treated together with the basic zone for the sake of simplicity.

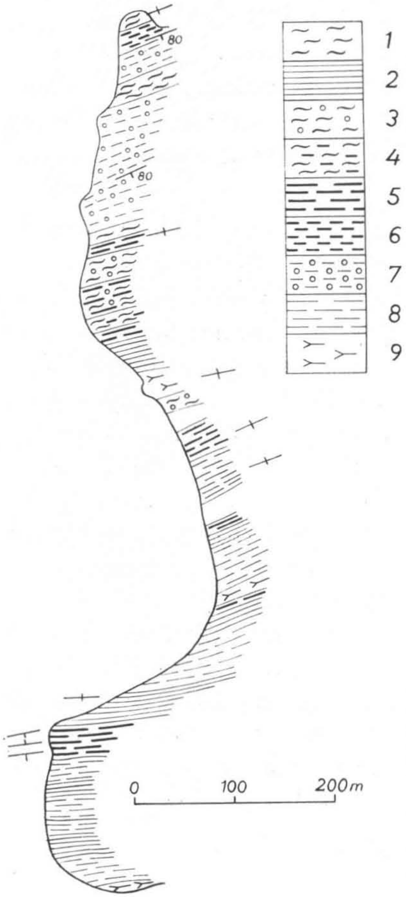

Fig. 10. Sketch of the NW shore of the island of Attu, 1. veined mica gneiss, 2. veined leptitic gneiss, 3. veined leptitic gneiss with feldspar porphyroblasts, 4. veined leptitic gneiss with hornblende porphyroblasts, 5. diopside amphibolite, 6. amphibolite with large hornblende grains, 7. amphibolite with large plagioclase grains, 8. banded fine-grained amphibolite, and 9. gneissose granite.

PORPHYRITES

In the SE part of the island of Attu there are easily recognizable uralite porphyrites with associated tuffites without blastoporphyres as well as one observed agglomerate. The phenocrysts consist of uralitic hornblende, sometimes also of augite with a shell of hornblende. The ground mass consists of plagioclase and augite. Another zone of uralite porphyrites cuts the NW island of Kuggskär SE of Örö.

In a small island about 100 metres E of the NE point of Nagu Sandö a plagioclase porphyrite zone occurs on the W shore. The plagioclase phenocrysts lie at random in the inner part of the zone but close to the contacts they are subparallel. This indicates that the porphyrite probably is a weakly metamorphosed lava flow (Fig. 34).

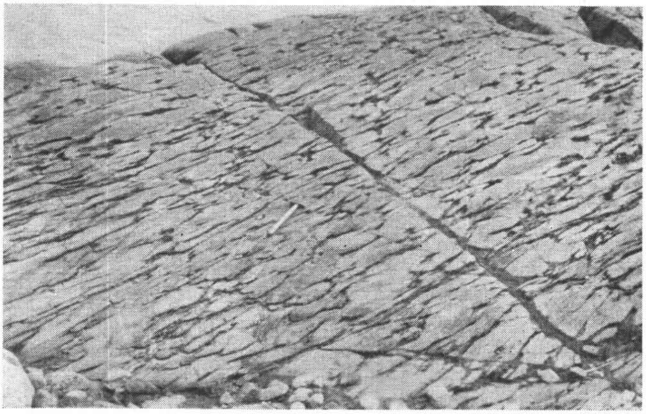

Fig. 11. Pillow-lava. Island 1 kilometre ESE of the S point of the island of Perkal, parish of Iniö.

Porphyrites occur also as ungranitized remnants in migmatites, sometimes without any recognizable connection with other rocks of the basic zone, e.g. in the island of Holma and in the island of Skogskär (Fig. 2 Edelman 1949c).

AMPHIBOLITES

The amphibolites of the basic zone are quite similar to the amphibolites of the banded series. They are dark schistose rocks, fine- to medium-grained. They consist mainly of plagioclase and hornblende. Only some odd types need a closer description.

The amphibolites are as a rule banded. It may sometimes be the result of a tectonic deformation, but often it is a relic bedding. Amphibolite layers occur also as intercalations in the mica gneisses and the leptites.

There is in the island of Nilsholm W of the island of Kasnäslandet an amphibolite with a pillowlava-like structure. On the W shore of this island the pillows are elongated and the rock is gradually transformed into a banded rock. The pillow-structure seems to be a primary lava structure but other explanations of its origin may be conceivable. The interstice between the grey pillows is black by hornblende. The pillows consist mainly of a green and a colourless amphibole, and of plagioclase.

Other pillowlava-like rocks have been met with on the N shore of the island of Brännskär E of Nötö and on some islands SE of the island of Perkal (Fig. 11). The zone in the lastmentioned place is rather broad. The interstice between the pillows is in these cases often greenish and it has commonly weathered out to grooves in the rock surface. Remnants of calcite have

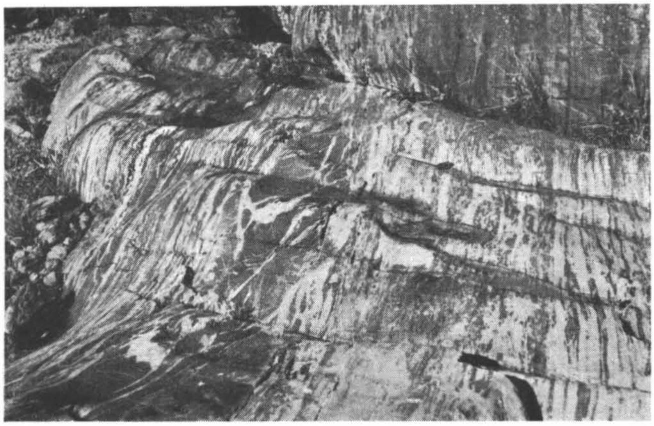

Fig. 12. Diopside amphibolite. NW shore of the island of Attu, parish of Pargas.

also been found in these furrows. A small remnant of a pillowlava-like rock is seen on the E shore of the island of Ekholm about 800 metres N of the NW point of Heisala.

PYROXENE AMPHIBOLITES

Pyroxene-bearing amphibolites are most common in the zone Pargas—Nagu—Korpo. The principal type is a medium-grained green diopside-bearing amphibolite with black bands or lenses. Sometimes it resembles the above-mentioned pillowlava-like rocks. It occurs e.g. on the W shore of Attu (Fig. 12), in the islands of Lill-Nagu, Nagu, and Korpo, in a zone N of the island of Brunskär, in a zone in the island of Mossala, and in a zone S of the island of Velkua.

The diopside amphibolite consists of diopside, hornblende, and plagioclase The hornblende is concentrated in the black bands or lenses. Some types may contain other minerals in noticeable amounts, as, e.g., in Attu epidote, in Lill—Nagu scapolite, or garnet. Calcite is often observed also as veins. Sphene is a common accessory.

In the area of Ålö-Kyrklandet the diopside amphibolites are of a different type (Metzger 1945). They are dark, schistose and rather homogeneous, and megascopically they resemble the common amphibolite. They contain markedly less diopside than the above-described types.

The banding of the diopside amphibolites is often regular, and it may be a primary bedding. This is especially the case in the fine-grained types of the island of Djupplåten NE of Rosala. In the diopside amphibolite zone

Fig. 13. Amphibolite with pyroxene porphyroblasts. Granvik on the S shore of the island of Stortervo, parish of Pargas.

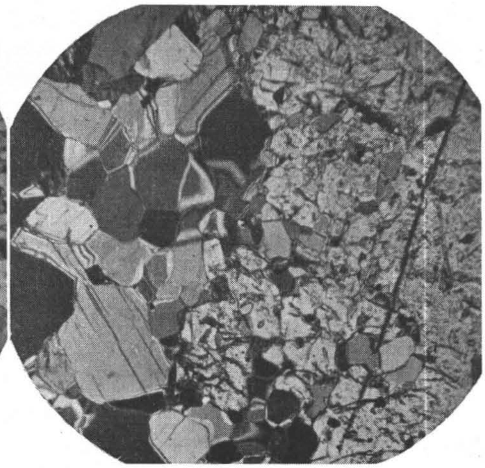

Fig. 14. Hornblende skarn with pyroxene porphyroblasts. Crossed nicols. 20 x. Granvik on the SE shore of the island of Stortervo, parish of Pargas.

SE of Velkuanmaa some parts have a conglomerate-like structure with rounded fragments but the likelihood is that they are tectonic breccias.

Pyroxene amphibolites are rare in the basic zone of the banded formation in the parish of Hitis. On the island of Djupplåten NW of Rosala there occur, however, two types of these rocks. They are fine-grained, thin-bedded, dark brownish or greenish rocks. The composition is plagioclase, hornblende, and diopside or hypersthene. They are cut by some amphibolitic dikes, which are folded together with them.

The diopside amphibolites are interpreted as metamorphic marls. The clayey part of the marls has probably been partly tuffitic because potash-rich minerals are quite lacking and volcanic rocks are common in the basic zone.

A peculiar pyroxene amphibolite forms a lens some tens of metres thick and one kilometre long in the microcline granite on the SE shore of the island of Stortervo. The dip is rather gentle to the W. The main type is an amphibolite with nearly equal amounts of plagioclase, hornblende, and pyroxene (Fig. 13). Two types of quartzite occur there, viz. a rather pure quartzite and a thin-bedded pyroxene-banded one. The pyroxene of this quartzite resembles that of the amphibolite. Furthermore there occurs a coarse-grained hornblende rock or skarn (Analysis 3, Table IV). A part of this contains abundantly pyroxene porphyroblasts (Analysis 4, Table IV) with numerous inclusions of hornblende (Fig. 14). The hornblende is in slices brown like biotite, and Analysis 3, Table IV, gives a good idea of its composition because the rock consists of only hornblende and apatite. The pyroxene is very similar in as different rocks as amphibolites and quartzites. This shows that the conditions during the metamorphism had a determining effect upon the pyroxene generated (Sørensen 1953).

LIMESTONES AND SKARNS

The greatest part of all the limestones of the region lies in the basic zone. Only a few and commonly small occurrences lie outside this zone or in stratigraphically uncertain connections. In the parishes of Pargas and Korpo the limestones are very thick and occupy a considerable part of the basic zone (Metzger 1945, 1947, Laitakari 1916, 1921).

Calcite is the predominant carbonate mineral, but dolomite and ankerite have been observed (Metzger 1945). In general the limestones contain intercalations of skarn and also of other silicatic rocks. Only the largest deposits are rather free from impurities and hence workable. The most common skarn minerals are garnet and diopside, but some deposits of the parish of Pargas are renowned for their richness of different skarn minerals (Laitakari 1921). The sulphide ore with zinc, lead, and silver in the island of Attu is associated with skarn, limestone, and ore quartzite (Pehrman 1931).

Although skarn commonly occurs together with limestone, there are some skarn occurrences without limestone. For the greatest part, this pure skarn lies, however, in the basic zone of the banded series in the parish of Hitis, where the movements and the metamorphism have been very strong. These skarns are as all other brittle rocks brecciated. The skarn breccias in many cases resemble the ultrabasic ones, but in most cases it is possible to distinguish them from each other because of differences in the composition, colour, and zonary structure of the fragments.

The biggest skarn body lies on the N shore of the island of Stora Klobbskär. It seems to be a rounded or lens-shaped lump around which the leptites curve. It is coarse-grained and consists principally of hornblende and garnet. This rock has been counted among the skarns on the basis of its mineral composition, but for the present quite convincing proof of its origin from limestones is lacking.

ULTRABASIC ROCKS

Ultrabasic pyroxenitic and hornblenditic rocks are much more common in the E part of the region than in the W, and they are especially common in the surroundings of the island of Rosala. They occur in the last-mentioned area partly as brecciated massifs but mainly as narrow breccia bands or zones concordantly intercalated in the banded series. The largest massif is that of the island of Djupplåten or Jubblåten (Fig. 15). The composition is

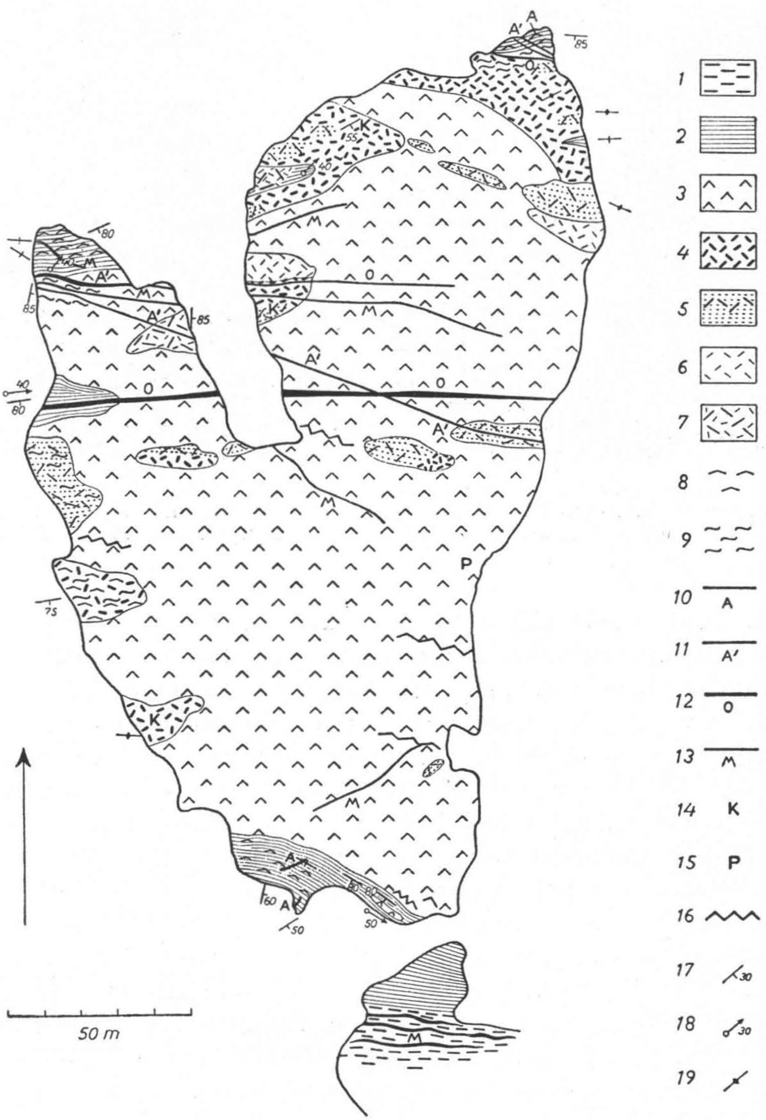

Fig. 15. Geological map of the island of Djupplåten, parish of Hitis, made by Tor Stolpe (1952). 1. banded formation, 2. thin-bedded pyroxene amphibolite, 3. pyroxene hornblendite breccia, 4. hornblende gabbro, 5. gabbro pegmatite and amphibolite with hornblende needles, 6. diorite, 7. diorite with plagioclase porphyroblasts, 8. fragments of thin-bedded amphibolite (2), 9. fragments of diorite with plagioclase porphyroblasts (7), 10. older amphibolite dikes, 11. younger amphibolite dikes, 12. oligoclase granite dikes, 13. pegmatite rich in microcline, 14. limestone and skarn, 15. prehnite-quartz dikes, 16. strong brecciation, 17. bedding, 18. fold axis, and 19. foliation.

Fig. 16. Brownish nucleus of ultrabasic fragment, hypersthene-bearing. 20 x. Island of Djupplåten, parish of Hitis.

Fig. 17. Greenish shell rich in diopside, ultrabasic fragment. 20 x. Island of Djupplåten, parish of Hitis

pyroxenitic or hornblenditic and in the area around Rosala the fragments have as a rule a zonary structure (Fig. 9). A brownish nucleus rich in hypersthene (Fig. 16) is surrounded by a greenish shell rich in diopside (Fig. 17) and this again is surrounded by a thin black hornblenditic shell. In some cases there is a zone with small weathered pits along the border between the brownish nucleus and the greenish shell. Exceptions to these rules are common; often, e.g., the brownish nucleus is lacking. Härme and Laitala (1955) have described gabbro fragments surrounded by darker rims from an area farther E in the same zone, but the rim has quite a different composition there, and consequently their origin is also apparently different. Sørensen (1953) has described brecciated ultrabasic bands in banded amphibolites in West Greenland. The fragments there also have hornblenditic borders. (See also the chapter dealing with the dark bordered pegmatites in this paper.)

Many odd types of gabbroic and dioritic rocks are associated with these ultrabasic breccias, as, e.g., the gabbro with hornblende porphyroblasts in the island of Ossmanskär, anorthositic gabbros with almost colourless hornblende, gabbro pegmatites (Fig. 18), fine-grained amphibolites with hornblende needles situated at random, etc. (Edelman 1956).

A brecciated amphibolite zone occurs on the SW cape of the island of Rosala. The amphibolite is a supracrustal rock with preserved bedding in the fragments. Clots of a medium-grained gabbro-like rock occur within the amphibolite fragments and in some cases one can follow the same gabbroic clot from one fragment to another. The contacts of these clots against the amphibolite are irregularly rounded and often somewhat indistinct. The

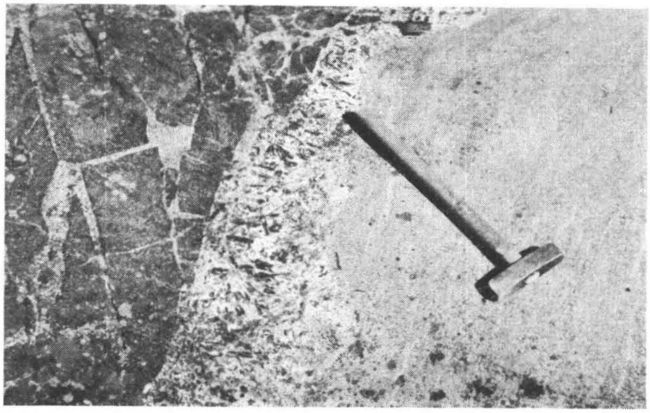

Fig. 18. Pegmatitic border between ultrabasic breccia and granitic dike. Bay on the SE shore of Djupplåten, parish of Hitis.

gabbroic clots must hence be older than the brecciation. They are rather a result of a recrystallization than of any magma intrusion for the following reasons: 1) visible feeding channels have not been found, 2) the contacts between the gabbroic rock and the amphibolite show no signs of intrusion, no dikes, no bending of the schistosity of the amphibolite, 3) the gabbro clots are small, being less than one metre in length and the intrusion of such small magma quantities would rather take the shape of dikes than of irregular lobate clots.

The ultrabasic rocks belonging to the banded formation of the area around Rosala consist principally of pyroxenes and hornblendes. Plagioclase occurs in the gabbroic types. The only mineral which is almost idiomorphic is the rhombic pyroxene: all the other minerals are xenomorphic, sometimes porphyroblastic. The rhombic pyroxene, a hypersthene, is the dominating mineral of the brownish nuclei of the fragments, whereas a clinopyroxene gives the inner shell its greenish colour, although these parts also contain hornblende to a considerable amount. The outer black shell consists of hornblende, but a few grains of biotite or pyroxene may be found in it. The hornblende of the gabbros is of two different types, a darker one which sometimes appears to be older than the clinopyroxene, because it occurs as inclusions in the latter, and a pale one with weak pleochroism. The latter pale type has often grown as large porphyroblasts enclosing all the other minerals of the rock. In some cases the pale hornblende contains numerous inclusions of small grains of iron ore, which as a rule are concentrated in clearly limited parts of the hornblende grains. The hornblende often has a

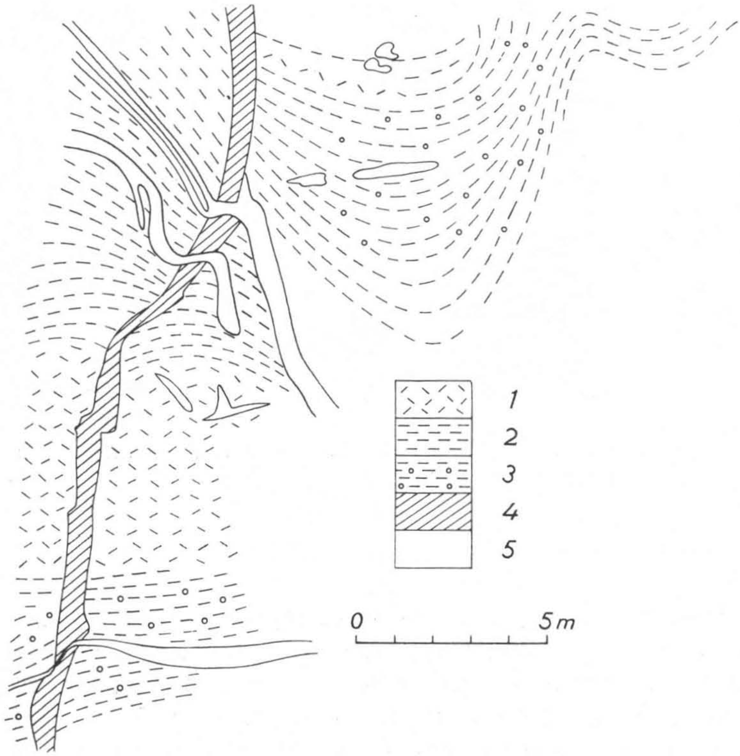

Fig. 19. Sketch of a gabbro exposure on the shore of the bay of Vadviken, W shore of the island of Attu, parish of Pargas. 1. gabbro, 2. banded or schistose gabbro, 3. schistose gabbro with big garnet grains, 4. amphibolite dike, and 5. pegmatite dikes.

darker green colour in some parts (Fig. 17), e.g., around the parts with ore inclusions. Seemingly the ore grains are remains of the iron content of earlier minerals richer in iron. It is possible that in age the clinopyroxene is between the two hornblende generations, but the relations are not quite clear.

In a brecciated zone on the contact between a hornblende gabbro and a migmatic granite in a small skerry S of the SW cape of Rosala the fragments consists of clinopyroxene with a few grains of chlorite or chloritized hornblende. The texture is granoblastic. The pale gray dike around this fragment is a pure anorthositic rock, with some grains of calcite and epidote filling openings between some plagioclase grains.

In the zone of Attu—Korpo the ultrabasic rocks are of a somewhat different type. Breccias are rare and breccias with fragments revealing a zoned structure are lacking with the exception of the SW point of the island of Korpo, where ultrabasic fragments resembling the ones of the banded series occur. In other cases the ultrabasic rocks there are hornblenditic or pyroxenitic. Some of them contain olivine, which mineral has not been found in the S part of the region. Another peculiar type is the basic gabbro of Attu (Fig. 19), which contains an exceedingly dark hornblende and plagioclase as well as furthermore clinopyroxene, orthopyroxene, olivine, and garnet, partly together, partly in different varieties (Pehrman 1927, Edelman 1949 c). The iron content of this gabbro is quite high and a small titaniferous iron ore occurs in it (Pehrman 1927). Another similar ore has been worked in the village of Hväsby on the island of Korpo (Öhman 1952). It lies in an amphibolite in the basic zone on the S side of the syncline of central Korpo.

Summary

When comparing the rocks of the basic zone of the different parts of the region, one finds that the limestone and diopside amphibolite zones are much broader and longer in the zone of Pargas—Korpo—Houtskär than in the S part of the region. The ultrabasic rocks on the other hand are more common in the E part, particularly in the SE, than farther W. Olivine has only been found in the area of Attu—Lill-Nagu—Kimito. The tectonic movements again have been strongest in the zone of Rosala—Utö.

The origin of the basic zone is an exceedingly complicated problem. Many different rocks together form the association of the basic zone and the genetic relations are obscure. The uralite and plagioclase porphyrites and probably a great part of the other amphibolites are volcanic rocks. The limestones, skarns, and diopside amphibolites are supracrustal and probably principally sedimentary, but it is not impossible that a part of them may be sinters, as they occur in the same zone as the volcanic rocks. Especially the type of diopside amphibolite that occurs in the zone Attu—Korpo—Houtskär closely resembles some diopside amphibolites I have seen in the Pellinge region. There they are associated with uralite porphyrites and are probably metamorphic derivates of a lava rich in cavities filled with calcite. Similar rocks may, however, originate in different ways.

The origin of the ultrabasic rocks is more difficult to solve, because the now available facts are too few. In spite of the relatively high content of calcium in the breccia of Djupplåten (Analyses 1 & 2, Table IV) it is somewhat difficult to explain these ultrabasic rocks as metamorphosed skarns or diopside amphibolites, because they differ remarkably from these rocks in appearance and mineralogical composition. In the island of Djupplåten, for instance, the ultrabasic breccia is in contact with pyroxene amphibolites with well-preserved primary structures, e.g., bedding. Berthelsen has, however, observed skarn-rich amphibolites grading into gabbro-anorthosite

(1957). Wegmann and Kranck (1931) have explained some hornblendites as metamorphic supracrustal rocks and Kranck has later (1937a) described hornblendites from the archipelago of Ekenäs, the continuation E-wards of the zone with the banded formation of Hitis, as metamorphic limestones. On the other hand it seems rather improbable that all the ultrabasic rocks were ophiolitic intrusives, because they form very thin intercalations in the banded formation without any observed cutting dike, but the possible dikes have of course been broken into fragments too by the orogenic movements. The possibility of the existence of ultrabasic magmas has been doubted by many geologists, and particularly in the cases here discussed it does not seem quite conceivable that ultrabasic magmas would have been able to intrude the banded formation forming principally large but thin sills. Furthermore the observations of gabbroic clots in the amphibolite breccia (p. 26) and of gabbro-like layers in well-preserved gneisses (p. 12) indicate the possibility of the formation of basic rocks through metamorphic processes. The origin of hornblenditic borders around pegmatites as a result of metamorphic differentiation will be discussed later (p. 39), but this likewise points to the possibility of a metamorphic origin in regard to some ultrabasic rocks. The two generations of amphibolites with an intervening generation of pyroxene indicate that these ultrabasic rocks have had a long and intricate metamorphic history with rising and sinking PT-conditions (Wegmann 1956). The formation of pyroxene at the expense of amphiboles may either depend on a rising temperature or sinking external pressure in a breccia, providing conditions that have given the water good possibilities to escape (Edelman 1948). The hornblende and pyroxene-hornblende rocks or skarns on the SE shore of Stortervo have pyroxene and hornblende quite similar as to the quartzites and amphibolities in the immediate vicinity (p. 23), which points to a long metamorphic history in common and to chemical similarities in the parent rocks. Many ultrabasic rocks may thus be metamorphic derivates of basic volcanic rocks or of some types of marls.

In the case of the gabbros and ultrabasic rocks of Attu and NW Kimito a magmatic origin seems, on the other hand, more probable because of their composition, texture, structure, and behaviour in the field as large massifs not intimately connected with the supracrustal rocks. Furthermore, some of them in the island of Attu (Pehrman 1927) and in the island of Korpo (Öhman 1952) contain titaniferous iron ores. The ore of Storstrand, Attu, (Pehrman 1927) seems, however, to lie in supracrustal amphibolites. In the N part of the region the differences between metamorphic basic rocks with a doubtful origin and basic rocks with a probable magmatic origin are greater than in the S part.

A pecularity is the fact that nearly all the ultrabasic rocks occur in the basic zone, a stratigraphic horizon (Mikkola 1955). Metzger has proposed the explanation that the magmas in general have intruded along the limestone horizon, which has been a zone of weakness and movements in the earth's crust. This seems very probable, but he deals with more acid rocks, principally granodiorites (Metzger 1945). The limestones are, on the other hand, small and rare in the S part of the region, wherefore Metzger's explanation seems to be less plausible in this area. On the other hand, zones of weakness and movements are also zones of strong metamorphism. The brecciation is a proof of strong movements after the origin of the basic layers, which have been the parent rock of the basic or ultrabasic fragments, and these movements may have caused the metamorphism (Sørensen 1953). These movements are, however, younger than the possible intrusion of an ultrabasic magma because they have brecciated the ultrabasites. Sørensen (1951, 1953, 1954a, 1955) has proposed a metamorphic origin for some ultrabasic rocks in W Greenland and in Norway. The rock associations in the areas described by him are very similar to that of the present region. Mikkola (1955) has also explained the ultrabasic rocks in the Orijärvi region as having originated by metamorphic processes. The explanation proposed herein is only a hypothesis and the problem of the origin of the ultrabasic rocks in the present region cannot be solved before much more detailed investigations and more chemical analyses have been made. It is conceivable, however, that ultrabasic rocks may originate from different primary rocks in different ways. It may be that certain metamorphic conditions cause basification. The ultrabasites may, e.g., be results of a metamorphic differentiation.

ALKALI-CALCIC ROCKS

Rocks with the composition of alkali-calcic igneous rocks occur as lenses or zones, more seldom as more irregular massifs, in all parts of the region. Their colour varies from light gray to nearly black in accordance with the composition, which varies from plagioclase aplitic to hornblenditic and peridotitic. The parallel structure is in general better developed in the acid members than in the basic ones and it has often been made more pronounced by oriented dark inclusions, e.g., in the island of Lökholm W of Sorpo (Edelman 1949c Fig. 2, Pl. I) or by banding. When the banding is strong, it is very difficult or impossible to distinguish the alkali-calcic rocks from rocks belonging to the banded formation. The borderline between them is therefore arbitrary, although the typical members are quite different (see p. 19). The contacts between the alkali-calcic rocks and the banded formation are commonly gradual or interfingered. In general the contacts of the alkali-calcic rocks are concordant, but clearly cutting contacts have been found,

Fig. 20. Gneissose granite brecciating leptitic gneisses. Island 0.6 kilometres W of the island of Långholm W of Mossala, parish of Houtskär.

as, e.g., the brecciating dikes in an island 0.6 kilometres W of the island of Långholm W of Mossala (Fig. 20).

The texture of the alkali-calcic rocks is in general granoblastic, rarely porphyroblastic. A blastohypidiomorphic gabbro occurs on the island of Hundholm. The gabbro of the island of N Storskär in the SE corner of the region has rather well-preserved plagioclase crystals and a texture somewhat resembling the ophitic one. The best preserved hypidiomorphic texture has been found in the gabbro of the skerries of Lasanletot in the N part of the region about 2 kilometres S of the rapakivi contact. This gabbro shows scarcely any signs of metamorphism, wherefore it may be late- or postorogenic and hence younger than the microcline granite. Because the contacts are hidden by the sea, the age of the gabbro cannot be determined with certainty.

The mineral composition of the alkali-calcic rocks is in general rather monotonous. The acid members consist principally of plagioclase, quartz, and biotite, the basic ones again of plagioclase, hornblende, and often biotite, and the ultrabasic ones commonly of hornblende. The gabbros and peridotites of the island of Kimito contain, further, olivine, and the gabbros also augite and hypersthene (Pehrman 1945). Also the S gabbro zone of Attu contains many different minerals, as has already been mentioned in connection with the basic zone (p. 29) (Pehrman 1927, Edelman 1949c).

The composition of the plagioclase varies in accordance with the basicity of the rocks. Sericite, epidote, and calcite occur often as alteration products in the plagioclase. The hornblende is commonly dark green with a pleochroism from green to black, contrary to the hornblende of the »gabbros» associated with the banded formation in the SE part of the region. In many cases it contains inclusions of biotite, particularly in the area SE of Nötö (Fig. 21). Hornblende occurs also as porphyroblasts in a gneissose granite S of Sjöholm in the SE part of the region. Monoclinic as well as orthorhombic pyroxenes occur in some small lenses or zones of diorite or quartz diorite, charnockitic rocks, in many places N of the islands of Nagu and Lill-Nagu and also in the parish of Houtskär (Hausen 1944a).

Judging from the contact relations and the microscopic textures, there have been found only a few alkali-calcic rocks with a certain magmatic

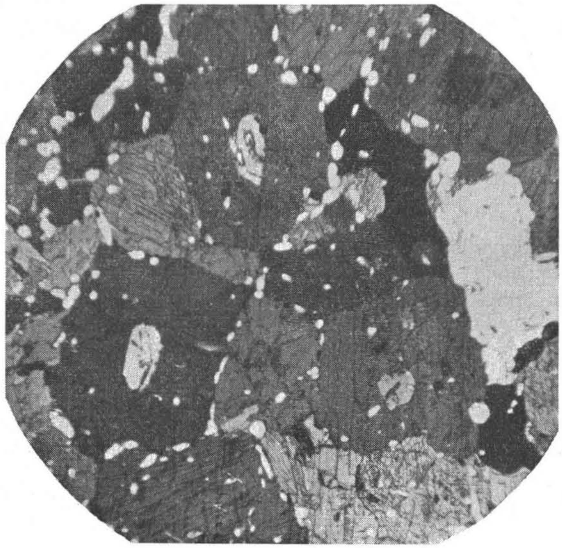

Fig. 21. Hornblende gabbro with dark green, strongly pleochroic hornblende. Biotite inclusions in the centre of the hornblnde grains. The small light grains are apatite. 20 x. Island N of the island of Sandholm S of Nötö, parish of Nagu.

origin within the region but the real number must be greater. It is, for instance, very improbable that all the zones or lenses of gneissose granite, which may be several metres thick and lie between well-preserved leptites, could be metamorphic gneisses, although examples of such transformations have been found (p. 18 and Edelman 1949c). Many of the rocks without preserved magmatic features are certainly metamorphic magmatic rocks but, on the other hand, many metamorphic supracrustal rocks have been counted among the alkali-calcic rocks owing to their similarity to the latter. A further example of a gradual transition from a supracrustal gneiss to a rocks resembling a gneissose granite may be mentioned. On the S shore of the island one kilometre S of V. Rockelholm a fine-grained gneiss inclusion or lens changed within one metre in the direction of the strike into a medium-grained rock quite similar to a gneissose granite (Fig. 22). Sederholm (1926) has described many instances of transitions from leptites into gneissose granites.

It can be established that among the rocks which have been mapped as alkali-calcic rocks many probably are metamorphic supracrustal rocks, as Backlund (1936) and Kranck (1937a) have proposed. The greatest part of them have a problematic origin. It is for the present impossible to estimate

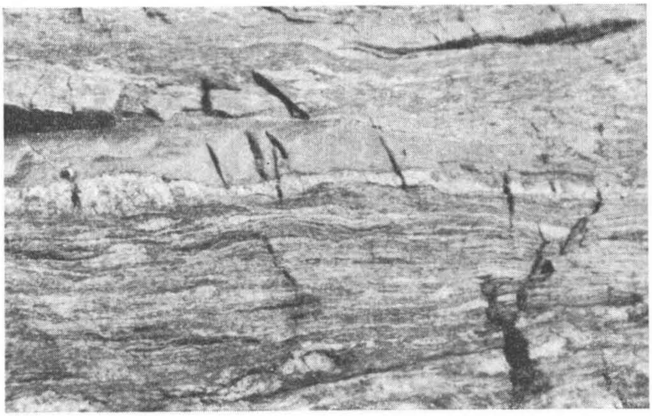

Fig. 22. Fine-grained leptitic remnant in a gneiss which resembles a gneissose granite. Gradual transition from leptite to the gneiss in the right part of the figure. The largest of the islands S of the island of W Rockelholm, parish of Nagu.

how great a part of them is supracrustal and how great a part truly magmatic (Magnusson 1953, 1957). On the map they have been divided only according to their composition into quartz-bearing and quartz-free types without regard to their origin.

DARK-BORDERED PEGMATITES

Pegmatites with dark hornblenditic borders present an odd problem. They are common in the area S of Nötö (Edelman 1956). From the dark-bordered pegmatites herein treated we must distinguish the pegmatites with typical reaction rims against the country rock, e.g., biotitic rims between dikes rich in potash and gabbros, or amphibolites. The hornblenditic borders cannot be explained as simple reaction rims, because no reaction producing hornblende can take place between a plagioclase pegmatite and a diorite.

The typical dark-bordered pegmatites occur predominantly in alkali-calcic rocks and to a less extent in supracrustal amphibolites. They have the shape of dikes or lenses of plagioclase, and quartz bordered by comparetively thick zones of pure hornblende. Therefore the dikes somewhat resemble composite dikes (Fig. 23). Sederholm has described a composite dike with hornblenditic borders from the island of Följskär in the parish of Kökar W of the present region (1924). He has also described dark borders rich in biotite between porphyritic granites and aplitic or pegmatitic dikes (Sederholm 1912, Figs. 4 & 6). Sometimes the pegmatite material is lacking

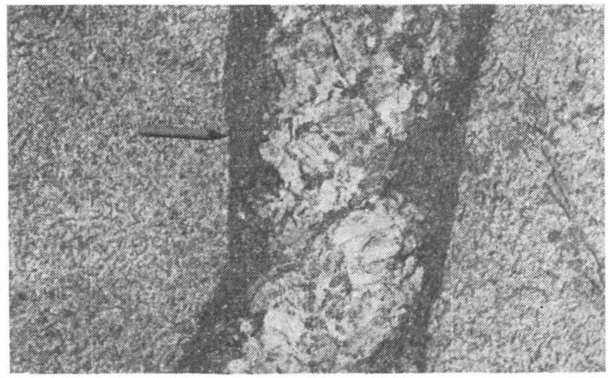

Fig. 23. Pegmatite with dark borders in diorite. Island 1.3 kilometres W of the SW point of the island of Borstö, parish of Nagu.

in parts of the dike and the dark borders touch each other (Fig. 24). Fig. 25 shows a lens-shaped pegmatite with dark borders. The parallel structure of the surrounding diorite is sharply cut by the dark borders instead of bent around the lens. This fact shows that the lens has made room for itself by replacement rather than by intrusion. The lens is seemingly younger than the country rock as it cuts the parallel structure. An intruding magma would have bent the schistosity around itself more or less concordantly or it would have pressed the older material out from the place where the

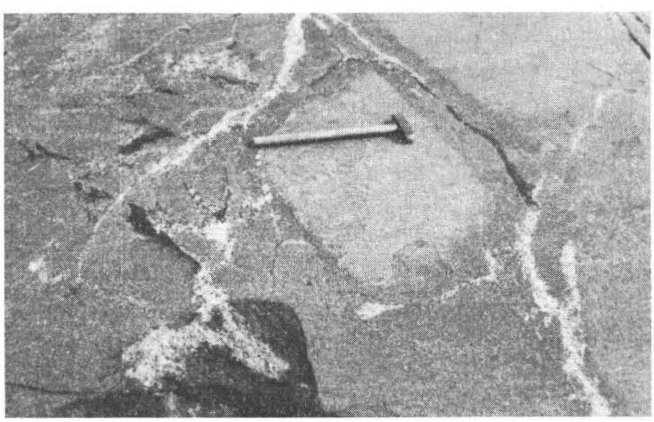

Fig. 24. Dark-bordered pegmatite in diorite. Right of the hammer the pegmatitic material has been squeezed out, leaving the dark borders which now resemble a basic dike. The NW one of the islands NE of Sandholm, parish of Nagu.

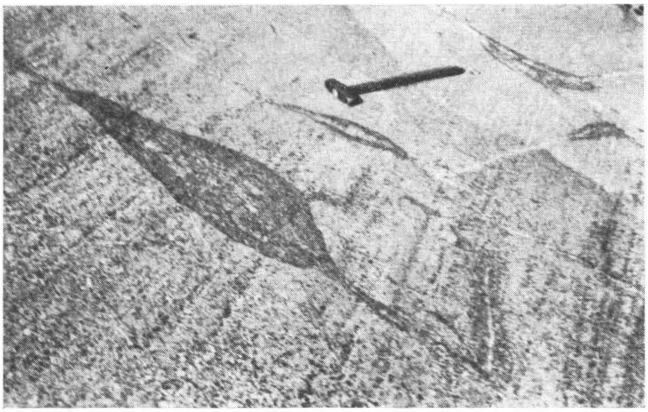

Fig. 25. Lens-shaped pegmatites with dark borders. The parallel structure of the surrounding granodiorite is cut by the dark borders. N shore, the largest island of the group W of Borstö, parish of Nagu.

pegmatite is now situated. The former has not taken place and the latter possibility is highly improbable, because the pegmatite as well as the outsqueezed material should in this case have had the shape of a pipe. The squeezing out of such a pipe needs such great forces that the rock had yielded much more easily in other modes.

In a small skerry 50 metres N of Sandholm one finds in the diorite light zones, which cut the rock in different directions (Fig. 26). These light zones are coarser than the parent rock and they often contain visible grains of magnetite. Some pegmatites in this island contain such great amounts of magnetite that specimens of them might be classified as ores. The light zones divide the parental rock into fragments. The outermost shells of these fragments along the light zones are coarser and richer in hornblende than the dioritic parent rock in general. There are in this skerry transitions between these light zones and rather well-developed dark-bordered pegmatites. Dark-bordered fragments have also been observed in some breccia zones. Related to these pegmatites are others rich in hornblende. The hornblenditic borders are in these cases thin or absent. The hornblende occurs in these pegmatites as large grains or crystals. The shape of these pegmatites is somewhat different; they are as a rule irregular lobate clots, but dikes occur too.

The mineral composition of the dark-bordered pegmatites is plagioclase and quartz. Biotite and hornblende occur as minor constituents, the latter, however, as a main mineral in the last-described type of pegmatite. Microcline is lacking or secondary. Magnetite occurs often, sometimes even as a main

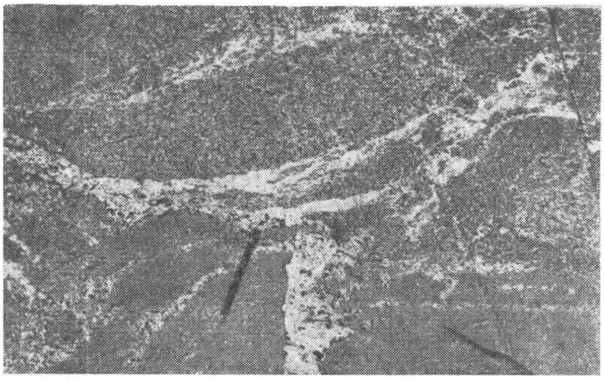

Fig. 26. Light zones in a gabbro-diorite, incipient recrystallization. The light material and magnetite grains have been concentrated in the middle of the zones, whereas the outer borders of the fragments have become darker and richer in hornblende. Island N of the NE point of the island of Sandholm, S of of Nötö, parish Nagu.

constituent. The texture is granoblastic and the grain size varies from medium to coarse.

The mineral composition of the dark borders is simple. A green hornblende, sometimes very dark and pleochroic from green to black, is the main constituent. It often contains inclusions of biotite, which mineral also occurs as larger grains. Apatite may in some cases occur in rather considerable amounts, as in the dioritic or gabbroic country rock.

Especial interest is afforded by a breccia zone on a small skerry 0.3 kilometres SW of the skerry of Ådgrundet between Lökholm and Borstö (Fig. 27). The dike rock of this breccia consists principally of plagioclase, quartz, and some hornblende. The fragments have as a rule the composition of an amphibolite or a hornblende gabbro. Often they have hornblenditic borders. In one fragment a part of the nucleus consists of hornblende and dirty plagioclase, the other part of hornblende and clinopyroxene. The pyroxene occurs principally as small grains between the hornblende grains, but there are some larger pyroxene grains, which contain hornblende inclusions with a simultaneous extinction. This fact points to the possibility that the pyroxene is younger than the hornblende. It has been mentioned earlier that the hornblende seems to be younger than the biotite in the hornblenditic borders as well as in the country rock (p. 32). The evolution seems therefore to have proceeded in the direction from biotite to hornblende and sometimes also further to pyroxene. This is quite opposite to the Bowen's

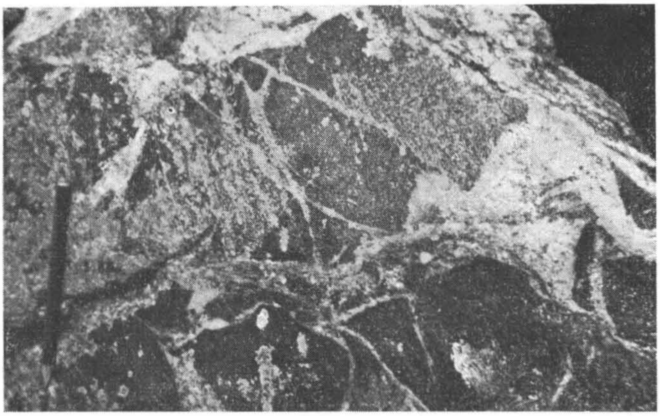

Fig. 27. Breccia zone in a gabbro-diorite. The fragment in the upper part has a thin hornblenditic border. The right part of the nucleus consists of hornblende and plagioclase, whereas the left part consists of hornblende and clino-pyroxene. Skerry 0.3 kilometres SW of the island of Ådgrundet, NW of Borstö, parish of Nagu.

crystallization series of igneous rocks and indicates a rising temperature and hence a secondary metamorphic origin of the hornblende and the pyroxene. Sørensen (1953) has explained ultrabasites as results of metamorphic differentiation caused by the increased temperature in shear zones. It is easily conceivable that compression and friction can cause a rise in the temperature in breccia zones but it is another question whether the heat produced suffises as a rule for the necessary reactions.

On the W shore of another island 1.5 kilometres NW of Borstö another peculiar recrystallized rock occurs in a somewhat banded amphibolite. Hornblende porphyroblasts about 1 centimetre across partly form dark clots of irregular shape and partly lie scattered in a light, rather coarse rock. Even in the dark clots the hornblende grains are often surrounded by light reddish rims. A thin section of this rock shows hornblende porphyroblasts in a medium-grained pyroxene amphibolite. The green hornblende grains contain numerous inclusions of biotite, sphene, and in addition some plagioclase grains. Some porphyroblasts contain so many inclusions of quartz and plagioclase that the hornblende proper only forms a skeleton between the inclusions. The medium-grained matrix consists principally of hornblende, plagioclase and clino-pyroxene. The pyroxene has as a rule inclusions of hornblende. Also in this case Bowen's crystallization series is inverted. The evolution has not here led to dark-bordered pegmatites, but the light and dark minerals show, however, a tendency to separate.

Furthermore, the previously mentioned layers with hornblende porphyroblasts in the well-preserved supracrustal gneisses in the island E of Nagu Sandö are worthy of notice in this connection (p. 12).

When summarizing all the in the foregoing presented facts there seems to be very little reason for assuming a juvenile magmatic origin for these pegmatites. The structural behaviour in respect to the country rock points to replacement or recrystallization rather than to intrusion. The minerals of the pegmatites and the dark borders are quite similar, sometimes seemingly identical to the minerals of the country rock. The pegmatites together with the hornblenditic borders have on the whole almost the same composition and basicity as the country rock. The texture is granoblastic or porphyroblastic without traces of any relic hypidiomorphic texture, and the crystallization series is inverted. The dark-bordered pegmatites are results of some kind of metamorphic differentiation (Eskola 1932). A conceivable explanation is as follows. The free interfacial energy is seemingly considerably greater between grains of different minerals than between grains of the same mineral. This difference may cause a tendency in the minerals to separate and form more or less monomineralic aggregates (Edelman 1950, DeVore 1958).

The rising temperature during the metamorphism caused recrystallization in the rock, particularly along joints or planes of weakness but also starting from certain points. The grain size has grown during the recrystallization. Simultaneously a metamorphic differentiation has taken place and the light material has concentrated in the middle of the zones or clots, whereas the hornblende has collected along the surfaces of the unaltered rock. We may also assume that the light material has segregated from the country rock, leaving the hornblende behind. Sederholm (1912) explained biotitic borders of pegmatites in a similar way. Barth (1947) and Berthelsen (1955) have proposed the same explanation for similar phenomena. Reitan (1956) and Ljunggren (1957) have discussed such dark-bordered pegmatites more in detail. It is for the present not possible to estimate to what extent a metasomatic exchange of material has occurred in connection with the recrystallization. The fact that the pegmatites often seem to be old joints shows that there have been good possibilities for the material to migrate. Movements and squeezing have probably had a great influence upon the degree of segregation or differentiation (Sørensen 1954b, 1955). In some cases the light material has been squeezed out, and the hornblende borders left behind appear as cutting dikes.

AMPHIBOLITE DIKES

Amphibolite dikes are rather rare in the present region. Most of them occur in the S and SE parts. This may depend on the fact that these parts have been most thoroughly investigated, but there may also be real differences in their distribution within the region. The amphibolite dikes cut the supracrustal rocks as well as the alkali-calcic rocks, but they have been granitized by the migmatic granite (Sederholm 1907, 1924, 1926, Edelman 1949c, 1956). In respect to the age they may be classified between the origin of the alkali-calcic rocks and the formation of the migmatic granite. In the islands of Långharu and Stenharu a garnetiferous diorite occurs partly as dikes, partly as a small intrusive. This has an unknown shape and extension because it continues under the sea. The contacts are of a cutting type and the dikes cut straight through folded supracrustal gneisses but are themselves not folded. They are accordingly younger than the folding but they are older than the granitization, because they are locally granitized (Fig. 28). There are, however, amphibolitic dikes of other ages; e.g., in the island of Djupplåten two generations of amphibolite dikes occur. The older generation there is seemingly related to the supracrustal rocks because the dikes have been folded together with these rocks. Similar old »greenstone» dikes occur also in Sweden (Magnusson 1936). One dike belonging to the younger generation in the island of Djupplåten is dislocated and seems to be cut by a plagioclase granitic dike (Stolpe 1952).

The amphibolite dikes commonly have a schistosity almost parallel with the contact but in the long dike of Djupplåten the schistosity makes a considerable angle with the contact. The texture is granoblastic and exceptionally blastoporphyritic, as, e.g., in a dike with feldspar phenocrysts on the N shore of the island of Gubbholm between Attu and Kimito. The mineralogical composition is simple, principally hornblende and plagioclase, in some cases almost only hornblende. Quartz, microcline, and biotite occur in granitized dikes. Accessory minerals and alteration products are rather rare.

MICROCLINE GRANITE

A microcline granite, commonly migmatic, dominates in many parts of the region. The map probably gives an exaggarated idea of its distribution, because it generally forms the hills, whereas gneisses form the depressions. A good example of this rule is the E part of Stortervo (Edelman 1949c, p. 11). As the depressions commonly are covered by sea or loose deposits, little or no information on gneiss zones is often obtainable. The granites which form the hills, therefore, dominate the exposures and hence also the map.

Granitization has been the principal metamorphic or ultrametamorphic process during the later stage of the orogenic evolution and it has more or less affected most of the region. Quite ungranitized are only a few limited areas. The granitization has, however, often stopped half way, so one can follow the transition back to the primary rocks. The term granitization is here applied to the gradual transformation of different supracrustal and infracrustal rocks into granites independently of the state of aggregation and the chemical processes involved in the transformation. [1]) Because the primary material may have almost any composition whatsoever and the transformation into granites can follow quite different paths, the »granitization» must be caused by different processes. The modes of granitization depend on differences in the composition and structure of the primary material as well as on the conditions prevailing during the transformation. The rapid changes in the degree of granitization are very puzzling. Within a few metres there are variations from almost unaffected older rocks into rather homogeneous granites, even though the primary material seemingly remains the same. This is easily observable in banded rocks where one can follow the granitization of certain bands. In general the light bands of banded rocks have been granitized much more easily than the dark ones, but in some cases the granitization seems to have proceeded almost independently of the primary composition.

In spite of all such peculiarities there seems to be some general rules for the granitization. Acid rocks are commonly granitized more easily than basic ones. The granitization of a gneiss or a leptite may be nearly a pure recrystallization, whereas the granitization of an amphibolite or a gabbro demands a considerable exchange of material (Du Rietz 1949). Therefore, the basic rocks often remain as more or less unchanged remnants of a different shape in the granite.

The structure of the older rocks determines in a high degree the ways along which the granitizing substances can most easily migrate. Bedding and schistosity planes of the supracrustal rocks are openings suitable for transport and crystallization. Therefore these types of rocks have commonly transformed into veined gneisses. The more homogeneous infracrustal rocks, on the other hand, do not present as good points of attack. They are, however, in general rather brittle and therefore have often been broken into breccias by the tectonic movements. In the opened joints the granitization substances have then had possibilities to migrate and to form pegmatites. The dark-bordered pegmatites have been described in the preceding chapter. From the joints the granitization can proceed in the fragments, transforming

[1]) I will not discuss the problem in what state of aggregation the granitization takes places because such a discussion would probably be rather barren on the basis of our present knowledge. I want, however, to point out that in case we assume the granitization to take place in the intergranular film, it is logically senseless to discuss the state of aggregation. The intergranular film has so few particles besides one another that it is outside the range of signification of the concept of a state of aggregation.

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them into nebulitic remnants. For such granitized breccias Sederholm used the term agmatite.

In some cases the tectonic movements have caused microscopic crushed zones in infracrustal rocks. These zones have an increased tendency to undergo chemical reactions owing to the fine grain-size. Microcline has often grown as porphyroblasts in these zones, transforming the rock to a »porphyritic granite» (Kranck 1933, Edelman 1949a). Some larger crushing zones or mylonites have been transformed into granitic dikes of a kind (Edelman 1949c).

The granitization may also take place without observable feeding channels. This is a »secret» mode of granitization. On the glacially polished surfaces the old structure is easily visible in the ghostly or nebulitic remnants in the granite (Sederholm 1907). On a fresh broken surface the rock may, however, appear already to be a homogeneous granite.

It is clear that these rules are not laws, and accordingly exceptions to them are often observed. Furthermore, these different modes of granitization rarely occur alone. Commonly, they have occurred either together at the same time or one after another. Very often the older rocks of breccias or veined gneisses have been granitized through the »secret» mode into ghostly remnants. In other cases one can find veined gneisses or porphyroblastic granites as fragments in the agmatites. Microcline porphyroblasts have sometimes grown together into pegmatitic lenses in veined gneisses and in one case a microcline porphyroblast has grown into a veined gneiss, so that a part of it lies in the granite vein, the remainder in the older rock.

This short summary of the megascopically different modes of granitization is by no means complete. It shows, however, that »granitization» is a sack name for all the different metamorphic processes which produce migmatites and migmatic granites. There seems to be very little chance to explain all the modes of granitization in the same way. The granitization seems to be an interaction of many different forces, leading in different ways to rather similar end products. Perhaps one can find even in the almost homogeneous microcline granites minute structural and chemical differences which depend on the mode of origin. Every attempt to explain the origin of all granites on one single principle, whether magmatic, metasomatic, or metamorphic violates many observed facts, although it may agree with many other facts. It is a sign of narrowness of outlook to believe that nature can produce granites in only one way.

I have distinguished four principal types of migmatic microcline granite and migmatites:

1) veined,
2) agmatic (brecciated),
3) porphyroblastic,
4) even-grained homogeneous.

V e i n e d t y p e s. Banded or schistose rocks are in general transformed into veined gneisses when granitized. The granitic material forms medium- or coarse-grained veins between the bands of the older rocks. These concordant veins are in many cases connected with cutting dikes of the same granite. The older material commonly consists of supracrustal gneisses or amphibolites, but even hornblende gabbros and diorites can under certain condition form veined gneisses, as, e.g., on the NW shore of the island of Bodö S of Rosala. The older rock has often been split up and broken into lenses in the granite and commonly also gotten a more granitic composition when the granitization has proceeded further. The banded formation is sometimes transformed into another kind of veined gneiss by a selective granitization or recrystallization of the leptitic bands.

A g m a t i c t y p e s. Rocks which are harder and less schistose than the gneisses break as a rule into angular fragments when affected by orogenic forces. The granitizing material has filled the opening joints, thus forming granite or pegmatite dikes. The fragments have commonly been transformed into more or less granitic rocks. It is principally infracrustal alkali-calcic rocks that have been granitized in this way, but even leptites may in some cases form the fragments in breccias or agmatites.

P o r p h y r o b l a s t i c t y p e s. Microcline porphyroblasts have in some cases grown in different rocks, giving them a more granitic composition. In some cases the porphyroblasts have grown together, forming pegmatitic lenses. Other kinds of granitization may simultaneously have taken place. In the zone of Dunskär the older rock has probably been a diorite and the growth of porphyroblasts has there been connected with microscopic cracks and crushing zones (Edelman 1949a). Kranck (1933) has earlier proposed this explanation and Seitsaari (1951) has discussed this mode of granitization. In this case the matrix is still rich in plagioclase, but microcline porphyroblasts occur also in other types of migmatic rocks. They are rather common in veined gneisses. The porphyroblasts have sometimes grown only in certain bands of banded rocks avoiding the other bands, which have not presented suitable conditions, viz., microscopic crushed zones. A special type is the porphyroblastic granite where the matrix is microcline granitic, e.g., the Perniö and the Mattnäs granites (Eskola 1914, Hausen 1944a). They have large often twinned grains of microcline in a homogeneous ground mass rich in microcline. They are commonly free from inclusions of other rocks, but they show, however, transitions to more migmatic types, as, e.g. in the NE part of Lill-Nagu (Hausen 1944a).

E v e n-g r a i n e d h o m o g e n e o u s t y p e s. The purest microcline granite is an even-grained type with rather few pegmatites. The schistosity of the older rocks is often preserved as relic structure in the ghostly remnants. This granite is the final product of granitization. It is principally acid rocks that have reached this final stage of granitization. These more or less homogeneous granites have been formed through the secret mode of granitization, often combined with one or more of the other modes.

Texture, structure, and composition. The texture of the migmatic granite is granoblastic or porphyroblastic. The microcline porphyroblasts are as a rule parallelly arranged. Garnet porphyroblasts, which are common in some areas, occur occasionally in certain zones of the otherwise homogeneous granite, indicating an alternation of bands or beds of different composition in the primary rock (Edelman 1949c). Relic structures and remnants of the older rocks often give a clue to the nature of the palaeosom of the granites.

The mineral composition is relatively monotonous in the granitic parts of the migmatites and the granites: microcline, plagioclase, quartz, and biotite. Garnet occurs in some types as porphyroblasts; hornblende is rarer. Chlorite, epidote, calcite, and sericite are the main alteration products. Apatite, zircon, sphene, graphite, and ore minerals are the principal accessories. The pegmatites of Kimito are rich in many rare minerals. They have been described by Pehrman (1945).

Contacts. The microcline granite shows manifold contact types. Cutting dikes, interfingering veins, breccias, and gradual transitions are the main types. Most of them have commonly been called intrusive contacts. One sometimes observes, however, seemingly intrusive contacts that can hardly result from any intrusion. Such cases have previously been described from this region (Edelman 1949c, pp. 24—25, Figs. 7 & 9 Pl. II). An additional example is seen in Fig. 28. A dike of a garnetiferous diorite (p. 40) in the island of Stenharu cuts a sequence of locally folded gneisses and a thick intercalated zone of microcline granite. The granite has, however, granitized the diorite dike and must hence be younger than the diorite. If the granite should have intruded like a wedge between the gneiss layers, it is hardly conceivable that it would have left the diorite dike unbroken. In this case it must have drawn the diorite dike out from the gneisses like a vorm from the earth. If, on the other hand, we assume that the granitic zone is a result of granitization in situ, then it is easy to understand that the diorite dike had been left as an ungranitized remnant of the older rocks and now seems to cut the granite in one place and to be older than the latter in another place. The dike is older than the granitization and owing to its rather basic composition has been more resistant and therefore remained relatively intact. It is hardly necessary to describe more similar instances in order to prove that microcline granites at least in some cases originated through granitization in situ. To what degree melting also took place is difficult to estimate. The intrusive contacts which often have been used as proofs of a magmatic origin are only evidence of a plastic state (pp. 55—56). Intru-

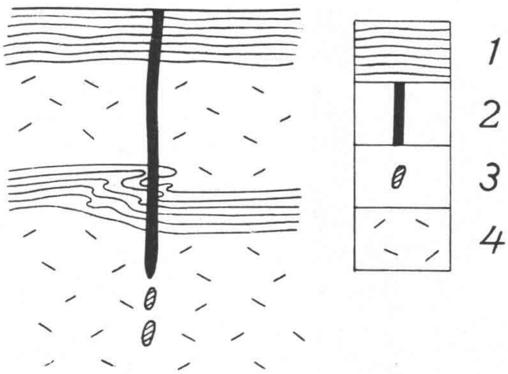

Fig. 28. Garnetiferous diorite dike cutting folded gneiss zones and microcline granite. The dike is granitized by the granite. 1. gneiss, 2. diorite dike, 3. granitized remnants of the dike, and 4. microcline granite. Island of Långharu, parish of Nagu.

sion is a proof of differences in plasticity of the material and not of the state of aggregation. Therefore one must leave the question open to what extent metasomatism, recrystallization, and remelting have taken part in the origin of the migmatic microcline granites.

DIABASE DIKES

Sharply cutting diabase dikes are comparatively common in the NW part of the region, while in other parts they are rare. They are still more common in the parish of Brändö W of the NW part of the region.

The dikes are as a rule narrow, commonly less than one metre. The strike of the dikes is in general between NE and NW and the dip steep, but also one dike dipping 10° N has been found in the island of Högland (Edelman 1949c). The dikes are porphyritic with a dense matrix and dense to glassy contact zones. Plagioclase occurs as phenocrysts and some grains of pyroxene have been found. The minerals of the matrix are difficult to identify because of the iron pigment and the small size of the grains. Some alterations have taken place as indicated by the presence of such minerals as chlorite and epidote. Diabase dikes from this region have earlier been described by Moberg (1887a & b, 1890), Laitakari (1921), Pehrman (1933), Metzger (1945), Hietanen (1947), and Edelman (1949c).

The diabase dikes are younger than all the afore-described rocks and younger than the Svecofennidic orogeny too, judging from the cutting contacts and the lack of metamorphic features. In the island NE of Bjurholm,

Fig. 29. Diabase dike with fragments of the country rock cut by a dike belonging to the Fjälskär granite. SW shore of the NW one of the islands NE of Bjurholm close to the Fjälskär granite massif, parish of Houtskär.

which lies SW of the Fjälskär granite (p. 47), a diabase dike is cut by aplitic dikes that can scarcely belong to any other granite (Fig. 29). According to current opinion, these olivine-free diabases are older than the rapakivi granites. The afore-mentioned observation supports this age relation. The same diabase dike locally contains fragments of the country rock and this is the only instance of inclusions in a diabase which I have observed in the present region. On the E shore of the bay NE of the limestone quarries of Ovensor, a diabase dike has some lens-shaped protuberances in the country rock. The irregular shape of these lenses is exaggarated by the oblique section on the shore, but the dike shape is of course not the only possible one for the diabase.

POST-OROGENIC GRANITES

Some granites occur in the region; being younger than the Svecofennidic orogeny, they do not show any signs of metamorphism. The S border of the rapakivi area of Vehmaa is seen along the N border of the map. This rapakivi granite has been described by Kanerva (1928) and Hietanen (1943, 1947). Some additional observations may be mentioned in this connection. The contacts are often sharp without any signs of contact metamorphism, but on the S shore of the island of Santasaari some hybrids between the rapakivi and the granitic country rock occur. The contact is there irregular, partly straight, partly lobate and the country rock is penetrated by rapakivi dikes with varying shapes. About ten metres from the contact the ovoids disappear from the dikes, which become fine-grained and aplitic. In many places there are hybridic types between the rapakivi and the surrounding granite. They are even-grained and differ from the parent rocks in colour, structure and other features. The most conspicuous microscopic feature of these hybrids is the granophyric intergrowth of quartz and microcline. The cross-grating of the microcline disappears in the centre of the large grains, indicating that the inner parts may be orthoclase. The quartz in general does not have an undulatory extinction. Similar hybridic contact types occur in the island of Långskär.

A small, rounded massif of a coarse, possibly young granite in the island of Tammo, in the parish of Pargas, has been described earlier (Edelman, 1949c, p. 18).

The granite of Fjälskär has been only briefly mentioned by Sederholm (1924), and therefore I will describe it somewhat more in detail, especially because the morphologically similar Åva granite about 20 kilometres NW of it has recently been described thoroughly by Kaitaro (1953). The Fjälskär granite is mainly covered by the sea and it is easily visible on the map as an elliptical area of open water 4—6 kilometres across. It is surrounded by conformable rings of islands. The contacts are as a rule hidden by the sea or by quaternary deposits. In the S part of the island of Österholm the contact is exposed (Fig. 30). There it cuts the gneisses obliquely to the strike. A few fragments of the country rock lie close to the contact in the granite but generally it is free from inclusions. Slight signs of granitization can be observed in some of the fragments. Aplitic and granitic dikes starting from the contact penetrate the country rock. On the SE end of one of the islands NE of Bjurholm the contact zone of the granite is exposed, consisting of a breccia with pegmatite and aplite dikes. The aplites transect the pegmatites and are hence somewhat younger. Dikes which probably belong to the Fjälskär granite occur in many places in the surroundings, e.g., on the S shore of the island of Espskär 2.5 kilometres N of the granite. Pegmatites cutting the granite proper as well as the country rock occur too.

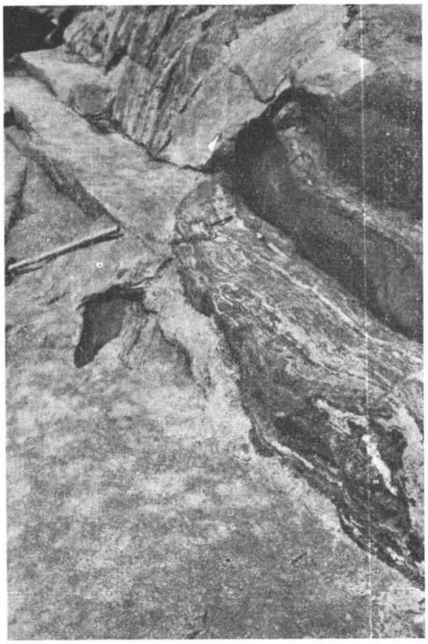

Fig. 30. Contact between the Fjälskär granite and a veined gneiss with a fragment of the gneiss in the granite and a dike of the granite in the gneiss. Island of Österholm, parish of Iniö.

The Fjälskär granite is red, medium- to coarse-grained, and massive. Medium-grained and paler types occur mostly close to the contact. The texture is hypidiomorphic and porphyritic. The phenocrysts are microcline. Quartz occurs in two generations, the older one being idiomorphic against the microcline. The mineral composition is: microcline, quartz, plagioclase, muscovite, biotite, fluorite, and sometimes ore minerals. The composition of the dikes is almost identical. The cross-grating of the microcline phenocrysts becomes finer toward the centre of the grains, but remnants of orthoclase in the microcline have not been identified.

The Fjälskär granite has had a remarkable effect upon the structure of the surroundings. The strike of the country rocks is in the S part mostly conformable with the contact, whereas in the W, N and E parts it seems to be more or less discordantly cut by the contact. This difference is, however, not visible in the morphology. The islands close to the NW contact of the granite are, for instance, elongated parallel to the contact and obliquely to the strike of the gneisses. The morphological forms are caused by joints running parallel to the contact and the granite thus seems to be surrounded by ring joints. Along the S border the joints coincide with the bedding or foliation of the country rock.

Judging from the foregoing facts, the intrusion of the granite seems to have been accompanied in the country rock both by fracturing and by bending. This indicates that the crust was rather brittle during the intrusion. The shape of the contact as well as the rareness of inclusions of country rock indicate that also the granite had a rather high viscosity during the intrusion. The granite and aplite dikes, which start from the contact, show that the granite apparently was in a liquid state right to the contact, whereas the pegmatite dikes, which occur within the granite, show that residual magma squeezed out also after the solidification of the border zone. There are probably pegmatites, or aplites of different ages, because some of the pegmatites are cut by aplites, whereas other pegmatites cut the border zone of the granite close to the place where the aplites start from the contact.

The Fjälskär granite belongs according to Sederholm to the rapakivi group. This opinion he based principally on petrographic similarities, but also the sharply cutting contacts speak in favour of this opinion. On the other hand, the Fjälskär granite closely resembles the Åva granite morphologically, but it differs on account of its lack of basic differentiates. The Åva granite belongs to Sederholm's third group of granites. Earlier mention has been made of the diabase cut by granitic dikes close to the contact of the Fjälskär granite (p. 46.) These dikes are petrographically very similar to the granite and belong obviously to it. All the observed facts thus agree with Sederholm's opinion.

SANDSTONE

Sandstone occurs locally in the present region as erratic boulders in such amounts that one must assume the existence of a number of sandstone occurrences hidden by the sea or mantle rock. Only in two places has sandstone been observed in the bedrock. A rather loose sandstone occurs together

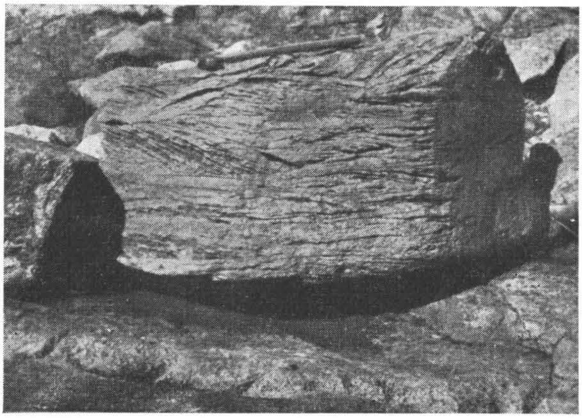

Fig. 31. Boulder of cross-bedded sandstone. Island S of Bodö, parish of Hitis.

with kaoline in the limestone quarry of Limberg in Pargas. It has been described by Hausen (1934). The other occurrence is an angular dike of sandstone in granite in the little skerry of Sejsan or Sisan 5 kilometres SE of Örö (Edelman 1956). The dike is about 5 centimetres thick and consists of quartz, with the exception of a few large grains of fedspar. The quartz grains are from 0.005 to 0.8 millimetres across. The roundness and the sphericity of the grains are not especially well developed. The cement is quartz.

With a semi-quantitative boulder count (Edelman 1951) it was possible to locate a probable remnant of sandstone in the area N of Örö (Fig. 1). There is quite a marked drop in the number of sandstone boulders, and also the dimensions of the boulders up to about 2 cubic metres indicate that the transport has been short. A brief description of this sandstone seems therefore to be justified. The colour is white, grey, greenish, yellowish, red, or brown. Cross-bedding is sometimes visible in large boulders (Fig. 31). The red, rather fine-grained types often show ripple marks of both oscillation and current type (Figs. 7 & 8 in Simonen and Kouvo 1955). One ripple-marked specimen also has minute pits resembling rain imprints. Conglomeratic types likewise occur among the boulders and in some of them ventifacts have been found. Many types contain greenish or rusty brown clay galls.

The composition varies from pure quartz sandstone to arkose. The roundness and sphericity of the grains is greater in the former type than in the latter. The arkoses contain, besides feldspars, other minerals that easily weather. The most common minerals of the sandstones are the following: quartz, microcline, plagioclase, ore minerals, biotite, apatite, and some others of the accessories of the archean rocks. The principal cement is quartz, but calcite occurs also, especially in concretions. A very fine-grained silica mineral about 0.005 millimetres across occurs as cement or as grains (aggregates?) in some sandstones. It is more common in arkoses than in quartzose sandstones. In a coarse conglomerate with stones 10—15 centimetres across, the cement is quartz, partly with a crystal shape.

No fossils have been found in these sandstones; but on the basis of petrographic similarities with other sandstone occurrences in SW Finland, one may assume that the sandstone dike and the other quartzose sandstones are Cambrian, whereas the arkoses seem to be Jotnian (Tanner 1911, Eskola 1913, Simonen and Kouvo 1955). The sandstone of the limestone quarry in Pargas is according to Hausen, probably much younger, perhaps Mesozoic. Here there should thus occur sandstones of three different ages, which indicates that the history of this region hardly has been so simple as might at first be believed because of the scarcity of preserved remnants from the many hundred million years which have elapsed since the origin of the rapakivi granite. Martinsson (1955) has recently published a review of our knowledge of Cambro-Silurian in bedrock and boulders in SW Finland. Boulders of Silurian limestone have been found principally in the SW part of the present region (Eklund 1948).

STRUCTURAL GEOLOGY

STRUCTURES IN GENERAL

The structures of the migmatites are in general very complex. The geologic structures have, however, been studied with success in many Archean areas and this proves that structural problems can be solved also in such regions (Wegmann and Kranck 1931, Kranck 1933, 1937a, Metzger 1945, Edelman 1949c). There are of course many difficulties. The rocks of highly metamorphic areas have been subject to many different transformations and the latest strong metamorphism has often more or less completely destroyed the structures of older phases. The degree of metamorphism varies quite considerably, sometimes even within a few metres; but this is by no means any proof of age differences, being only a sign of highly changing conditions. The granitization stage of the orogeny probably had the greatest influence on the tectonic style because the rocks were then extremely plastic and because this stage was the latest period of stronger movements. The often uneven plasticity of the rocks has produced a style which resembles the style of the folded salt deposits. The granites often form, for instance, diapiric domes. Furthermore, the contacts of intrusive rocks in migmatic regions are commonly deformed, observed angular unconformities are as a rule tectonic, and many rocks have been rejuvenated through granitization. One can therefore find many exceptions to simple tectonic rules and therefore the value of many methods is problematic in migmatic terrain.

CUTTING CONTACT AND BRECCIAS

Brecciation is quite common in the region under discussion. This is due partly to the wide distribution of brittle ultrabasic and basic rocks as intercalations between more plastic ones, partly on the strength of the movements. The plastic or brittle behaviour of a rock depends on the composition, temperature, and pressure as well as the velocity of the movements, on the properties and direction of the stress, on the difference in plasticity between adjacent rocks, etc. It is very difficult to evaluate the importance of all these different conditions, especially as they have locally varied greatly.

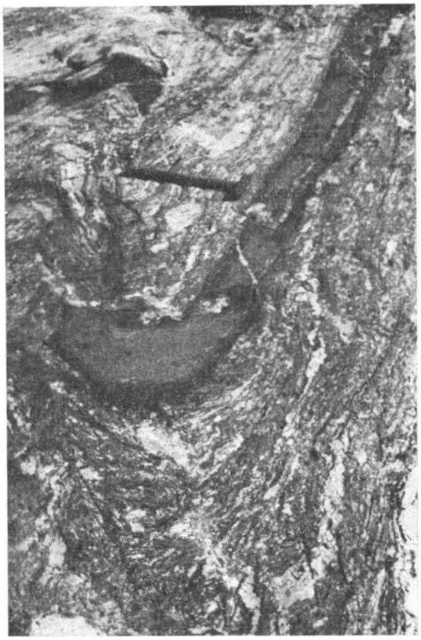

Fig. 32. Folded and sheared amphibolite layer in a veined mica gneiss. E shore of the island of Jämmerskärsgrundet, E of Lökholm parish of Nagu.

The movements have often caused strong deformations of the fragments, e.g., in the surroundings of Rosala. In the island of Djupplåten, zones of fragments deformed to eye-like lenses occur in a breccia, where in general only narrow joints have opened between the angular fragments. Hence the movements have, principally taken place there along certain zones, whereas the other parts of the rock have only broken into angular fragments (Oftedal 1956). The light material is schistose in the zone of movements and the streaks of the dark minerals curve there around the eye-like fragments.

It is also difficult to gain a conception of the limits within which the PT-conditions have varied. The nuclei of the ultrabasic fragments are commonly pyroxene-bearing, whereas the dark borders and rocks of the banded series are in general hornblende-bearing. It has not, however, been ascertained whether this mineralogical difference is due to differences in mineral composition of the ultrabasic fragments and the obscure age relations between the amphiboles and pyroxenes make much more thorough petrographic investigations necessary before we would be justified in drawing any conclusions from the petrography to solve structural problems here.

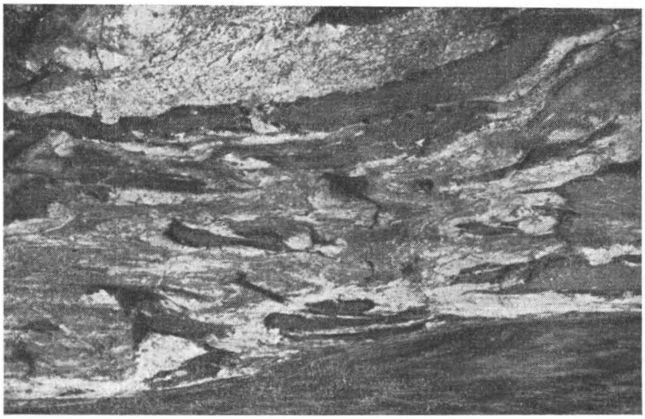

Fig. 33. Breccia with fragments of broken amphibolite layers in a veined mica gneiss which has homogenized so that it resembles a gneissose granite. About 50 metres W of Fig. 32 on the same outcrop.

It is much easier to obtain a conception of how the plasticity depends on the mineral composition and fabric of the rocks. Dark and basic layers have commonly yielded through fracturing, when surrounding light and acid layers have been plastically deformed. Breccias are most common in basic and ultrabasic rocks and the brecciated rocks are with few exceptions more basic than the rocks which form the dikes between the fragments. Breccias with rather acid fragments have been mentioned in connection with the granitization (p. 42—43).

A highly instructive case of brecciation occurs in the skerry of Jämmerskärsgrundet, about 3 kilometres E of Lökholm (SE of Nötö). The E part of this skerry consists of a gneiss with intercalated amphibolite layers (Fig. 32). The supracrustal origin of these rocks is there easily recognizable, but the degree of metamorphism increases rapidly in a westerly direction. The bedded fine-grained gneiss becomes coarser and more homogeneous westwards, and hence it there resembles a gneissose granite. In the W part of the skerry the amphibolite layers have broken into angular fragments, which have moved and rotated in the gneissose, granite-like rock, and the rows of mica of the light rock curve around and between the fragments (Fig. 33). This breccia could hardly be distinguished from a true magmatic intrusive breccia if the easterly continuation were not exposed. Similar examples have been described by Oftedal (1956).

Many other instances of such intrusions in a solid state, or »cold intrusions», have been observed, e.g., in boudinages (Edelman 1949c, Fig.

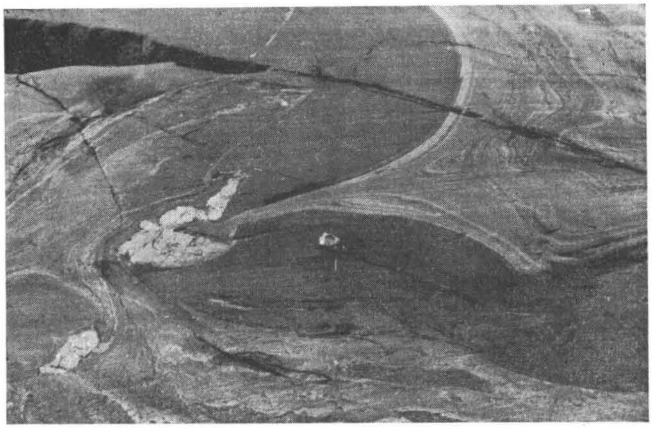

Fig. 34. Fine-grained gneiss intruded between the fragments of a plagioclase porphyrite layer. Pegmatite has also originated in the open space. Skerry about 100 metres E of the NE point of the island of Nagu Sandö, parish of Nagu. Foto M. Härme.

9 Pl. II), where plastic material has been squeezed between fragments of intercalated layers. In some cases the result is a structural discordance, as, e.g., on the W shore of Stora Hästskär, where one gneiss is truncated by another one (Edelman 1956, Fig. 16, Pl. IV). On the island about 100 metres E of the NE point of the island of Nagu Sandö, supracrustal fine-grained gneisses have intruded like dikes between fragments of plagioclase porphyrites (Fig. 34). One of these dikes is several metres long.

Instances of dikes that penetrate a granite but are granitized by the same granite are sometimes observed on the well exposed shores. Such an instance has been described earlier (Edelman 1949c, Fig. 15, Pl. III). Also in the case cited from the island of Långharu (p. 44, Fig. 28), the only conceivable explanation from the tectonic point of view is that the granite has been formed through granitization is situ.

Intrusive contacts have often been accepted as proofs of magmatic intrusions and age differences but all the afore-mentioned instances make their conclusive power in this respect more or less questionable. A breccia or a dike can originate in many ways and an intrusion can take place without magmas (Sederholm 1928, Wegmann 1956). Even when a minor part of the intruding material has been in a noncrystalline state, it does not justify using the term magma, as bedding or some older schistosity may be clearly visible in the intruding dikes (Fig. 34). The ultrabasic breccia zones in the banded formation seem to be tectonic breccias, i.e., broken parts of brittle basic rocks arranged in strings or zones, probably indicating the former mode of occurrence. These fragments have sometimes been flattened to thin lenses, which by further deformation have given the rock a banded appearence often resembling a bedding. On the other hand, primary basic layers have broken into fragments. The evolution has accordingly taken place in both directions: from banded rock to breccia and from breccia to banded rock (Figs. 6—9). Kranck (1937a) has described a similar evolution from the Porkala area, farther E from the present region.

Brecciation is more common in the present region, principally in its S part, than in many other parts of the Svecofennidic mountain chain. This seems to be due to the fact that brittle basic rocks are common here as intercalations between plastic rocks. Probably the movements have been stronger here than in general elsewhere in the Svecofennides. Moreover, the PT-conditions have seemingly varied within such limits that the differences in plasticity between basic and acid rocks have been suitable for brecciation.

CONTACTS OF THE GRANITES

There seems to be reason for comparing the contact relations of the different granites belonging to the Svecofennidic orogeny, because the contacts have played an important role in the discussions about stratigraphical and petrographical questions, and because the conclusive power of a cutting contact may be doubtful as shown in the preceding chapter.

The seemingly true magmatic rapakivi granites often have cutting contacts, but fragments of the country rocks are almost entirely lacking in them.

The contacts of the microcline granite are often cutting, breccias and agmatites are common, fragments of the country rock are scarsely ever quite lacking in the granite, and pegmatitic dikes are as a rule numerous in the granite as well as in the country rock. The granites often occur as large »batholiths» or domes which on a large scale are conformable with the structure of the surrounding rocks.

The gneissose granites, on the other hand, occur in general as lenses or zones with concordant contacts against the older rocks. The contacts, when cutting, are commonly tectonic or tectonized. Fragments of the country rocks are rare; only dark amphibolitic inclusions are common in some zones. Dikes belonging to the gneissose granite are rare, in most cases quite lacking.

The facts mentioned seem to indicate that the microcline granite rather than the gneissose granite was a true magmatic intrusive rock, but this is quite contrary to the current opinion about the origin of these granites. This opinion is based on observations made in all well studied parts of the Svecofennides and some facts have been mentioned in the foregoing. The fact that many metamorphic supracrustal rocks have been counted among the gneissose granites during the field work does not explain the general lack of cutting contacts in the true magmatic types. This lack is obviously due to the conditions prevailing during the intrusion. The viscosity is generally lower in melts rich in sodium than in melts rich in potassium, and therefore a sodium-rich melt adapts itself better to the structure of the country rock. When the alkali-calcic magmas intruded at the beginning of the orogeny, the degree of metamorphism was still low in the country rocks, which were accordingly softer and more ductile than later. The magmas had opportunities to slip in along the bedding planes, forming zones and lenses. In the beginning of the granitization stage the supracrustal rocks had been transformed into crystalline schists and the alkali-calcic magmas had crystallized. The rocks were thus comparatively hard and brittle. This seems to be contradicted by the fact that the most plastic structures occur among the migmatites, but we must remember that the rocks were rather brittle before the granitization. In the beginning of the granitization the migration took place along joints, which often cut the older structure but also often coincided with the planes of schistosity and bedding. The jointing depends very much on the physical properties of the rock and it therefore varies greatly in the different rocks. During the later stages of the granitization the rocks became more plastic, but the breccias already formed remained, although they were transformed into agmatites. In the final stage of the granitization the rocks again became more brittle and cutting joints filled with pegmatites or aplites were formed once more. Also the direction of the movements has an effect upon the shape of the originating contacts. The diapiric rising of the microcline granites broke the country rocks in a higher degree than the earlier folding, which was principally a lamellar gliding along bedding and schistosity planes. Volatiles, melts, and other mobile material collected in every opening joint irrespective of whether it was parallel with the schistosity or cut it, and they formed there pegmatitic veins or dikes. Depending on the local circumstances the older rock was then transformed into a veined gneiss or an agmatite. In better preserved areas farther away from the migmatic centre, quartz veins originated in the rocks.

There is no reason for believing that the conditions necessarily have been identical in all parts of the migmatic areas. One can for instance observe great differences in the degree of metamorphism and granitization within a few metres. This indicates the inhomogeneity of the conditions and the slowness of the reactions. It is therefore not surprising that the same granite behaves in a different manner in different parts. Together with some rocks it forms veined gneisses, with other rocks again agmatites; in some parts it may have been in a molten state, while in other parts it originated principally through recrystallization and a metasomatic exchange of material. The granites are so many and diversified that there seems to be no possibility to explain all of them with a single theory irrespective of whether it were an orthodox magmatic theory or a heretical metasomatic one. Particularly must it be emphasized that the granite problem cannot be solved solely by laboratory work and desk work.

FOLD AXIS

The fold axis has principally been used for construction of cross sections of folds and mountain chains. Such a cross section at right angles to the axis gives a clearer picture of the structure and the folding style than the map, which in general represents an oblique section. It is in many cases rather easy to draw a cross section on the basis of a geological map, but in migmatic regions there are many possibilities for errors and misinterpretations owing to the great number of diverging axial directions, which are results of the complex history of the region.

There are in the mountain chains many folding styles owing to several factors. The most important of these are the type of forces, e.g., compression or couple of forces, the PT-conditions, the properties of the rocks under the existing conditions, and the rock associations, e.g., thick homogeneous zones or thin-banded rocks.

The evolution of a migmatic area may be outlined as follows. An association of soft supracrustal rocks and magmas is transformed to crystalline schists in the beginning of the orogeny. Later these hardened rocks sink into greater depths in the mountain chain, and become more or less plastic migmatites. Thereafter the rocks harden again when the area approaches the earth surface as a result of the denudation which removes the mountains above. The physical properties of the rocks vary from stage to stage and the folding style must also vary in a corresponding manner (Wegmann 1930). The result of this is that different folding styles become superimposed upon each other. A force or a movement has possibilities to transform all older folds and other structural features, but on the other hand older structures have an effect upon younger forces as they afford better possibilities in certain directions for the movements. Furthermore old structures have in many cases been preserved seemingly intact under younger movements in the vicinity, although the area has been strongly granitized. This apparently irregular behaviour often makes it difficult to distinguish the folds of different orogenic stages. Moreover we are never a priori justified in supposing that the folds have their primary position and shape still unchanged. These facts make an interpretation of the structures only on the basis of the fold axes very doubtful.

Almost every kind of folding, e.g., flexure folding, shear folding, and plastic folding (flow folding) occurs in the present region. The superimposition

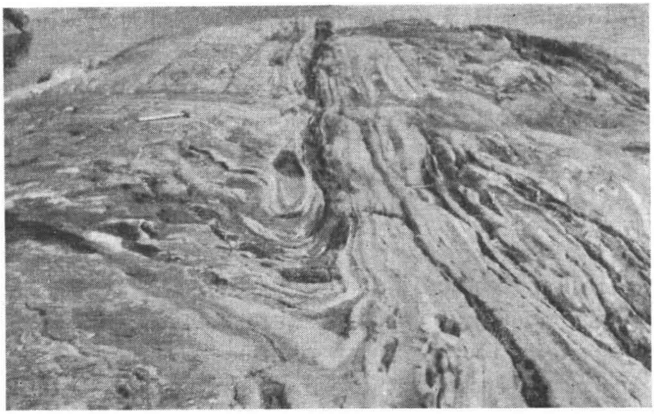

Fig. 35. Adjacent folds in the same beds with the axes 50° 50° NE (to the left) and 320° 70° NW (in the middle). Skerry 100 metres E of the NE point of the island of Nagu Sandö, parish of Nagu.

of different styles upon each other may have transformed a sinuous flexure fold to an S-shaped dragfold, to an isoclinal fold, to an intricate plastic fold, etc. Movements may also turn the axial direction of a fold to a considerable degree. I will show here with some examples how a schematic use of the fold axis may lead to absurdities or awkward misinterpretations.

There is on the SW shore of Söderö a small exposure measuring less than a square metre. Four quite different fold axis occur close to one another in the folded gneiss layers of this exposure. The axes make angles of several dozens of degrees with each other and similar cases occur in many places in the present region. Among such a multitude of axes it is impossible in the field to single out the axis which can explain the regional structures and which should therefore be used in the construction of the cross section.

Rather often can one find in the same exposure two folds whose axes have the same strike but different pitch, although the axes lie in the same layers close to each other. Such echelon folds have been observed, e.g., in the small skerry 100 metres E of the NE point of Nagu Sandö (Fig. 35) and in a skerry SE of the channel of Pargas port between Attu and Sorpo. Many folds in the vicinity of Hamnholmarna (Fig. 37) seem to be similar en echelon folds. One can hardly explain these folds otherwise than as having been caused by the same force or movement, because they are very similar with the exception of the pitch. The simplest explanations to such echelon folds are that they are caused either by compression at right angles to the axial plane or by a couple of forces in the axial plane parallel to the obtuse angle between the axes (Fig. 36). In the latter case the folds are dragfolds making an oblique angle with the forces. Folds with axes situated obliquely to the originating forces have been described by, e.g., Willis (1923, Fig. 94) and Mead (see Lahee 1941, Fig. 136).

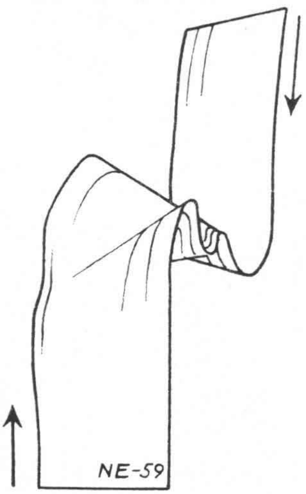

Fig. 36. Sketch of en échelon folds with axes pitching in opposite directions.

In the cases mentioned the fold axes do not necessarily coincide with the elongation of the mountain chain. A cross section perpendicular to the axis of one fold does not cut the other folds in the neighbourhood at right angles to their axes and therefore the cross sections do not present comparable projections of the different folds. In the case of echelon folding we must choose between two equivalent axes, which have different directions and hence give different results, both of which probably are wrong. If we observe only one axis, there is, however, the possibility that it is one of two echelon axes or that it has originated in another way obliquely to the forces.

One can of course raise the objection that we may not use single axes but statistical average axial directions. The statistical method has been tried in the surroundings of Hamnholmarna in the parish of Hitis (Fig. 37). This area is intensely folded and it lies between the E ends of two granites there where the compressed zone widens eastward. The strike as well as the dip is, however, rather constant in the banded rocks within the area discussed. The diagram (Fig. 38) shows 132 fold axes from this area in stereographic projection. The axes lie in almost every direction in the plane of schistosity or bedding. The maximum in the centre may be too pronounced, because folds with steep or vertical axes are more easily observed on the flat shore exposures than folds with horizontal or gently pitching axes.

There are four possibilities for drawing cross sections on the basis of the four different principal axial directions in this area, viz., the horizontal, the westward pitching, the vertical, and the eastward axes (Fig. 39). A cross section at right angles to the horizontal axis does not solve the question of the structure. In this case the granites may form synclines just as well as anticlines. The vertical axis, the statistical maximum, solves neither the structure nor the question of top and bottom. According to this axis the map is a cross section, and as vertical axes very common in nearly all parts of the Svecofennides, the whole of southern Finland and central Sweden would be a cross section of the mountain chain, which consequently would continue right down towards the centre of the earth and right up towards the

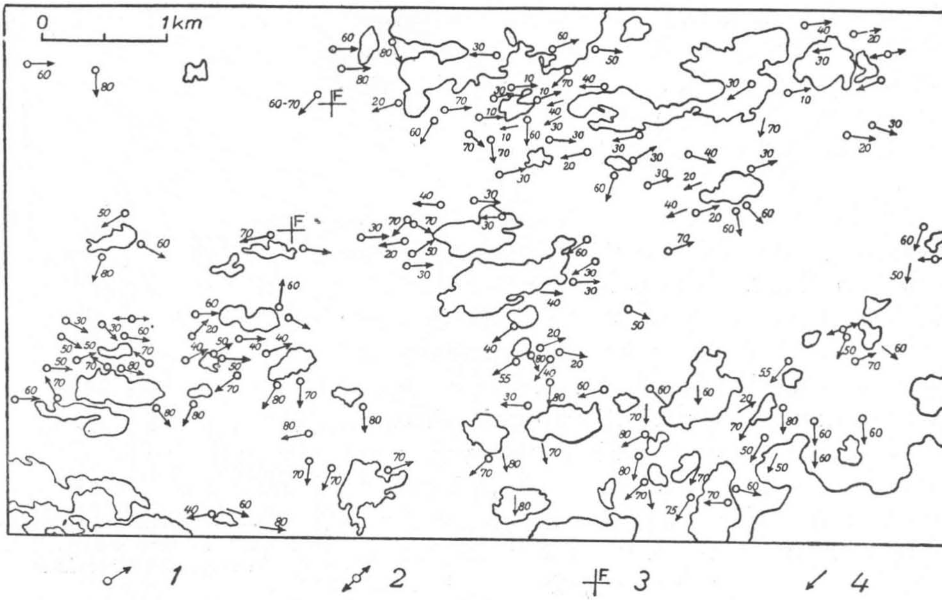

Fig. 37. Fold axes and lineations in the area around the islands of Hamnholmarna, parish of Hitis. 1. pitching axis, 2. horizontal axis, 3. vertical axis, and 4. lineation.

sky. The statistical method has led to this absurdity and it shows that it is inapplicable in the present region and probably in migmatic regions in general. The axis pitching W makes the granites into synclines and the banded formation into an anticlinal ridge, whereas the axis pitching E makes the granites into domes and the banded formation into a syncline between them. It is rather easy to determine which of these conceptions of the structure is the correct one. When studying the E borders of the granites one finds that the dip is often rather flat and almost without exception directed away from the granites. The dip is also in other parts of the border zones of the granites more often directed away from the granites than towards them. The simplest explanation is that the granites are domes, or anticlines and the zone of the banded formation hence a syncline between them. We do not, however, need any axis for this conclusion, only the attitude of the contacts and the layers, or bands. The analysis of the fold axes was only an impasse, because we needed other facts for the solution of the problem.

If the number of available observations of fold axes is less than in the example cited, there are still greater possibilities for errors. The observed axes may belong to secondary folds, to oblique echelon folds, or to quite local folds and hence they may be useless for an analysis of the gross structures.

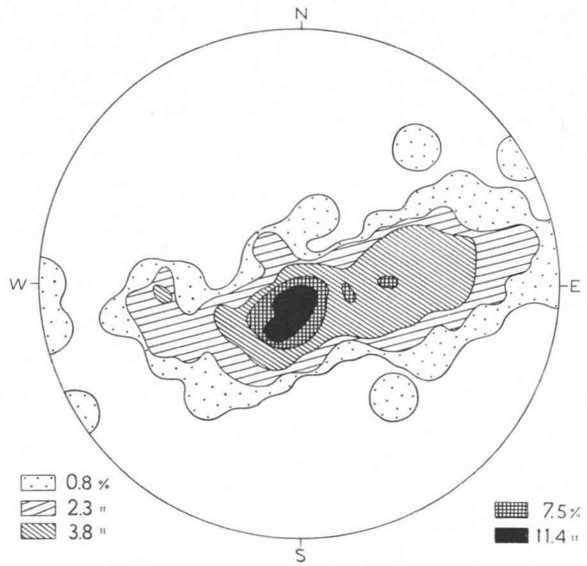

Fig. 38. 132 fold axes in stereographic projection. All these axes are from the area seen in Fig. 37.

Another instance showing how an uncritical use of the fold axis may lead to wrong results is the area of Örö—Stockhamn. The fold axes pitch E in the islands NE of Örö as well as in the island of Stockhamn. A section at right angles to these axes shows that the granite of Örö—Stockhamn lies as a clot in the banded formation and that the same zone or horizon lies above the granite as well as below it. If we take into consideration that this zone seemingly continues as lens-shaped remnants in the seaward skerries, we find that the granite is surrounded on all sides by the same horizon. The simplest explanation is that the granite is a dome overturned to the west (Fig. 40). The easterly axial pitch in the area around the island of Stockhamn is thus a secondary direction arrived at through overturning against the west.

In the E end of the granite dome of Örö—Stockhamn one can observe exceptions to another tectonic rule of the textbooks. Drag folds of incompetent strata are according to the rule overturned against the crest of the anticlines, because the upper strata have moved upward as compared with the lower ones. This rule has been used for the determination of top and bottom in folded sequences. In the E end of the granite dome of Örö—Stockhamn the drag folds do not agree with this rule. The greatest part of the drag folds there shows a rotation counterclockwise on both sides of

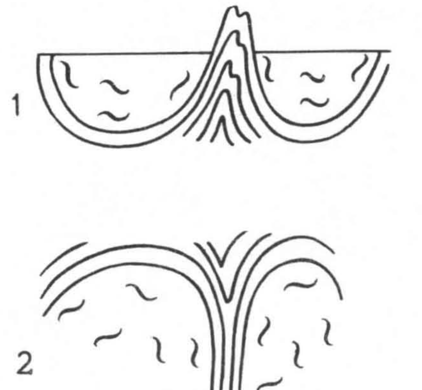

Fig. 39. Schematical cross sections of the SE part of the present region at right angles to the four principal different directions of the fold axes in Fig. 38. 1. westerly pitching axis, 2. vertical axis, 3. easterly pitching axis, and 4. horizontal axis.

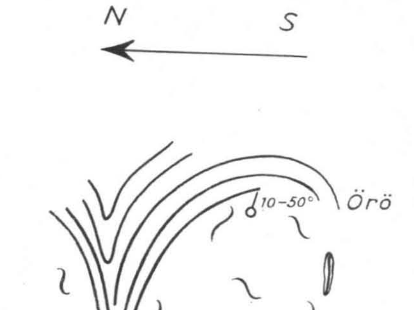

Fig. 40. Sketch of the area Stockhamn—Örö. A cross section at right angles to the axes would show a granite with the same formation above and below. The longitudinal section shows that the granite is a dome tilted over to the W. The axes at opposite ends of the dome have turned from a primary flat pitch about 180° in opposite directions and have become almost parallel again.

the crest line. The upper layers in the S limb have consequently moved against the crest line, in the N limb away from it. This divergence from the rule, which is reported to be valid in the upper parts of the mountain chains, seems to be caused by the regional movements in the area here in discussed. The greatest part of the drag folds in the SE part of the Gullkrona region shows a rotation counterclockwise independently of their position in larger folds or domes.

All the said facts show that the folding in a migmatic area is complicated and that a schematical use of the fold axis in the structural analysis may lead to misunderstanding of the whole region. Many other minor structural features connected with the folding are at least as uncertain as the axis, especially if their relations to the forces and movements are obscure. Such features are for instance the lineation, the petrofabric, and the joints. Their use in analysis is not justified before their behaviour in migmatic regions is methodically studied. The structural analysis is no simple mathematical equation, in which one can put the tectonic elements like factors and addenda (Cloos 1948).

METHOD OF STRUCTURAL ANALYSIS

Some critical remarks on the use of some structural elements in the analysis have been presented in the previous chapter, but this does not mean that a structural analysis of migmatic areas should be impossible. I should like here to describe the manner of interpreting structures used in the present investigation.

First of all I wish to point out that the purpose of the analysis has been to get an idea of the building-plan and the structural style of the region. The thorough investigation, description, and classification of the structural elements such as folds, axes, lineations, attitudes of bedding and schistosity, faults, etc., are only means and not the ultimate purpose of the structural analysis (Cloos 1948).

As mentioned in the foregoing (p. 51) the rocks have been unevenly plastic and therefore quite local conditions have had a great effect upon the minor structures. I have therefore begun the analysis with such features as are least susceptible to local forces. The attitude of the bedding or of the schistosity seems to be best adapted for this purpose, because it is commonly rather easy in large exposures to discriminate between the main attitude and local deviations. By using the geological map and the attitudes, we get a conception of the major structures, such as large folds, domes, and basins. The pitch of the axes of the major folds may be read from the map, if there are sufficient observations of the attitude in the crests of the folds (Wegmann 1929). After that we can evaluate the significance of some minor structural features, e.g., interpret the fold axes observed in the field by comparison with the regional structures. We now have at least a theoretical possibility to connect associated axes even if they have different directions and discriminate between parallel axes of different origin. For instance the axes of the opposite ends of domes or basins may make large angles with one another but nevertheless be of the same age and origin. On the other hand the local axis in one part of the region may be parallel with the main axis in another part, although they have quite different origins.

When the problems of the axes are solved, then we can continue the analysis of other minor structural details, e.g. lineation, joints, and eventually petrofabrics, and other microscopic features. How far it is possible to continue the analysis, i.e., what details we are able to decipher, is still unknown and depends very much on the region in question. A petrofabric analysis of rocks deformed by local movements has a principal bearing upon microtectonical problems but may be useless for the solving of the regional structures. The study of the structural geology of migmatic areas must therefore begin with the gross structures which are comparatively simple and then step by step go to the more and more problematic details. Kranck (1937a) points out the great differences between structural details and regional structures. Not until, if at all, a sufficient number of investigations of the relations between the structural details and the regional structures are made, might it be possible in simple cases to begin the analysis with the details. It is of course quite self-evident that we cannot reach farther back in geologic history with the analysis than to the origin of the oldest structures. If for instance the primary bedding has been entirely destroyed by a secondary schistosity, the evolution before the origin of this schistosity lies outside the limits of our knowledge. The opinion herein presented does not mean that the structural details are unimportant and that they may therefore be left unnoticed in the field, it only means that their position in the analysis is after the solving of the regional problems — and not before.

REGIONAL STRUCTURES

The style of the regional structures is in the present area that of alternating domes and basins. The domes are broad and consist principally of granite. The basins and synclines in the S part of the region are commonly narrow, filling the interspace between the domes, whereas in the N part they often have a more typical shape of a basin. They consist mainly of gneisses and amphibolites.

The dome of Örö—Stockhamn in the S part of the area is elongated in an easterly direction and is composed of two, possibly three minor domes (Fig. 41). The S limb is seen as lenses in the few, small seaward skerries. On the N side of this dome a zone of the banded formation is compressed to an isoclinal synclinorium against the Gullkrona granite dome. This zone broadens fan-like in its E part. The Gullkrona dome is separated from its westerly continuation, the Berghamn-Vidskär dome, as well as from its easterly continuation, the dome of W Kimito, by cross synclines of gneisses striking almost S (Fig. 42). The E one of these synclines reaches at least to Helsingholm; farther S it becomes more granitized and disappears grad-

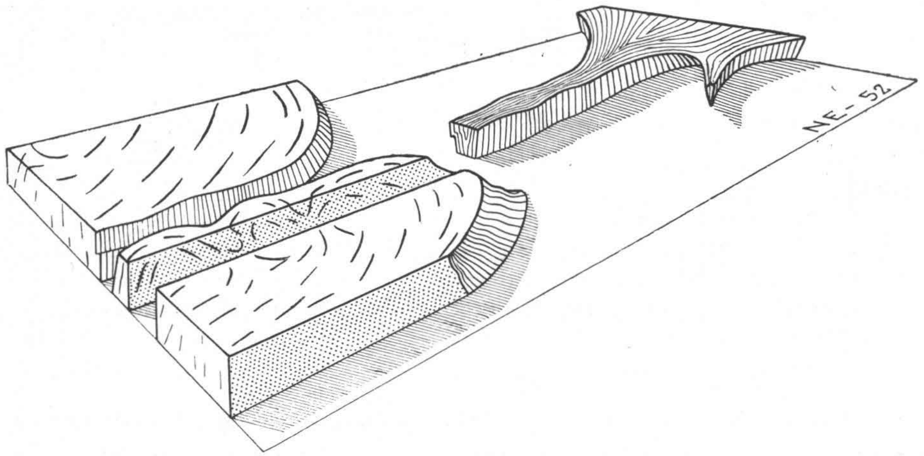

Fig. 41. Block stereogram of the SE part of the region. The banded formation has been drawn out in order to show better the shape of the granite domes.

ually. The W cross syncline has a sinuous shape being convex against E. Along the N side of these granite domes of W Kimito, Gullkrona, and Berghamn—Vidskär, a zone of leptites cuts the whole region from E to W and the cross synclines are branches of this zone. In the island of Korpo this zone divides into two rather well developed synclines or basins. The N one is comparatively broad in its W end but it narrows off eastwards to an amphibolitic zone. In the S part of Lill-Nagu a granitized branch connects this zone with the basin of Nagu and Lill-Nagu. The connecting branch curves around the E end of an indistinct granite dome. The basin of Ålö and Kyrklandet in the parish of Pargas is still more regular and much broader than the ones mentioned (Metzger 1945). In the parish of Houtskär some synclines and basins occur, but farther N the structures become less clear. In the area around Attu two S-shaped folds and a rather large anticline occur. All these structures have been constructed on the basis of the geological map and the attitudes of bedding, banding, or schistosity.

The present earth surface cuts the migmatic roots of the Archean mountain chain. The major structures are to a high degree a result of the struggle for space between the migmatic microcline granite and the rocks less affected by granitization. The plastic microcline granites have striven upwards in the mountain chain probably principally owing to their greater mobility and lower gravity than the rocks above (Wegmann 1930, Wegmann and Kranck 1931). The weakest parts of the roof have been suitable points of attack for the granites rising like diapires. The resulting movement had taken on the nature of »convection currents», with the granite domes moving

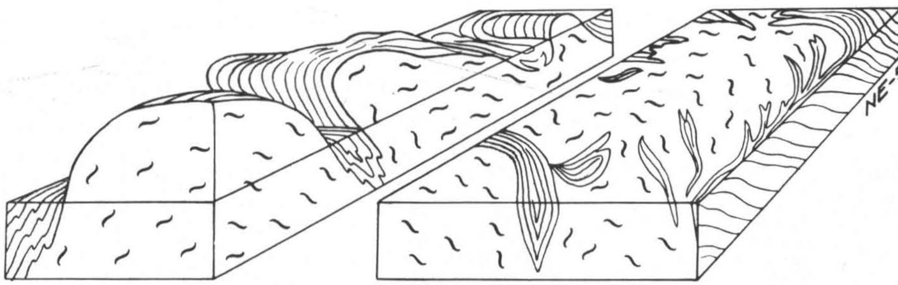

Fig. 42. Block stereogram of the Gullkrona dome and its surroundings.

upwards and the gneiss zones or basins sinking between the domes. The formerly broad gneiss zones are compressed upon sinking into the narrow interspace between the domes (Fig. 43, Metger 1945, 1947). The compression causes folding, flattening, and brecciation. It depends on the conditions, on the rock associations, and on the strength of the movements which of these types of deformation will dominate in the area. In the Hitis area the brecciation is quite pronounced because brittle and ductile rocks alternate in the banded formation. Farther W in the zone Vänö—Borstö—Jurmo, the movements between the domes have been so strong that the same association of rocks has been mangled to more or less homogeneous gneissose granites, diorites, or gabbros. The primary bedding is destroyed, the possible breccias have been flattened to banded rocks, and the banding, whatever its origin may be, has been blotted out to a high degree. In the middle part of the region, the zone of Pargas—Nagu—Korpo, the destruction of the primary structures has in general not been so intense as farther S. The movements have seemingly here been weaker. The incompetent rocks, schists and limestones, which are more common in this part, have acted as lubricants. The movements have therefore been concentrated to certain incompetent zones, leaving other parts more intact.

The structures are easily seen on the maps, sections, and block stereograms and therefore they scarcely need closer descriptions. A comparison of the style of the different parts of the region shows noticeable differences. The dome and basin structure seems to be better developed in the eastern and central parts of the region than in the western part. In the southern part of the region the granite domes have rather regular rounded or oval shapes, whereas the gneisses and amphibolites form long zones which curve around and fill the interspace between the domes. In the zone of Pargas—Korpo on the other hand the basins with supracrustal rocks have an elongated oval shape in the surrounding microcline granite. This difference in style may have many causes. The present earth surface may for instance be an

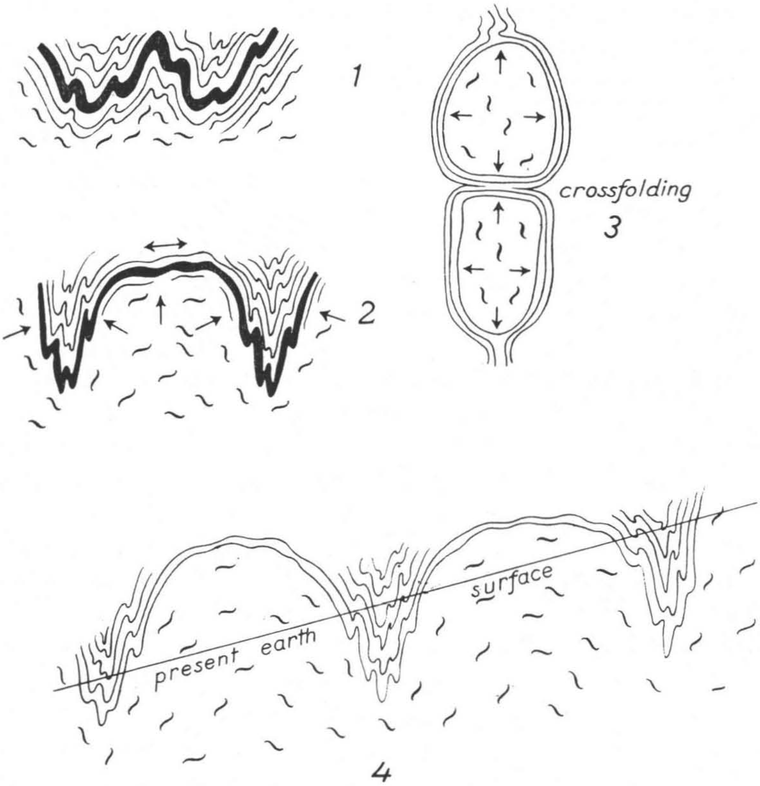

Fig. 43. Sketches showing evolution of granite domes. 1. Granitization begins in the lower levels of the mountain chain. 2. The granite rises in anticlines, whereas the synclines are drawn downwards. The synclines are compressed between the granite domes and the folds on the tops of the domes are stretched and flattened. 3. Sketch map showing the cross folding caused by the compression between domes, which lie one after the other in the longitudinal direction of the mountain chain. 4. Cross section through domes and basins cut obliquely by the present earth's surface. In the left part the basin structure is more typical, in the right part the dome structure again.

oblique cut through the mountain chain and the N part could then represent a deeper level. The separate basins there were the deepest protrusions of the gneiss zones. The S part were then an upper level, where the gneiss zones are continuous and the well-shaped domes the topmost parts of the granites (Fig. 43). It is obvious that the basins are separated from one another in the deeper parts, whereas the domes have the most typical shape in the upper parts from the same cause. There may, however, be other explanations to this difference in style.

A closer examination shows that the domes are more or less unsymmetrical in sections striking E. The dip is at the E ends often gentle or moderate to the E. At the W ends on the other hand the dip is as a rule vertical or steep, in exceptional cases even moderate to the E. One can observe this fact in most of the domes and this tilting of the domes towards the W indicates that the rising movement has been accompanied by a thrust westwards (Figs. 41 and 42).

The upper parts of the domes have moved to the W in relation to the lower part. The Örö—Stockhamn dome shows the strongest tilting, the dip being about 40° E at the W end. Tuominen (1957) mentions an overthrusting to the W in the Orijärvi region some tens of kilometres E of the present region. The axes have therefore a moderately easterly pitch at both ends of the dome. Such a tilt may be one explanation to the often observed fact that the fold axes pitch in the same direction over long distances in the direction of the mountain chain (Tuominen 1957). There are of course many other possible explanations. Similar tilted domes have earlier been described, e.g., in the Tampere schist belt by Härme and Seitsaari (1950), and in West-Greenland by Berthelsen (1950).

The cross folding which is related to the migmatite stage and which in the present region is connected with a westward thrust may be a result of the rising movement of the granites. A granite dome striving upwards must cause stresses in all directions outwards from itself (Fig. 43). The stress at right angles to the mountain chain will only strengthen the older folding, making the folds isoclinal, but the stress in the direction of the mountain chain will produce crossfolds. Therefore in many cases no other forces than the rising of the granites are needed to explain cross folding. In the present region we must, however, assume a slight thrust westwards, which cannot be explained by the rising alone.

STRATIGRAPHY

SEQUENCES

Stratigraphic studies face many difficulties in granitized Archean regions. The lack of fossils and the rarity of preserved features suitable for determination of top and bottom make the age relations between adjacent formations as a rule uncertain. Furthermore the fact that the supracrustal rocks often occur as limited areas isolated from one another by granites makes it difficult to connect the formations of the different parts of the region. In many cases, however, it may be observed that certain formations occur in a fixed order although one cannot in all cases determine the facing of the beds. The achieved conception of the regional structures offers a clue for solving this question. If we suppose that the layers in the large basins are as a rule right side up, then the succession of the formations can be determined in some cases. If these sequences agree with one another, it is probable that the statement is right and that the synclines are true synclines and not recumbent anticlines. In the following is a description of the sequences observed in the particular areas, and after that a correlation of them is presented.

R o s a l a a r e a. The Rosala area is structurally a synclinorium between two granite domes. In the island of Nilsholm, close to the island of Kasnäs, a »pillow lava» seems to face SE. This is the only determination of top and bottom in this area and even so it is problematic. It supports, however, the conception of this area as a synclinorium. The outermost formation would accordingly be the oldest one and the innermost formation the youngest one. When going from the middle of the synclinorium to the NW, the sequence is as follows:

acid banded gneiss-amphibolite, banded formation
basic zone consisting of basic banded gneiss-amphibolite, basic and ultrabasic breccias, pyroxene amphibolites, limestones, and skarns, basic banded formation
acid banded gneiss-amphibolite, banded formation
leptite
(mica gneiss?, a problematic case, island of Vikland)

Lökholm area, SE of Nötö. This area is structurally obscure, because the gneiss zones strike straight into the Gullkrona dome from the SW corner of it. Therefore also the stratigraphy is doubtful. A mica gneiss seems to lie below the banded formation.

Linnskär area. In this area a cross syncline strikes almost S between the granite domes of Gullkrona and Berghamn—Vidskär. A diopside amphibolite and a limestone lies between a leptite and a mica gneiss. If the problematic conglomerate of Linnskär is a true basal formation then the beds face SW and the leptite is in this case with certainty the lowermost formation. In the island of Gråbåten SW of Linnskär a mica gneiss seems to lie below a banded gneiss with alternating mica-poor and mica-rich bands. The successions seem therefore to be as follows:

Linnskär	Gråbåten
mica gneiss	banded gneiss
diopside amphibolite and limestone	mica gneiss
leptite	

The sequence of Linnskär is equivalent to the sequences farther N, including that of Gråbåten and the doubtful one of Lökholm, where the mica gneiss seems to be older than the banded formation. In the present case the same mica gneiss is seemingly in question in both sequences and therefore we cannot explain it on the assumption of two different mica gneiss formations. The other possibility, that there were two leptite formations, does not seem plausible, because this is the only example of such a succession. The third possibility is that one of the sequences is overturned. This is rather likely because the position between two granite domes tends to bring about structural complications. Therefore we are not justified in drawing any far-reaching conclusions from these observations, especially as there are few exposures in this area.

Brunskär area. Here the acid banded formation is commonly separated from a leptite or a gneiss with alternating mica-poor and mica-rich bands by a diopside amphibolite. The E end of this supracrustal zone rises over a granite and there the structures are rather complex. In the SW part of the island of Bredskär a banded gneiss with alternating mica-poor and mica-rich bands seems to underlie the banded formation. In this locality the diopside amphibolite, however, is absent. The sequence seems to be as follows, but the determination of top and bottom is questionable.

banded formation (acid banded gneiss-amphibolite)
diopside amphibolite (sometimes lacking)
banded gneiss

K o r p o a r e a. Two supracrustal basins occur in Korpo. They have an outer basic zone consisting of amphibolites, diopside amphibolites, and limestones and an inner part of mica gneiss often rich in garnet, and cordierite. Outside the basic zone some remnants of leptite have been found and farther E in the area S of the island of Nagu leptites are in contact with the basic zone on its outer side. The island of Gyltö SW of Korpo contains an amphibolite and a gneiss with alternating mica-poor and mica-rich bands but the relation between them is not quite clear, because the structures are there disturbed by granites. The sequence in the Korpo area is to a comparatively high degree of certainty as follows:

mica gneiss
basic zone with amphibolites, diopside amphibolites, and limestones
leptite

H o u t s k ä r a r e a. The Houtskär area does not offer such good possibilities for stratigraphical studies as the Korpo area, but in several places diopside amphibolites, and limestones, are found between the leptite and the mica gneiss, e.g., on the NE shore of the island of Maskinnamo, in the surroundings of the island of Järvsar and in the island of Högskär. In the first two cases mentioned the structures indicate that the leptite is the oldest formation. In the small skerries SW of Norrskata the leptite lies below a diopside amphibolite. In the N part of Hyppeis a diopside amphibolite lies between a leptite and a mica gneiss, but the structure is complicated. The sequence of Houtskär area seems to be as follows:

mica gneiss
basic zone with diopside amphibolite, amphibolite, and limestone
leptite

I n i ö a n d V e l k u a a r e a. The NW part of the area is not suitable for stratigraphical studies, but there is, however, in some small islets S of the island of Velkua a zone of diopside amphibolite which lies between a mica gneiss in the W and another gneiss, seemingly leptitic, in the E. The latter gneiss is poorly exposed and granitized, making its leptitic character somewhat problematic.

mica gneiss, in the vicinity often banded with leptite layers
basic zone with diopside amphibolite
leptite?

N a g u a n d L i l l-N a g u a r e a. There is in the islands of Nagu and Lill-Nagu a well-preserved basin similar to the basins of Korpo. It consists of an outer basic zone of amphibolites, diopside amphibolites, limestones, and some hornblenditic or pyroxene hornblenditic lenses. A

Table I. Sequences in

Hitis	Brunskär	Linnskär	Korpo	Nagu
banded gneiss-amphibolite	banded gneiss-amphibolite	mica gneiss	mica gneiss	mica gneiss
amphibolites, ultrabasites, limestones	diopside amphibolites	diopside amphibolites, limestones	amphibolites, diopside amphibolites, limestones	amphibolites, ultrabasites, limestones
banded gneiss-amphibolite	banded gneiss	banded gneiss, leptite	banded gneiss, leptite	leptite
leptite				
mica gneiss?				

mica gneiss often rich in garnet or cordierite lies inside this basic zone. Leptite is lacking there but N of a small syncline in the NE part of Nagu Sandö a granitized leptite occurs, apparently situated below the plagioclase porphyrite. The sequence is thus as follows:

mica gneiss
basic zone with porphyrites, amphibolites, limestones and ultrabasic rocks
leptite

Attu area. In the island of Attu a mica gneiss with garnet and cordierite lies over an amphibolite with diopside amphibolite intercalations. Limestone occurs as two horizons, the lower one between the amphibolite and the mica gneiss, the upper one in the mica gneiss 100—200 metres from the former. Leptite zones occur in the folded amphibolite (Fig. 10) and are probably parts of the underlying leptite formation. The amphibolite is separated from the uralite porphyrite of the SE shore by gabbros and granites; and another gabbro zone, which is in places almost ultrabasic, separates again the porphyrite from gneisses rather rich in garnet farther S. The lower part of the sequence is therefore doubtful. The facing of the beds in the upper part is determined from the large S-shaped folds with axes pitching moderately W in the NW part of the island of Attu.

mica gneiss
limestones, two horizons
amphibolite with diopside amphibolite
leptite?

Ålö—Kyrklandet area. The stratigraphy of the area of Ålö and Kyrklandet in the N part of the parish of Pargas is according to Metzger (1945) as follows:

the present region

Attu	Pargas	Houtskär	Velkua
mica gneiss	mica gneiss	mica gneiss	banded gneiss—mica gneiss
diopside amphibolites, porphyrites, ultrabasites, limestone	amphibolites, diopside amphibolites, limestones; two horizons	diopside amphibolites, limestones	diopside amphibolites
leptite?	mica gneiss	leptite	leptite

mica gneiss (kinzigite)
amphibolite and limestone
mica gneiss (kinzigite)
amphibolite and limestone
mica gneiss (kinzigite) with pyroxene diorites

Metzger has estimated the thickness of the exposed part of the sequence at 420—1750 metres. These values show the minimum thickness in different parts of the basin. The total thickness is greater because neither the top nor the bottom of the sequence has been preserved.

There are great similarities between the sequences of the different areas although they are not of course identical, because the evolution has not been quite the same in all parts of the geosyncline. The fact that the sequences in the typical synclines of Pargas, Nagu, Korpo, and Hitis resemble one another very much shows that these troughs probably are true synclines and not overturned anticlines. This gives a clue to the stratigraphy of the whole region. Table I shows how the sequences seemingly fit together.

The basic zone seems to be a suitable key horizon and we can roughly divide the stratigraphic colomn into three, probably four parts. The formations under the basic zone are as a rule leptites, to a great part metamorphic psammites with arkosic compositions. In the N and NE parts of the region the leptites seem to be replaced by mica gneisses (Metzger 1945) or the transitional type with alternating layers of leptite and mica gneiss. This type is common in the zone Linnskär—Brunskär—Houtskärs Berghamn, and farther N, e.g., in the parish of Velkua, it seems to dominate. In the Linnskär area it seems to form the upper part of the leptite formation. The problematic position of some gneisses below the leptites in the areas of

Lökholm, and Rosala become more acceptable when we take into consideration that the leptites seem to be replaced by mica gneisses in the N part of the region. The banded formation of the zone Rosala—Utö consists of alternating bands of leptite and amphibolite and is underlain by purer leptites. It seems to be a metamorphic sand- or siltstone with intercalations of volcanic rocks, for the main part tuffites.

The composition of the basic zone varies considerably within region. In the Rosala area amphibolitic layers, and ultrabasic, or basic breccia layers are predominant, whereas the pyroxene amphibolites are rare and the limestone layers thin. In the Attu area amphibolites and uralite porphyrites are predominant. Diopside amphibolites occur and the limestone layers are somewhat thicker than in the Rosala area. Furthermore gabbros with ultrabasic parts form there broad zones. Farther W in Nagu and Korpo they become rarer and smaller. In the Brunskär area the basic zone consists almost exclusively of diopside amphibolites. In the parish of Houtskär and in the N and NW parts of the parish of Korpo diopside amphibolites and limestones dominate. In the area of Ålö—Kyrklandet in the N part of the parish of Pargas the limestones are thick and the basic zone is divided into two separate zones. The amphibolites there often contain diopside but differ remarkably, however, from the diopside amphibolite type of Attu—Nagu—Korpo. Farther northwards the number and size of the limestone and diopside amphibolite occurrences decrease remarkably. Either the basic zone tapers out or is not exposed there.

The basic zone is in the N and central parts of the region overlain by the mica gneiss formation, in the S and SW parts again by the banded series. The light bands of the banded series are poor in mica, in contrast to the mica gneiss, which commonly also contains garnet, or cordierite. The mica gneiss formation also contains amphibolitic layers, but they are not so numerous as in the banded formation. Furthermore the mica gneiss contains intercalations of graphite- and sulphide-bearing gneisses.

Summarizing the stratigraphy, the following picture is obtained. The oldest formation, the lower mica gneiss formation, is not preserved in all areas. It consists of pelites probably belonging to the graywacke series according to Pettijohn's terminology (1949). The leptite formation consists of arkosic silts or acid volcanic rocks and indicates an increased denudation. In the S part of the region the leptites are mingled with layers of basic volcanic rocks, comprising the banded formation. The basic zone is the most varying formation with both sedimentary rocks and igneous ones. The sediments are characterized by high contents of organic material; they are principally limestones or marls. The igneous rocks are porphyrites, gabbros, or ultrabasites. They are intrusive as well as extrusive and the composition is basic to ultrabasic. They may accordingly be equivalent to the ophiolites of the Alps. The youngest formation, the upper mica gneiss formation, consists of silts or clays probably belonging to the graywacke series.

The close similarities between the sequences of the different areas is a proof of the validity of the method of structural analysis used, and of the assumptions that the strata in general are right side up and that the major structures are rather simple. The structural basins are true synclinoriums, because otherwise all the basins discussed would be recumbent folds, which is very improbable. The stratigraphy and the structural geology support each other and the results, which agree with both of them, are therefore rather sure.

COMPARISON WITH OTHER REGIONS

Stratigraphic studies of Svionian rocks have been made in many areas with good results, although the difficulties as a rule are great. Well-preserved supracrustal areas are commonly separated from one another by granites, by regions with highly complex structures, or by areas hidden by loose deposits or the sea. Therefore every attempt to connect sequences of different regions must be more or less hypothetical, especially as the environmental conditions have varied within the geosyncline. One may assume that the formations change character along the geosyncline as well as across it. Although a thorough discussion of the similarities and differences of the sequences is outside the scope of this paper, a short comparison may, however, be justified.

Table II shows some stratigraphic sequences recorded in Fennoscandia (Fig. 44). A summary of them has been published earlier (Edelman 1957). The sequences are here of course simplified because many minor rock units, e.g., some limestones or conglomerates, are quite local and without equivalents in other areas. The sequence from the Grythytte area (Sundius 1923) is representative for Central Sweden according to Magnusson (1957) and it is completed with the sequences from Uppsala (Lundegårdh 1956) and Åmmeberg (F. Kautsky 1955). The sequence from Kola peninsula and the White Sea is taken from Simonen's summary (1957) of the geology of these regions after an excursion in the USSR.

As a general scheme for the sequences of the Svionium, we may use the following:

upper mica gneiss formation

basic zone

leptite formation

lower mica gneiss formation

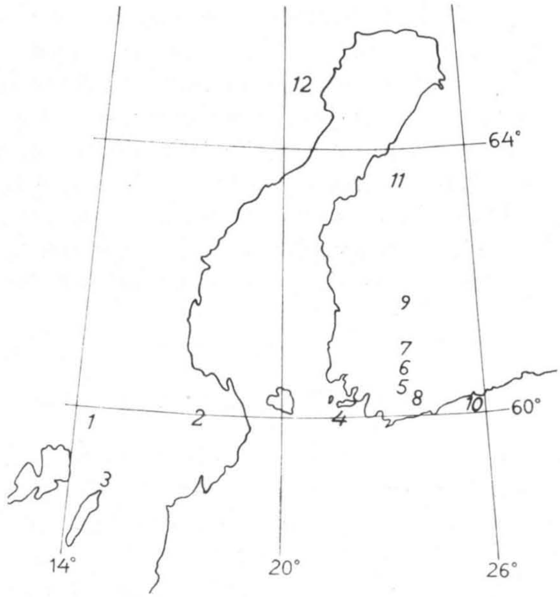

Fig. 44. Stratigraphically studied areas in the Svecofennides in Finland and Sweden mentioned in Table II. 1. Grythytte area (Central Sweden), 2. Uppsala area, 3. Åmmeberg area 4. archipelago of S.W. Finland, 5. Suomusjärvi area, 6. Somero area, 7. Forssa area, 8. Mustio—Svartå area, 9. Tampere—Tammerfors area, 10. Pellinge area, 11. East Bothnia, and 12. Skellefte area.

Table II. Svionian sequences

Grythytte area Central Sweden	Uppsala area	Åmmeberg area	Archipelago of	SW Finland	Suomusjärvi	Somero
			S. part	N. part		
gray schists (Larsbo series)	sedimentary gneisses		banded gneiss-amphibolite	mica gneiss		
black schists, graywackes, basic volcanic rocks	plagioclase porphyrites, basic leptites		amphibolites, limestones, ultrabasites	amphibolites, limestones, ultrabasites	amphibolites	amphibolites
leptites, limestones	leptites, limestones, quartzites	leptites, quartzites	banded gneiss-amphibolite, leptites	leptites, mica gneisses	pyroxene gneisses, limestones mica gneisses	mica gneisses
		mica schists	mica gneisses?			
Sundius 1923, Hjelmqvist 1938, Magnusson 1957 simplified	Lundegårdh 1956, simplified	F. Kautsky 1955			Salli 1955a, Mikkola 1950, simplified	Simonen 1954

The lower mica gneiss formation has not been observed in all areas. The lowermost formation has, of course, to a higher degree than the formations higher up in the sequences, been exposed to the granitization. For instance, in the synclines of Nagu and Korpo the supracrustal rocks below the basic zone have been almost entirely granitized. Therefore we cannot expect that the lower mica gneiss formation will be recognizable in all areas.

The leptite formation is best preserved in Central Sweden and in Finland in the Kisko—Kimito zone, which continues W-wards through the present region. In many cases the leptites and hälleflintas have been transformed into coarser gneisses poor in mica. As to origin they seem to be either arkosic silts or acid volcanic rocks. The proportion between sedimentary and volcanic rocks varies from one area to another. In some cases, e.g., in Somero, mica gneisses lie immediately below the basic zone. In this area the leptite formation is likely to be lacking, or these mica gneisses may represent another sedimentary facies than the leptites. Farther from land clay may be deposited at the same time as sand and gravel along the shores.

The basic zone is the most inhomogeneous formation in Svionium. It consists mainly of basic volcanic rocks, basic to ultrabasic infracrustal rocks, black schists, limestones, and diopside amphibolites, primary marls. The thickness of this formation varies considerably but this is quite natural for a volcanic formation. The sequence of the Pellinge region is rather much

in Fennoscandia

Forssa	Mustio—Svartå	Tampere—Tamerfors	Pellinge area	East Bothnia	Skellefte area N. Sweden	Kola peninsula N. Russia
mica schists	mica schists				schists, psammites, graywackes. Elvaberg series	mica gneisses Louhi formation
basic volcanic rocks	basic volcanic rocks	basic volcanic rocks	basic volcanic rocks	basic volcanic rocks	basic volcanic rocks, black schists. Skogsheden &Petikträsk series	amphibolite-mica gneiss Hiitolampi formation
mica schists, arkose gneisses, graywackes	leptites, limestones	leptites	quartzites, leptites, limestones	mica schists, graywacke schists leptite	Maurliden volcanic rocks, acid	gneisses, Kieretti formation
		graywacke slates			Maurliden schists	
Neuvonen 1954a, simplified	Härme 1954b	Simonen 1953, simplified	Sederholm 1923, simplified & corrected	Salli 1955a	G. Kautsky 1957 simplified	Simonen 1957

simplified on the basis of my observations in this area in the summer of 1954. I could not find any hiatus between the Pellinge and the Pernå formations and there are among the supracrustal rocks below these locally thick volcanic leptites.

The upper mica gneiss formation seems to be widespread in SW Finland. It is equivalent to the Larsbo series of Central Sweden (Hjelmqvist 1938) and the gray schists of the Grythytte area. Lithologically and petrographically the upper mica gneiss formation seems to resemble the lower mica gneiss formation very much, so in many cases it may be quite impossible to decide to which of the two formations a certain mica gneiss or schist belongs.

In spite of many differences in details there are such striking similarities between the sequences that the established general stratigraphic scheme seems to be valid for the Svionium in most parts of the Svecofennides. This attempt to correlate the stratigraphy of such a large region is desk work and therefore contains the source of error that, inter alia, the supracrustal rocks have not been classified in identical ways by all students. The fact that, however, such good results are obtained upon connecting the sequences observed by different geologists is rather good evidence of the correctness of the result. However, much work is needed to correct the scheme herein presented and to complete it in detail. The present solution of the stratigraphic problem is only a step, but I hope a step in right direction.

GEOLOGIC HISTORY

The ultimate purpose of geological studies is to arrive at a conception of the origin and evolution of the bedrock of a region, or in other words of the history of the region. In order to do this one must fit together into one whole the puzzle pieces offered by the auxiliary sciences of petrography, tectonics, and stratigraphy. In spite of the actualistic principle one must remember that the conditions on the earth's surface have not been quite identical during all geological times (Metzger 1929). The greatest difference has been the lack of flora during earlier geological ages. Erosion must then have been more rapid and decomposition slower. The weathering products were then to a high degree transported by wind, as nowadays in the deserts. This may explain the scarcity of pure quartzites and abundance of leptites in the Svionian formations. The pure quartzites are commonly a result of repeated weathering of older sediments (Pettijohn 1949).

The orogenic history of the present region can be divided into two main parts

1) the geosynclinal or Svionian period and
2) the orogenic or Svecofennian period

I use here Svionium for the sedimentation period and Svecofennium for the orogenic period, even if it may be difficult to draw a distinct borderline between them. We must remember that borderlines occur principally in classification but scarcely in nature. Simonen (1953) has proposed the term Bothnium for the formation of basic volcanic rocks. This formation lies, according to the scheme presented in the foregoing in the middle of the Svionian rocks and therefore it seems to be better for the present to abandon this term. It will cause confusion if we use Bothnium, which formerly was considered to be much younger than the Svionium, for a formation within the Svionian group. I have not used Väyrynen's term »Fennonium» either,

Table III. Geologic evolution in the archipelago of SW Finland

Period	Process	Rock
Pleistocene	glaciation	glacial drift
Tertiary (?)	faulting, »graben»	
(?)	peneplaination	
(?)	sedimentation	kaoline sandstone in Pargas
Silurian	»	limestone (only boulders)
Cambrian	»	sandstone dike and boulders
Sub-Cambrian	peneplaination	
Post-Jotnian	intrusion	olivine diabase (only boulders)
Jotnian	sedimentation	arkose sandstone (only boulders)
Sub-Jotnian	peneplaination	
»	intrusion	rapakivi granites
(?)	»	diabase dikes (trap dikes)
(?)	»	granites of Sederholm's third group (Åva granite NW of the region)
Svecofennian:		
serorogenic stage	granitization, folding	migmatites, migmatic granites, pegmatites
intraorogenic pause	intrusion along joints	amphibolite dikes
primorogenic stage	folding, metamorphism, intrusion	crystalline schists, alkali-calcic igneous rocks
Svionian, geosynclinal period		
Upper Svionian	sedimentation	upper mica gneiss formation,
Late middle »	volcanic activity	basic volcanic rocks and calcareous sediments
Early middle »	sedimentation	leptite formation
Lower »	»	lower mica gneiss formation

because he has not exactly defined it. If I have understood Väyrynen correctly he includes under the term Fennonium the mica gneisses, the limestones, and the para-amphibolites, whereas the porphyries and the porphyrites belong, according to him, in the category of Svionium. In other words the sediments come under the leading Fennonium and the volcanic rocks under Svionium. This is, however, a pure lithologic or petrographic classification but not a stratigraphic one. Therefore I have included all the geosynclinal rocks in the category of Svionium and divided them into four formations to which I have applied lithologic or petrographic names for the sake of simplicity. I have avoided names derived from type localities for the formations because the stratigraphic scheme herein presented may undergo many transformations before it is accepted; and therefore it is best to leave such terminological questions open, also because such names do not say anything to a reader who has never visited this locality.

The stratigraphy gives us a conception of the evolution of the geosyncline (Pettijohn 1949, Krumbein & Sloss 1951). Roughly outlined the evolution has been as follows. A sinking geosynclinal trough was filled with pelitic sediments, which were probably poorly sorted. These formed the lower mica gneiss formation. Thereafter a land area began to rise S of the present region, as a result of which the sediments became coarser, arkosic silts. Clays were still deposited in the N parts of the region farther from the source area. The movements were accompanied by a volcanic activity producing acid volcanic rocks. In the present region acid volcanic rocks are rare, but the rocks of the leptite formation are often so strongly metamorphosed that it is very difficult to determine their origin. The next epoch is characterized by decreased sedimentation and increased volcanic activity. This indicates stronger movements downwards within the geosyncline. The earth crust was fractured and basic magmas rose upwards, forming sills, lava flows, or ash beds. These basic igneous rocks are probably equivalent to the ophiolites of the Alps. In the S part of the region the basic volcanic rocks were intermingled with leptites, forming the banded formation. The basic zone within this formation shows the culmination of the volcanic activity. At the same time limestone and marls are deposited in the N parts of the region. The clastic sedimentation was then at a minimum and the former land area in the S was at this time mainly denudated or submerged.

After the deposition of the basic zone the sedimentation of clastic rocks became again predominant. The silty facies did not reach as far N as during the first period. The silts alternate with volcanic beds in the S and SW parts of the region. In the middle and N parts clays dominated. Volcanic beds are there more subordinate. Intercalations of black shale are on the other hand rather common there, but they occur already in the formation below the basic zone. Black shales originate principally in two ways, either by rapid burial of material rich in organic substance or under toxinic conditions in basins with poor ventilation. In geosynclines they may originate in both these ways. The burial is rapid because of the high rate of sedimentation in geosynclines, and poorly ventilated basins may often arise in geosynclines as a result of the movements in the crust.

The folding history of a part of the region has been outlined in an earlier paper (Edelman 1949c) and it is very similar to the history of other parts of the Svecofennides (Wegmann and Kranck 1931, Magnusson 1936). The observations made in the other parts of the region agree well with the scheme presented there and therefore a short summary may be sufficient. The first phase of deformation produced principally rather simple folds with seemingly flat-lying axes pitching E or W. In connection with this deformation the sediments and the volcanic rocks recrystallized to schists, gneisses, and amphibolites of different types. At the same time alkali-calcic magmas were intruded principally along bedding planes and weak zones. They commonly formed lens- or sheet-shaped bodies of gneissose oligoclase granites, diorites, and gabbros, i.e., the primorogenic intrusives according to Wahl (1936). Some gneisses, and amphibolites were either during this period or later transformed into rocks, which very closely resemble these gneissose magmatic rocks.

During the first phase of deformation the sediments and other supracrustal rocks grew harder and the magmas crystallized into hard rocks. After that followed a more quiet phase, during which the rocks yielded with fracture to the tectonic forces. Basic magmas intruded along the joints and formed the amphibolitic dikes. It is remarkable that these dikes are rather rare in the present region and have been met with principally in the SE part of it.

After this interval the deformation again grew stronger. The region had been pressed down to greater depths, where the conditions were suitable for granitization. The rocks became more plastic and granitic veins appeared in them, probably both by palingenesis and intrusion. Many rocks were in a higher or lower degree transformed into granites, the ser-orogenic microcline granite according to Wahl (1936) which began to force themselves upwards like domes in the mountain chain, whereas other rocks at the same time moved downwards. The forces and movements were during this phase principally vertical, contrary to the mainly horizontal ones during the first phase of the deformation. The only regional horizontal movement which seems to have taken place during the granitization phase is a slight thrusting W-wards. This movement has tilted the granite domes to some extent, only in one case so much that the strata have become overturned.

After the granitization phase the orogenic movements ceased. The rocks became harder, and the diabases and young granites were intruded. Later on the denudation transformed the former mountain chain into a peneplain, on which different sandstones and other sediments were deposited and later again almost entirely eroded away.

This paper is only a stratum in the column of literature about the Svecofennides. Investigations in the future will erode away a great part of the thoughts presented here, but I hope that these will nevertheless have some positive significance for the studies of these regions just as every grain of sand has its own significance in the evolution of a geosyncline and a mountain chain.

Table IV. Analyses

	1	2	3	4
SiO_2	48.73	51.72	46.93	50.85
TiO_2	0.39	0.32	1.64	0.67
Al_2O_3	13.29	3.56	7.39	7.47
Fe_2O_3	1.59	1.10	1.64	1.80
FeO	6.66	9.57	10.98	13.32
MnO	0.21	0.26	0.20	0.17
MgO	12.27	20.17	14.90	20.68
CaO	13.98	11.23	10.68	3.85
Na_2O	0.83	0.43	1.38	0.45
K_2O	0.37	0.14	0.38	0.09
P_2O_5	0.03	0.00	1.83	
H_2O+	2.13	0.97	2.01	0.32
H_2O-	0.00	0.16	0.16	0.00
	100.48	99.73	100.12	99.67

[1]) Hornblende gabbro, Djupplåten, Hitis. Anal. H.B. Wiik.
[2]) Brown nucleus of an ultrabasic fragment, Djupplåten, Hitis. Anal. H.B. Wiik.
[3]) Hornblende skarn, Granvik, Stortervo, Pargas. Anal. H.B. Wiik.
[4]) Pyroxene from hornblende skarn with pyroxene porphyroblasts, containing hornblende (anal. 3) as impurities, about 20 per cent, Granvik, Stortervo, Pargas. Anal. H.B. Wiik.

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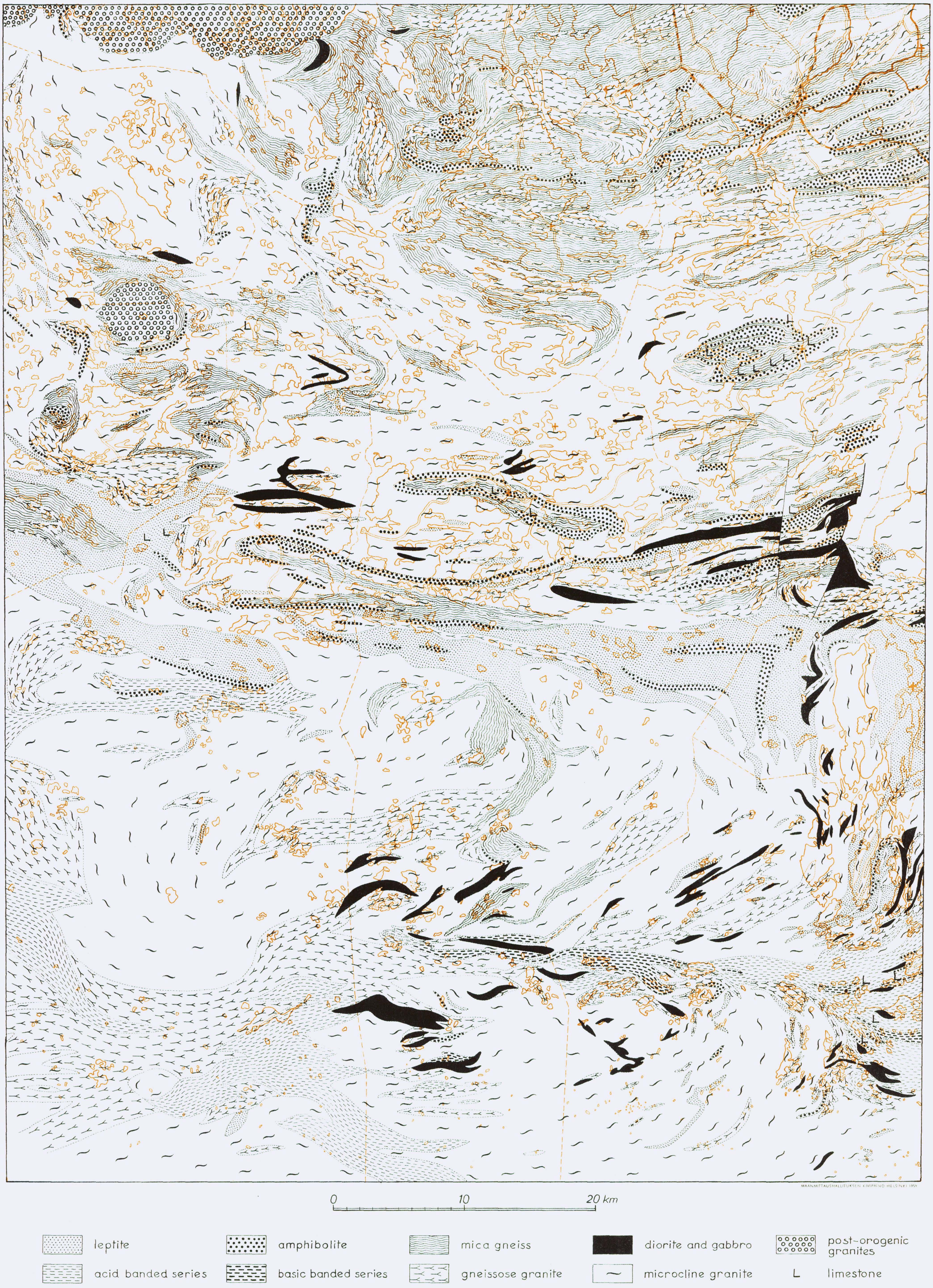
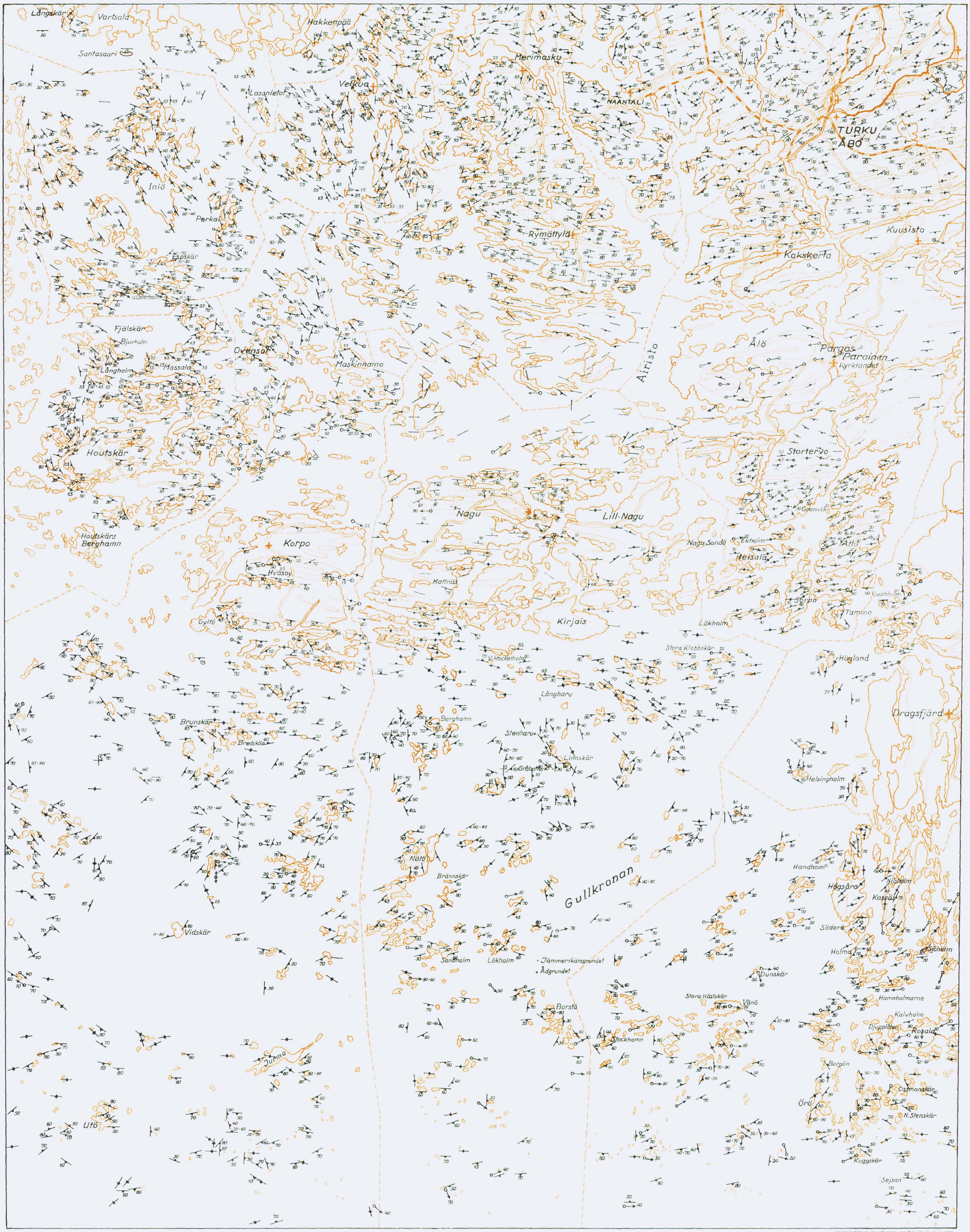
LITHOLOGICAL MAP OF THE ARCHIPELAGO SOUTHWEST OF TURKU (ÅBO)

compiled by Nils Edelman



TECTONIC OBSERVATIONS IN THE ARCHIPELAGO SOUTHWEST OF TURKU (ÅBO)

compiled by Nils Edelman



0 10 20 km

Foliation Bedding Lineation Fold axis